Australian Government

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National Inventory Report 2015

Volume 2

The Australian Government Submission to the United Nations Framework Convention on Climate Change

Australian National Greenhouse Accounts

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6.1 Emission trends

The net emissions from the *land use, land use change and forestry* (*LULUCF*) sector were -7.7 Mt CO_2-e in 2015.

Table 6.1 Land Use, Land Use Change and Forestry net CO_2-e emissions, 2015

Greenhouse gas source and sink categories	CO_2-e emission (Gg)				
	CO_2	CH_4	N_2O	Total 2015 CO_2-e	Preliminary 2016 estimate CO_2-e
4 Land use, land use change and forestry	-21,839.3	8,657.8	5,463.8	-7,717.6	-9,089.5
A. Forest land	-39,910.6	3,239.3	820.2	-35,851.1	-38,416.0
A.1 Forest land remaining forest land	-26,846.0	3,195.6	741.0	-22,909.3	-24,122.3
A.2 Land converted to forest land	-13,064.6	43.7	79.2	-12,941.7	-14,293.7
B. Cropland	-622.1	115.2	55.2	-451.6	-572.6
B.1 Cropland remaining cropland	-4,638.1			-4,638.1	-5,622.5
B.2 Land converted to cropland	4,016.0	115.2	55.2	4,186.4	5,050.0
C. Grassland	22,792.1	5,285.0	4,538.5	32,615.6	34,159.9
C.1 Grassland remaining grassland	-5,909.1	4,582.3	4,078.8	2,752.0	2,728.2
C.2 Land converted to grassland	28,701.3	702.6	459.7	29,863.6	31,431.7
D. Wetlands	-51.9		33.3	-18.7	37.2
D.1 Wetlands remaining wetlands	-44.5		33.3	-11.2	-37.0
D.2 Land converted to wetlands	-7.5			-7.5	74.1
E. Settlements	752.9	18.4	16.5	787.8	1,139.1
E.1 Settlements remaining settlements	-67.4			-67.4	-67.9
E.2 Land converted to settlements	820.4	18.4	16.5	855.3	1,207.0
F. Other land	NO,NA	NO,NA	NO,NA	NO,NA	NO,NA
G. Harvested wood products	-4,799.7			-4,799.7	-5,437.1

Notes: NE = not estimated (voluntary reporting categories), IE = included elsewhere (reported in the agriculture sector), NA = not applicable, NO = not occurring.

Forest land (4A) comprises emissions and removals from *forest land remaining forest land* and *land converted to forest land*. *Forest land remaining forest land* includes plantations, harvested native forests and other native forests. Emissions from *fuelwood consumption* and biomass burning in forests (*controlled burning* and *wildfire*) are also included as are the removals associated with post-fire recovery. *Land converted to forest land* includes grassland and wetlands (tidal marsh). The *forest land* category is estimated to have constituted a net sink of -35.9 Mt CO_2-e in 2015. The preliminary estimate for 2016 is -38.4 Mt CO_2-e, a change of around 7 per cent on 2015 levels.

Cropland (4B) comprises emissions and removals from *cropland remaining cropland* and *forest land* and *wetlands converted to cropland*. The *cropland* category is estimated to have constituted a net sink of -0.5 Mt CO_2-e in 2015. The preliminary estimate for 2016 is -0.6 Mt CO_2-e, a change of around 27 per cent on 2015 levels.

Grassland (4C) comprises emissions and removals from *grassland remaining grassland* and *forest land and wetlands converted to grassland*. The *grassland* category is estimated to have constituted a net source of 32.6 Mt CO_2-e in 2015. The preliminary estimate for 2016 is 34.2 Mt CO_2-e, a change of around 5 per cent on 2015 levels.

Wetlands (4D) comprises emissions and removals from *wetlands remaining wetlands* and *forest land converted to wetlands*. *Wetlands remaining wetlands* estimates represent N_2O emissions from aquaculture use in tidal wetlands and net emissions due to human-induced changes in the area of sparse woody vegetation. The *wetlands* category is estimated to have constituted a net sink of -0.02 Mt CO_2-e in 2015. The preliminary estimate for 2016 is a net source of 0.04 Mt CO_2-e.

Settlements (4E) comprises emissions and removals from *settlements remaining settlements* and *forest land* and *wetlands converted to settlements*. The *settlements* category is estimated to have constituted a net source of 0.8 Mt CO_2-e, in 2015. The preliminary estimate for 2016 is 1.1 Mt CO_2-e, a change of around 45 per cent on 2015 levels.

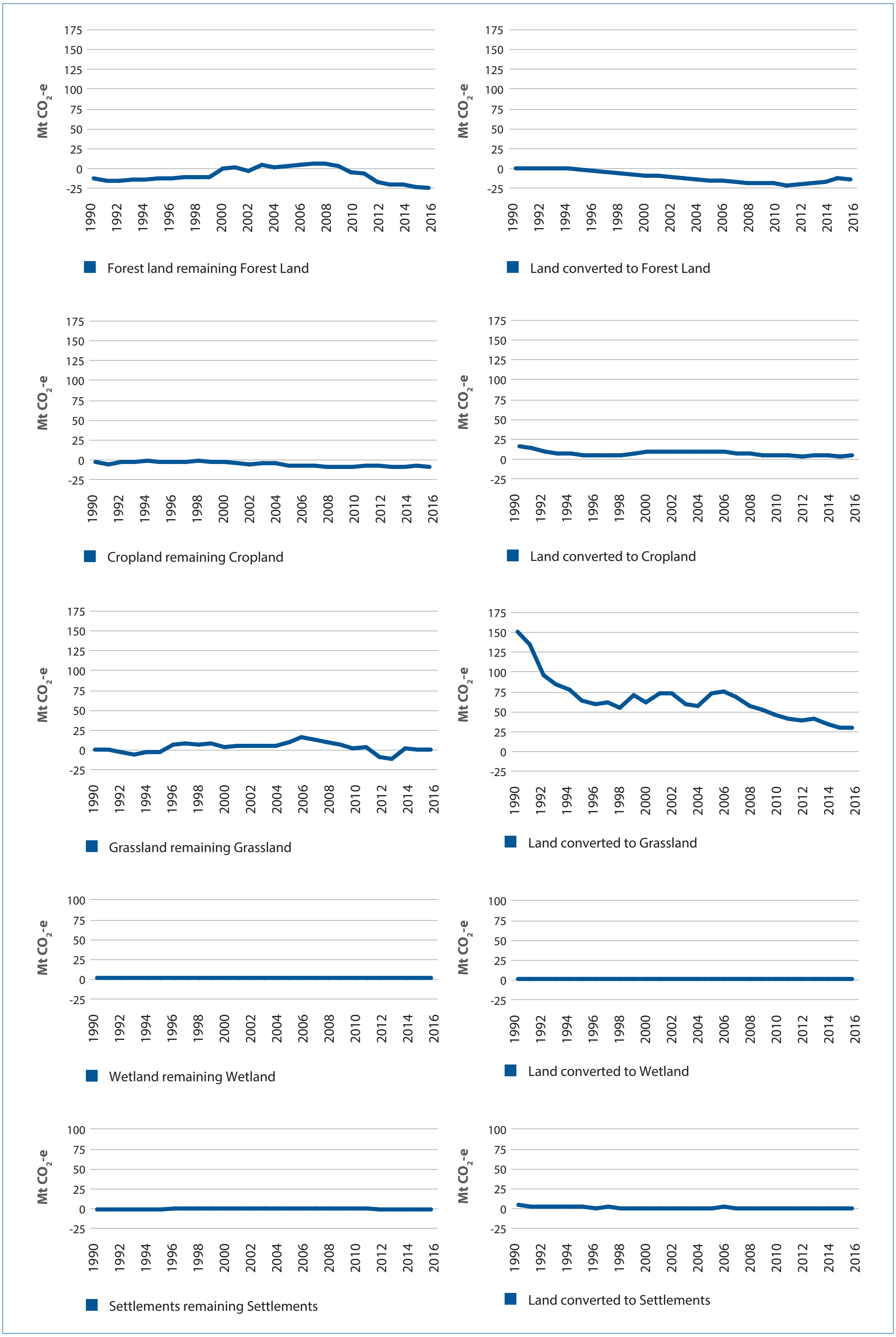
Forest land converted to cropland, *to grassland, to wetlands and to settlements* together constituted a net source of 33.7 Mt CO_2-e in 2015. The preliminary estimate for 2016 is 36.6 Mt CO_2-e, a change of around 8 per cent on 2015 levels.

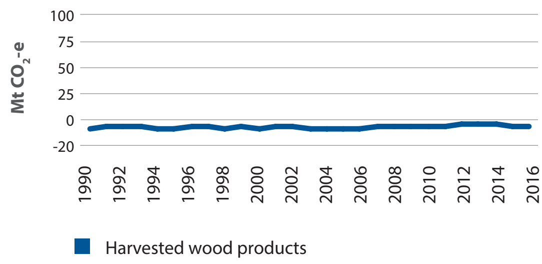
The net accumulation of carbon in the *harvested wood products* pool equated to 4.8 Mt CO_2-e in 2015, including net accumulations in solid waste disposal sites. The preliminary estimate for 2016 is 5.4 Mt CO_2-e, a change of around 13 per cent on 2015 levels.

Net *LULUCF* emissions decreased from 159.5 Mt CO_2-e in 1990 to -7.7 Mt CO_2-e in 2015. The preliminary estimate for 2016 is -9.1 Mt CO_2-e, a change of around 18 per cent on 2015 levels (Table 6.1).

The underlying trend of declining emissions from *LULUCF* since 1990 has been mainly driven by the decline in emissions from *forest land converted to cropland and grassland* (Figure 6.1) as well as, in recent years, declining net emissions from the harvest of native forests.

Figure 6.1 Net CO_2-e emissions from land use, land use change and forestry, by sub-category, 1990–2015 (includes a preliminary estimate for 2016)





The principal drivers of change in carbon fluxes across the Australian landscape relate to losses and gains of woody vegetation. The loss of woody vegetation is mainly reported under three classifications – *forest conversion to other land uses*, *forest land remaining forest land*, and *grassland remaining grassland*.

Permanent losses of woody vegetation that have been classed as *forest land* are reported under forest conversion to other land use classifications. In 2015, the additional area reported under forest conversion to other land uses was 134 kha.

Temporary losses of woody vegetation on *forest land* are reported under the *forest land remaining forest land* classification. In 2015, the area of temporary loss of vegetation - or area of harvest from native forests – was 57 kha (Figure 6.2). All forests subject to harvest events are monitored over time to ensure that the forest regenerates – if this does not happen, these areas are reported under forest conversion.

Losses of woody vegetation that is not classed as *forest land* (called 'sparse' woody vegetation) – both permanent and temporary – are reported under *grassland remaining grassland*, *wetlands remaining wetlands* and *settlements remaining settlements*. In 2015, the area of sparse woody vegetation lost was 1,935 kha (Figure 6.4).

Increases in woody vegetation cover classed as *forest land* are reported under *land converted to forest land*. These changes include both plantations on land previously used for other uses and the regeneration of forest from natural seed sources. In 2015, the additional area reported under *land converted to forest land* was 114 kha.

A regeneration of forest following a harvest event is reported under *forest land remaining forest land* as no change in land use has occurred.

Increases in area of sparse woody vegetation not classed as *forest land* are reported under *grassland remaining grassland*, *wetlands remaining wetlands* and *settlements remaining settlements*. In 2015, the area of gains in sparse woody vegetation was 2,474 kha. (Figure 6.4)

Forest land

Net emissions from *forest land* (4A) were -35.9 Mt CO_2-e in 2015 compared with -11.9 Mt CO_2-e in 1990, a difference of -23.9 Mt CO_2-e. Within *forest land*, *forest land remaining forest land* net emissions were -22.9 Mt CO_2-e in 2015 compared with -12.6 Mt CO_2-e in 1990, while the net emissions from *land converted to forest land* were -12.9 Mt CO_2-e in 2015 compared with 0.6 Mt CO_2-e in 1990.

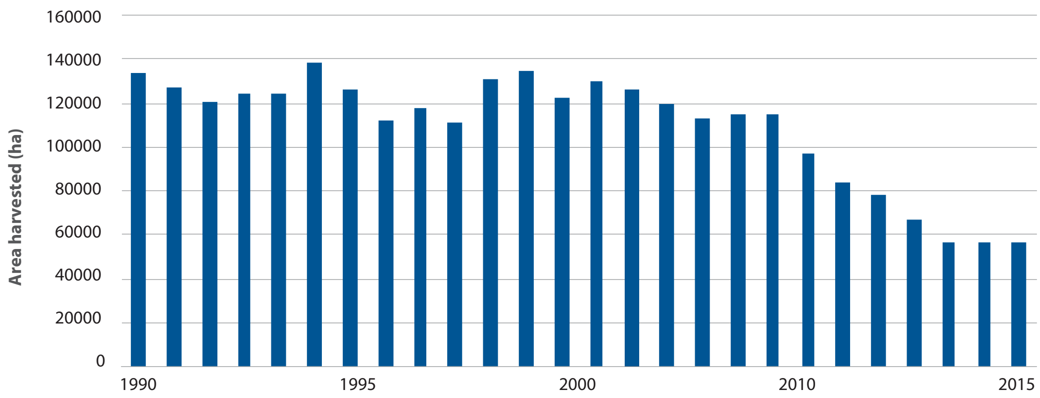
On average, since 1990, *forest land* has been accumulating carbon stocks of approximately 4.8 Mt of carbon each year (equivalent to a sink of approximately 17.6 Mt CO_2 per year, see Figure 6.1).

The key drivers of variation in *forest land* outcomes are annual harvest areas, the age classes of the forests, prescribed burning, climate and wildfires.

Harvesting in Australia's native forests, including multiple use forests and private native forests, is the key driver of human induced emissions and removals in these forests. Over recent years, harvesting in the native forest sector reached historically low levels (Figure 6.2).

The correct areas of new plantations from 1990 to 2015 are shown in Figure 6.3.

Figure 6.2 Area harvested in native forests 1990–2015

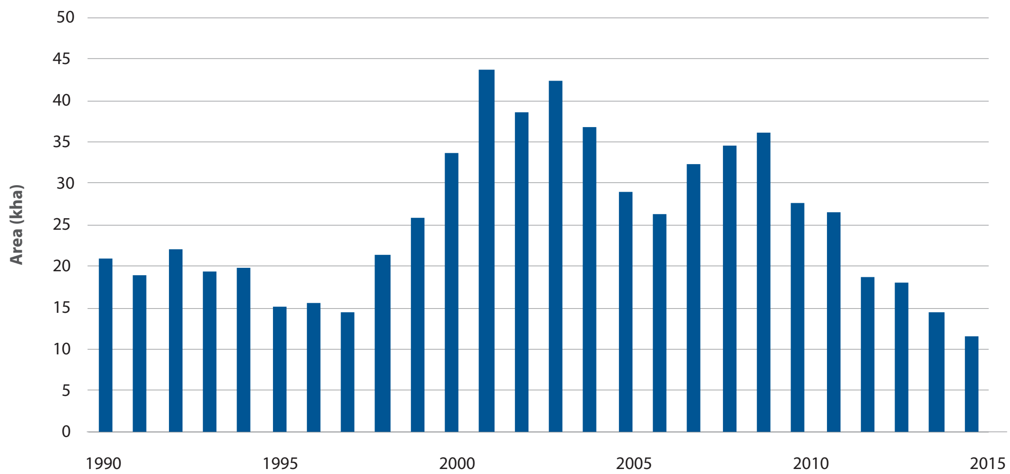


Wildfires are the largest cause of variability in emissions from *forest land remaining forest land*. Wildfires occur annually across Australia's 132 million hectares of forests with the area burnt varying considerably from year to year. In addition, *forest land remaining forest land* is subject to significant non-anthropogenic natural disturbances including wildfires that are beyond control despite extensive efforts of emergency management organisations.

All anthropogenic fires are included in reporting. Approaches have been developed to identify non-anthropogenic natural disturbances on *forest land remaining forest land*, and emissions and subsequent removals from non-anthropogenic natural disturbances are modelled to average out over time, leaving greenhouse gas emissions and removals from anthropogenic fires as the dominant result. Prescribed fires are all considered to be anthropogenic in nature. Disturbance areas are monitored for permanent changes in land use, in which case emissions are reported in the appropriate land conversion category, and salvage logging emissions are reported.

Net emissions due to wildfire in forests in 2015 were -3.9 Mt CO_2-e.

Figure 6.3 Area of new plantings 1990 to 2015, kha



Cropland

Net emissions from *cropland* (4.B) were an estimated -0.5 Mt CO_2-e in 2015. Within cropland, *cropland remaining cropland* net emissions were -4.6 Mt CO_2-e in 2015 compared with -0.07 Mt CO_2-e in 1990, Since 1990, there has been no significant overall trend in emissions, with transient variations driven by fluctuations in climatic conditions and shifts in management practices.

The net emissions from *land converted to cropland* were 4.2 Mt CO_2-e in 2015 compared with 16.8 Mt CO_2-e in 1990. This sub-category includes *forest land converted to cropland* and *wetlands converted to cropland.*

Grassland

Net emissions from *grassland* (4.C) were an estimated 32.6 Mt CO_2-e in 2015. Within *grassland*, *grassland remaining grassland* net emissions were 2.8 Mt CO_2-e in 2015 compared with 3.0 Mt CO_2-e in 1990.

Grassland remaining grassland

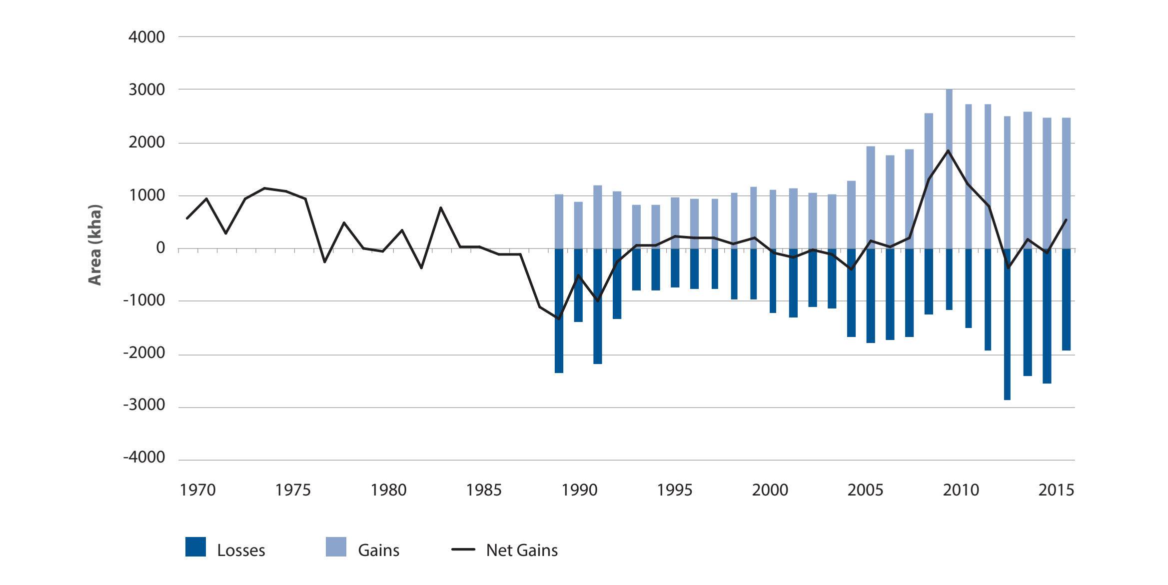
As with *cropland remaining cropland*, the longer term trend in emissions is difficult to discern for *grassland remaining grassland*. Changes in carbon stocks in *grassland remaining grassland* are largely affected by changes in land management practices. These factors determine the amount of live biomass and dead organic matter (DOM) as well as the amount of residues, root and manure inputs to soil carbon. The results are reported in three components to reflect the three elements of the emission estimation:

- herbaceous grassland (sparse woody vegetation soil carbon and N mineralization, leaching and runoff);
- changes in sparse woody or shrubland extent; and
- fire.

In the reported estimates for herbaceous grasslands, there has been no significant trend in emissions in recent years (Table 6.43 in section 6.8.2). In the arid and semi-arid regions of central Australia, soil carbon stocks under natural grassland have reached a steady state.

Woody shrubs are a key component of grassland ecosystems in semi-arid and arid regions of central Australia. Emission and removals on these shrublands are driven by land management and transitions between shrubs and grasses. These processes are driven by anthropogenic activities such as clearing of vegetation as well as climatic factors. Annual area gains and losses of sparse woody vegetation are shown in figure 6.4 below.

Figure 6.4 Area of sparse woody vegetation gains and losses, kha, 1970–2015



Net changes in shrub or sparse woody vegetation appear to be strongly correlated with the El Niño Southern Oscillation Index (Bureau of Meteorology), but also reflect the incidence of fire (55 per cent of all lost sparse vegetation in the Northern Territory coincides with a fire event) and mechanical clearing activity by land managers.

According to the Queensland Government Department of Science, Information Technology and Innovation (DSITI, 2015), over 50 per cent of all clearing permits issued in 2013-14 were for the purpose of providing fodder for animals. In drought conditions woody vegetation, for example in the Mulga lands, is an important source of feed for sheep and cattle.

The Department of the Environment and Energy's analysis of the Queensland DSITI data shows that, in 2014, the clearing of non-forest vegetation for fodder and other purposes across the *grasslands remaining grasslands* category amounted to around 150,000 hectares with the remainder of vegetation losses reported in the inventory due to non-mechanical causes.

Fire is also an important management action as well as natural disturbance to Australia's grasslands. Areas affected by fire are reported in section 6.8.1.3 and net emissions include carbon dioxide and non-carbon dioxide gases.

Land converted to grassland

The net emissions from *land converted to grassland* were 29.9 Mt CO_2-e in 2015 compared with 153.2 Mt CO_2-e in 1990. This subcategory includes *forest land converted grassland* and *wetlands converted to grassland*. Forest conversion to grassland is the dominant contributor to both the level and trend in net emissions in this subcategory.

Forest land converted to cropland and grassland

In 2015, total emissions from *forest land converted to cropland* and *forest land converted to grassland* were around 81 per cent (135.9 Mt CO_2-e) lower than in 1990. The permanent transition from forest to non-forest land use results in an immediate loss of carbon as trees are cleared and burnt, as well as an ongoing loss of soil carbon as it decays to a new equilibrium stock level.

The management of native vegetation and the majority of forest conversion processes in Australia is governed by the *Native Vegetation Framework,* which is an intergovernmental agreement among all levels of Australian government under the Council of Australian Governments (COAG).

Individual jurisdictions implement the national *Native Vegetation Framework* commitments in accordance with their own individual circumstances and land management practices and legislative frameworks.

Examples of administrative processes include compliance with regional ecosystem plans established under legislation, individually negotiated property management plans or additional approval processes / permit processes for clearing. Permits for conversion of all forests to grasslands for agriculture are required in the Northern Territory, Western Australia, Victoria, South Australia and Tasmania, with minor exceptions. In Queensland and in New South Wales, the processes are more complex.

Figures 6.5a and b illustrate the trend in forest land conversion to cropland and grassland in Australia between 1990 and 2015 and show the contribution of conversion of mature primary forest and re-clearing of secondary forest cover that has re-grown on previously cleared land. The relative stability of the rate of re-clearing, including of juvenile forest already converted to grassland and cropland, indicates an ongoing and cyclical need of land managers to re-clear certain areas on the fringe of agricultural regions where seed from adjacent forests has supported forest regeneration. Figure 6.5b also shows the annual areas of forest regrowth identified on previously cleared land.

Figure 6.5a Area of primary forest conversion, Australia, 1990–2015

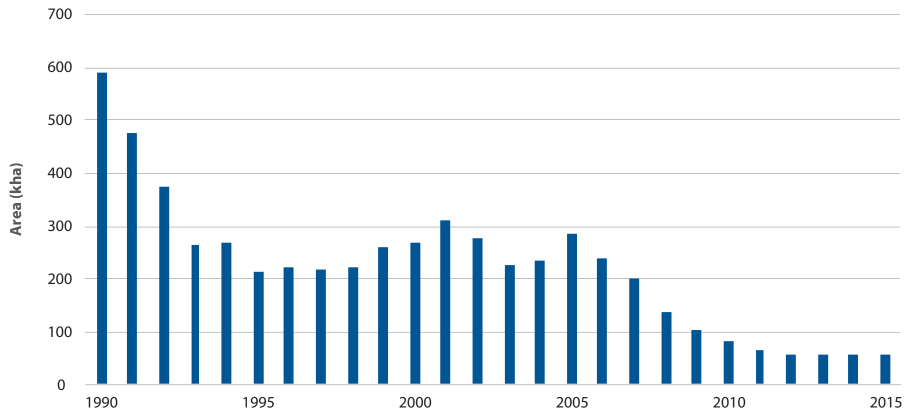
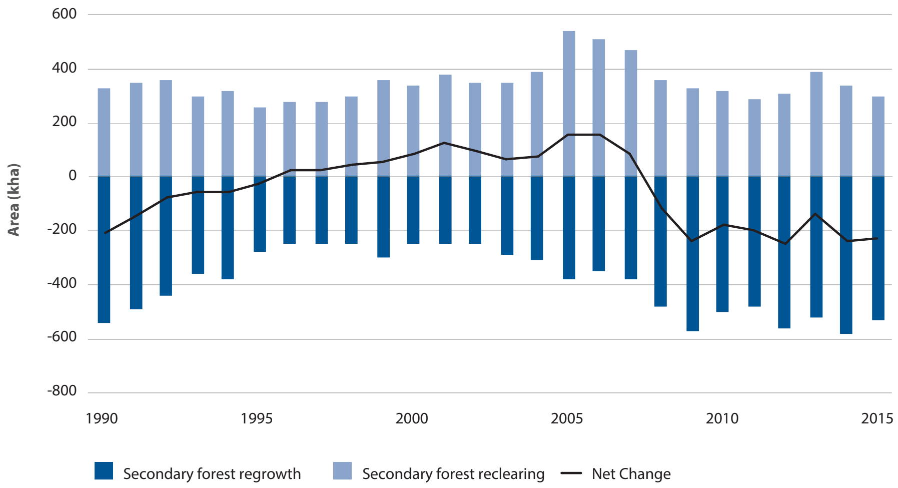


Figure 6.5b Secondary forest clearing and regrowth, Australia, 1990–2015



Note: Loss of woody vegetation that falls below the threshold for a forest are shown in Figure 6.4.

Within this national *Native Vegetation Framework*, economic considerations remain important drivers of the demand for forest conversion to alternative uses.

Most forest land converted in Australia is used for cattle grazing but also for crop production, settlements and mining. For graziers and other landowners, economic considerations are an important driver of forest land conversion. When the prices of agricultural products, for example beef, are high, landowners have a strong incentive to clear land and expand production.

Although economic conditions are also a factor, the effects of the more restrictive policy changes implemented in 2007 may be seen in the drop in first-time conversion from 2007 onwards (Figure 6.5a). In addition, the decline may also reflect land managers bringing forward decisions to clear land to the period 2004 and 2006 – the period between the announcement of new policies and before they came into force.

The shift in the balance between first-time conversion and re-clearing evident in Figures 6.5a and b also contributes to the ongoing decrease in emissions from *forest land converted to cropland* and *grassland*. Where land is re-cleared the biomass stock at clearing will be significantly less than the initial biomass of first time conversion.

To illustrate the importance of this effect, for the purpose of the Tier 2 forest conversion model (see Appendix 6.H) it is assumed that the biomass of re-cleared forests is 32 per cent of the mature forest biomass.

Note that net emissions from the temporary loss of vegetation that meets the criteria for a forest but which was harvested for timber or which was subject to a fire event are classified under *forest land remaining forest land*. Net emissions from the conversion of an orchard to another crop type are classified under *croplands remaining croplands*. Net emissions from the loss of woody vegetation which does not meet the criteria for a forest are classified under *grasslands remaining grasslands*, *wetlands remaining wetlands* or *settlements remaining settlements*.

Wetlands

Net emissions from *wetlands* (4.D), reported for the first time as part of Australia's National Inventory Report, are estimated to be -0.02 Mt CO_2-e in 2015. Within wetlands, *wetlands remaining wetlands* net emissions were -0.01 Mt CO_2-e in 2015 compared with 0.2 Mt CO_2-e in 1990 (See section 6.10.2). The estimate included net changes in sparse vegetation, and N_2O emissions from aquaculture operations (Table 6.55). The former factor was the dominant influence on both the level and trend in emissions reported over the time period.

The net emissions from *land converted to wetlands* were -0.01 Mt CO_2-e in 2015 compared with 0.6 Mt CO_2-e in 1990. This sub-category comprises *forest land converted to flooded lands* (e.g. reservoirs) (Table 6.57 in section 6.11.2).

Settlements

Net emissions from *settlements* (4.E), reported explicitly for the first time as part of Australia's National Inventory Report, are estimated to be 0.8 Mt CO_2-e in 2015. Within the *settlements* category, *settlements remaining settlements* net emissions were -0.07 Mt CO_2-e in 2015 compared with -0.1 Mt CO_2-e in 1990 (See section 6.12.2). The estimate comprises net changes in sparse vegetation (Table 6.59).

The net emissions from *land converted to settlements* were 0.8 Mt CO_2-e in 2015 compared with 5.0 Mt CO_2-e in 1990 (table 6.62). This sub-category comprises mangrove and other *forest land converted to settlements* and *wetlands* (tidal marsh) *converted to settlements*. Conversion of tidal marsh is assumed to occur along with any clearing of mangroves for settlements - as such the trends are identical. The key drivers of variation over the time period have been urbanisation and population growth.

6.2 Source category description and methodology

6.2.1 National circumstances

Australia has a land area of 769 million hectares containing unique land, water, vegetation and biodiversity resources. Australia is a dry continent where rainfall is highly variable and floods and droughts are a common feature. There are a number of distinct climatic zones, with summer dominant rainfall in the tropics/subtropics in the north, Mediterranean climates in the south, arid and semi-arid regions in the centre, and areas of high rainfall on the coastal fringes and in the ranges of the east (Figure 6.6 and Figure 6.7).

Australia has a diversity of soil types ranging from old, highly weathered and infertile, to younger, more fertile soils derived from volcanic rocks and alluvium. Approximately 50 per cent are dominated by sandy surface soil horizons, 37 per cent are dominated by loam and sandy clay loams in the surface horizon and 13 per cent are dominated by light to medium clay textured soil in the surface horizon. Most of these soils have low levels of nitrogen, phosphorus and other nutrients.

The areas of the continent under different land uses are shown in Figure 6.8. Significant agricultural activities include wool, beef, wheat, cotton and sugar production. Australia is also an exporter of dairy produce, fruit, rice and flowers. Australia's forest resources consist of native forests (primarily dominated by *Eucalyptus* species), which are used for wood production, recreation and conservation, and plantations of native (primarily *Eucalyptus* species) and exotic species (primarily *Pinus* species).

Cropland is generally located along a broad inland fringe across the southern and eastern areas of Australia, with the highest yields commonly obtained in the south west and eastern regions. In the southern regions, *cropland* is dominated by wheat production, with barley, oats, lupins and canola being the other dominant crops. In the north; wheat, sugarcane, sorghum and cotton production dominate.

The majority of *grassland* areas occur in inland Australia and are used for extensive grazing of both sheep and cattle. In Australia, grazing occurs across very diverse climate, ecosystem and management systems. The pasture types and associated management intensities range from highly improved to extensive rangeland systems in the semi-arid and arid regions of Australia. Native or naturalised pastures are the major pasture type, occupying approximately 17 per cent of Australia's land area with sown and fertilised pastures occupying only 4 per cent of the land area. Sown pastures are represented by mixed annual grasses and legumes as well as mixed perennial grasses and legume species depending upon rainfall and regional location. Irrigated pastures represent about 1 per cent of all pastures and are generally confined to the dairy and feedlot industries.

Australia's coastal wetlands

The three floristically diverse tidal wetland communities covered in the Wetlands Supplement, namely mangrove forests, tidal marshes and seagrasses are present in Australia. Together they cover 8 to 12 million hectares of coastal wetlands around Australia's 60,000 kilometre coastline (mainland plus islands) and store an estimated 3 billion tonnes of carbon, mostly in the soil (mean value, range = 1.4 to 6 billion tonnes – Lawrence *et al.*, 2012).

Australia's continental expanse incorporates a wide range of climate zones and coastal features that together determine the character of its coastal wetlands, including their carbon emissions and removal capacity.

Mangrove forests are one of eight native forest types under Australian national reporting (Commonwealth of Australia, 2014). They are found in the intertidal zones of tropical, subtropical and sheltered temperate coastal rivers, estuaries and bays. They grow in fine sediments deposited by rivers and tides, where they are regularly exposed to tidal inundation and lack of oxygen in the soil. They occupy an estimated 913,000 hectares around the Australian coastline (Bridgewater and Cresswell, 2014; Commonwealth of Australia, 2014). Mangroves meet Australia's definition of forests, and estimates of emissions and removals are reported under the appropriate forest land sub-categories (See sections 6.5.1.2 and 6.11).

Tidal marshes comprise salt tolerant succulent herbs, sedges and grasses covering an estimated area of 1.4 million hectares in Australia. They are situated high in the intertidal zone, with the highest areas of tidal marsh only inundated at the highest spring tides. They are often subject to hypersaline conditions. Tidal marsh species diversity increases with increasing latitude in Australia, an association that appears strongly linked to mean minimum daily temperature (Saintilan and Rogers, 2013).

Seagrasses are a diverse group of marine flowering plants adapted to a submerged life. Seagrasses are found along both tropical and temperate Australian coasts, where they may occupy intertidal flats, as well as the sub-tidal near-shore and deeper offshore locations. They cover an estimated area of 5 to 9 million hectares in Australia. Species diversity is greatest in tropical waters, but biomass per unit area increases with increasing latitude in Australia (Butler and Jernakoff, 1999).

Tidal marshes and seagrass meadows are distinct plant communities and will be treated in the Australian Inventory as subdivisions under *wetlands remaining wetlands*. This initial inventory reports emissions and removals of tidal marsh, with seagrass to be included in the 2018-16 National Inventory Report.

Aquaculture (use) is also reported in the wetlands inventory. This sub-category accounts for N_2O emissions from the production of finfish and crustaceans in aquaculture systems located in coastal wetland habitats.

Figure 6.6 Long-term average annual rainfall

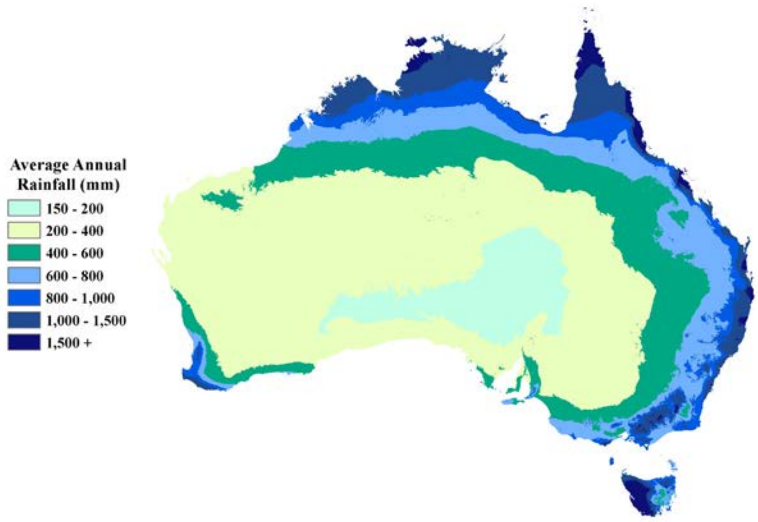


Figure 6.7 Long-term average annual temperature

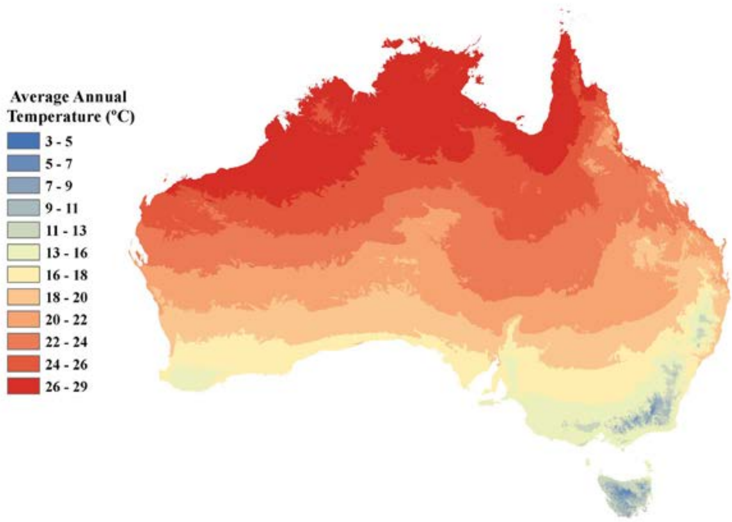
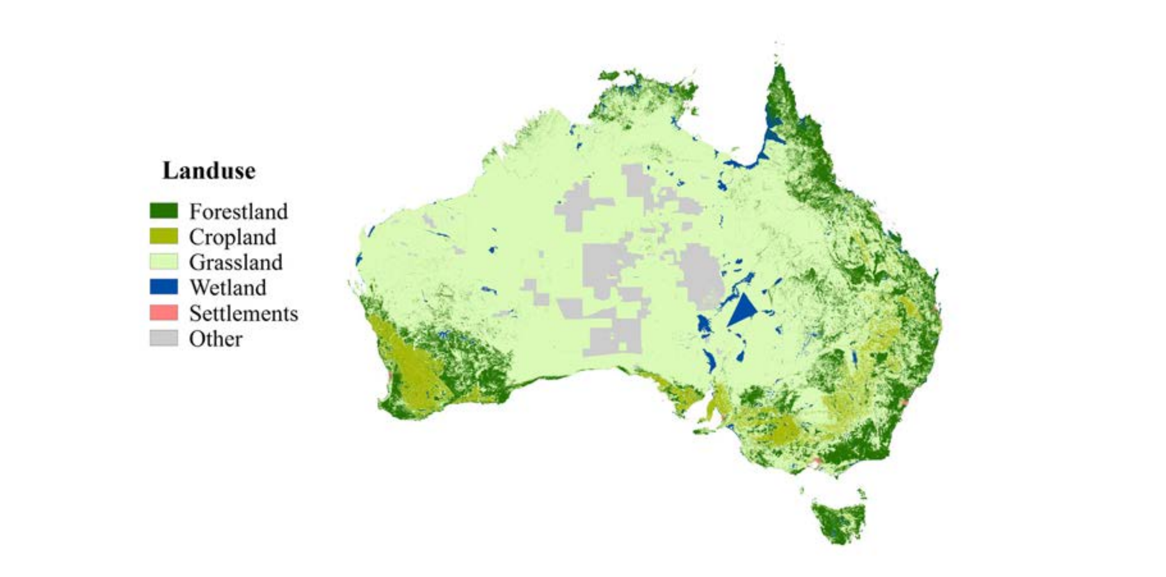


Figure 6.8 Map of land use in Australia



6.2.2 Methodology

Land use and management activities influence a variety of vegetation and carbon system processes that affect greenhouse gas fluxes. The focus of reporting for the *LULUCF* sector is the estimation of emissions and removals of carbon dioxide (CO_2) from these activities. Carbon dioxide fluxes between the atmosphere and managed land systems are primarily controlled by uptake via plant photosynthesis and releases from respiration, decomposition and oxidation of organic material. Nitrous oxide (N_2O) may be emitted from the system as a by-product of nitrification and denitrification and the burning of organic matter. Other gases released during biomass burning include methane (CH_4), carbon monoxide (CO), other oxides of nitrogen (NO_x) and non-methane volatile organic compounds (NMVOC).

Predominantly country specific methodologies and Tier 3 models (Table 6.2) are used for *LULUCF*. The methods used in the estimation of the *LULUCF* categories of the inventory are described in detail in Appendices 6.A to 6.K.

Table 6.2 Summary of methodologies and emission factors – *LULUCF* sector

Greenhouse Gas Source And Sink	CO_2		CH_4		N_2O		NO_x, CO and NMVOC	
	Method applied	EF	Method applied	EF	Method applied	EF	Method applied	EF
4. Land Use, Land Use Change and Forestry								
A. Forest Land								
1. Forest land remaining Forest land								
Harvested native forests	T2	M						
Other native forests	T2	CS						
Pre-1990 Plantations	T2	M						
Fuelwood	T2	CS						
2. Land converted to Forest land								
Grassland converted to forest land	T3	M						
Wetlands converted to forest land	T2	CS						
B. Cropland								
1. Cropland remaining Cropland	T3	M						
2. Land converted to Cropland								
Forest converted to cropland	T3	M						
Wetlands converted to cropland	T1	D						
C. Grassland								
1. Grassland remaining Grassland	T3, T2	M, CS						
2. Land converted to Grassland								
Forest converted to grassland	T3	M						
Wetlands converted to grassland	T1	D						
D. Wetlands								
1. Wetlands remaining Wetlands	T2	CS			T1/2	D		
2. Land converted to Wetlands	T2	CS						
E. Settlements								
1. Settlements remaining Settlements	T2	CS						
2. Land converted to Settlements								
Forest converted to settlements	T2, T3	CS, M						
Wetlands converted to settlements	T2	CS						
F. Other Lands								
1. Other Lands remaining Other Lands	NA	NA						
2. Land converted to Other Lands	NO	NO						
G. Harvested wood products								
Harvested Wood Products	T3	M						
4(I) Direct nitrous oxide (N_2O) emissions from nitrogen (N) inputs to managed soils (a)					IE	IE		
4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils (b)	NE	NE	NE	NE	NE	NE	NE	NE

Greenhouse Gas Source And Sink	CO_2		CH_4		N_2O		NO_x, CO and NMVOC	
	Method applied	EF	Method applied	EF	Method applied	EF	Method applied	EF
4(III) Direct nitrous oxide (N_2O) emissions from nitrogen (N) mineralization/ immobilization associated with loss/gain of soil organic matter resulting from change of land use or management of mineral soils (c)					T2	CS		
4(IV) Indirect nitrous oxide (N_2O) emissions from managed soils (c)					T2, CS	D		
4(V) Biomass burning (c)	IE	IE	T2	CS	T2	CS	T2	CS
H. Other	NA	NA	NA	NA	NA	NA	NA	NA

(a) In accordance with footnote 5 of CRF Table 4(I), Australia reports all N_2O emissions from N inputs to managed soils in the Agriculture sector
(b) Australia does not estimate emissions for this voluntary reporting category
(c) Emissions from this source include emissions from land classifications 4.A to 4.E
EF = emission factor, CS = country specific, D = IPCC default, M = Model, NA = not applicable, NE= not estimated, NO = not occurring, IE=included elsewhere, T1 = Tier 1, T2 = Tier 2 and T3 = Tier 3,

Australia's land sector inventory system integrates spatially referenced data with an empirically constrained, mass balance, carbon cycling ecosystem model (*FullCAM*) to estimate carbon stock changes and greenhouse gas emissions (including all carbon pools, gases, lands and land use activities). The system supports Tier 3, Approach 3 spatial enumeration of emissions and removals calculations for the following sub-categories:

- *Forest land converted to cropland, grassland, and settlements*
- *Grassland converted to forest land*; and
- The agricultural system components of *cropland remaining cropland* and *grassland remaining grassland*.

Spatial enumeration is achieved through the use of a time-series (since 1972) of Landsat satellite data which is used to determine change in forest extent at a fine spatial disaggregation. The forest cover change information is coupled together with spatially referenced databases of climate and land management practices which allows a comprehensive quantification of emissions (see Appendices 6.A and 6.B).

FullCAM can also be configured to operate in a Tier 3, Approach 2 mode where spatially explicit data are unavailable. In this configuration, known as the 'Estate' module, *FullCAM* uses age-based growth data to estimate living biomass and dead organic matter (DOM) from both turnover and harvest residue. The 'Estate' module of *FullCAM* is used to scale regional models of carbon stock change by the areas of each forest type (see Richards and Evans (2000a)).

The other principal reporting elements, *forest land remaining forest land, cropland remaining cropland, grassland remaining grassland*, *wetlands remaining wetlands* and *settlements remaining settlements* are reported using Tier 2 and Tier 3 methods.

6.3 Representation of lands

Land representation must be consistent over time and land units must be represented in only one category in order to meet the criteria for good practice established in the IPCC (2006).

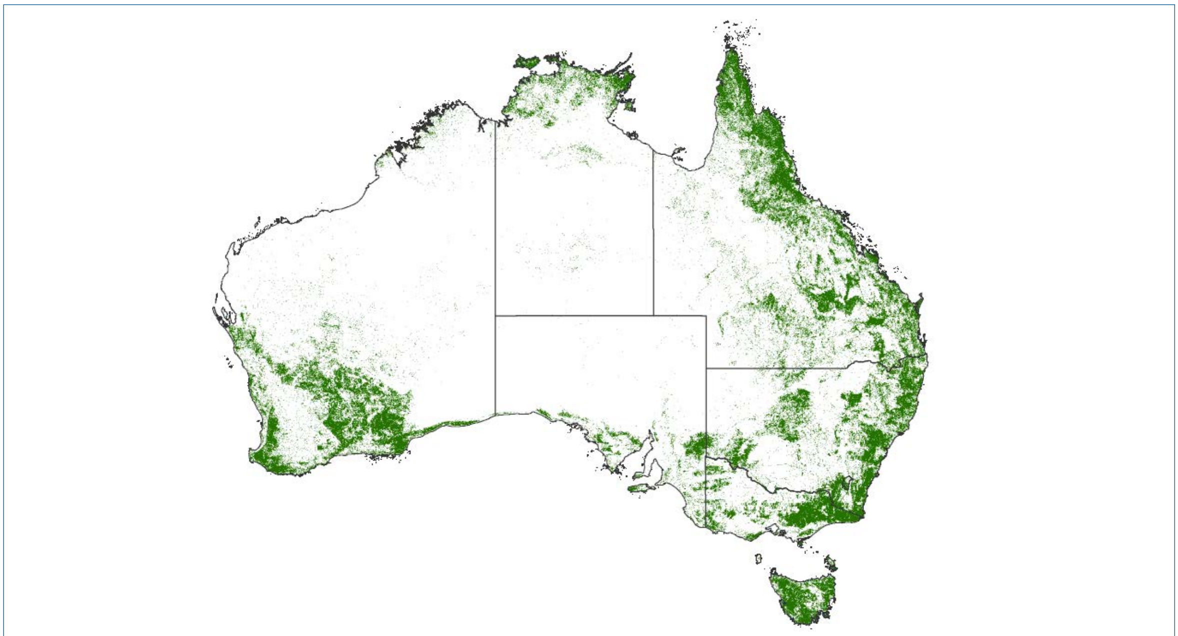
6.3.1 Land classifications

Forest land includes all lands with a tree height of at least 2 metres and crown canopy cover of 20 per cent or more (Figure 6.10) and lands with systems with a woody biomass vegetation structure that currently fall below but which, *in situ,* could potentially[1] reach the threshold values of the definition of *forest land*. Young natural stands and all plantations which have yet to reach a crown density of 20 per cent or tree height of 2 metres are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of either human intervention, such as harvesting, or natural causes, but which are expected to revert to forest.

Forest land does not include woody horticulture which meets the forest threshold parameters; this land is classified as croplands.

The forest cover definition is consistent with the definition used in Australia's National Forest Inventory that has been used for reporting to the Food and Agriculture Organisation and Montreal Process. Australia has adopted a minimum forest area of 0.2 ha.

Figure 6.9 Forest extent in Australia

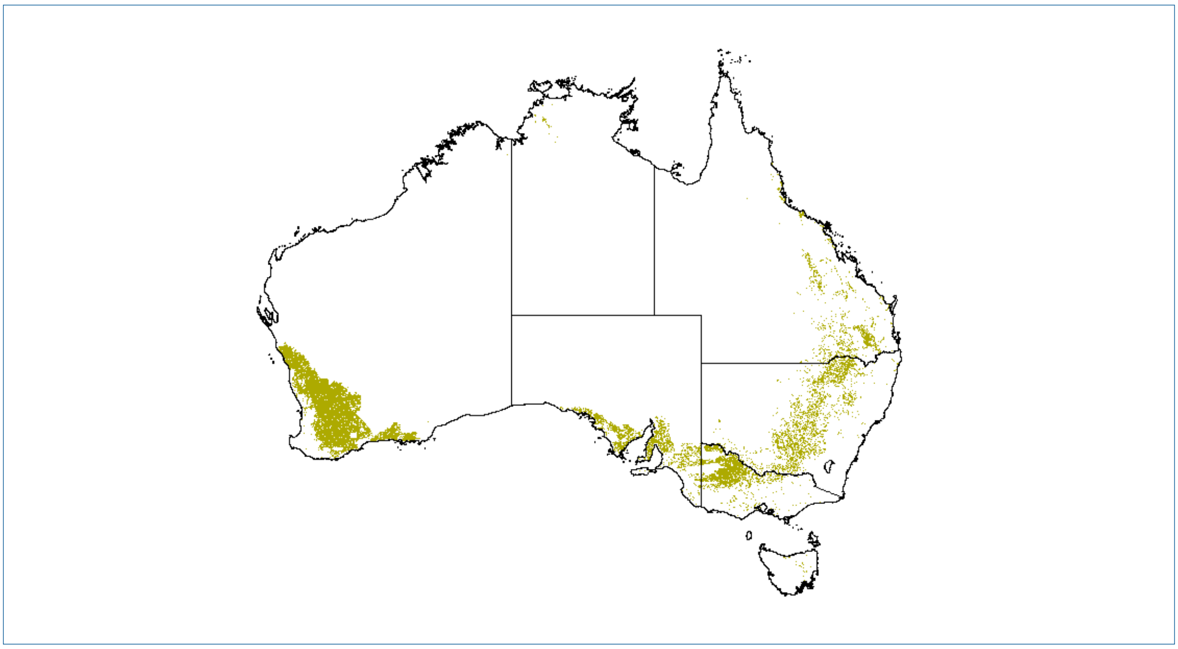


Cropland includes all land that is used for continuous cropping and those lands managed as crop-pasture (grassland) rotations (Figure 6. 10) (ABARES, 2014).

Non-CO_2 emissions from *cropland remaining cropland* are reported in the Chapter 5 *Agriculture* sector.

1 This potential is evidenced from the Landsat series that the land had previously supported forest.

Figure 6.10 *Cropland remaining cropland* distribution in Australia



The *grassland* category represents a diverse range of climate, management and vegetation cover (Figure 6.11) (ABARES, 2014). The *grassland* category also includes sub-forest forms of woody vegetation (shrubs).

Figure 6.11 *Grassland remaining grassland* distribution in Australia

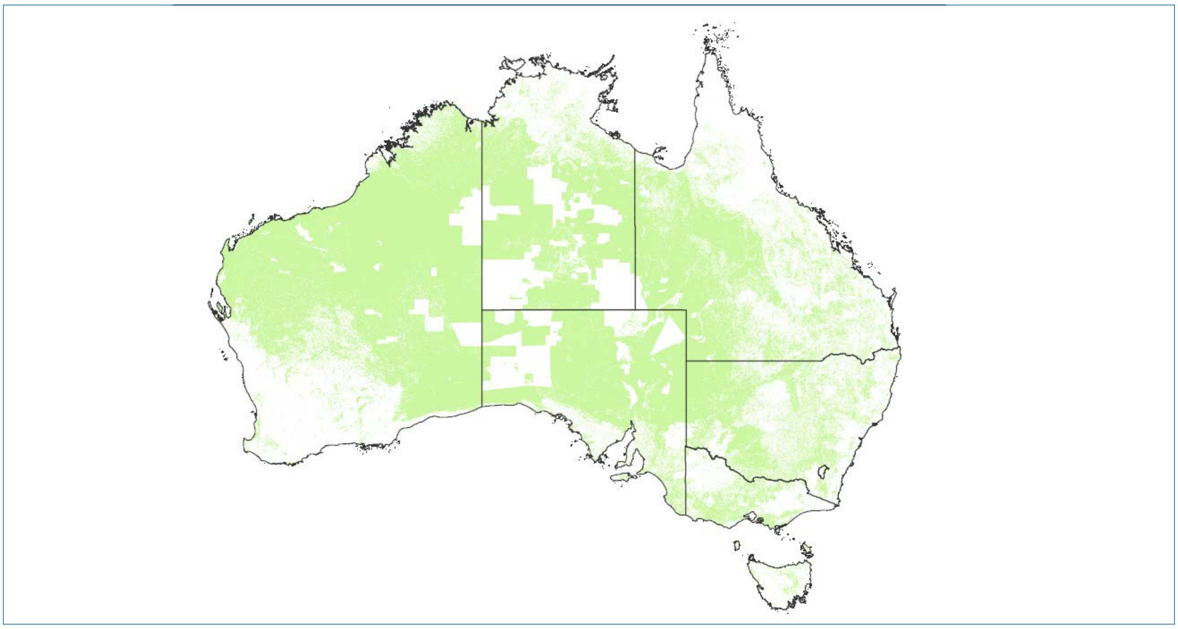


Figure 6.12 Examples of forest types and clearing activity

Closed Forest (>80%) Barron River, Qld

Open Forest (50-80%) Wombeyan, NSW

Woodland Forest (20-50 %) – Undara NP, Qld

Sparse Woody Vegetation (5-20%) NT

Permanent forest conversion

Clearing for fodder

Source: (top and centre row) MIG/NFISC (2013), (bottom left) ABC 2016, (bottom right) DNRM 2013)

Settlements include areas of residential and industrial infrastructure, including cities and towns, and transport networks. The area of the *settlements* land use classification is based on the latest information sourced from the ABARES catchments scale land use data (Version 5, 2014), and includes additional land use classes such as manufacturing and industry, commercial services, transport and communications including airports etc.

Land areas that meet the definition of forest land are reported under the *forest land* category.

Wetlands include areas of perennial lakes, reservoirs, swamps and major water course areas derived from the Australian Hydrological Geospatial Fabric (AHGF) data published by the Australian Bureau of Meteorology, and all existing wetlands as defined in the Directory of Important Wetlands in Australia (DIWA) dataset published by the Department of the Environment and Energy. Land areas that meet the definition of *forest land*, such as mangroves, are reported under the *forest land* category.

The *other land* category includes bare soil, rock and other land areas that do not fall into any of the other five categories according to ABARES' catchment scale land use map of Australia (version 5).

The allocation of forest conversion areas to *cropland* or *grassland* is designated by the relative frequency of the management practices within the particular ABS Statistical Local Areas and soil type in which it occurred.

Where there has been direct human-induced conversion from grass to forest these lands are classified and reported as *land converted to forest*. The generation of woody vegetation on *grassland* from natural seed sources is classified as *land converted to forest land* or *grassland remaining grassland*, depending on whether the vegetation meets the criteria for *forest land*.

In cases where there is a temporary change in forest cover, due to a forest harvest or fire, the land remains in the *forest land* category unless a subsequent land use change is identified.

The permanent conversion of *forest land* to other land uses is distinguished from a temporary removal or loss of forest cover. Changes in forest cover due to natural events (e.g. fire, drought) or changes that occur within land tenures where it is expected that the land will revert to forest (e.g. harvested forest, national park) are monitored for a period of time, depending upon the type of forest land use (2.6.2.1 of IPCC 2014). In the absence of land use change, areas without forest cover that have entered the monitoring system continue to be classified as "forest" provided that the time since forest cover loss is shorter than the number of years within which tree establishment is expected. After that time period, lands that have lost forest cover due to direct human-induced actions, have undergone land use change, and failed to regenerate are classified as converted to the appropriate non-forest land use classification.

6.3.2 Land monitoring systems

Australia uses Approaches 1 and 3 as described in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* to monitor land use, land use change and forestry.

The principal monitoring system is a remote sensing programme used to identify *forest lands* and changes in forest cover. Significant improvements to the remote sensing programme have been implemented in 2016 resulting in high quality outputs which are discussed in Appendix 6.A.

The remote sensing programme is implemented by the Department of the Environment and Energy. The system monitors national forest cover on an annual basis using Landsat satellite data (collected by MSS, TM, ETM+ and OLI sensors). The time series of national maps of forest cover extends across 25 time epochs from 1972 to 2016 and has been assembled on an annual basis since 2004. These maps are able to detect fine scale changes in forest cover at a 25 m by 25 m resolution.

Within the *forest land remaining forest land*, data on areas of forest management are drawn from Australia's National Forest and Wood Products Statistics (ABARES 2016a), Australia's State of the Forests Report (ABARES 2008) and Lucas *et al.* (1997).

Supplementary spatial information from the Land Use Mapping programme of Australia's Bureau of Agricultural Resource Economics and Sciences (ABARES, 2014) is used to identify land areas in the *cropland*, *grassland, wetlands, settlements*, and *other land* categories. This information supports an Approach 1 representation of land, where only total areas are known for the areas under these land areas, not the prior land-use. In accordance with the *2006 IPCC Guidelines* where the prior land-use is not known, emissions and removals are estimated using the methods for land remaining in a land category for conversions to these land uses. Further information on reporting of conversions between different land uses is included in Annex 5 (Completeness).

Identified changes in forest area from the remote sensing programme are assessed through a series of automated analytical tools and are quality controlled through inspection by trained operators to determine if these changes are due to human activity and are followed by land use change (e.g. forest clearing for agriculture, mining or urban development). The full details of the remote sensing and attribution analysis are provided in Appendix 6.A.

Once classified as a *forest conversion* event, land remains in the "conversion" sub-category for 50 years. This period of time reflects the long term impacts of conversion on carbon dynamics in Australian systems. After 50 years, the lands will be moved into the "land remaining" sub-categories. Archives of satellite data currently support only 43 years of conversion monitoring so that additional methods and data sources are used to identify amounts of land subject to conversion prior to 1972 (see Appendix 6.A).

Planned improvements are underway to develop a fully spatially explicit time series of land-use maps to apply Approach 3 land representation to all land-uses, to enable reporting of separate activity data and emissions estimates for all conversion categories.

6.3.3 Land representation matrix

Areas of forest cover change are supported by spatially referenced databases of land management information held by the Department of the Environment and Energy. Reconciliations are performed on a land unit by land unit basis to ensure that there are no gaps or overlaps which would lead to omission or double counting of areas of land.

The representation of land areas for Australia for 1990–2015 is reported in Tables 6.3 and 6.4.

Table 6.3 Land representation matrix (1990 to 2015)

Land use	1990(b) (Mha)	2015 (Mha)	Net Change (Mha)
Forest land total (c)	**138.0**	**132.2**	**-5.9**
Forest land remaining forest land	137.6	128.3	-9.3
Harvested Native Forest	10.2	10.2	0.0
Plantation (pre-1990)	0.8	0.8	0.0
Other forest land	126.7	117.4	-9.3
Land converted to forest land	0.4	3.8	3.4
Grassland converted to forest land	0.4	3.8	3.4
Wetland converted to forest land	0.0	0.0	0.0
Grassland total (c)	**514.8**	**519.4**	**4.7**

Land use	1990(b) (Mha)	2015 (Mha)	Net Change (Mha)
Grassland remaining grassland	506.5	503.2	-3.4
Land converted to grassland	8.3	16.3	8.0
Forest converted to grassland (c)	8.2	16.2	8.0
Wetland converted to grassland	0.0	0.0	0.0
Cropland total	**35.2**	**36.2**	**1.1**
Cropland remaining cropland	34.0	34.0	0.0
Land converted to cropland	1.2	2.2	1.0
Forest converted to cropland	1.2	2.2	1.0
Wetland converted to cropland	0.0	0.0	0.0
Wetlands total	**19.4**	**19.3**	**-0.1**
Wetlands remaining wetlands	19.4	19.3	-0.1
Land converted to wetlands	0.0	0.0	0.0
Forest land converted to wetlands	0.0	0.0	0.0
Settlements total	**0.9**	**1.1**	**0.2**
Settlements remaining Settlements	0.8	0.8	0.0
Land converted to settlements	0.1	0.3	0.2
Forest converted to settlements	0.1	0.3	0.2
Wetlands converted to settlements	0.0	0.0	0.0
Other land	**60.7**	**60.7**	**0.0**
TOTAL LAND AREA(a)	**769.0**	**769.0**	**0.0**

a) Total area does not include external territories.
b) The net change represents the change in land area including change that occurred in 1990 through to 2015 inclusive.
c) *Forest converted to grassland* includes a total of 4.3 Mha of previously cleared areas where forest cover has subsequently regrown. This is not considered a permanent land-use change and these areas remain classified as *forest land converted to grassland* until a permanent land-use change is observed based on additional management data or after the 50 year transition period has elapsed. The total area under forest cover in 2016 is 136.5 Mha, including such areas which are not classified as forest land.

Table 6.4 Land area in IPCC land use classifications 1990–2015 (Mha)

Year	4.A.1 Forest land remaining Forest land	4.A.2 Land converted to forest land	4.B.1 Cropland remaining cropland	4.B.2 Land converted to cropland	4.C.1 Grassland remaining grassland	4.C.2 Land converted to grassland	4.D.1 Wetlands remaining wetlands	4.D.2 Land converted to wetlands	4.E.1 Settlements remaining settlements	4.E.2 Land converted to settlements	4.F.1 Other land remaining other land	Total
1990	137.63	0.41	34.00	1.17	506.51	8.26	19.38	0.02	0.78	0.15	60.69	769.00
1995	134.93	1.06	34.00	1.41	505.88	10.65	19.37	0.02	0.78	0.21	60.69	769.00
2000	132.87	1.58	34.01	1.63	505.37	12.44	19.35	0.02	0.78	0.26	60.69	769.00
2005	130.54	2.25	34.01	1.93	504.71	14.43	19.33	0.03	0.78	0.31	60.69	769.00
2006	130.09	2.36	34.01	1.97	504.60	14.82	19.33	0.03	0.78	0.32	60.69	769.00
2007	129.72	2.49	34.01	2.02	504.47	15.14	19.33	0.03	0.78	0.33	60.69	769.00
2008	129.46	2.65	34.01	2.05	504.32	15.36	19.32	0.03	0.78	0.33	60.69	769.00
2009	129.26	2.82	34.01	2.07	504.15	15.54	19.32	0.03	0.78	0.33	60.69	769.00
2010	129.09	3.04	34.01	2.10	503.93	15.68	19.32	0.03	0.78	0.33	60.69	769.00
2011	128.94	3.33	34.01	2.12	503.64	15.79	19.31	0.03	0.78	0.34	60.69	769.00
2012	128.80	3.52	34.01	2.14	503.46	15.91	19.31	0.03	0.78	0.34	60.69	769.00
2013	128.63	3.67	34.01	2.17	503.31	16.06	19.31	0.03	0.78	0.34	60.69	769.00
2014	128.48	3.71	34.02	2.19	503.27	16.18	19.30	0.03	0.78	0.34	60.69	769.00
2015	128.35	3.83	34.02	2.21	503.16	16.29	19.30	0.03	0.78	0.35	60.69	769.00

6.4 Forest Land Remaining Forest land (Source Category 4.A.1)

There are four broad sub-divisions to *forest land remaining forest land*: harvested native forests, plantations, other native forests and fuelwood.

Harvested native forests are those forests comprised of endemic species arising from natural regrowth. Various silvicultural techniques may be applied to initiate and promote particular growth characteristics. The areas included in this sub-division include Multiple-use public forests as at 2008 (MPIG, 2008) and private native forests subject to harvest, or regrowing from prior harvest.

Plantations included within *forest land remaining forest land* are commercial plantations (hardwood and softwood) established in Australia up to the end of 1989. Softwood plantations make up the vast majority of these pre-1990 plantations with hardwood plantations (primarily eucalypt species) making up only a minor part of the plantation estate. Until the mid-1960s, most new areas of softwood plantation were derived from clearing of native forest or scrublands. In later years, some of the hardwood plantations were also established after clearing native forest (Snowdon and James, 2008). By the mid-1980s, clearing of native forests for the establishment of plantations had ceased in most states, and most new plantations were established on farmland.

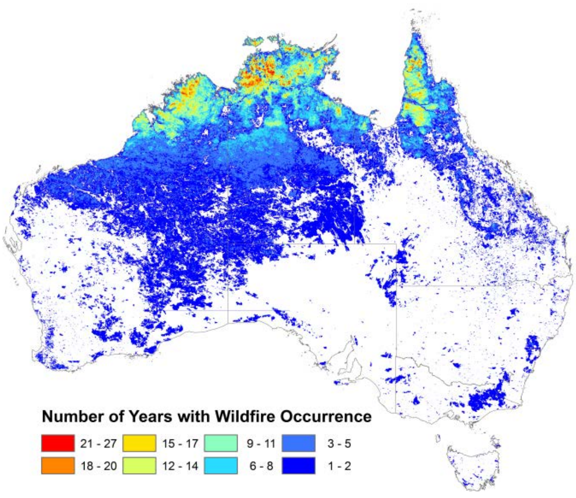
Other native forests include those forests that are comprised of endemic species, which are not harvested native forests or plantations. The other native forests sub-division includes protected areas (such as Wilderness areas and National Parks) not previously subject to harvesting and areas of extensive forests including woodlands.

The main processes affecting emissions and removals from these forests include fire management practices and wildfires. Accordingly net emissions are estimated for the following activities:

- prescribed burning of temperate forests;
- wildfire in temperate forests; and
- prescribed burning and wildfire in tropical, sub-tropical and semi-arid forests.

Most Australian forests are adapted to fire, and fires, whether wildfires or prescribed fires, are generally not stand replacing. Many eucalypt species continue growing, with burned leaves and twigs quickly regrowing from epicormic shoots with no effect on stand age-class. In most eucalypt forests, fires do not cause significant changes in the rate of turnover of living biomass to dead biomass, particularly following lower intensity fires which primarily burn only litter and deadwood (Raison and Squire *et al.* 2008, Bradstock *et al.* 2012, Fairman *et al.* 2015). Fire regimes differ widely in regards to fire frequency and intensity across Australia as shown in Figure 6.13, with implications for the estimation of carbon stocks.

Figure 6.13 AVHRR burned area frequency and extent (1988–2013)



In the northern and central Australian wet/dry tropical, subtropical and semi-arid forest ecosystems, burning occurs for a variety of reasons including pasture management, fuel reduction, prevention of uncontrollable wildfires, and traditional indigenous burning.

In temperate forests, prescribed burning includes managed fires that aim to mitigate the risk and severity of wildfires by reducing debris loads in forest biomass burning. Prescribed burning is typically low intensity, consuming only a proportion of the dead organic matter present in the forest.

Wildfires can range from moderate intensity burns through to high intensity wildfire, which can remove most debris as well as under-storey vegetation, foliage, and small branches.

Some wildfires constitute non-anthropogenic natural disturbances as they are beyond the control of, and not materially influenced by, Australian authorities and occur despite costly and on-going efforts across regional and national government agencies and emergency services organisations to prevent, manage and control the fires.

In this inventory, anthropogenic fires include prescribed fires and wildfires. Non-anthropogenic natural disturbances are modelled to average out over time, leaving anthropogenic emissions and removals as the dominant result.

Harvested wood products are not reported in this category and carbon stocks in wood products are transferred to category *4.G Other – harvested wood products*.

As for all forests, the harvested native forests sub-category is monitored for forest conversions. Areas that are identified as direct human induced forest conversions are excluded from forest land remaining forest land, and any harvesting associated with the conversion event is also excluded to avoid double-counting.

6.4.1 Methodology

6.4.1.1 Harvested native forests

The emissions and removals from *harvested native forests* are estimated using the non-spatially explicit Estate modelling capability of *FullCAM*.

Estimating changes in living biomass

The annual change in living biomass in *harvested native forests* is the net result of uptake due to forest growth (above and below ground as determined from the growth models) and losses due to forest harvesting. Losses occur with the removal of forest products (transferred to *4.G Other – harvested wood products*) and movement of residue material (including belowground biomass) to dead organic matter (DOM) and soils.

Harvested native forests are modeled based on forest types which are consistent with reporting used under the Montreal Process National Forest Inventory (MPIG, 2013) and National Vegetation Information System Major Vegetation Groups (NVIS, see NLWRA, 2001). A comparison table with the inventory forest classes is shown in Table 6.5 (Waterworth *et al.* 2015). Age classes and growth rates (t C ha^{-1} yr^{-1}) for each forest type in multiple-use public forests were reported by Lucas *et al.* (1997) (Table 6.6, 6.7).

The changes in carbon stock are estimated using *FullCAM,* which is configured using the area of each forest type and age class in Table 6.6 and using biomass increments based on the growth rates reported in Table 6.7. Forests of unknown age, or those which contain two or more age classes, were assumed to be equivalent to the 'Mature' age class (Table 6.6).

Post-harvest growth is modelled according to the type of harvest that took place. Areas subject to clearfell harvest regrow from age zero. Areas subject to partial harvest continue to grow at the same rate as they were growing prior to the harvest (i.e. there is no thinning effect at the stand level, either positive or negative, on the rate of biomass accumulation despite the reduction in stem numbers).

Table 6.5 Forest classification comparison table

Inventory forest class (Lucas *et al.* 1997)	NVIS Major Vegetation Groups	National Forest Inventory (SOFR 2013)
Rainforest	Rainforest and vine thickets	Rainforest
Tall dense eucalypt forest	Eucalyptus tall open forest	Eucalypt tall closed
		Eucalypt tall open
Medium dense eucalypt forest	Eucalyptus open forest	Eucalypt medium closed
		Eucalypt medium open
Low dense eucalypt forest	Low Closed Forests and Tall Closed Shrublands	Eucalypt low closed
		Eucalypt low open
Tall sparse eucalypt forest	Eucalypt Open Forests	Eucalypt tall woodland
Medium sparse eucalypt forest		Eucalypt medium woodland
Low sparse eucalypt forest	Eucalyptus woodland	Eucalypt low woodland
	Eucalyptus open woodland	
	Other Open Woodlands	
	Tropical woodlands and grasslands	
	Eucalypt Low Open Forests	
Eucalypt Mallee	Mallee Woodlands and Shrublands	Eucalypt Mallee open
	Mallee Open Woodlands and Sparse Mallee Shrublands	Eucalytpt Mallee woodland
Callitris forests	Callitris Forest and Woodlands	Callitris
Acacia forests	Acacia forest and woodlands	Acacia
Other forests	Casuarina Forests and Woodlands	Casuarina
	Melaleuca Forests and Woodlands	Melaleuca
	Mangrove	Mangrove
	Acacia Open Woodlands	
	Eucalypt Woodlands	

(Waterworth *et al.* 2015)

Table 6.6 Areas by forest type and age classes in 1990 in multiple-use public forests (ha).

Forest Type	Establishment 1-10 yrs	Juvenile 11-30 yrs	Immature 31-100 yrs	Mature 100–200 yrs	Senescent > 200 yrs	Forests of unknown age (a)	Two Aged	Three or More Aged	Total
Rainforests				842,580					842,580
Tall Dense Eucalypt Forests	46,728	95,470	234,898	292,095	230,102	641,646	115,683	388,188	2,044,810
Medium Dense Eucalypt Forests	14,576	97,742	173,424	829,088	168,152	1,659,839	273,720	1,022,136	4,238,677
Medium Sparse Eucalypt Forests					345,153	274,270		663,366	1,282,789
Cypress pine Forests						42,258		144,182	186,440
Other Forests						673,019		141,686	814,705
Totals	61,304	193,212	408,321	1,963,763	743,407	3,291,031	389,404	2,359,558	9,410,000

(a) The unknown and mixed age classes were represented in the model consistent with the 'Mature' age class.

Table 6.7 Aboveground growth rates by forest type and age class (t C ha^{-1} yr^{-1})

Forest Type	Establishment 1-10 yrs	Juvenile 11-30 yrs	Immature 31-100 yrs	Mature 100–200 yrs	Senescent > 200 yrs
Rainforests	-	-	-	0.58	0
Tall Dense Eucalypt Forests	6.44	4.41	2.23	0.74	0
Medium Dense Eucalypt Forests	4.24	2.80	0.99	0.18	0
Medium Sparse Eucalypt Forests	0.24	0.24	0.24	0.24	0
Cypress pine Forests	0.25	0.25	0.25	0.25	0
Other Forests	0.23	0.23	0.23	0.23	0

Partitioning of biomass to tree components

The ratios used to partition biomass to the different tree components (Table 6.8) are drawn from a synthesis of available data compiled by Snowdon *et al.* (2000) and the results of Ximenes and Gardner (2005) and Ximenes *et al.* (2005).

Table 6.8 Partitioning of biomass to each of the tree components

Forest Type	Fraction of biomass allocated to:					
	Stems	Branches	Bark	Leaves	Coarse roots	Fine roots
Rainforest	0.60	0.08	0.09	0.03	0.17	0.03
Tall Dense Eucalypt Forest	0.55	0.12	0.10	0.03	0.17	0.03
Medium Dense Eucalypt Forest	0.50	0.15	0.12	0.03	0.17	0.03
Medium Sparse Eucalypt Forest	0.47	0.15	0.12	0.03	0.20	0.03
Cypress pine Forest	0.47	0.15	0.12	0.03	0.20	0.03
Other forest	0.47	0.15	0.12	0.03	0.20	0.03

Carbon fraction of biomass

The carbon fractions of the tree components (Table 6.9) are based on studies of Australian vegetation (Gifford, 2000a and 2000b).

Table 6.9 Carbon Fraction of biomass for each tree component based on Gifford (2000a and 2000b)

Tree component	% Carbon
Stems	52
Branches	47
Bark	49
Leaves	52
Coarse roots	49
Fine roots	46

Forest harvest

The amount of carbon removed as products in a harvest is dependent upon age class, forest type and the type of harvest.

The area of *harvested native forests* harvested in each broad forest type and age class was derived from roundwood log volumes removals for each state (ABARES, 2016a) using a historical relationship between roundwood removals and harvest area data collated by state agencies (Table 6.10).

Table 6.10 Estimated total area of native forest harvested

Year	Area harvested (ha)
1990	133,871
1995	137,963
2000	130,704
2005	119,959
2006	112,710
2007	114,515
2008	114,832
2009	97,285
2010	84,185
2011	77,725
2012	66,950
2013	56,964
2014	56,875
2015	57,022

Source: Derived from ABARES 2016a.

The broad silvicultural systems applicable to each state are reported in Table 6.11. Information on the forest type and silviculture method applied also varied in the level of detail available. Where the information was not explicitly reported, it was inferred from the best available information, including information within the state agency reporting, publications from state agencies (e.g., Forestry Tasmania, 2008; FPA, 2007; Forests NSW, 2008; Vic Forests, 2008) and from Raison and Squire (2008). It was assumed that no harvesting occurred in the Establishment (1-10 years) and Juvenile (11-30 years) phases as these are generally too young to produce forest products in Australia's native forests.

Most states began phasing out logging of rainforests in the 1980s, and for the most part, logging was entirely phased out prior to 1990 (Raison and Squire, 2008). It was not possible to separate cold temperate rainforest logging from logging in wet temperate eucalypt forests in Tasmania. The harvested area for rainforests in Tasmania was therefore modelled as tall and medium dense eucalypt forests, which are closest to cold temperate rainforests spatially and in successional sequence (Hickey, 1994).

Table 6.11 Broad silvicultural systems used in the *harvested native forests* model

Forest type	Silviculture	% of trees harvested	Post harvest management
Tall dense eucalypt forest	Clearfell with pulpwood	100%	Regeneration burn
	Clearfell without pulpwood	100%	Regeneration burn
	Partial harvest with pulpwood	35-50%	Slash left on-site
	Partial harvest without pulpwood	25%	Slash left on-site
Medium dense eucalypt forest	Clearfell with pulpwood	100%	Regeneration burn
	Clearfell without pulpwood	100%	Regeneration burn
	Partial harvest with pulpwood	35-75%	Slash left on-site
	Partial harvest without pulpwood	40%	Slash left on-site
Medium sparse eucalypt forest	Partial harvest without pulpwood	30%	Slash left on-site
Callitris forest	Partial harvest without pulpwood	40%	Slash left on-site

Once harvested, in the model, the removal of products at harvest is assumed to result in a transfer of carbon to the *harvested wood products* modelling (see section 6.12) (based on production statistics).

Estimating changes in debris

The annual change in DOM in *harvested native forests* is the net result of additions from turnover and losses due to decay and turnover into soils. Losses are caused by decomposition of both natural accumulation and harvest residue, and burning of residues as part of some silvicultural systems.

The initial amount of forest debris for each forest type and age class combination is based upon model simulations, cross checked with published estimates of debris in Australian forests. For each forest type, a clearfell event was simulated using initial debris levels. This simulation was then run to equilibrium over 200 years. The final debris pools from this simulation were then used as the initial conditions for a final simulation. The results of the final simulation were used to define the initial debris for each age class for each respective forest type. This method produced debris quantities that are comparable with published estimates of debris in Australian forests (e.g., Woldendorp and Keenan, 2005, Hingston *et al.* 1981).

The turnover rates applied for each plant component in the model are shown in Table 6.12. There is limited information on decomposition rates in the *harvested native forests* of Australia. The decomposition rates for the different debris pools were drawn from the best available information including Mackensen *et al.* (2003), Mackensen and Bauhaus (1999), O'Connell (1997) and Paul and Polglase (2004a). The rates used are shown in Table 6.13.

Table 6.12 Turnover for tree components

Tree component	Turnover $year^{-1}$
Branches	0.05
Bark	0.07
Leaves	0.50
Coarse Roots	0.10
Fine Roots	0.85

Table 6.13 Decomposition rates for debris pools used in the *harvested native forests* model.

Debris component	Breakdown yr^{-1}	
	Decomposable	Resistant
Deadwood	0.05	0.05
Bark litter	0.50	0.50
Leaf litter	0.80	0.80
Coarse dead roots	0.40	0.10
Fine dead roots	1.00	1.00

The amount of residue produced by a harvest is also dependent upon the harvest type, forest age and forest type. Information on the production of harvest residue by broad forest type, harvest type and forest age was sourced from Raison and Squire, 2008 and studies of residue production (Ximenes and Gardner, 2005; Ximenes *et al.* 2005).

Estimating changes in soil organic carbon

Soil carbon is estimated using *FullCAM* operating in estate mode with a national soil carbon map (Viscarra-Rossell *et al.* 2015) (Appendix 6.E) as the base input data. *FullCAM* simulates changes in soil carbon using the Roth-C soil carbon model. The Roth-C model computes turnover of organic carbon in soils, taking into account clay content, temperature, moisture content, plant material inputs and plant cover.

Harvested native forests – biomass burning

Wildfires and prescribed fires on *Harvested native forests* are modelled as temperate forest fires consistent with *Other native forests* – see section 6.4.2.3.

The CO_2 emissions associated with slash burning in *harvested native forests* are estimated by *FullCAM*. The mass of carbon burnt annually (FC_{jk}) is taken directly from *FullCAM* and is used to estimate the CO_2 and non-CO_2 gas emissions associated with slash burning.

There are no direct measurements of trace gas emissions from slash burning in Australia; however it is considered that these fires will have similar characteristics to hot prescribed fires and wildfires (Hurst *et al.* 1996).

The algorithms for total annual emissions of CH_4, CO and NMVOCs are:

$$E_{ijk} = FC_{jk} * EF_{ijk} * C_i \quad \text{(4.A.1\_1))}$$

and for total annual emissions for NO_x and N_2O are:

$$E_{ijk} = FC_{jk} * NC_{jk} * EF_{ijk} * C_i \qquad (4.A.1\_2))$$

Where FC_{jk} = annual carbon burnt in slash burning (obtained from *FullCAM*) (Gg),

EF_{ijk} = emission factor for gas *i* from vegetation (Table 6.K.10-6.K.12),

NC_{jk} = nitrogen to carbon ratio in biomass (Appendix 6.K.8)

C_i = factor to convert from elemental mass of gas species *i* to molecular mass (Appendix 6.K.9).

6.4.1.2 Plantations

The emissions and removals from *plantations* are estimated using *FullCAM* operating in Estate mode which uses location specific climate and site data, combined with region-specific silvicultural practices.

The carbon pools considered for *plantations* include above and below ground biomass, DOM and soil.

The areas of *plantations* have been drawn from Australia's National Forest Inventory. Since 1990, using Landsat imagery, new forest establishment has been able to be distinguished from second rotation forests, as described in Appendix 6.A.

Harvested wood products are not reported in this category. Carbon stocks removed as products are reported under 4.G *Harvested wood products*.

Estimating changes in living biomass

For the *plantations* category, tree growth is modelled using the tree yield formula embedded into the *FullCAM* code (see Appendix 6.A and 6.D and also Waterworth *et al.,* 2007; Waterworth and Richards, 2008).

For the *plantations*, 34 *FullCAM* models representing the key species and management practices within each National Plantation Inventory (NPI) region were developed.

The plantation management database incorporated in the *FullCAM* modelling system contains information on tree species characteristics including forest growth model parameters, carbon allocation to tree components over time, biomass carbon percentages, basic wood density, turnover rates for each tree component, decay and product use data. These data allow *FullCAM* to model forest growth for any point based on the site and climate data.

FullCAM is parameterised to allocate biomass to different plant parts, depending upon species and age of the forest. *FullCAM* calculates the partitioning using an empirical approach derived from expansion factors reported in Snowdon *et al.* (2000) and Mokany *et al.* (2006). This method allows allocation to vary between sites and species within set ranges based on age, site productivity and level of stand development.

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

Studies of the carbon fractions of above and below ground biomass components for Australian vegetation were used to provide the parameters for the carbon fractions of tree components in the model (Gifford, 2000a and 2000b). Carbon fractions were examined for a range of species and growing conditions, which provided a range for the carbon fractions with a recommended estimate. There was little variability in the results, and more importantly, no cause to suspect bias in any set of environmental conditions or plant groups. These results could be considered as robust and reliable estimates, providing little source of uncertainty in the carbon models. The carbon contents are listed in Table 6.16.

Estimating changes in debris

The amount of carbon moved from living biomass to the DOM pools due to forest harvesting is determined in the model by the age, type of harvest and species characteristics. The turnover rate of leaves and fine roots affects both the amount of fine litter on the forest floor, and subsequently, most of the contribution to soil carbon. The tree component turnover rates applied in the model were guided by work by Paul *et al.* (2004b and 2017). The tree component turnover rates are shown in Table 6.14.

Decomposition rates determine the rates of loss of carbon back to the atmosphere as the debris breaks down. The rates of decomposition applied in the model have been guided by the work of Mackensen and Bauhus (1999). Table 6.15 shows the decomposition rates applied. The balance of these two factors determines the amount of debris on site, excluding the effects of management.

Fires on *Plantations* are modelled as temperate forest fires consistent with *Other native forests* – see section 6.4.1.3.

Table 6.14 Tree component annual turnover rates

Tree Component	Softwood Turnover yr^{-1}	Hardwood Turnover yr^{-1}
Branches	0.03	0.05
Bark	0.05	0.07
Leaves	0.30	0.50
Coarse Roots	0.07	0.10
Fine Roots	0.80	0.85

Table 6.15 Debris decomposition rates

Debris Component	Breakdown Rate yr^{-1}
Deadwood	0.1
Bark Litter	0.5
Leaf Litter	1.0
Coarse Dead Roots	0.5
Fine Dead Roots	1.0

Table 6.16 Plantation types, wood densities, carbon contents and management regimes

Region(s)	Species	Density	CC% Leaf	CC% Branch	CC% Wood	CC% Bark	CC% Fine Roots	CC% Coarse Roots	Regime Description [(a)]
Green Triangle	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 54% thinning @ 13 years, 25% @ 18, 28% @ 23, CF @ 30
Green Triangle	Pinus (other than radiata)	440	52	51	52	53	46	49	Average Sites – 54% thinning @ 13 years, 25% @ 18, 28% @ 23, CF @ 30
NSW Northern Tableland	Southern Pine (P. elliotti, P. taeda, Araucaria cunninghamii)	440	52	51	52	53	46	49	Average Sites – 27% thinning @ 14 years, 47% @ 20, CF @ 30
NSW	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – 67% @ 20 years, 47% @ 35, CF @ 45
NSW	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 20
Qld	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – 67% @ 20 years, 47% @ 35, CF @ 45
Qld	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 20
Qld	Southern Pine (P. elliotti, P. taeda, Araucaria cunninghamii)	440	52	51	52	53	46	49	All Sites – 35% @ 18 years, CF @ 35
South Australia	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 20
South Australia	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 15
South Australia	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 25
South Australia	Pinus (other than radiata)	440	52	51	52	53	46	49	Average Sites – 54% thinning @ 13 years, 25% @ 18, 28% @ 23, CF @ 30
Tasmania	Eucalyptus nitens	550	52	47	52	49	46	49	All Sites – CF @ 30
Tasmania	Eucalyptus nitens	550	52	47	52	49	46	49	All Sites – CF @ 15
Tasmania	Eucalyptus nitens	550	52	47	52	49	46	49	All Sites – CF @ 25
Tasmania	Pinus radiata	440	52	51	52	53	46	49	Average Sites – CF @ 35
Tasmania	Pinus (other than radiata)	440	52	51	52	53	46	49	All Sites – CF @ 35
Victoria (Central)	Pinus radiata	440	52	51	52	53	46	49	Average Sites -34% thinning @ 15 years, 18% @ 22, 24% @ 28, CF @ 35
Victoria (Central)	Pinus radiata	440	52	51	52	53	46	49	Average Sites – CF @ 30

Region(s)	Species	Density	CC% Leaf	CC% Branch	CC% Wood	CC% Bark	CC% Fine Roots	CC% Coarse Roots	Regime Description [a]
Victoria (Central Gippsland)	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 25
Victoria (Central Gippsland)	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 20
Victoria (Central Gippsland)	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 30
Victoria (Central Gippsland)	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 35
Victoria (Central Gippsland)	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 33% thinning @ 15 years, 37% @ 20, CF @ 30
Murray Valley	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 47% thinning @ 14 years, 35% @ 22, 29% @ 29, CF @ 30
Murray Valley	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 47% thinning @ 14 years, 35% @ 22, CF @ 30
Murray Valley	Pinus radiata	440	52	51	52	53	46	49	Very Good Sites – 44% thinning @ 14 years, 31% @ 18, 27% @ 23, CF @ 30
Victoria and NSW	Pinus radiata	440	52	51	52	53	46	49	Average Sites – CF @ 30 years
Victoria and NSW	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 65% thinning @ 16 years, CF @ 30
Victoria and NSW	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 65% thinning @ 16 years, 57% @ 24, CF @ 30
Victoria and NSW	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 65% thinning @ 16 years, 57% @ 24, 27% @ 30, CF @ 35
Victoria and NSW	Pinus radiata	440	52	51	52	53	46	49	Poor Sites – 26% thinning @ 18 years, 32% @ 24, CF @ 30
Victoria and NSW	Pinus radiata	440	52	51	52	53	46	49	Poor Sites – CF @ 30 years
Western Australia	Eucalyptus globulus	550	52	47	52	49	46	49	Clear fall @ 10
Western Australia	Pinus pinaster	470	52	51	52	53	46	49	Average Sites – 65% thinning @ 18 years, 37% @ 25, CF @ 40
Western Australia	Pinus radiata	440	52	51	52	53	46	49	Average Sites – 51% thinning @ 12 years, 39% @ 18, 32% @ 24, CF @ 35

(a) The default timing of Clear Fell (CF) elements in a regime are not used for post-1990 plantations where spatial imagery demonstrates a more accurate time of harvest for individual plantations. Planned improvement projects will extend this application to pre-1990 plantations in the future.

Estimating changes in soil carbon

Soil carbon is estimated using *FullCAM* operating in estate mode with a national soil carbon map (Viscarra-Rossel *et al.* 2014) (Appendix 6.E) as the base input data. *FullCAM* simulates changes in soil carbon using Roth-C soil carbon model. Roth-C model computes turnover of organic carbon in soils, taking into account clay content, temperature, moisture content, plant material inputs and plant cover.

Activity data

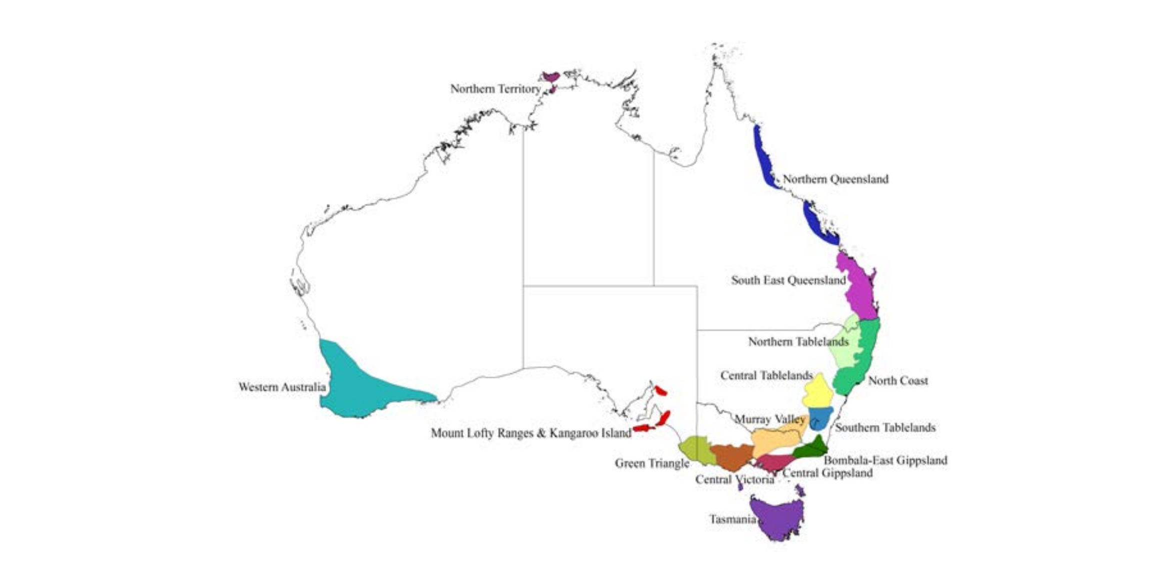
Activity data for *plantations* is sourced from the NPI, which provides area data in terms of plantation establishment and harvesting activity on this area. The plantation area data is reported on the basis of the 15 NPI regions (Figure 6.14). Three broad classes of forest are defined – Short Rotation Hardwood (SRH), Long Rotation Hardwood (LRH) and Softwood (SW). This data is subsequently annualised (cumulative area divided by number of years) from within the blocks of years reported by Spencer *et al.* (2001). Table 6.17 shows the plantation establishment activity derived through this method.

Allocations of the SRH, LRH and SW classes are made to the region and species specific plantation models as described by Turner and James (2002). Timing of harvesting and thinning is also based on region and species specific management practices.

Table 6.17 Areas of land converted to plantation from 1940-1989

Year	Area (ha)	Year	Area (ha)
1940	386	1965	15,684
1941	587	1966	18,017
1942	788	1967	20,351
1943	989	1968	22,689
1944	1,191	1969	25,014
1945	1,099	1970	27,352
1946	1,346	1971	28,520
1947	1,593	1972	29,687
1948	1,840	1973	30,854
1949	2,087	1974	32,021
1950	2,415	1975	32,119
1951	2,498	1976	32,281
1952	2,581	1977	32,605
1953	2,664	1978	32,281
1954	2,747	1979	32,119
1955	2,743	1980	29,489
1956	2,828	1981	27,853
1957	2,913	1982	24,581
1958	2,998	1983	27,853
1959	3,083	1984	29,489
1960	6,311	1985	31,125
1961	8,651	1986	32,761
1962	10,991	1987	34,397
1963	13,331	1988	36,033
1964	15,671	1989	37,669

Figure 6.14 The National Plantation Inventory regions



6.4.1.3 Other native forests

Wildfire emissions and removals are estimated using a Tier 2 method with an Approach 3 representation of lands (spatially explicit model tracking areas of vegetation burned and recovery from fires in previous years).

The same methods, factors and data are used to estimate emissions and removals from fire in sparse woody vegetation in the grassland land category to ensure consistent estimation of emissions and removals across land classifications.

Stratification of forests

Other native forests are stratified into three geographic / climatic zones where fires demonstrate significantly different behaviour.

a) Tropical zone forests – the northern part of the Northern Territory (NT), Western Australia (WA) and Queensland (Qld), is characterised by wet/dry tropical woodland and higher rainfall than the arid centre and is known as the 'Top End'. The Top End corresponds to the Interim Biogeographic Regionalisation for Australia (IBRA)[2] version 4.1 zones AEZ 1, AEZ 2 and AEZ 3 which are predominantly woodland with smaller areas of open forest and grassland;

b) The open woodlands and grasslands of the arid interior of central Australia ('the Centre') comprise AEZ 5, AEZ 6 and AEZ 11 of the NT, WA, Qld, South Australia (SA) and New South Wales (NSW) and these zones are used as the inventory definition of subtropical and semi-arid zone forests; and

c) Temperate forests – comprising forests in zones AEZ4 and AEZ zones 7-10.

Tropical zone forests are further disaggregated into ten vegetation classes (Table 6.18). These classes are derived using a combination of validated vegetation, land use and geological data sets (Lynch *et al.* 2015; Meyer and Cook, 2015).

2 IBRA is a framework used for sustainable resource management and conservation planning. The 80 IBRA regions in IBRA version 4.1 represent a landscape-based approach to classifying the land surface from a range of continental data on environmental attributes such as vegetation, geology, soils and climate. Background information and a map of the IBRA regions is available at www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra/index.html

Table 6.18 Symbols used in algorithms for biomass burning of forest land

State (i)	Vegetation Class (j)	Rainfall Zone (k)	Fire Variant (l)	DOM size class (m)
1 = ACT	1 = Wet/dry tropical zone		1 = Early Dry Season (EDS)	1 = Fine
2 = NSW	1a = Woodland hummock	1 = High	2 = Late Dry Season (LDS)	2 = Coarse
3 = NT	1b = Shrubland hummock	1 = High	3 = Other fire	3 = Heavy
4 = SA	1c = Woodland mixed	1 = High	4 = Temperate Wildfire	4 = Shrub
5 = Tas	1d = Open forest mixed	1 = High	5 = Temperate Controlled burning	5 = Aggregated
6 = Qld	1e = Melaleuca woodland	1 = High		
7 = Vic	1f = Shrubland (heath) with hummock grass	2 = Low		
8 = WA	1g = Woodland with mixed grass	2 = Low		
	1h = Open woodland with mixed grass	2 = Low		
	1i = Woodland with tussock grass	2 = Low		
	1j = Woodland with hummock grass	2 = Low		
	2 = Subtropical and semi-arid zone	3 = NA		
	3 = Temperate zone	3 = NA		

Carbon stock changes

The main processes leading to emissions and removals in these forests are related to fire management practices, which affect the DOM pool. It is assumed that living biomass stocks and soil carbon in these forest areas are in equilibrium, with annual increments balanced by annual losses.

Accordingly, changes in carbon stocks in other native forests are calculated in accordance with Equation 2.18 of the IPCC 2006 Guidelines (Volume 4) for estimating annual change in carbon stocks in dead wood or litter for areas remaining in a land-use category:

$$\Delta C_{DOM} = \Sigma_{ijklm} (A \times (DOM_{in} - DOM_{out}) \times CF) \qquad (4.A.1\_3))$$

Where Subscripts $_{ijklm}$ are the dimensions over which DOM is stratified for the purposes of this estimate (see table 6.18)

ΔC_{DOM} = annual change in carbon stocks in the DOM pools;

A = area of land remaining in land-use catgory

DOM_{in} = average annual transfer of biomass into the dead wood / litter pool due to annual processes and disturbances (Eqn 4.A.1.4);

DOM_{out} average annual carbon loss out of dead wood or litter pool (Eqn 4.A.1.8)

CF = carbon content (Appendix 6.K.7);

DOM stocks ($DOM_{ijkm\ t}$ kt/ha) are dependent on vegetation class, DOM pool size class, and fire interval.

Where supported by empirical data, the default IPCC DOM classes of litter and dead wood are further disaggregated into fine (grass and leaf litter <6mm), coarse (6mm – 50mm), heavy (>50mm) and shrub (live herbs and shrubs) (Appendix 6.K.4). These DOM classes are modelled at different levels of aggregation based on climatic zones, as shown in table 6.19.

Table 6.19 Disaggregation and reporting of DOM classes by climate zone

Climate zone	Total DOM				
	Aggregate	Litter		Deadwood	
		Fine	Shrub	Coarse	Heavy
Wet/dry tropical zone	NA	R	R	R	R
Subtropical and semi-arid zone	R	NA	NA	NA	NA
Temperate zone	R (grasslands)	R (forest lands)		R (forest lands)	

R: stock changes are reported for this DOM class.

The average annual transfer of biomass into the debris pool reflects annual processes and the rate of recovery in carbon stocks across the landscape following disturbance. This is determined from the disturbance history for each location (carbon stocks recover more quickly in the initial years following fire) and the vegetation class.

The average annual net transfer of biomass into the debris pools (DOM_{in} kt) is calculated from the increment in DOM stocks prior to considering losses due to disturbances in the reporting year:

$DOM_{in\ ijklm,YSLB} = (DOM_{ijklm,YSLB\ t} - DOM_{ijklm,YSLB\ t-1})$ .... (4.A.1_4))

Where $DOM_{ijklm,YSLB\ t}$ = dead wood / litter stocks prior to disturbances in the reporting year (t DM / ha) as calculated in equations 4A.1_5-7;

$DOM_{ijklm,YSLB\ t-1}$ = dead wood / litter stocks at the end of the previous reporting year (t DM / ha) as calculated in equations 4A.1_5-7; and

$_{YSLB}$ = age class of DOM stocks based on the number of years since last burned.

DOM stocks prior to disturbance vary with past fire frequency (Equations 4A.1_9 to 11) and are modeled using a non-linear Olson curve which describes initially rapid recovery after fire, followed by slower accumulation. The basic recovery curve is modified to consider incomplete combustion during fires, by accounting for residual DOM stocks remaining after burning (see Equations 4A.1_7 and 8).

Stocks of fine litter are calculated from the accumulation of litter and biomass as:

$DOM_{ijklm=1,\ t} = (L_{ijklm}/D_{ijkm} \times (1 - e^{-Dt}) + DOM_{0,ijklm} \times e^{-Dt}) \times Gc_{ijkm} \times 10^{-3}$ .... (4A.1_5)

Where $DOM_{0,\ ijklm}$ = average residual DOM stocks remaining (Kt) after burning (t = 0 (YSLB)) (Appendix 6.K.1)

L_{ijklm} = average annual rate of fresh litter input (Appendix 6.K.1);

D_{ijkm} = average decay constant (Appendix 6.K.1);

Gc_{ijkm} = Grass biomass adjustment factor (value of 1 for temperate forests) (Appendix 6.K.1);

t = years since the last burn (YSLB).

The coarse and heavy DOM stocks are calculated as:

$DOM_{ijklm=2,3,\ t} = (L_{ijklm}/D_{ijkm} \times (1 - e^{-Dt}) + FL_{0,ijklm} \times e^{-Dt}) \times 10^{-3}$ .... (4A.1_6)

Where $DOM_{0,\ ijklm}$ = average residual DOM stocks (Kt) remaining after burning (t = 0 (YSLB)) (Appendix 6.K.2 and 3)

L_{ijklm} = average annual rate of fresh litter input (Appendix 6.K.2 and 3);

D_{ijkm} = average decay constant (Appendix 6.K.2 and 3);

t = years since the last burn (YSLB).

In temperate forests, where repeat burning is uncommon, DOM stock at the time of the fire is assumed to be at equilibrium. This equilibrium (or 'steady state') stock level in the absence of fire is given by:

$$DOM_{SSijklm} = (L_{ijklm} / D_{ijkm}) \times 10^{-3} \quad \text{(4A.1\_7)}$$

Where $DOM_{ss\ ijklm}$ = steady state stock level (Kt) in the absence of disturbances

L_{ijklm} = average annual rate of fresh litter input (Appendix 6.K.1);

D_{ijkm} = average decay constant (Appendix 6.K.1).

For some components of DOM stocks (i.e. grasses, fine and shrub components) the carbon lost during the fire is assumed to recover within a few months to a few years, so there is no net change in carbon stocks. Non-CO_2 emissions are estimated and reported for all DOM classes as these fluxes are not recovered in subsequent re-growth.

The average annual disturbance carbon loss (DOMout Kt / ha) is calculated as:

$$DOM_{out} = DOM_{ijklm,t} \times P_{kl} \times BEF_{jklm} \times 10^{-3} \quad \text{(4.A.1\_8)}$$

Where: $DOM_{ijkm,t}$ = dead wood / litter stocks at the time of the fire (t DM / ha) as calculated in equations 4A.1_5-7;

P_{kl} = patchiness of the fire (Appendix 6.K.5);

BEF_{jklm} = burning efficiency of the fire (Appendix 6.K.6);

Burning efficiencies

The amount of DOM loss during a disturbance depends on the fraction exposed to flame that is volatilised (completeness of combustion or burning efficiency (BEF)), and the fraction of overall fire-affected area that is actually burnt, i.e. the fire patchiness (P).

In the wet/dry tropical zone, fires are classified by the season of burning as either early dry season (EDS) or late dry season (LDS). EDS fires are characterised by low intensity or severity, a high degree of patchiness, a greater propensity to extinguish spontaneously and reduced total DOM consumption. LDS fires are characterised by high intensity, low levels of patchiness, a greater propensity to spread and high total DOM consumption. For the vegetation classes burning efficiency is a function of seasonality, severity of fire and DOM stock size class.

The average date of transition from EDS to LDS is the last day of July. This date is based on indigenous fire management practices and observations of the seasonal patterns of fire behaviour (C. Meyer, J. Russell-Smith pers. comm.). On average, changes in ambient humidity and wind speed at this time are sufficient to support fire propagation through the night; which allows fires to spread for several days and to reach high intensities (Haynes 1985; Russell-Smith *et al.* 1997).

For subtropical and semi-arid forests, burning efficiencies are assumed to be constant from year to year and throughout the year. In temperate forests, while different burning efficiencies are applied for prescribed fires and wildfires, these are not further disaggregated based on seasonality.

Emissions factors

The emission factors used in the Australian methodology are derived from direct field measurements from fires across Australia (Meyer and Cook 2015; Roxburgh *et al.* 2015; Meyer *et al.* 2012; Hurst *et al.*1994a, b) Table 6.K.10 to Table 6.K.12.

Non-CO_2 emissions

For CH_4, CO, and NMVOCs calculate emissions as:

$$E = \Sigma_{ijklm\ YSLB} (A \times DOM_{out\ ijklmYSLB} \times CC_{jkm} \times EF_{g,jkm} \times C_g) \quad (4A.1\_9)$$

and for NO_X, N_2O:

$$E = \Sigma_{ijklm\ YSLB} (A \times DOM_{out\ ijklmYSLB} \times CC_{jkm} \times NC_{jkm} \times EF_{g,jkm} \times C_g) \quad (4A.1\_10)$$

Where E = emissions from fires (Gg);

A = Area of land remaining in land-use category

$DOM_{out\ ijklm}$ = DOM losses in fire (Gg);

CC_{jkm} = carbon content (Appendix 6.K.7);

NC_{jkm} = nitrogen:carbon ratio (Appendix 6.K.8);

$EF_{g,jkm}$ = emission factor (g N or C emitted as trace species / g DOM N or C emitted) (Tables 6.K.10 - 6.K.12);

C_g = elemental to molecular mass conversion factor (Appendix 6.K.9); and

$_{YSLB}$ = age class of DOM stocks based on the number of years since last burned.

Identification of natural disturbances

The fire-adapted ecology of Australian eucalypt-dominated forests leads to infrequent, extreme wildfires. Such natural disturbances are beyond the control of, and not materially influenced by, Australian authorities and occur despite costly and on-going efforts across regional and national government agencies and emergency services organisations to prevent, manage and control natural disturbances to the extent practicable.

Under the Tier 3 method applied in this inventory, natural disturbances are explicitly identified in the activity data. The net effects of natural disturbances on carbon are explicitly modelled to average out over time leaving greenhouse gas emissions and removals from anthropogenic fires as the dominant result in the national inventory (IPCC 2006 Volume 4 1.5).

Natural disturbances evident in the activity data are identified in two steps, summarised in Table 6.21.

First, at the national level, emissions from the area burned are assessed on a year by year basis for extreme fire events where outcomes at the national level were beyond the control of authorities to manage. This is done by comparing each year's data with a threshold level or 'margin' based on two standard deviations above the mean of gross annual emissions from all fires and after iteratively excluding outliers. The national natural disturbance threshold is calculated for the calibration period of 2000–2012.

Second, once natural disturbance years are identified at a national level, natural disturbances are spatially identified and the area burnt tracked at the sub-national level. Natural disturbances at the State and Territory level were identified where the area burned during their local fire season exceeded a State or Territory natural disturbance threshold equal to the average area of the calibration period plus one standard deviation of the non-natural disturbance years.

Natural disturbance areas are identified at the level of each State or Territory for a year in which both the area burned exceeds the State or Territory natural disturbance threshold and the national emissions from total area burned exceeds the national natural disturbance threshold. Anthropogenic emissions and removals are estimated using the time series of area burned in anthropogenic fire in each State or Territory. A modelling approach is applied to ensure that emissions and subsequent removals from non-anthropogenic natural disturbances average out over time, leaving greenhouse gas emissions and removals of anthropogenic fires as the dominant result.

The methodology for identifying natural disturbance events does not preclude long-term changes in fire management practices (such as prescribed burning) affecting trends in anthropogenic emissions and removals.

Wildfires that constitute natural disturbances are reported in Table 6.20.

Table 6.20 Forest wildfire and natural disturbance areas, Australia, ha, 1990–2015

Year	Natural disturbances	Temperate wildfire	Tropical & semi-arid forest fire
1990	0	238,803	5,427,724
1991	0	232,235	5,148,739
1992	0	220,218	4,862,122
1993	0	230,751	4,734,125
1994	743,809	154,873	4,293,540
1995	0	115,832	4,551,356
1996	0	144,103	4,914,587
1997	0	175,101	5,107,310
1998	0	147,937	5,235,060
1999	0	212,872	5,708,007
2000	0	240,964	5,881,600
2001	0	202,456	5,623,143
2002	527,716	197,588	5,864,842
2003	2,555,271	234,747	5,922,766
2004	0	193,210	5,285,589
2005	0	237,739	5,192,219
2006	0	300,616	5,586,003
2007	1,287,562	377,969	5,842,115
2008	0	341,633	6,216,698
2009	0	317,511	6,642,211
2010	796,220	333,262	6,926,862
2011	0	312,043	7,458,970
2012	0	231,923	7,121,608
2013	501,254	267,013	7,246,713
2014	1,019,871	255,327	7,844,042
2015	0	177,970	7,240,831

Table 6.21 Calculations for the natural disturbance test in States and Territories, 1990–2015

	Calibration period	Calculation details	Threshold	Number of natural disturbance years 1990-2015
Step 1: National Level Test	2000-2012	Applied to: gross emissions (not including removals). Threshold calculation: mean plus two standard deviations of calibration period.	28,890 Kt CO_2-e	8
Step 2: Regional test	2000-2012	Only applies in national outlier years (following Step 1 test). Applied to: annual area burned. Threshold calculation: mean area burned plus one standard deviation of background (non-outlier) years.		
ACT			8.94 kha	1
NSW			141.31 kha	5
Qld			184.93 kha	3
Tas			25.54 kha	2
Vic			276.12 kha	3
SA			50.57 kha	2
WA			333.24 kha	3

All fire areas are monitored for any permanent change in land use, which would trigger reporting of emissions in the appropriate land conversion category. Emissions from salvage logging are reported as part of *harvested native forests*.

To ensure the transparency and demonstrate complete reporting of anthropogenic and natural disturbance emissions and removals, the following additional information has been included:

1. Identification of lands subject to natural disturbances and monitoring for forest recovery
2. Monitoring for land-use changes to ensure that no land-use change has occurred on lands subject to natural disturbances
3. Demonstrating practicable efforts to prevent, manage and control wildfires in Australia
4. Inclusion of salvage logging emissions.

1. Identification of lands subject to natural disturbances and monitoring for forest recovery

A monitoring system based on the Advanced Very High Resolution Radiometer (AVHRR) has been implemented to identify and map natural disturbance impacts due to wildfire on forest lands. The system has been designed to comply with the following safeguard mechanisms:

- the use of geolocated time series wildfire activity data,
- coverage of all forest lands,
- the ability to monitor if there is a permanent land use change on those lands following a wildfire event during the commitment period,
- the inclusion of emissions associated with salvage logging in the accounting, and
- identification of lands where the natural disturbance is followed by another disturbance event, in order to avoid double counting.

The AVHRR burnt area product produced by the Western Australian Land Authority (Landgate), is tailored to Australian conditions and based on the visual interpretation of fire areas by experienced operators. The data was assessed by the Royal Melbourne Institute of Technology (RMIT) 2014, and compared with a range of alternative datasets, and was found to be the most suitable and highest quality time series data available

2. Monitoring for land-use changes to ensure that no land-use change has occurred on lands subject to natural disturbances

All forest land is monitored for harvesting and land-use change events. Where forest cover loss events are identified, these areas visually attributed by experienced operators to either direct, human-induced land-use change, or a temporary forest loss which does not constitute land-use change such as harvesting, fire and other non-anthorpogenic disturbance.

3.Demonstrating practicable efforts to prevent, manage and control wildfires in Australia

In Australia, wildfires threaten life and property, and are addressed in disaster response plans and management arrangements in each state and territory. Common frameworks for national, state and territory fire management policies include: reducing the likelihood of fires occurring, for example through fuel reduction burning and fire bans; managing or controlling the fire during its occurrence; monitoring programs and early warning systems; and fire fighting operations. In addition to such disaster management policies, there is also a significant research effort into understanding and better managing wildfires, and following many significant fire events, inquests or enquiries are held to assess the disaster response and potential for improvement.

There are fire management policies and plans in place at the national and the state and territory level to control for the risks, events and consequence of wildfire to the extent that this is possible. These documents set out frameworks for:

- Reducing the likelihood of a wildfire occurring, for example, through the use of prescribed burning;
- Managing or controlling the disturbance during its occurrence;
- Monitoring programs and early warning systems; and
- Fire fighting operations.

The implementation of plans and strategies to avoid and minimise risks to life and property from wildfires is documented in the following section.

National level

The National Bushfire Management Policy Statement for Forests and Rangelands (FFMG 2014)[3] outlines Australian, state and territory government objectives and policies for the management of landscape-level fire in Australia's forests and rangelands. The statement was developed by the Forest Fire Management Group, a national body within the Council of Australian Governments, with the role of providing information to governments on major forest fire-related issues, policies and practices affecting land management. The Australasian Fire and Emergencies Authorities Council is the national peak organisation that provides advice on a range of polices and standards. Research on bushfires is performed by a number of organisations, including:

- the Bushfire Cooperative Research Centre, which brings together experts from universities;
- the Commonwealth Scientific and Industrial Research Organisation (CSIRO);
- other Australian, state and territory government organisations, and;
- the private sector for long-term programs of collaborative research.

The national Bureau of Meteorology publishes fire weather warnings and has a role in the declaration of fire bans when weather conditions are conducive to the spread of dangerous bushfires. Warnings are generally issued within 24 hours of the potential onset of hazardous conditions. Warnings are also broadcast on radio and television.

3 https://www.semc.wa.gov.au/riskmanagement/Documents/NationalBushfireManagementPolicy_2014.pdf

Fire agencies determine Fire Danger Ratings. In most States and Territories, fire agencies declare fire bans based on a range of criteria including forecast weather provided by the Bureau.

The Bureau also incorporates Total Fire Ban Advices into warnings, if one is being enforced at the time of issue, and an action statement from local fire authorities detailing areas where the ban is in effect.

Fire Weather Warnings are distributed through the media, fire agencies and other key emergency service organisations. Warnings are normally issued in the afternoon for the following day so to be available for evening television and radio news broadcasts. Warnings are renewed at regular intervals and generally at the same time major forecasts are issued. However, warnings may be issued or amended and reissued at any time if a need is identified. If there is a Fire Weather Warning current, the Bureau will mention this in State, Territory and District weather forecasts for that area.

In each State the issue of a Fire Weather Warning has different impacts on restrictions for lighting fires.

The Bureau of Meteorology does not have the power to declare a Total Fire Ban. This responsibility resides with designated fire agencies in each State and Territory. However, in South Australia, Northern Territory, Victoria, New South Wales and Tasmania, the Bureau does issue Total Fire Ban Advices to assist publicising and distributing the message. The Bureau also includes information about the existence of current fire bans in weather forecasts and warnings.

The areas covered by fire bans do not align with Bureau forecast districts in New South Wales, Tasmania and Northern Territory.

State and territory level

Each state and territory has published a document which sets the framework for the management of bushfires. These plans include information on the use of public information campaigns and requirements around the declaration and publication of fire bans and fire danger ratings during fire seasons. In Queensland the documents are published for a number of regions within the state, rather than at the state level.

New South Wales

The aim of the State Bush Fire plan is to set out the arrangements for preparedness, prevention, mitigation, response to and recovery from bush fire events by combat, participating and support agencies in NSW.

This plan describes the arrangements for the control and coordination of the response to Class 2 and 3 bush and grass fires, including those managed under the provisions of section 44 of the Rural Fires Act 1997 (RF Act), and the provisions for emergency warnings at all classes of fires.

These arrangements ensure that the two combat agencies, New South Wales Rural Fire Service (NSW RFS) and Fire & Rescue NSW (FRNSW), are able to manage bush and grass fires, utilising assistance from the other fire fighting authorities being the National Park & Wildlife Service (NPWS) and Forestry Corporation NSW (FCNSW).

The NSW State Bush Fire plan is available here:
https://www.emergency.nsw.gov.au/publications/plans/sub-plans/bush-fire.html

Victoria

Victoria's State Bushfire Plan provides an overarching view of responsibilities of agencies, government and communities in bushfire management.

The first version of the State Bushfire Plan was developed in 2012 in conjunction with the Country Fire Authority, the Metropolitan Fire Brigade, the Department of Environment and Primary Industries and the Fire Services Commissioner.

The second version of the State Bushfire Plan was produced in 2014, with updates to reflect the changes in Victorian emergency management legislation and the emergency management sector.

The plan reflects an integrated approach and shared responsibility for bushfire management between government, agencies, business, communities and individuals.

Although intended as a reference document for fire and emergency management agencies, the State Bushfire Plan will be of equal interest to anyone who works or volunteers in bushfire management.

The State Bushfire Plan is a sub-plan of the State Emergency Response Plan (SERP), found in the Emergency Management Manual of Victoria (EMMV), the principal document for guiding the State's emergency management arrangements.

Victoria's State Bushfire Plan is available here:
http://www.emv.vic.gov.au/plans/state-bushfire-plan/

Queensland

In Queensland, fire management policies and plans are developed at regional rather than at the state level. The Queensland government provides an overview of the approach to disaster management in Queensland here: http://www.disaster.qld.gov.au/

Western Australia

Western Australia has developed a series of State Emergency Management Plans (Westplans) including an integrated urban and bushfire management plan. The plan is available here:
https://www.semc.wa.gov.au/Publications%20and%20Resources/Westplan%20-%20Fire.pdf

South Australia

The South Australian State Emergency Management Plan is available here:
http://www.safecom.sa.gov.au/site/emergency_management/emergency_management_arrangements/state_emergency_management_arrangements.jsp

Tasmania

Tasmania's state fire protection plan is available here:
http://www.fire.tas.gov.au/userfiles/stuartp/file/Publications/StateFireProtectionPlanVersion2_2.pdf

Northern Territory

Bushfire management and control in the Northern Territory is managed through the framework provided by the Regulations under the Bushfires Act (1980). The regulations are available here:
http://notes.nt.gov.au/dcm/legislat/legislat.nsf/2afcb7bfe1e1348e6925705a001697fb/f809e4153030055269257d9000221450/%24FILE/ATTTAP7M.pdf/Repb004R2.pdf

Australian Capital Territory

The Standard Operating Procedures of the ACT Rural Fire Services provide the framework for the management of bushfires in the ACT. The Standard Operating Procedures are available here:
http://esa.act.gov.au/actrfs/publication-and-links/standard-operating-procedures/

4. Inclusion of salvage logging emissions.

Emissions from salvage logging are included in estimates for *harvested native forests* and *pre-1990 plantations*. Estimates of forest harvesting are based on log production information that includes the products of salvage logging. These production statistics do not differentiate between material sourced from conventional clear felling and salvaging activities following wildfire or other natural disturbances.

A review of salvage harvesting by ABARES (Finn *et al.*, 2015) identified that this is a very minor activity compared to either total harvesting activity or total areas burned. Salvage harvesting is generally opportunistic, determined as much by commercial factors as biophysical factors.

6.4.1.4 Fuelwood

Emissions of CO_2 from the consumption of *fuelwood* are estimated using data on the residential consumption of wood and wood-waste obtained from the Department of Industry and Science. Carbon stocks lost through emissions from consumption of fuelwood from the residential sector are assumed to be collected from DOM in forests. To ensure no double counting with modeled decay or fires affecting the DOM pool, these instant losses through fuelwood consumption are offset against an Olson fuel accumulation curve ($T_{95\%}$ = 11 years).

There is no double counting of *Fuelwood* between the *LULUCF* and Energy sectors as emissions from biomass consumption are provided as an information item but are not reported as emissions in the Energy sector.

6.4.2 Emission estimates

Anthropogenic emissions and removals from *forest land remaining forest land* are shown in Table 6.22.

Table 6.22 Emissions and removals from forest land remaining forest land (1990-2015) (Gg CO_2-e)

Year	Harvested native forests	Plantations	Other native forests	Fuelwood	Total
1990	-4,767	-12,234	3,967	446	-12,588
1995	-1,287	-12,054	1,215	501	-11,625
2000	-1,040	-2,327	3,314	244	191
2005	-2,837	1,629	4,209	-419	2,582
2006	-7,575	6,173	6,478	-491	4,585
2007	-7,392	5,446	9,244	-555	6,743
2008	-6,085	5,127	7,315	-612	5,746
2009	-10,204	8,051	6,354	-664	3,537
2010	-15,326	4,918	6,832	-712	-4,288
2011	-16,865	4,850	6,119	-756	-6,652
2012	-24,353	7,124	541	-576	-17,264
2013	-27,964	5,983	2,626	-439	-19,794
2014	-28,405	5,850	3,810	-414	-19,159
2015	-29,242	6,847	-49	-465	-22,909

6.4.3 Uncertainties and time series consistency

Uncertainties for the *forest land remaining forest land* sub-category are estimated to be ±33.5% for CO_2. The majority of this uncertainty is due to the *other native forest* sub-division. Uncertainty in the *plantations* is expected to be less than 10 per cent. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

6.4.4 Source Specific QA/QC

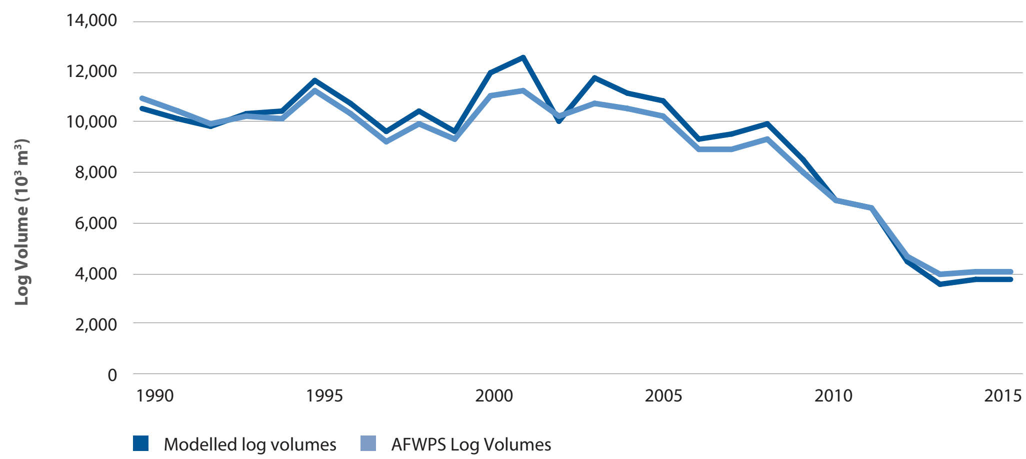
6.4.4.1 Harvested native forests

Data on native forest harvesting is derived from roundwood log volumes for each state (ABARES, 2015a) using a historical relationship between roundwood removals and harvest area data collated by state agencies. Roundwood log volumes are published in the biannual Australian Forest and Wood Products Statistics report (ABARES, 2015a), a comprehensive dataset relating to Australia's forestry sector, including time series data on forest and wood products resources, production, consumption, trade and employment. Historical harvest area data was obtained from a combination of annual reports of Australian State agencies, financial statements, and spatial harvest area data. These data sets have been subject to review processes and financial auditing.

Data on stem to whole tree conversions, carbon contents and wood densities are within the ranges published in Gifford, 2000a; Gifford, 2000b; Ilic *et al.* 2000; and Snowdon *et al.* 2000. The estimated slash produced by forest harvesting is in line with independent studies of slash production from forest harvesting for major Australian harvested forests (Snowdon *et al.* 2000; Ximenes *et al.* 2008a).

The *harvested native forests* model was verified by comparing the log volume, calculated using the harvested native forest model used for emissions estimation with national statistics of round wood production in native forest, (ABARES, 2015a) (Figure 6.15). The log volume from the *harvested native forest* model was estimated by converting the carbon removed from forests as forest products to stem volume, assuming a stemwood carbon percentage of 50 per cent and average wood basic density of 800 kg m-3. The modelled log volumes closely track the published statistics over time.

Figure 6.15 Estimated removals in Harvested Native Forests, *FullCAM* model outputs compared to national harvesting statistics (ABARES, 2015a)



6.4.4.2 Plantations

Biomass (including the effects of ongoing management) and soil carbon are estimated using *FullCAM* operating in estate mode (Tier 2). It comprises of 34 models implementing the tree yield formula.

The calibration and validation of the *FullCAM* model, along with the associated quality assurance and quality control program are described in Appendix 6.B. An independent review of the models used to estimate emissions and removals in the *plantations* category was undertaken by CSIRO in 2001.

6.4.4.3 Other native forests

The reporting of net emissions from other native forests, in particular anthropogenic wildfires in temperate forests, has been subjected to independent review (Federici, 2016a).

The identification and separation of non-anthropogenic natural disturbances in temperate forests results in both carbon dioxide emissions and removals from natural disturbances averaging out over time without impacting anthropogenic net emissions.

Over time, net emissions of CO_2 from non-anthropogenic emissions and subsequent removals will approach zero, as shown in the historical accounting and projections of Table 6.23, demonstrating that the approach neither over- nor under-estimates net emissions in the long term. Over the 50 years from 1983–2032, the average net carbon dioxide emissions from natural disturbances is zero.

Natural disturbance emissions and removals are not in exact balance over the 1990-2014 period due to a number of recent disturbances from 2007 to 2014, recovery from which is ongoing. Given the Olson curves used for DOM recovery, it is projected to take between 7 and 22 years without further disturbance for average net emissions to equal zero. For this reason, a modelling approach is used to ensure that these natural disturbances net emissions and removals average out within the reporting timeframes.

Table 6.23 Balancing of natural disturbance CO_2 emissions and removals

Year	Natural disturbance CO_2 removals	Natural disturbance CO_2 emissions
	Mt CO_2	
1983	0.00	45.22
1984	-13.66	0.00
1985	-9.32	0.00
1986	-6.44	0.00
1987	-4.50	0.00
1988	-3.17	0.00
1989	-2.25	0.00
1990	-1.74	0.00
1991	-1.10	0.00
1992	-0.80	0.00
1993	-0.59	0.00
1994	-1.45	34.51
1995	-7.21	0.00
1996	-5.53	0.00
1997	-4.28	0.00

Year	Natural disturbance CO_2 removals	Natural disturbance CO_2 emissions
	Mt CO_2	
1998	-3.35	0.00
1999	-2.66	0.00
2000	-2.06	0.00
2001	-1.64	0.00
2002	-1.32	25.52
2003	-8.17	110.74
2004	-33.21	0.00
2005	-25.08	0.00
2006	-18.13	0.00
2007	-13.53	46.23
2008	-22.36	0.00
2009	-16.61	0.00
2010	-12.37	34.53
2011	-17.27	0.00
2012	-12.38	0.00
2013	-9.81	20.02
2014	-16.36	40.74
2015 (projected)	-21.42	0.00
2016 (projected)	-15.47	12.08
2017 (projected)	-15.20	0.00
2018 (projected)	-11.39	0.00
2019 (projected)	-6.64	0.00
2020 (projected)	-4.91	0.00
2021 (projected)	-3.52	0.00
2022 (projected)	-2.56	0.00
2023 (projected)	-2.15	0.00
2024 (projected)	-1.59	0.00
2025 (projected)	-2.84	0.00
2026 (projected)	-0.52	0.00
2027 (projected)	-0.44	0.00
2028 (projected)	-0.37	0.00
2029 (projected)	-0.48	0.00
2030 (projected)	-0.24	0.00
2031 (projected)	-0.21	0.00
2032 (projected)	-1.28	0.00
Total (1983 - 2032)	-369.60	369.60
1990-2014 net average	2.9	
1983-2032 net average	0.0	
1990-2014 net standard deviation	27.1	

All fire areas are monitored for any permanent change in land use or salvage logging (which, if identified, would trigger reporting of emissions in forest conversions or harvested native forests, respectively).

No systematic bias is introduced into the inventory by the separation of natural disturbances from anthropogenic fires. The approach does not introduce any artificial trend in reported emissions and removals (that is, it avoids the expectation of credits or debits).

The approach also improves the quality, accuracy and time series consistency of annual estimates by reducing the high levels of inter-annual variability in the time series. The coefficient of variation in the time series of fires including natural disturbances on forest lands is 3.74, after separation of non-anthropogenic emissions the coefficient of variation is reduced to 0.58.

6.4.5 Recalculations since the 2014 Inventory

The recalculations reported in the current submission are shown in Table 6.24 and include:

Harvested native forests and plantations

A. Recalculation of harvest attributable to deforestation events (resulting from recalculations described in section 6.9.5.1). As described in Section 6.4.1.1 areas that are identified as direct human induced forest conversions are excluded from *forest land remaining forest land*, and any harvesting associated with the conversion event is also excluded to avoid double-counting.

B. Implementation of new rounding policy for emission factor precision. This resulted in change to the precision of the emission factor used for direct emissions from nitrogen mineralisation in mineral soils.

C. Alignment of estimation periods for carbon stock estimates, consistent with Annex A sectors and other parts of forest land - for example biomass burning which was reported based on temperate fire seasons.

D. Data improvements (update to long term average climate data with 2015 information, affecting soil carbon).

Other native forests

E. Updated area of other native forests due to improvements in remote sensing and forest detection algorithms (for more information see geospatial monitoring enhancements described in Section 6.9.5.1), resulting in recalculation of net emissions.

Also contributing to the recalculation are other incidental changes resulting from the improvements listed above, for example nitrogen mineralisation and slash burning changes as a consequence of points A – E. above.

Table 6.24 Forest land remaining forest land: recalculation of total CO_2-e emissions (Gg), 1990–2014

Year	2016 submission	2017 submission	Change		Changes included in 2017 recalculation					
	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)	%	A. Recalculation of harvest attributable to deforestation events	B. Rounding policy	C. Alignment with sectoral estimation periods	D. Data improvements (climate long term average)	E. Updated area of other native forests (3 class CPN)	Other
1990	-11,678	-12,588	-910	-8%	177	3	681	47	-1,815	3
1995	-13,194	-11,625	1,569	12%	664	2	1,295	43	-456	-22
2000	993	191	-802	-81%	-41	2	-841	40	58	19
2005	802	2,582	1,780	222%	-825	1	2,436	39	105	-24
2006	5,173	4,585	-588	-11%	-862	1	24	38	230	20
2007	7,862	6,743	-1,119	-14%	-889	1	-523	38	285	31
2008	4,385	5,746	1,360	31%	-912	2	2,136	38	87	-9
2009	1,743	3,537	1,794	103%	-930	2	2,624	38	44	-16
2010	-4,438	-4,288	149	3%	-943	3	846	38	225	19
2011	-7,972	-6,652	1,320	17%	-959	2	3,614	38	-1,413	-38
2012	-16,710	-17,264	-554	-3%	-974	2	1,539	38	-1,156	3
2013	-18,434	-19,794	-1,361	-7%	-1,000	2	-28	38	-799	-428
2014	-16,768	-19,159	-2,391	-14%	-1,029	1	104	37	-2,388	-883

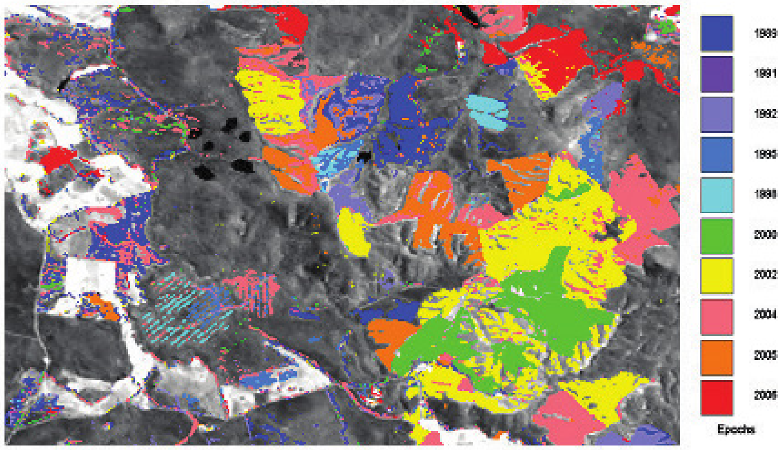
6.4.6 Source specific planned improvements

Harvest native forests and plantations

The Department of the Environment and Energy is continuing to develop capacity to have comprehensive use of Tier 3, Approach 3 modelling in the future for the *plantations* and *harvested native forests* sub-categories. This will allow incorporation of recent empirical research into aboveground biomass, allometrics, turnover and decay factors into the plantations and harvested native forests sub-categories.

A preliminary map showing the distribution of pre-1990 plantations has been developed which will be updated further based on remote sensing and other ancillary information.

Figure 6.16 An example of harvested area detection using Australia's time-series remote sensing data. Coloured areas represent detected harvest areas in a particular epoch



Other native forests

Analysis and testing is underway to assess the feasibility of moving towards a fully spatially explicit, Tier 3 model for estimating emissions from biomass burning using the *FullCAM* modelling system.

6.5 Land Converted to Forest Land (Source Category 4.A.2)

Land converted to forest land includes the sub-categories *grassland converted to forest land* and *wetlands converted to forest land*.

Grassland converted to forest land contains forest established on land that was previously non-forest. These conversions include plantations and regeneration from natural seed sources on land protected as forest by State or Territory vegetation management policies.

Wetlands converted to forest land comprises land on which mangrove forest has been detected to emerge on tidal marsh.

6.5.1 Methodology

6.5.1.1 Grassland converted to forest land

The emissions and removals from *grassland converted to forest land* are estimated using the spatially explicit (Approach 3) capabilities of the Tier 3 *FullCAM* modelling system. A full description of the modelling system is provided in Appendix 6.B and 6.D, and Waterworth *et al.*, 2007; Waterworth and Richards, 2008.

Reporting includes carbon in living biomass, dead organic matter (DOM) and soil pools.

The areas of *grassland converted to forest land* are drawn from remotely sensed data as per the methods described in Appendix 6.A. The time-series of Landsat satellite data (25 m) is analysed to provide the previous vegetation cover, area, time of establishment, time of harvesting and, if applicable, type of plantation (Caccetta and Chia, 2004).

Each individual 25 m × 25 m pixel identified as being a *plantation* is modelled through time from the time of establishment. Each 25 m × 25 m model takes into account the age, plantation type, management (including time of harvesting as detected from satellite imagery) and site conditions to estimate emissions and removals.

Estimating changes in living biomass

Forest growth

As described in detail by Waterworth *et al.* (2007), to estimate growth of above-ground biomass in Australian plantations, the generic forest regrowth model in FullCAM (Appendix 6.B and 6.D) is supplemented to include functions that represent Type 1 and Type 2 growth responses (Snowdon and Waring, 1984) and the impact of using non-endemic species (Appendix 6.F). Type 1 management practices advance or retard stand development (effectively age) but do not increase underlying site productivity over the life of the rotation (e.g. weed control at establishment). Type 2 treatments increase (or decrease) a site's carrying capacity in the longer term (e.g. phosphorus application).

The net emissions from land converted to forest through regeneration from natural seed sources are estimated using *FullCAM* operated in Approach 3 mode (Appendix 6.B and 6.D). The model is parameterised to model the growth of native forest vegetation from seed (Richards and Brack, 2004a, Fig. 2).

Partitioning of biomass and growth of below-ground biomass

FullCAM calculates below-ground biomass (coarse and fine roots) and the partitioning of above-ground biomass (stems, branches, bark and leaves), using an empirical approach as outlined by Paul *et al.* (2017). This method allows allocation to vary between tree species based on stand age (Table 6.25).

Table 6.25 Example of the different partitioning of biomass to each of the tree components under different types of plantation species. Estimates are provided for a stand age of 10 years

Forest Type	Fraction of biomass allocated to:					
	Stems	Branches	Bark	Leaves	Coarse roots	Fine roots
E. globulus; short rotation	0.41	0.20	0.07	0.09	0.19	0.04
E. nitens; long rotation	0.43	0.20	0.07	0.08	0.19	0.04
P. pinaster	0.37	0.11	0.05	0.06	0.32	0.08
P. radiata	0.51	0.15	0.07	0.07	0.16	0.03

Carbon contents

The carbon fractions of above and below ground biomass components for Australian vegetation are reported in Table 6.26 and taken from Gifford, 2000a and 2000b.

Table 6.26 Percent carbon of tree components – *land converted to forest land*

Tree Component	Hardwood carbon content %	Softwood carbon content %	Other (environmental plantings) carbon content %
Stems	50.0	51.0	50.0
Branches	46.8	51.4	46.8
Bark	48.7	53.3	48.7
Leaves	52.9	51.1	52.9
Coarse roots	49.2	50.4	49.2
Fine roots	46.1	48.4	46.1

Forest management practices

The Tier 3, Approach 3 modelling system is supported by a comprehensive database of the plantation management practices used in Australia since 1970 (Waterworth and Richards, 2008). The plantation management database contains information on management practices for each tree species within each region. The range of possible management actions is shown in Table 6.27. The management regimes are assigned frequencies within each region to enable time series management regimes to be developed for each plantation pixel through time (Table 6.28) (Waterworth and Richards, 2008).

Table 6.27 Management actions, the *FullCAM* events used to represent them and the choices available through parameterisation of the *FullCAM* event

Management action	FullCAM event type	Effect in model	Standard event options
Mechanical weed control	Plough (agriculture)	Moves herbaceous species carbon to debris, mulch and soil	Spot Strip Broadcast
Chemical weed control	Herbicide event (agriculture)	Kills herbaceous species cover, moving it to debris	Spot application Strip application Broadcast application
Chopper roll	Chopper roll (forest)	Transfers woody debris to faster decaying 'chopped wood' pool	Chopper roll
Management fires	Forest fire (forest)	Transfers carbon from trees to debris and atmosphere, and debris to the atmosphere or soil pools.	Prescribed burn Broadcast burn Windrow and burn
Wildfire[1]	Forest fire (forest)	Transfers carbon from trees to debris and atmosphere, and debris to the atmosphere or soil pools.	Trees killed Trees not killed
Grazing	Graze (agriculture)	Removes aboveground herbaceous species mass and varies root slough	Normal Heavy
Plant trees	Plant trees (forest)	Establishes trees on a site	Different initial masses depending on stocking
Cultivation	Plough (agricultural)	Moves herbaceous species carbon to debris, mulch and soil	Spot cultivation Strip cultivation Broadcast cultivation
Forest thin and harvest and pruning	Forest thin (forest)	Moves tree components to products or debris, debris to bioenergy	Varies by time, species and region.

Management action	FullCAM event type	Effect in model	Standard event options
Fertiliser application[2]	Type 1 or 2 event (forest)	Varies tree growth based on the type and intensity of fertilisation (see Snowdon, 2002).	Normal N fertilisation Applied to any treatment that affects tree growth
Fertiliser application[3]	Fertiliser application (forest and agriculture)	Adds N to the mineral N pool	Different levels of N addition (kg ha-[1])

Source: Waterworth and Richards (2008)
1 Although not a management practice, wildfire events allow for the future spatial modelling of their effect on carbon stocks. See the discussion for more details.
2 *FullCAM* only requires kg N ha^{-1} when using the nitrogen cycling model capacity.
3 Applies only when using the nitrogen cycling model capacity.

Table 6.28 Plantation management database – Time series management regime

Year	Day	Species	Management action	FullCAM event
0	152	Agricultural species	Cultivation: Strip plow	Plow
0	166	Agricultural species	Weed control initial: Blanket herbicide	Herbicide
0	196	Pinus radiata	Plant trees: seedlings normal stocking	Plant trees
0	196	NA	Forest percentage -> determined by tree yield formula	Forest percentage Change
0	196	Pinus radiata	Weed control – Standard (All 1980-present)	Type 1 Forest Treatment
0	196	Pinus radiata	Starter fertiliser – normal	Type 1 Forest Treatment
1	196	Agricultural species	Weed control post planting: Strip herbicide	Herbicide
10	196	Pinus radiata	Thin 1 (SthnTbl ACT 1978-1996)	Forest Thin
10	196	Pinus radiata	Fertilisation: Mid-rotation (Medium)	Type 1 Forest Treatment
10	197	Pinus radiata	Prune (Selective 33%)	Forest Thin
20	196	Pinus radiata	Thin 2 (SthnTbl ACT 1978-1996)	Forest Thin
20	196	Pinus radiata	Fertilisation: Mid-rotation (Medium)	Type 1 Forest Treatment
30	196	Pinus radiata	Thin 3 (SthnTbl ACT 1987-1996)	Forest Thin
See note	196	Pinus radiata	Thin clearing Pa (SthnTbl ACT 1987-1996)	Forest Thin

Note: The year of plantation harvesting is determined using satellite imagery.

The species table in *FullCAM* contains information on tree species characteristics including forest growth model parameters, carbon allocation to tree components over time, biomass carbon percentages, basic wood density, turnover rates for each tree component, decay and product use data. These data allow *FullCAM* to model forest growth for any point based on the site and climate data using the methods described previously.

Estimating changes in debris

Turnover and decomposition rates

The turnover rate of leaves and fine roots (Table 6.29) affects both the amount of fine litter on the forest floor and subsequently most of the contribution to soil carbon. The tree component turnover rates applied in the model are based on datasets reviewed by Paul *et al.* (2017). Decomposition rates determine the rates of loss of carbon back to the atmosphere as the debris breaks down.

The balance of these two factors determines the amount of debris on site, excluding the effects of management. The amount of carbon moved from living biomass to the DOM pools due to forest harvesting, and is determined in the model by the age, type of harvest and species characteristics.

Table 6.29 Tree component annual turnover rates

Tree Component	Turnover % yr^{-1}
Branches	8.5
Bark	4.8
Leaves; Softwood	31.2
Leaves; Hardwood	40.4
Leaves; Other Environmental Plantings	15.7
Coarse Roots	10
Fine Roots	80

The rates of decomposition (Table 6.30) are based on datasets reviewed by Paul *et al.* (2017).

Table 6.30 Debris decomposition rates

Debris Component	Breakdown Rate % yr^{-1}
Deadwood	14
Bark Litter	16
Leaf Litter, decomposable*	100
Leaf Litter, resistant* - softwoods	20
Leaf Litter, resistant* - non-softwoods	28
Coarse Dead Roots	30
Fine Dead Roots	100

* The fraction of leaf litter that was resistant was 77% and 85% for hardwood and softwood plantings, respectively.

Estimating changes in Soil Carbon

Soil carbon is estimated using the fully spatially explicit approach described in Appendix 6.B and Appendix 6.E, with a recent soil carbon map as the base input data for modelling post-1990 *plantations.*

Parameters governing the input of carbon to the soil following the decomposition of DOM are the fractions of decomposed DOM that is lost to the atmosphere as CO_2-C. The remaining decomposed DOM that is not lost as CO_2-C is predicted to enter the pools of soil C. Values for these parameters were calibrated using forest soil carbon studies as described by Paul *et al.* (2017).

Activity data

The activity data for the grass*land converted to forest land* classification is drawn from the remote sensing program(see Appendix 6.A) (Table 6.31).

Table 6.31 Cumulative area of *grassland converted to forest land* 1990–2015

Year	Area (ha)
1990	409,260
1995	1,057,836
2000	1,577,873
2005	2,247,038
2010	3,040,604
2011	3,329,672
2012	3,519,895
2013	3,668,554
2014	3,712,700
2015	3,826,836

6.5.1.2 Wetlands converted to forest land

The emergence of mangrove forest is identified using satellite imagery, as for the *grassland converted to forest* sub-category. Given mangrove forests are generally bordered by water on the lower side and salt marsh on the higher side, it is reasonable to assume that any emerging coastal mangrove forest does so on land which was previously tidal marsh.

Carbon dioxide emissions and removals are modelled using mangrove-specific parameter values in a Tier 2 Excel™based growth model. The changes in above- and below-ground biomass, soil carbon, and dead organic matter (as woody and non-woody litter) are captured using a sigmoidal equation. The equation, based on equation 8 in Yin *et al.* (2003) was modified to employ non-zero minimum values, according to the procedure of Shi *et al.* (2016):

$$W_t = [W_0 + (W_{max} - W_0) \times (1 + (t_{max} - t_t)/(t_{max} - t_{mg})) \times (t_t/t_{mg})^{tmax/(tmax-tmg)}] \times \text{Area converted},$$

where W_t = total mass at time t for AGB, BGB, Woody litter, non-Woody litter, or Soil organic carbon (SOC)

W_0 = initial mass per hectare

W_{max} = maximum mass per hectare

t_t = time t, years

t_{max} = time when maximum mass is reached, 30 years

t_{mg} = time when maximum growth rate is reached, 23 years

The minimum and maximum values for each parameter (Table 6.J.1) are established from the scientific literature. However times to maximum growth rate, and to maximum biomass, are established through interpretation of a single study that described mangrove development over time (Semeniuk, 1980). The developmental milestones were plotted against time and the transitions smoothed by generating a six order polynomial trend line in MS Excel™. Time to maximum growth rate (23 years) and time to maximum biomass (30 years) were then estimated against the trend line.

This equation was developed by the above authors to model biomass growth in individual plants. It is used in this model to estimate the annual change in mass of individual carbon pools associated with growing a mangrove stand from establishment to maturity. It is assumed that the value of each carbon pool is directly proportional to the mass of an even-aged and sized mangrove stand in which the trees continue to grow synchronously and without self-thinning.

Activity data

The activity data for the *wetlands* converted to forest land classification is drawn from the remote sensing program (see Appendix 6.A) (Table 6.32).

Table 6.32 Cumulative area of *wetland converted to forest land* 1990–2015

Year	Area (ha)
1990	69
1995	308
2000	448
2005	686
2010	806
2011	873
2012	925
2013	1,003
2014	1,015
2015	1,035

6.5.2 Emission estimates

The annual net emissions for the *land converted to forest land* category for the period 1990 to 2015 are in Table 6.33 below.

Table 6.33 Annual net emissions for *land converted to forest land,* 1990–2015 (Gg CO_2-e)

Year	Grassland converted to forest land	Wetlands converted to forest land	Total
1990	651.9	-8.2	643.7
1995	-1,578.7	-36.6	-1,615.3
2000	-8,732.0	-60.1	-8,792.0
2005	-14,709.5	-125.0	-14,834.4
2006	-15,448.9	-143.6	-15,592.5
2007	-16,151.3	-162.9	-16,314.2
2008	-18,113.3	-185.9	-18,299.2
2009	-17,574.5	-212.7	-17,787.2
2010	-18,317.9	-243.1	-18,560.9
2011	-21,678.6	-282.8	-21,961.4
2012	-19,921.8	-324.9	-20,246.7
2013	-18,679.4	-374.0	-19,053.4
2014	-16,823.0	-419.1	-17,242.1
2015	-12,472.9	-468.8	-12,941.7

6.5.3 Uncertainties and time series consistency

Uncertainty in the *land converted to forest land* sub-category is expected to be 17.3%. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

Under *wetland converted to forest land* the confidence intervals associated with 2013 IPCC guidance values for parameters associated with land use, land use change involving coastal wetlands range from 24% to over 200%. This inventory applies available country-specific values, sourced from the scientific literature, to reduce that level of uncertainty. Although a formal uncertainty analysis is not yet available, the level of uncertainty is anticipated to be towards the lower end of the guidance values, and is considered to be within the medium range.

While there is a higher uncertainty in *wetlands converted to forest land* than in *grassland converted to forest land estimates,* the former category makes only a small contribution to the overall uncertainty of *land converted to forest land* due to its lower emissions.

6.5.4 Source Specific QA/QC

The calibration and validation of the *FullCAM* model, along with the associated quality assurance and quality control program are fully described in Appendices 6.B and 6.F.

Up until the 2016_14 NIR, to conduct quality control of the Tier 3, Approach 3 model, a series of Tier 2 models based on 48 plot files drawn from within the *FullCAM* modelling framework were selected. The Tier 2 models were parameterised with site average climate (rainfall, temperature and open pan evaporation) and forest productivity data. The selected plot files are representative of the most common species and management regimes within each state and National Plantation Inventory (NPI) region (Figure 6.14).

The area of each type of forest (hardwood, softwood and native planting) in each region was determined from the land sector remote sensing program. As *FullCAM* is used for both the Tier 2 and Tier 3 models, the model inter-comparison primarily represents a test of the Approach 3 component of Australia's inventory method for *grassland converted to forest land*; and use of annually updated, spatially explicit climate and forest productivity data (Tier 3) as compared to site average data (Tier 2).

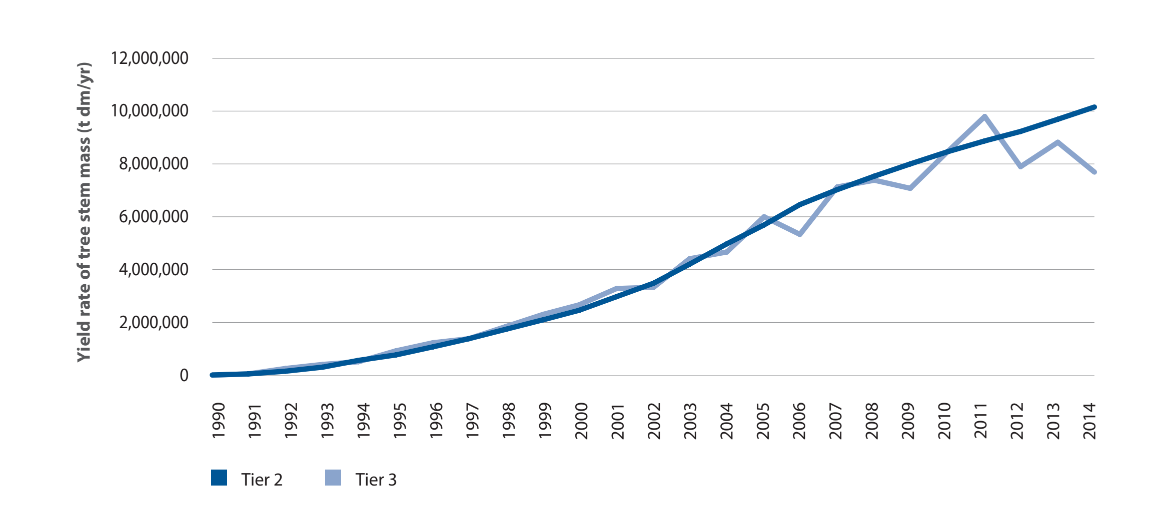
A comparison of the yield rate of tree stem mass (Figure 6.17) showed a close agreement between the two models. The Tier 3 model results are more variable, reflecting the ability of the Tier 3 model to represent the effects of spatial and temporal variability in climatic variables on plant growth.

Over the period 2010–2015, the Tier 3 yield rate of stem mass increased and decreased relative to the Tier 2 models (Figure 6.17). These variations were due to conditions for plant growth being close to optimal in 2011 and then becoming less optimal during 2012 to 2015. In 2014 conditions for plant growth within the post 1990 plantation estate were worse than average. The variability in plant growth in the Tier 3 model is driven by the spatially and temporally explicit Forest Productivity Index (Appendix 6.C), which is a parameter of the Tree Yield Formula (Appendix 6.B) within the *FullCAM* model framework.

The results of the Tier 3 soil carbon model (Figure 6.18) were also compared to the results of the Tier 2 model based on the same 48 plot files described earlier in this section. The comparison shows that the trend is similar but that emissions estimated from the Tier 3 model are more variable due to the effects of spatial variability in soil and climatic conditions and better representation of the effects of previous land use on initial soil carbon stocks.

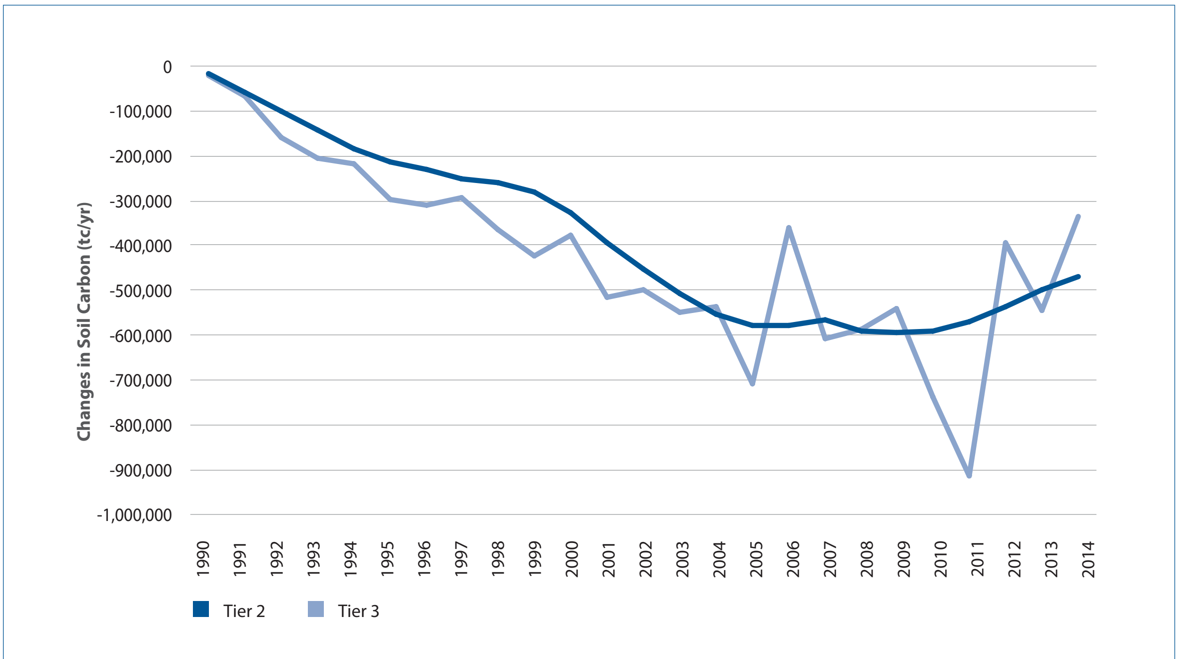
Due to the significant updates and improvements to activity data collection and estimation methods (see section 6.5.5 below), particularly satellite imagery-based spatio-temporal modelling of harvesting in post-1990 plantations, comparison with the Tier 2 model as described above is no longer strictly valid. However, historical use of the model as described above remains valid, and the factors driving the changes between the 2016_14 and 2017_15 NIRs are well understood and explained, along with their impacts, in section 6.5.5 below. As per the improvement plan, Australia will review and update the current Tier 2 model to ensure it remains a valid QA check for future inventories.

Figure 6.17 Yield rate of tree stem mass (dm t/yr) output from Tier 2 and Tier 3 methodology, 1990–2014



Quality control of the Excel™-based Tier 2 coastal wetland models is based on the comparison of model outcomes against expected outcomes from test data sets used as model inputs. In addition, the area of mangrove forest is determined from the land sector remote sensing program and is subject to the associated quality control and quality assurance protocols described in Appendix 6A. Initial quality assurance of the coastal wetland models is based on in-house reviews of the models, underlying assumptions, and parameter and emission factor values, and is informed by the latest scientific literature published by members of the wetland advisory group, an external and independent advisory panel to the Department of the Environment and Energy.

Figure 6.18 Soil carbon (t C/yr) output from Tier 2 and Tier 3 methodology, 1990–2014



6.5.5 Recalculations since the 2014 Inventory

Improvements and updates made to estimates of emissions and removals in the *land converted to forest land* sub-category included:

A. FullCAM simulation improvements, including

   a. An enhanced (3-class) approach to identifying forest and sparse vegetation cover change to improve the precision of inventory estimates of emissions/removals. This enhancement led to an average of around 7% of additional land, and a similar proportion of additional removals being reported in the *grassland converted to forest land* sub-category.

   b. Integration of satellite-based, spatio-temporal detection of harvesting activities in plantations, with the FullCAM forest growth model to improve the accuracy of emissions and removals estimates across plantation management cycles.

   c. Update/recalibration of key FullCAM forest model parameters. These included updates to parameters governing the allocation of biomass amongst tree components during growth, rates of turnover of these components to debris and subsequent decomposition (including turnover to the soil carbon pool).

B. The addition, for the first time, of the w*etlands converted to forest land* sub-caterory.

C. Expansion of FullCAM simulations to include all available satellite imagery tiles, and the regular application of updated spatial inputs on other environmental information for all tiles.

D. Updates to calcuations as described in *forest converted to grassland* which have an impact on any subsequent conversion to forest.

E. Implementation of new rounding policy for emission factor which has resulted in a change in precision.

F. Alignment of estimation periods for carbon stock estimates, consistent with Annex A sectors and other part of *forest land*.

Table 6.34 *Land converted to forest land*: recalculation of total CO_2-e emissions (Gg), 1990–2014

Year	2016 submission	2017 submission	Change		Reasons for Recalculation					
					A. FullCAM and simulation improvements*	B. First inclusion of Wetlands converted to Forest land	C. Updated and expanded spatial inputs	D. Impacts consequent of revisions to Forest Conversions	E. Rounding Policy	F. Aligning of estimation periods
	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)	(%)	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)
1990	815	644	-172	-21.1%	3	-8	74	-95	1	-147
1995	-2,152	-1,615	537	25.0%	451	-37	35	-747	2	832
2000	-8,601	-8,792	-191	-2.2%	144	-60	-133	-929	2	784
2005	-13,273	-14,834	-1,561	-11.8%	-787	-125	-1,224	-761	3	1,333
2006	-12,314	-15,592	-3,279	-26.6%	-646	-144	-1,104	-774	2	-614
2007	-14,967	-16,314	-1,347	-9.0%	-1,358	-163	-1,297	-649	3	2,116
2008	-14,841	-18,299	-3,458	-23.3%	-2,037	-186	-1,158	-672	3	591
2009	-13,104	-17,787	-4,683	-35.7%	-2,452	-213	-728	-637	3	-655
2010	-14,744	-18,561	-3,817	-25.9%	-5,014	-243	-567	-474	4	2,478
2011	-17,055	-21,961	-4,906	-28.8%	-5,216	-283	-266	-371	4	1,226
2012	-9,714	-20,247	-10,533	-108.4%	-8,392	-325	237	-505	3	-1,550
2013	-10,178	-19,053	-8,875	-87.2%	-9,157	-374	904	-590	3	339
2014	-7,306	-17,242	-9,936	-136.0%	-6,828	-419	87	-564	2	-2,213

*includes 3-class identification, spatial harvesting and revisions of parameters

6.5.6 Source specific planned improvements

Ongoing refinements to the Tier 3 *FullCAM* modelling parameters for forest/plantation growth and regeneration (including for pre-1990) are to be informed by empirical research.

More specifically:

Full implementation of updates to FullCAM parameters specifying allocation of tree biomass. Paul & Roxburgh (2017) outlined new empirical models that provide, as an output, the input for *FullCAMs* time-series tables for allocation of biomass for each tree species. Allocation varied with productivity of aboveground biomass (AGB). For many plantation species, productivity (i.e. TYF parameters) varies between regions, while for environmental and mallee plantings, productivity varies between regimes (i.e. stand density, configuration, species or species mix). Therefore, additional separate revised allocation input tables were generated for each region of each plantation species, and for each of the various regimes of environmental and mallee plantings. However, additional *FullCAM* programing would be required to enable allocation inputs to vary with region or regime. Given time limitations, the original *FullCAM* configuration of allowing for only one allocation input table for each forest type was used for the 2017-15 NIR. This required the revised allocation tables from a single region for a given plantation species to be applied to all other regions within which that species grows. Similarly, a single regime for temperate environmental (or mallee) plantings was applied to all other regimes. It is planned to complete implementation of the revised allocation inputs for the 2018-16 NIR.

Improved simulation of decomposition of debris. Further improvements are planned to the accuracy of dynamics in stocks of debris (and hence soil). The proposed improvements include:

a. *Including a 'standing dead' debris pool*. This would enable a large addition of harvest residues following clearing or harvesting, followed by a delay in decomposition as some of the C passes through a 'standing dead' pools. This would better reflect the fact that it takes some time for these residues to settle to the ground, and thereby become available for decomposition. Such changes would also be applied for crop land simulation given there is standing stubble post-harvest.
b. *Allowing dead fine roots to directly enter the soil pool.* This was suggested by Farquharson *et al.* (2013). It makes practical sense given fine roots are defined as roots with diameters of <2 mm. When sampling SOC, the soil is also defined as < 2mm. Hence, dead fine roots would be sampled as part of the SOC. If measured as SOC, dead fine roots should also be modelled as SOC.
c. *Allowing for greater flexibility in management of debris.* With the proposed revisions, management options would be available for:
    i. Harvesting of standing dead debris (harvest residues or crop stubble) for biomass or bioenergy, and;
    ii. Addition of soil amendments, e.g. biochar etc.

Also: Extension of the remote sensing program to improve spatio-temporal identification and attribution of transitions from tidal marsh and salt pan to mangrove forest.

Ongoing refinement to the wetlands (salt marsh) to forest (mangrove) modelling parameters informed by empirical research. This will provide enhancement to the Tier 2 spreadsheet-based model, and facilitate later integration into the *FullCAM* system as a Tier 3 model.

A project is ongoing to improve modelling and allocation of pre-1990 regeneration from natural seed sources and forest regrowth on previously cleared land (less than the 50 year transition periods).

6.6 Cropland Remaining Cropland (Source Category 4.B.1)

The *cropland remaining cropland* sub-category includes continuous cropping lands and lands that are cropped in rotation with pastures. Croplands are considered to be of high land value with a high return on production and of moderate to high soil nutrient status and are therefore not generally converted to *forest land* or *grassland* but remain as *cropland*.

Anthropogenic emissions and removals on croplands occur as a result of changes in management practices on cropping lands, from changes in crop type and from changes in land use. Permanent changes in management practices generate changes in the levels of soil carbon or woody biomass stocks over the longer term. Changes in carbon stock levels during the transition period to a new stock equilibrium are recorded under croplands.

Emissions and removals from *grassland converted to cropland* are reported under *cropland remaining cropland* because annual variations in area under cropping in Australian agricultural systems do not constitute a permanent land-use change. Activity data for crop-pasture rotations based on Australian national statistical information includes permanent conversions to croplands. This is appropriate for national circumstances and Australian agricultural systems which apply predominantly rain-fed cropping practices and respond to market fluctuations, resulting in seasonal variations in the lands under cropping rather than permanent land-use changes. The IPCC 2006 guidelines permit such an approach where appropriate based on the activity data (for example where prior-land use is not known, see *IPCC 2006 Guidelines*, Vol 4, Ch 5.3.3).

Anthropogenic emissions and removals from croplands are estimated from changes in specified management practices on croplands including:

- Total cropping area;
- Crop type and rotation (including pasture leys);
- Stubble management, including burning practices;
- Tillage techniques;
- Fertiliser application and irrigation;
- Application of green manures (particularly legume crops); and
- Soil ameliorants (application of manure, compost or biochar).

Conversion of pasture to cropping activities is included within the *cropland remaining cropland* estimates.

Carbon dioxide emissions from the application of lime are reported under *Agriculture*. Nitrous oxide emissions from the application of fertiliser are also reported under *Agriculture*.

6.6.1 Methodology

Emissions and removals from crop land activities are estimated using methods consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006), in conjunction with techniques described in the *2013 Revised Supplementary Methods and Good Practice Guidance for LULUCF Arising from the Kyoto Protocol* (IPCC, 2014)[4].

Carbon dioxide emissions and removals from the *cropland remaining cropland* soils component are estimated using *FullCAM* (Appendix 6.B). The CO_2 emissions and removals associated with changes in the area of perennial woody crops are estimated using the Tier 2 approach outlined below.

4 According to the IPCC (2014), in all cases, the aim of the estimation processes is to identify and report trends and systematic changes in the carbon stocks resulting from changes in management practices over time. More explicitly, (IPCC 2013, p2.135) countries are encouraged to use higher tier methods (Tier 2 or Tier 3) to develop emissions coefficients or models to represent the effects of management practices rather than those of inter-annual variability and natural disturbances on carbon stocks.

The areas of *cropland remaining cropland* are estimated using ABARES Catchment Scale Land Use of Australia 2014 (version 5) provided by the Department of Agriculture and Water at the mapping scale of 1:25 000 to 1:250 000.

Herbaceaous crops

FullCAM estimates emissions from soil as a result of an estimation process involving all on-site carbon pools (living biomass, dead organic matter (DOM) and soil). For non-woody crops in *cropland remaining cropland* the changes in the soil carbon pool are reported. Carbon stock changes from living biomass and DOM of non-woody annual crops are reported to be zero, consistent with the guidance in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* that indicates that the increase in biomass stocks in a single crop year may be assumed equal to biomass losses from harvest and mortality in that year – thus there is no net accumulation of biomass carbon stocks (IPCC 2006, p5.7). In general, croplands will have little or no dead wood, crop residues or litter (IPCC 2006, p5.12).

In most croplands, the main carbon flux associated with changes in land use and management is from changes in organic carbon in soil (IPCC 2014, p2.140). The CO_2 emissions and removals from *cropland remaining cropland* soils are estimated using Tier 3, Approach 3 *FullCAM*. When configured for *cropland remaining cropland, FullCAM* uses the same climate, site and management datasets as those used in the *forest land converted to cropland* estimates as described in Appendix 6.B and 6.E.

Initial soil carbon values come from a baseline map of soil organic carbon (Viscarra-Rossel *et al.*, 2014) (Appendix 6.E).

Management practice change has been monitored using the Australian Bureau of Statistics' (ABS) Agricultural Resource Management Survey (ARMS), which surveyed 33 000 of Australia's 135 000 agricultural businesses (funded by the Department of Agriculture and Water). Data from the ABS agricultural censuses (which surveyed all agricultural businesses) have been used with data from the 2007–08 and 2009–10 ARMS to track trends in management practices. Details on data sources for changes in management practices are provided in Appendix 6.E.

Net emissions are estimated using a Tier 3 method that isolates the impacts of changes in human activities and which draws from techniques described in the *2013 Revised Supplementary Methods and Good Practice Guidance for LULUCF Arising from the Kyoto Protocol* (IPCC, 2014)[5].

To implement this technique, *FullCAM* is simulated once with management practices changing over time and once with management practices held constant at 1990 levels. The difference between the two simulations is an estimate of the effects of changing management practices over time (see Figure 6.19).

In this way, estimates of net emissions mimic the outcomes of a Tier1/2 approach in which the effects of management practice changes are isolated from all other impacts on soil carbon (IPCC 2014, p2.135) (for example, as is done for estimates of the emissions from liming in this report). Similarly, under *Agriculture*, in this report nitrous oxide emissions from the effects of management practice changes are isolated in Tier 1 or Tier 2 methods (for example, from the effects of the current year's application of fertiliser).

FullCAM simulations commence at the year 1970.

5 According to the IPCC (2014), in all cases, the aim of the estimation processes is to identify and report trends and systematic changes in the carbon stocks resulting from changes in management practices over time. More explicitly, (IPCC 2013, p2.135) countries are encouraged to use higher tier methods (Tier 2 or Tier 3) to develop emissions coefficients or models to represent the effects of management practices rather than those of inter-annual variability and natural disturbances on carbon stocks.

Perennial woody crops

The carbon dioxide emissions and removals from changes in the area of perennial woody crops are estimated using a country-specific Tier 2 approach. The Tier 2 method retains the basic Tier 1 approach from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, but with the differences to the period over which biomass accumulates (harvest/maturity cycle) and use of more accurate crop-specific coefficients.

Crop-specific coefficients were sourced from the literature to calculate CO_2 emissions and removals. The coefficients required are: total biomass carbon stock at harvest (tonnes C ha^{-1}), harvest cycle (yr), biomass accumulation rate (tonnes C ha^{-1} yr^{-1}) and plot density (trees ha^{-1}). The mathematical relationships between these coefficients are displayed in Table 6.35. Additionally, root to shoot ratios were sourced from the literature and biomass accumulations associated with fruit production were excluded from all calculations.

Table 6.35 Calculations used to develop tier 2 coefficients for perennial woody crops

	total biomass carbon stock at harvest (t C ha^{-1})	harvest cycle (yr)	biomass accumulation rate (t C ha^{-1} yr^{-1})
calculations	(X ÷ 2) × y	X	y
e.g. (oranges)	7.5	30	0.5

Note that x and y are sourced from literature and crop maturity is half of harvest cycle.

In total, 27 perennial woody crop types are grouped by major crop-type. The coefficients applied to each group were based on the dominant crop type (Table 6.36). The four main crop-types and dominant crops are: 1) citrus, with crop coefficients represented by orange data, 2) Nuts, with crop coefficients represented by macadamia data, 3) pomes, with crop coefficients represented by apple data and 4) stone fruit, with crop coefficients represented by peach data. Other smaller crops modelled included: olives, grapes, kiwifruit, avocados and mangoes. Grape crop coefficients were used to model kiwifruit, and avocado coefficients were used to model mangoes. Regarding nuts, while macadamias were used as the representative crop, almonds were estimated separately as almond-specific coefficients were available.

Estimates of changes in area of perennial woody crops are taken from the *ABS agricultural commodities statistics (ABS, 2015).* Most crop data are provided as tree number values and subsequently were converted to area statistics using crop-specific plot density coefficients (Table 6.36).

Table 6.36 Perennial woody crop Tier 2 coefficients

Crop type	total biomass carbon stock at harvest (t C ha^{-1})	harvest cycle (yr)	biomass accumulation rate (t C ha^{-1} yr^{-1})	plot density (trees ha^{-1})	root: shoot
Citrus					
Oranges	7.5	30 a	0.5 a	556 b	0.17 c
Nuts					
Macadamias	45	30 d	3 e	355 e	0.25 e
Almonds	15	25 a	1.2 a	222 f	
Pomes					
Apples	10.2 g	28 g	0.7	500 g	0.17 c
Stone fruit					
Peaches	9.8	15 a	1.3 a	740 h	0.17 c
Grapes	3.8	25 a	0.3 a	N/A	0.5 c

Crop type	total biomass carbon stock at harvest (t C ha^{-1})	harvest cycle (yr)	biomass accumulation rate (t C ha^{-1} yr^{-1})	plot density (trees ha^{-1})	root: shoot
Kiwifruits	3.8	25 a	0.3 a	N/A	0.5 c
Olives	6.67	20 i	0.67 j	250 k	0.145 c
Avocados	7.2 l	25 a	0.6	100 l	0.125 l
Mangoes	16 l	25 a	1.3	222 m	0.125 l
IPCC default	63	30	2.1		

Source and location of study is: *a* = Kroodsma & Field (2006) USA California, *b* = Morgan *et al.* (2006) USA Florida, *c* = German and/or Spanish National Inventory Reports (2013), *d* = Australian Macadamia Society website, *e* = Murphy *et al.* (2013) Australia, ***f*** = Fernandez-Puriatch *et al.* (2013) Spain, *g* = Haynes and Goh (1980) New Zealand, *h* = Marini & Sowers (2000) USA, *i* = Sanfelipe Olives website (2013) USA California, *j* = Villalobos *et al.* (2006) Spain, *k* = Olives Australia website (2013), *l* = Lovatt (1996) USA California and *m* = Western Australian Government Agricultural website (2013). Note that plot density is represented by N/A for Grapes and Kiwifruit as reported in hectares by ABS. All figures not referenced were determined using calculations in Table 6.35.

6.6.2 Emission estimates

Net annual emissions estimates for *cropland remaining cropland for the period 1990 to 2015 are shown* graphically in figure 6.19, and a breakdown by sub-category is shown in Table 6.37.

Figure 6.19 Net CO_2-e emissions from soils in *cropland remaining cropland*, 1990–2015

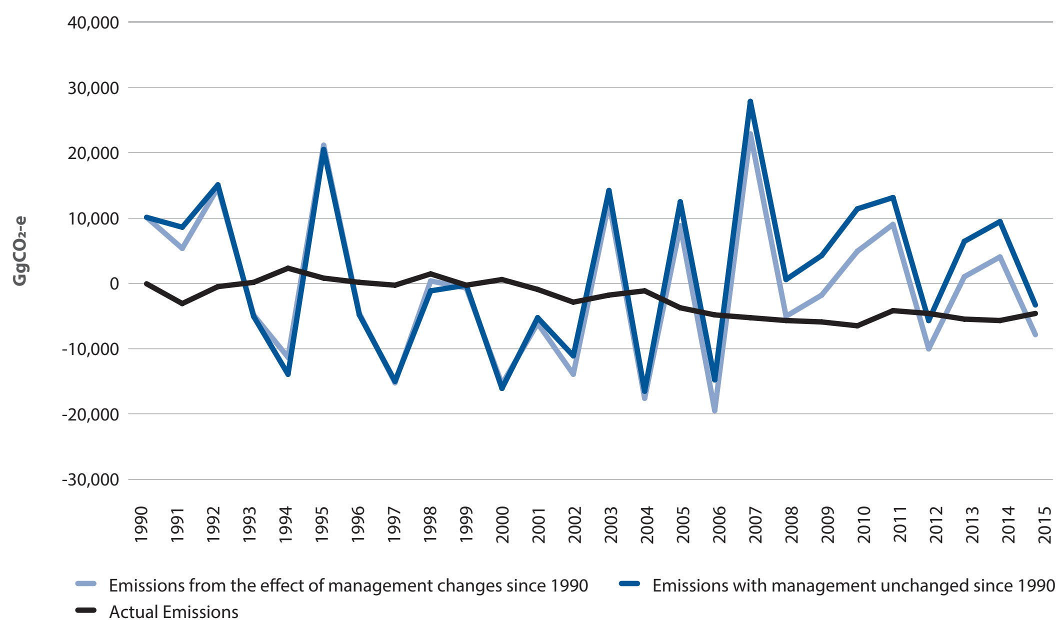


Table 6.37 Net emissions and removals from *cropland remaining cropland* sub-categories, 1990–2015 (Gg CO_2-e)

Year	Soil carbon	Perennial woody crops (biomass)	Total
1990	0	-69	-69
1995	759	-100	659
2000	538	-50	488
2005	-3,720	-162	-3,881
2006	-4,725	-175	-4,900
2007	-5,135	36	-5,100
2008	-5,615	-122	-5,737
2009	-5,910	-152	-6,062
2010	-6,449	-282	-6,731
2011	-4,169	-363	-4,532
2012	-4,530	-109	-4,640
2013	-5,408	94	-5,314
2014	-5,577	28	-5,541
2015	-4,555	-83	-4,638

6.6.3 Uncertainties and time series consistency

Based on a qualitative assessment the uncertainties for *cropland remaining cropland* were estimated to be medium. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

There are a number of gaps in the time series of *ABS commodities statistics* (ABS, 2015) for perennial woody crops. All data-gaps were filled using extrapolation and interpolation techniques consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

6.6.4 Source specific QA/QC

The calibration, validation and verification of the *FullCAM* model, along with the associated quality assurance and quality control programme are fully described in Appendix 6.B.

Additional category specific QA/QC activities are undertaken on the crop yield database and c*ropland remaining cropland* emissions and removal estimates. In relation to crop yields, CSIRO Agriculture and Food has tested the performance of the crop growth model against a database of crop yields (see Appendix 6.E).

The Department of the Environment and Energy also undertakes quality control processes in accordance with the Quality Assurance-Quality Control plan.

6.6.5 Recalculations since the 2014 Inventory

The recalculation of the *cropland remaining cropland time* series is presented in table 6.38, and an explanation of the key influences on the change in estimates follows:

Fine spatial resolution continental scale maps of the soil carbon fractions have been included for cropland remaining cropland for the first time (see Appendix 6.E.1 for further information).

An error in the allocation of wheat cropping regimes was corrected in *FullCAM* spatial simulations. This correction has resulted in a shift in the *cropland remaining cropland* time series trend for the period 1990 to 2000. The shift has made the cropping regime allocation time series now consistent with the yields and land use cropping areas derived for period's pre 1990 and the emissions time series post 2000.

The CSIRO have provided new crop yields for the 2015 year which also included extensive verification and analysis on the time series data which has resulted in minor updates across the various crop yield series. This has resulted in minor recalculations in the *cropland remaining cropland* emissions time series.

A new spatial grazing method has been implemented for croplands which modifies grazing pressure on pastures in cropping rotations to more accurately reflect livestock population data. Livestock grazing pressure is modified based on data from the ABS Agricultural Commodities (ABS, 2015) and is available annually from 1970 and across all regions of Australia. Livestock is disaggregated at the species cohort level. Beef cattle, dairy cattle and sheep have been included as the dominant grazing species on pasture. In general, this method of simulating grazing has reduced grazing pressure over time which is reflected in increased debris pools on harvest and accumulation from turnover which has a minor effect on increasing stocks of soil carbon in rotational cropping lands.

The allocation of cropping management regimes within the *FullCAM* model had been improved to better reflect the adoption and retention of no-till practices within cropland regions (see Appendix 6.E.3) while being consistent with the magnitude of management activities identified through the ABS agriculture surveys. No-till practices are associated with improved soil carbon sequestration and the uptake of these practices can be seen through increased soil carbon sequestration from the effect of human management through time.

The *FullCAM* plough and grazing events were investigated and tuned to better reflect the flows within the model. The timing of the grazing event was adjusted within the FullCAM simulation step so carbon flows from grazing occur in the same step that plant growth occurs. The plough event was expanded and calibrated to allow movement of carbon from the soil pools as a direct result of the plough. Both of these changes resulted in minor recalculations by shifting soil carbon movement within the time series forward or back in time.

The atmospheric percentage breakdown of products of the resistant and decomposable parts of the plant debris pools has been calibrated against the mapped soil carbon estimates by Viscarra-Rossel *et al.*(2014), which has resulted in a positive shift in the soil carbon stock trend.

Due to the nature of *FullCAM* simulations and the implementation of multiple changes and methodology updates in the latest NIR, it is difficult to quantify recalculations for each module. This limitation has been flagged for investigation in the future work plan to implement systems that may allow for more disaggregated reporting of recalculations within the *FullCAM* model.

Table 6.38 *Cropland remaining cropland:* Recalculation of CO_2-e emissions 1990–2014

Year	2016 submission	2017 submission	Change	
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	(%)
1990	-69	-69	0	0
1995	-9,133	659	9,792	107
2000	-8,463	488	8,951	106
2005	616	-3,881	-4,497	-730
2006	-23	-4,900	-4,877	-21,162
2007	-5,539	-5,100	440	8
2008	2,541	-5,737	-8,278	-326

Year	2016 submission	2017 submission	Change	
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	(%)
2009	711	-6,062	-6,773	-953
2010	-5,027	-6,731	-1,704	-34
2011	1,797	-4,532	-6,329	-352
2012	-3,279	-4,640	-1,360	-41
2013	-2,216	-5,314	-3,097	-140
2014	-1,416	-5,541	-4,117	-289

6.6.6 Source specific planned improvements

The handling of the below-ground debris pool within the FullCAM model requires investigation to determine the correct behavior of the relationship of the Roth-C implementation within FullCAM and changing management practices. Further investigation is planned into the initialisation of the FullCAM model and refinement of the processes to more accurately reflect the measureable carbon soil fractions at any given period in time.

FullCAM's modelling capability will be enhanced through an investigation of the option for enabling better modelling of the impacts of management strategies on the entry of crop residues into the soil as well as additions of various organic amendments derived from offsite.

FullCAM event functionality is planned to be further refined through a project focused on investigating the parameters driving certain events such as agricultural fire.

6.7 Land converted to cropland (Source Category 4.B.2)

The *land converted to cropland* subcategory includes *forest land converted to cropland* and *wetlands converted to cropland* subcategories.

Net emissions from the switching from pasture to cropping are included in *croplands remaining croplands* as it is common for cropping systems to include pasture/grazing rotations.

6.7.1 Methodology

6.7.1.1 Forest land converted to cropland

The methodology for the subcategory *forest land converted to cropland* is covered in detail under *forest land converted to grassland* (Section 6.9 below).

6.7.1.2 Wetlands converted to cropland

Areas of *wetlands converted to cropland* were estimated using IPCC Approach 2 using activity data acquired from the 1996 and 2010 Land use of Australia surveys (ABARES *National scale land use data*. Accessed 15 February 2017). Spatial information on final land uses, including grazing on native, improved and irrigated pastures, and cropping, irrigated cropping and perennial horticulture, was used in conjunction with available wetlands spatial data to estimate conversions to cropland.

Following IPCC guidance (Volume 1, Chapter 2.2.3), extrapolation and interpolation methods were used to calculate an average annual rate of conversion of wetlands to cropland over the required time period. The default IPCC time period of 20 years was used for land remaining in transitional categories so that converted lands remain in a transitional category for this period during which time emissions from organic soils continue to be estimated.

With respect to biomass and dead organic matter, only non-woody biomass is assumed to be present in the wetlands prior to conversion - noting that conversions of forested wetlands are already accounted for in the inventory. Therefore the IPCC tier 1 assumption, that no net change in biomass or dead organic matter stocks from conversion of wetlands to cropland occurs, was applied in this model. Consequently only emissions from the drainage of organic soils are estimated. For each state, Equation 2.26 from IPCC 2006 Guidelines Vol 4 was used to estimate those emissions and then aggregated to give the national total:

$L_{organic}$ = A x EF, where

- $L_{organic}$ = emissions from draining organic soils
- A = area converted
- EF = emission factor

IPCC default emissions factor for cool temperate zones was applied (5 t C / ha / yr - Table 5.6 IPCC 2006 GL, Vol 4), based on expert understanding of wetland ecosystems in areas where such conversions occur.

The activity data for the *forest land converted to cropland* classification is drawn from the remote sensing program (see Appendix 6.A).

Table 6.39 below shows the cumulative areas of *forest land* and *wetlands* that were *converted to croplands* over the period 1990 to 2015.

Table 6.39 Cumulative area of *land converted to cropland* 1990–2015 (ha)

Year	Forest land converted to cropland	Wetlands converted to cropland	Total
1990	1,160,933	12,660	1,173,593
1995	1,393,603	12,660	1,406,263
2000	1,615,525	12,660	1,628,185
2005	1,913,816	12,660	1,926,476
2010	2,085,438	12,660	2,098,098
2011	2,107,523	12,660	2,120,183
2012	2,130,273	12,660	2,142,933
2013	2,155,706	12,660	2,168,366
2014	2,179,285	12,660	2,191,945
2015	2,200,653	12,660	2,213,313

6.7.2 Emission estimates

As Table 6.40 below indicates, *forest land converted to cropland* is the dominant contributor to both the level and trend in net emissions in this sub-category.

Table 6.40 Net emissions from *land converted to cropland* by sub-category, 1990–2015 (Gg CO_2-e)

Year	Forest land converted to cropland	Wetlands converted to cropland	Total
1990	16,536	232	16,768
1995	5,653	232	5,885
2000	9,510	232	9,742
2005	9,840	232	10,072
2006	9,418	232	9,650
2007	8,336	232	8,568
2008	7,099	232	7,331
2009	5,978	232	6,210
2010	5,885	232	6,117
2011	5,620	232	5,852
2012	3,901	232	4,133
2013	5,902	232	6,134
2014	5,546	232	5,778
2015	3,954	232	4,186

6.7.3 Uncertainties and time series consistency

Uncertainties for *forest land converted to cropland* at the national scale were estimated to be ±27.3% for CO_2. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

Emissions estimated against *wetlands converted to cropland* are reported for the period 1990 to 2015. The current Tier 1 method relies on interpolation and extrapolation with respect to two observational years. ABARES does not report on uncertainty about the land use estimates. However these are likely fall in the medium to high range.

While there is a higher uncertainty *wetlands converted to cropland* than in *forest land converted to cropland,* the former category makes only a small contribution to the overall uncertainty of *land converted to cropland due to its lower emissions.*

6.7.4 Source specific QA/QC

The source specific QA/QC for the subcategory *forest land converted to cropland* is covered in detail under *forest land converted to grassland* (Section 6.9 below).

Quality assurance/quality control measures for *wetlands converted to cropland* involve internal reviews of data entry and model outputs, including a check on the consistency of land use statistics across Australian jurisdictions.

6.7.5 Recalculations

Recalculations for the two sub-categories are presented separately here.

6.7.5.1 Forest land converted to cropland

Table 6.41 provides the recalculation results, including reasons and quantified impacts.

See section 6.9.5 ('*forest converted to grassland*') for descriptions of the updates and improvements to activity data collection and estimation methods/models that underpinned these recalculations.

Table 6.41 *Forest land converted to cropland:* Recalculation of CO_2-e emissions 1990–2014

	Forest land converted to cropland				Reasons for Recalculations				
	2016 submission	2017 submission	Change		A. Enhanced Geospatial monitoring	B. FullCAM 'M' parameter update	C. FullCAM Tree parameter updates	D. Alignment with sectoral estimation periods	E. Rounding policy
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	%					
1990	15,300	16,536	1,235	8.1%	4,994	579	-4,274	-65	1
1995	6,444	5,653	-792	-12.3%	1,053	275	-3,557	1,436	1
2000	11,543	9,510	-2,033	-17.6%	-15	445	-1,621	-843	1
2005	11,332	9,840	-1,492	-13.2%	1,097	236	-2,953	127	1
2006	12,531	9,418	-3,113	-24.8%	-1,494	298	290	-2,207	1
2007	8,714	8,336	-378	-4.3%	524	172	-3,462	2,387	1
2008	7,494	7,099	-394	-5.3%	94	246	-2,191	1,456	1
2009	7,513	5,978	-1,535	-20.4%	-791	342	280	-1,367	1
2010	6,774	5,885	-889	-13.1%	29	385	-2,283	978	2
2011	5,726	5,620	-106	-1.9%	-359	277	-766	741	1
2012	6,772	3,901	-2,871	-42.4%	-1,270	235	446	-2,283	1
2013	5,973	5,902	-71	-1.2%	63	216	-1,207	856	1
2014	5,809	5,546	-263	-4.5%	-96	46	-1,152	938	1

6.7.5.2 Wetlands converted to cropland

Table 6.42 below provides the recalculation results for *wetlands converted to cropland* over the period 1990 to 2014.

There is a minor change due to implementation of a new rounding policy for emission factor precision.

Table 6.42 *Wetlands converted to cropland:* Recalculation of CO_2-e emissions 1990–2014

Year	2016 submission	2017 submission	Change	
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	(%)
1990	232.1	232.0	-0.1	-0.1%
1995	232.1	232.0	-0.1	-0.1%
2000	232.1	232.0	-0.1	-0.1%
2005	232.1	232.0	-0.1	-0.1%
2006	232.1	232.0	-0.1	-0.1%
2007	232.1	232.0	-0.1	-0.1%
2008	232.1	232.0	-0.1	-0.1%
2009	232.1	232.0	-0.1	-0.1%
2010	232.1	232.0	-0.1	-0.1%
2011	232.1	232.0	-0.1	-0.1%
2012	232.1	232.0	-0.1	-0.1%
2013	232.1	232.0	-0.1	-0.1%
2014	232.1	232.0	-0.1	-0.1%

6.7.6 Source specific planned improvements

The source specific planned improvements for the subcategory *forest land converted to cropland* is covered in detail under *forest land converted to grassland* (Section 6.9 below).

Planned improvements are underway to develop a fully spatially explicit timeseries of land-use maps that will improve reporting of activity data and emissions for *wetlands converted to croplands*.

6.8 Grassland Remaining Grassland (Source Category 4.C.1)

The *grassland remaining grassland* category includes all areas of *grassland* that are not reported under *land converted to grassland*. Areas that are in rotational use between *grassland* and *cropland* are reported under either *forest land converted to cropland* or *cropland remaining cropland*.

There are three components of the *grassland remaining grassland* emission estimates – the grasslands component, the shrubland transitions component and the carbon dioxide emissions and post fire removals associated with burning of northern, central Australian and temperate grasslands. Shrublands are areas of woody vegetation that are not, by definition, 'forest'. Shrublands are typically sparse tree and shrub formations and are not separable into areas made up of uniquely tree or shrub plant types.

Anthropogenic emissions and removals on grasslands result from changes in management practices on grasslands, particularly from changes in pasture, grazing and fire management; changes in woody biomass elements and from changes in land use.

Permanent changes in management practices generate changes in the levels of soil carbon or woody biomass stocks over the longer term. The national inventory does not record the new carbon stock levels directly, but it is affected during the transition from one carbon stock level to another from changes in the flow of carbon to and from the land. These effects on the national inventory are transitory and are not permanent and, after a time (25 years), the rate of net emissions or removals associated with the changed management practice will approach zero.

The distribution of land areas in the *grassland remaining grassland* sub-category are estimated using the ABARES Catchment Scale Land Use of Australia (ABARES, 2014) at the mapping scale of 1:25 000 to 1:250 000. The subset of areas of *grassland remaining grassland* that were shrub vegetation was established by the methods described below. The area that was only grasses was established by removing the areas of shrubland from the total *grassland remaining grassland* area.

6.8.1 Methodology

Carbon dioxide emissions from the *grassland remaining grassland* category are estimated using a mix of methods. The grasslands (grass only) component is estimated using *FullCAM* (Appendix 6.B), while the shrubland transition component and CO_2 emissions and removals associated with grassland fires are estimated using the Tier 2 methods outlined below.

6.8.1.1 Pasture

Emissions and removals for the pasture (grasslands) component are estimated using Tier 3, Approach 3 in *FullCAM*.

Anthropogenic emissions and removals from grasslands are estimated from changes in specified management practices including:

- the area under grasslands;
- pasture management from fertilisers, irrigation and other inputs and seed selection;
- the area under grazing and changes in grazing intensity;
- woody biomass management; and
- fire management.

FullCAM estimates emissions from all on-site carbon pools (living biomass, dead organic matter (DOM) and soil). For the herbaceous grass component only the changes in the soil pool are reported. Carbon stock changes from living biomass and DOM of non-woody annual crops are reported to be zero, consistent with the guidance in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* that indicates that the increase in biomass stocks in a single crop year may be assumed equal to biomass losses from harvest and mortality in that year – thus there is no net accumulation of biomass carbon stocks for non-woody biomass.

Stratification of grasslands

There are two main agro-ecological categories in grasslands:

- native arid grasslands which comprise sparse woody vegetation and woodlands, and remain as primarily native grasses; and
- high rainfall improved pastures.

The key management practices relevant to estimating changes in carbon stocks in the high rainfall pastures include: grazing intensity; pasture composition; fertiliser and organic amendments; and irrigation. For the native arid and semi arid grasslands, the key drivers include grazing intensity, fire management and the presence of woody vegetation.

Stratification of grasslands is undertaken based on climate and vegetation type. For the high rainfall pastoral regions, where cropping also occurs, the impacts of pasture composition and fertiliser and irrigation have been modelled (Appendix 6.E). In the arid rangelands areas it is assumed that these lands have remained native pastures and as such no stock changes are identified on these lands.

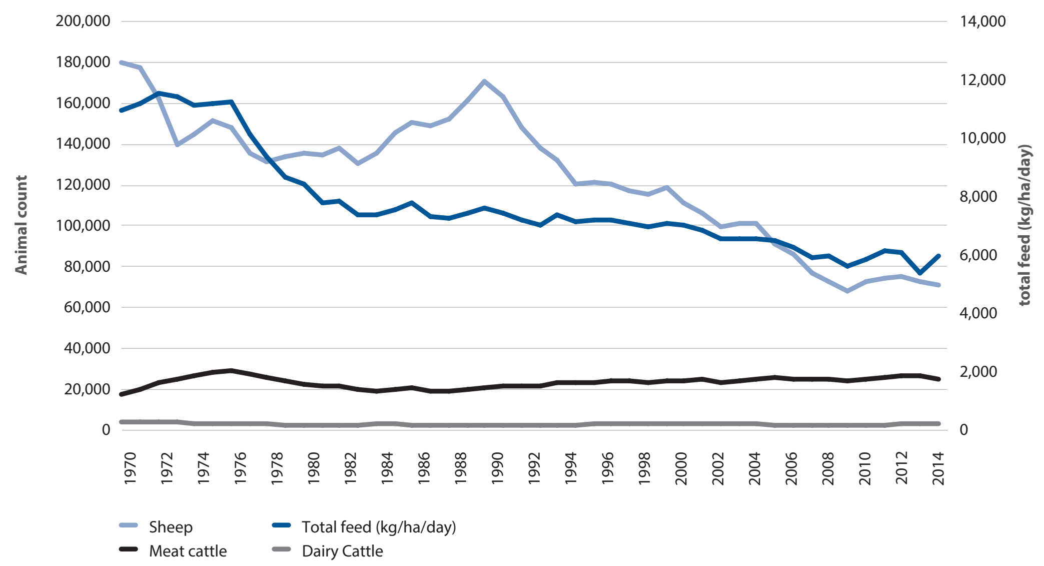
Data

Initial soil carbon values are taken from the baseline map of soil organic carbon (Viscarra-Rossel *et al.*, 2015) – see Appendix 6.E.

Management practice change has been monitored using the Australian Bureau of Statistics' (ABS) Agricultural Resource Management Survey (ARMS), which surveyed 33 000 of Australia's 135 000 agricultural businesses (funded by the Department of Agriculture). Data from the ABS agricultural censuses (which surveyed all agricultural businesses) have been used with data from the 2007–08 and 2009–10 ARMS to track trends in management practices.

Grazing pressure over time for each ABS Statistical Area 2 region is derived from the ABS Commodity Statistics (Figure 6.20).

Figure 6.20 Grazing pressure by animal type Australia, 1970-2015

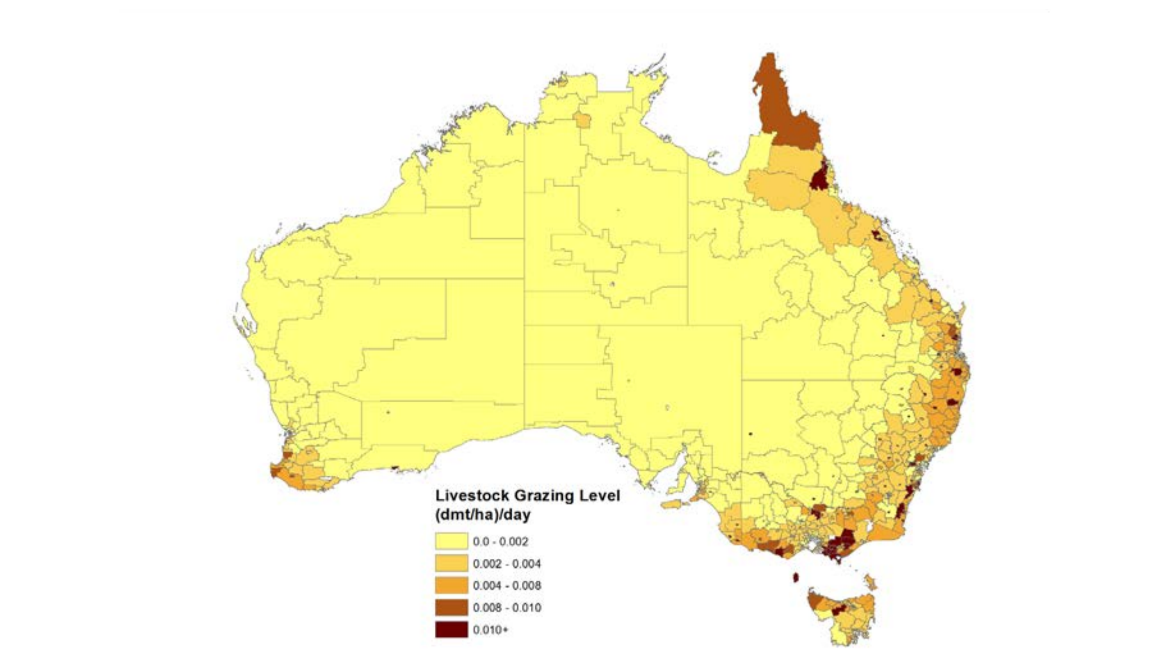


Published beef cattle, dairy cattle, and sheep population and age data from the Australian Bureau of Statistics Agriculture Commodities (ABS 2015) were used to derive average feed amounts for these livestock types. This data is combined to calculate the grazing pressure for each Statistical area 2 (SA2) which is then inserted into the *FullCAM* model as tonnes per hectare of standing dry matter eaten per day.

With respect to unmanaged grazing by native animals such as kangaroos, published data from the Department of the Environment and Energy (DOTE 2011) is used to determine the grazing pressure for each State of Australia.

The combination of both managed and non-managed grazing values are applied to grasslands. For croplands the managed grazing method is applied to pasture lands in a crop rotation. Figure 6.21 shows the spatial distribution and levels of biomass eaten in 2010.

Figure 6.21 Livestock grazing pressure levels for Australia (2010) at the SA2 level



Additional details on data sources for changes in management practices are provided in Appendix 6.E.

Methods

Net emissions are estimated using a Tier 3 method that isolates the impacts of changes in human activities, following the methods described in the *2013 Revised Supplementary Methods and Good Practice Guidance for LULUCF Arising from the Kyoto Protocol* (IPCC, 2014)[6].

To implement this technique, *FullCAM* is simulated once with management practices changing over time and once with management practices held constant at 1990 levels. The difference between the two simulations represents the effects of changing management practices (see Figure 6.27).

In this way, estimates of net emissions mimic the outcomes of a Tier1/2 approach in which the effects of management practice changes are isolated from all other impacts on soil carbon (IPCC 2014, p2.135) (for example, as is done for estimates of the emissions from liming in this report). Similarly, under *Agriculture*, in this report nitrous oxide emissions from the effects of management practice changes are isolated in Tier 1 or Tier 2 methods (for example, from the effects of the current year's application of fertiliser).

As for the *cropland remaining cropland* sub-category, *FullCAM* simulations commence in 1970.

6.8.1.2 Grass and shrub transitions

To supplement the forest extent mapping, a national mapping programme has been completed to assess both the extent, and changes in extent, of sub-forest forms of woody vegetation using the Landsat TM, ETM+ and OLI data for the years from 1988 to 2016 (Caccetta and Furby, 2004). This method builds on the 2-class (forest and non-forest) time series CPN classification technique, by incorporating an additional spatial texture measure

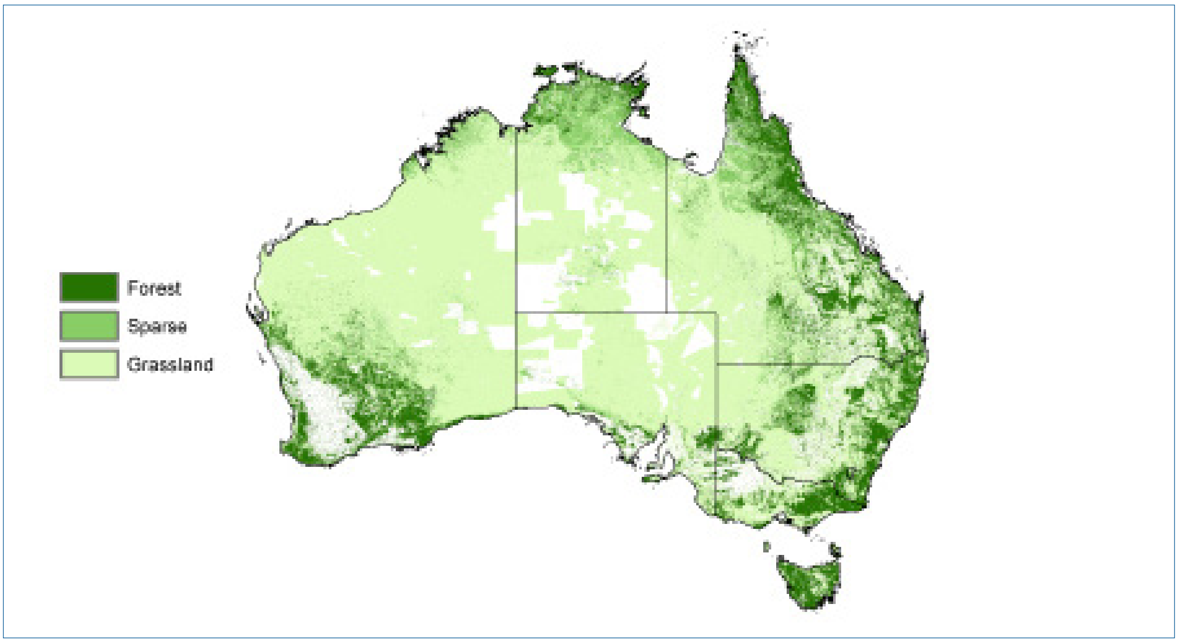
6 According to the IPCC (2014), in all cases, the aim of the estimation processes is to identify and report trends and systematic changes in the carbon stocks resulting from changes in management practices over time. More explicitly, (IPCC 2013, p2.135) countries are encouraged to use higher tier methods (Tier 2 or Tier 3) to develop emissions coefficients or models to represent the effects of management practices rather than those of inter-annual variability and natural disturbances on carbon stocks.

to distinguish between the sparse woody vegetation cover (5-7% to <20% canopy cover) and the forest cover (> 20% canopy cover). Figure 6.22 shows the extent of sparse vegetation in Australia.

Data on sparse woody vegetation extends for the period from 1988 to 2016, except for a few interior rangeland areas, for which current sparse woody coverage is limited to 2006. For the period 1970-1985, the net gain in area of sparse woody vegetation has been backcast using the El Niño Southern Oscillation index (Bureau of Meteorology) as a proxy variable.

To estimate the change in shrub biomass due to the change in shrub area, the net annual change in area was placed in a Tier 2 model. The model uses an average woody biomass of 10 t DM ha^{-1} (Raison *et al.,* 2003) and presumes a linear loss of that amount over a period of twenty years. At the time of disturbance, lands have been subject to a mix of regular cyclic clearing, on around a 15 year cycle (Fensham *et al.,* 2012), grazing management practices (Department of Agriculture and Fisheries, Queensland Government 2012) and natural disturbances such as drought and pests. Where the area of sparse vegetation increases it is assumed that these will regrow to 10 t DM ha^{-1} over twenty years (i.e. a growth rate of 0.5 t DM ha^{-1} yr^{-1}) (Fensham *et al.*, 2012 and Witt *et al.*, 2011).

Figure 6.22 Extent of sparse woody vegetation



6.8.1.3 Carbon stock changes in dead organic matter

Emissions and removals from the DOM pool (associated with the burning and subsequent regrowth) are modeled using the same methods, factors and data as described for *other native forests* reported in *forest remaining forest* (section 6.4.1.3).

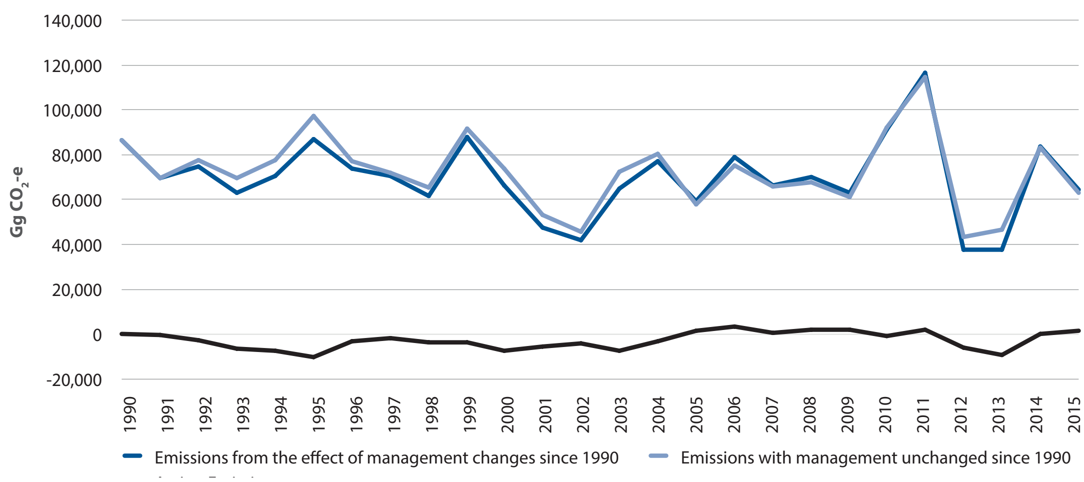
6.8.2 Emission estimates

Emission estimates for the components of *grasslands remaining grasslands* are reported in Table 6.43.

Table 6.43 Emissions and removals from *grassland remaining grassland*, by sub-category 1990–2015 (Gg CO_2-e)

Year	Herbaceous grasslands	Perennial woody biomass		All
	Soil Carbon and Nitrogen mineralisation and run-off	Live biomass (Transitions)	Dead organic matter (biomass burning and subsequent regrowth)	
1990	3,255	-2,975	2,687	2,968
1995	-6,814	1,768	5,513	468
2000	-4,799	2,297	9,579	7,077
2005	3,708	3,522	5,648	12,878
2006	6,677	3,363	8,658	18,698
2007	3,089	3,045	9,066	15,200
2008	4,914	898	6,504	12,316
2009	4,384	-1,987	6,837	9,234
2010	2,704	-3,581	5,674	4,797
2011	6,490	-5,016	4,338	5,811
2012	-4,417	-4,841	3,484	-5,774
2013	-7,483	-4,964	4,111	-8,336
2014	3,540	-4,858	5,837	4,519
2015	4,008	-5,105	3,850	2,752

Figure 6.23 Net CO_2-e emissions from soils in *grassland remaining grassland*, 1990–2015



6.8.3 Uncertainties and time series consistency

Based on a qualitative assessment the uncertainties for *grassland remaining grassland* were estimated to be medium. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

6.8.4 Source specific QA/QC

The calibration and validation of *FullCAM* along with the associated quality assurance and quality control programs are described in Appendices 6.B and 6.E. Additional category specific QA/QC activities are undertaken on the yield database and *grassland remaining grassland* emissions and removal estimates.

The quality assurance and control process associated with the yield data is the same as that performed for *cropland remaining cropland* (see section 6.6.4). The Department of the Environment and Energy also undertakes quality control processes on the outputs of the spatial *FullCAM* simulations by reviewing and evaluating them against the outputs from the previous inventory.

The QA/QC of the activity data for detecting gains and losses of woody vegetation is described in Appendix 6.A.4.

The fire affected area data for the shrubland component is collated and quality assured by Western Australian Land Authority (Landgate) before being received by the Department of the Environment and Energy.

6.8.5 Recalculations since the 2014 Inventory

Table 6.44 below provides the recalculation results, including reasons and quantified impacts.

A. Changes in pasture management

Fine spatial resolution continental scale maps of the soil carbon fraction (see Appendix 6.E.1) have been included for *grassland remaining grassland* for the first time. These maps were used to initilise the *FullCAM* model.

The CSIRO have provided updated pasture yields for 2015 which also includes verification and analysis which has resulted in minor updates throughout the yield time series. Pasture yields are now broken down into annual and perennial pasture species, which has been included in the Inventory for the first time.

Perennial standing dry matter is a function of the accumulation and loss of biomass through two parameters: growth and die-off, with a standing dry matter value used to initialize the model. More detail on the perennial growth model is provided in Appendix 6.E.4.

Yield data generated by the CSIRO Agriculture and Food Division assumes full biomass coverage was corrected for bare soil patches in the landscape using MODIS fractional cover data (see Appendix 6.E.4).

A new spatial grazing method (see also section 6.8.1.1) has been implemented for grasslands which modifies grazing pressure on pasture lands to more accurately reflect livestock population data. Livestock grazing pressure is modified based on data from the ABS Agricultural Commodities (ABS, 2015) and is available annually from 1970 and across all regions of Australia. Livestock is disaggregated at the species cohort level. Beef cattle, dairy cattle and sheep have been included as the dominant grazing species on pasture. Unmanaged grazing from native kangaroos has also been included for the first time. These new methods of simulating grazing have reduced grazing pressure over time which is reflected in increased debris pools on harvest and accumulation from turnover which has a moderate effect on increasing stocks of soil carbon in pasture lands.

The *FullCAM* grazing event was investigated and tuned to better reflect the flows within the model. The timing of the grazing event was adjusted within the *FullCAM* simulation step so carbon flows from grazing occur in the same step that plant growth occurs. This change resulted in minor recalculations by shifting soil carbon movement within the time series forward or back in time.

The atmospheric percentage breakdown of products of the resistant and decomposable parts of the plant debris pools has been calibrated against the mapped soil carbon estimates by Viscarra-Rossel *et al.*(2014), which has resulted in a positive shift in the soil carbon stock trend.

As indicated in section 6.6.5 in relation to *cropland remaining cropland*, due to the nature of *FullCAM* simulations and the implementation of multiple changes and methodology updates in the latest NIR, it is difficult to quantify recalculations for each module. This limitation has been flagged for investigation in the future work plan to implement systems that may allow for more disaggregated reporting of recalculations within the *FullCAM* model.

B. Implementation of rounding policy

Implementation of new rounding policy for emission factor precision. This resulted in change to the precision of the emission factor used for direct emissions from nitrogen mineralisation in mineral soils.

C. Change in live biomass

Activity data for grass and shrub transitions has been revised due to improvements in image classification for identifying changes in sparse cover.

D. Change in dead organic matter

Changes to the estimates of DOM stocks due to fire and subsequent regrowth occur in the years 2013 and 2014 and reflect corrections to activity data due to the availability of new monitoring data to August 2016.

Table 6.44 *Grassland remaining grassland*: Recalculation of CO_2-e emissions 1990–2014

Years	2016 Submission	2017 Submission	Total Change	% Change	A. Change in pasture management	B. Change due to rounding policy	C. Change in live biomass (shrub transitions)	D. Change in DOM (fires and regrowth)
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)		(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)
1990	-2,394	2,968	5,362	224%	75	112	5,175	0
1995	4,455	468	-3,987	-90%	-8,230	102	4,141	0
2000	6,479	7,077	598	9%	-1,484	61	2,022	0
2005	2,384	12,878	10,494	440%	10,072	49	373	0
2006	5,883	18,698	12,815	218%	12,162	43	611	0
2007	4,721	15,200	10,479	222%	10,302	43	134	0
2008	3,033	12,316	9,283	306%	10,984	30	-1,731	0
2009	960	9,234	8,274	862%	9,540	36	-1,302	0
2010	-2,173	4,797	6,970	321%	7,533	115	-678	0
2011	-6,804	5,811	12,616	185%	12,838	38	-260	0
2012	-9,900	-5,774	4,126	42%	2,427	15	1,684	0
2013	-8,976	-8,336	640	7%	-1,347	38	1,122	828
2014	-7,715	4,519	12,233	159%	9,060	37	1,446	1,691

6.8.6 Source specific planned improvements

Further refinement is planned to the spatial grazing model with the goal of modelling more diverse animal species such as feral camels and wild horses, and the improved calibration of grazing management data in the ABS Agricultural Commodities against the CSIRO pasture yield model

Improvements to the perennial growth model for pasture species to more accurately reflect changing livestock grazing pressure through time. The incorporation of MODIS ground cover is planned to be expanded to include a temporal series to reflect changes over time for these species.

The handling of the belowground debris pool within the *FullCAM* model requires investigation to determine the correct behavior of the relationship of the Roth-C implementation within *FullCAM* and changing managemen*t practices.*Further investigation of initialisation of the *FullCAM* model and refinement of the processes to more accurately reflect the measureable carbon soil fractions at any given period in time.

Develop an empirical model using machine learning algorithms with the aim to predict the changes of terrestrial soil carbon. This model is intended for use as a validation tool for the official estimates of greenhouse gas emissions from changes in soil carbon in Australia's pasture lands. Further development of the sparse transitions model is planned. For example, growth and decay models will be further developed, exploring options of non-linear transitions and region-specific biomass volumes, and including eventual integration into the tier 3 FullCAM model.

Development is underway towards a fully spatially explicit, Tier 3 model for estimating emissions from DOM due to burning of northern and central Australian grasslands using the *FullCAM* modelling system.

6.9 Land converted to grassland (Source Category 4.C.2)

The *land converted to grassland* category includes *forest land converted to grassland* and *wetlands converted to grassland* subcategories.

There are two types of land use changes accounted for in *forest land converted to grassland*.

The first is where forest is cleared and then is maintained as *grassland*. When the land use subsequent to a forest conversion is *grassland* only (i.e., no crops), associated emissions are reported under *forest land converted to grassland*. Lands which are managed under a crop-pasture rotation, or just cropping activity, are reported under *forest land converted to cropland*.

The second type of land use change is where forest is cleared, but then there is regrowth, which may or may not be followed by re-clearing of woody regrowth. This is reported under *forest land converted to grassland*. For example, land which has been monitored as being cleared since 1972, and which subsequently re-grew to become forest after 1990, remains in the *forest land converted to grassland* classification for continuity reasons.

The net emissions associated with harvesting of forest for timber are reported under *forest land remaining forest land* (as harvesting does not constitute a permanent land use change), unless a subsequent land use change occurs.

The net emissions associated with fires are reported under *forest land remaining forest land* (as fire does not constitute a permanent land use change), unless a subsequent land use change occurs.

The net emissions associated with the clearing of orchards are reported under croplands (as orchards are not defined as forests in the Australian inventory).

The net emissions from the clearing of sparse woody vegetation are reported under grassland (as sparse woody vegetation does not meet the definition of a forest in the Australian inventory).

6.9.1 Methodology

6.9.1.1 Forest land converted to grassland

The areas of forest conversion are identified and allocated to the *grassland* sub-category as described in section 6.3. Emissions and removals from *forest land converted to grassland* (and *cropland*) are estimated using the Approach 3, Tier 3 *FullCAM* as described in Appendix 6.B. The reporting includes all carbon pools (living biomass, dead organic matter (DOM) and soil). The model runs in a mixed configuration (i.e., both forest and agricultural systems) using the *CAMFor, CAMAg* and *Roth-C* sub-models. (Table 6.45 below shows the *FullCAM* configuration for modelling emissions and removals for this sub-category).

N_2O emissions from disturbance associated with land-use conversion to cropland and *grassland* are estimated using the methods described in section 6.18.2. Other non-CO_2 emissions that are not related to biomass burning from these lands are reported in the *Agriculture* sector.

Table 6.45 *FullCAM* configuration used for the *forest land converted to cropland* and *grassland* sub-categories

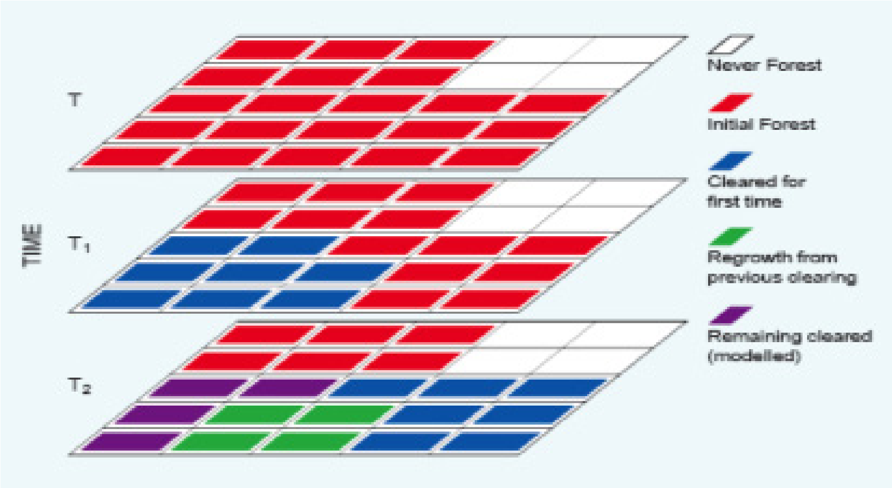
Component	Forest	Agriculture
Living biomass	CAMFor – Forest Productivity Index and Tree Yield Formula	CAMAg – Crop and pasture growth sub-models
Dead organic matter	CAMFor	CAMAg
Soil carbon	Roth-C	Roth-C
Offsite products	NA	NA

Entry of lands into forest land converted to grassland and cropland sub-categories

The fundamental analytic unit of Tier 3, Approach 3 land sector reporting in Australia is the land cover change pixel (25 m × 25 m) derived from the satellite remote sensing programme. Beginning in 1972, land clearing events are detected through the remote sensing programme. The first time a land clearing event is detected for a pixel, the pixel becomes 'active'. For each year after 1972, an extra set of active pixels which represent new land clearing events, are added to the previously accumulated set of active pixels. Therefore, in any given year, there will be three classes of forest pixels represented as shown in Figure 6.24.

The first class of forest pixel is 'inactive' (red). This means that the forest cover has not been subject to a land clearing event since 1972 and is not in the model. The second class of forest pixel is 'active for the first time'. This means that the forest on that pixel has undergone a land clearing event in the current year (T_1, blue). The pixel now triggers the initiation of *FullCAM* for the quantification of emissions. *FullCAM* calculates the emissions and removals on that pixel from the moment that the pixel becomes active and the tracking continues each year into the future (T_2, purple and green). These active pixels may remain cleared (purple) or may temporarily regrow some forest cover as part of a cyclic clearing/re-clearing management system (green).

Figure 6.24 Diagram representing the spatially explicit approach for estimating forest land conversion sub-categories



Modelling emissions and removals

Once lands enter the conversion category through a land clearing event, based on activity data, *FullCAM:*

- Randomly allocates date of clearing between the two dates of satellite images
- Obtains site, climate, management and initial assumed biomass (see Appendices 6.B to 6.E) data for that pixel from a series of spatial grids and databases
- Begins to model changes in living biomass, debris and soil carbon pools associated with the change in forest cover; and
- Sums the estimates for each pixel each year to estimate the emission/removals.

Where the forest has regrown after clearing (as identified from the remote sensing), *FullCAM* begins to regrow the forest. Where this regrowth is subsequently re-cleared, the biomass at re-clearing is based on actual age (through identification of time since regrowth).

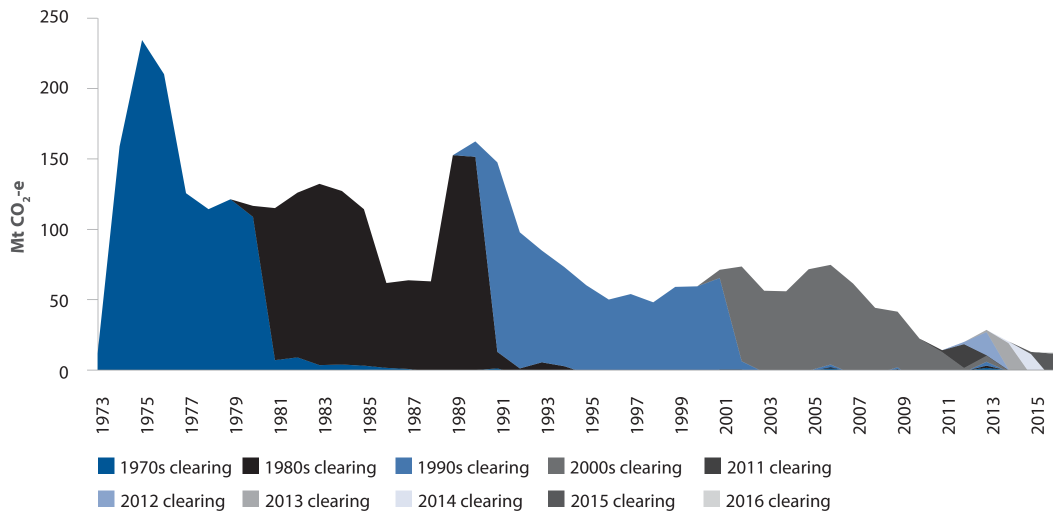
Estimating lagged emissions

Lagged emissions are emissions in any given year that result from a land clearing event in previous years. These lagged emissions are associated with the decay of DOM and soil carbon. As land remains in the conversion category for 50 years from the time of the initial clearing event, any lagged emissions are reported in the years subsequent to the clearing event.

The lagged emissions profile in Figure 6.25 shows that the greatest impact of lagged emissions on overall emissions estimates occurs within the first two years following a land clearing event (n.b. 2012 to 2014).

After 50 years, these forest conversion lands and their associated emissions/removals will be reallocated to the land remaining sub-categories.

Figure 6.25 Tier 3 FullCAM outputs for *forest land converted to cropland and grassland* showing emissions due to past clearing



Estimating changes in biomass

The initial forest biomass and subsequent forest re-growth is estimated using the approaches outlined in Appendices 6.B to 6.D and the parameters described below. The parameters needed to model the subsequent crop and pasture are detailed in Appendix 6.B.

Tree partitioning

The ratios used to partition biomass to the different tree components (Table 6.38) are drawn from a synthesis of available data compiled by Paul *et al.* (2017), with this partitioning varying as the stand matures, and being different for different forest types based on their typical productivity.

Table 6.46 Example of the different partitioning of biomass between the tree components under different types of major vegetation group (MVG). Estimates are for mature stands of assumed stand age 100 years.

Forest Type	Fraction of biomass allocated to:					
	Stems	Branches	Bark	Leaves	Coarse roots	Fine roots
Rainforest	0.43	0.21	0.12	0.05	0.16	0.02
Eucalyptus open forests	0.41	0.20	0.11	0.06	0.19	0.03
Eucalypt open woodlands	0.29	0.20	0.07	0.12	0.27	0.08
Acacia forest and woodland	0.28	0.20	0.07	0.12	0.25	0.09

The carbon content of various tree components (Table 6.47) are drawn from an analysis of a range of species across a range of environments by Gifford (2000a, 2000b).

Table 6.47 Carbon content of tree components – *forest conversion categories*

Tree Component	Carbon Content (fraction of dry matter)
Stems	0.50
Branches	0.47
Bark	0.49
Leaves and Twigs	0.52
Coarse Roots	0.50
Fine Roots	0.48

Estimating changes in debris (dead organic matter or DOM)

Turnover rates impact predictions of inputs to DOM under regenerating forests. But under simulations of both permanantely cleared and regenerated forests, decomposition of DOM will be important. The rates of turnover and decomposition (tables 6.48 and 6.49) were based on a recent review by Paul *et al.* (2017).

Table 6.48 Tree component turnover rates

Tree component	Turnover % $year^{-1}$
Branches	8.50
Bark	4.8
Leaves of forests (and woodlands or shrublands)	30.5 (and 14.3)
Coarse Roots	10
Fine Roots	80

Table 6.49 Decomposition rates for debris pools used in the harvested native forests model.

Debris component	Breakdown % yr^{-1}
Deadwood	14
Bark litter	16
Leaf litter, decomposable*	100
Leaf litter, resistant*	28
Coarse dead roots	30
Fine dead roots	100

*The fraction of leaf litter that was resistant was 77%.

Forest residue management

For each MVG, initial pools of debris just prior to clearing were based on equilibrium simulations of mature forests, with these simulations being undertaking in regions which typify their productivity. Post-clearing, the pools of live biomass are transferred to the DOM pools.

The principal methods of forest conversion involve the extraction of root material (e.g., tree pulling) to allow for subsequent cultivation for pasture and cropping.

Tree pulling usually involves forming 'wind rows' for subsequent burning. Burning of wind rows follows a period of curing (drying), but combustion is still not always complete. *FullCAM* has been developed to accommodate these processes by implementing a delayed burning, with subsequent decomposition of residual material.

The residual decomposing pool also includes 'standing dead' material from treatments such as poisoning. The proportion of biomass potentially affected by burning is set at 98 %, leaving 2 % of all biomass unaffected by burning. Further residue is left to decompose following incomplete combustion, with combustion efficiencies set at 90 % for deadwood, 95 % for bark, 95 % for leaf litter, 80 % for coarse dead roots and 70 % for fine roots. The predictions of post-clearing litter and coarse woody debris draws upon work by Murphy *et al.* 2002; Griffin *et al.* 2002; Harms and Dalal, 2003; Harms *et al.* 2005 and Mackensen and Bauhus, 1999.

Estimating changes in soil carbon

A full description of the soil carbon model (*Roth-C*) and the parameterisation of the model are provided in Appendix 6.B.

Parameters governing the input of carbon to the soil following the decomposition of DOM are the fractions of decomposed DOM that is lost as CO_2 to the atmosphere (CO_2-C). The remaining decomposed DOM that is not lost as CO_2-C is predicted to enter the pools of soil C. Values for these parameters calibrated using forest soil carbon studies as described by Paul *et al.* (2017).

Fires

Carbon dioxide emissions from on-site burning associated with land conversion are estimated using *FullCAM* and are reported under sub-categories 4.B.2, 4.C.2, 4.D.2 and 4.E.2. The mass of carbon burnt annually (FC_{jk}) is a *FullCAM* output and is used to estimate the non-CO_2 gases associated with burning (4V).

There are no direct measurements of trace gas emissions from the burning of cleared vegetation in Australia. However, it is considered that these fires will have similar characteristics to hot prescribed fires and wildfires (Hurst and Cook 1996).

The algorithms for total annual emissions of CH_4, CO and NMVOCs are:

$$E_{ijk} = FC_{jk} * EF_{ijk} * C_i \quad (4.C.2\_1)$$

and for total annual emissions for NO_x and N_2O are:

$$E_{ijk} = FC_{jk} * NC_{jk} * EFi_{jk} * C_i \quad (4.C.2\_2)$$

Where FC_{jk} = annual fuel carbon burnt in land conversion (Gg),

EF_{ijk} = emission factor for gas *i* from vegetation (Table 6.K.10-6.K.12),

NC_{jk} = nitrogen to carbon ratio in biomass (Appendix 6.K.9)

C_i = factor to convert from elemental mass of gas species *i* to molecular mass (Appendix 6.K.9).

Carbon dioxide emissions and removals associated with the burning and subsequent regrowth of northern, central Australian grasslands which occur on *land converted to grassland* are reported under sub-category 4.C.2. The method applied is the same as that for *grassland remaining grassland* fires (section 6.8.1.3).

6.9.1.2 Wetlands converted to grassland

The methodology for activity data collection and modelling of emissions and removals is similar to that underpinning estimates for *wetlands converted to croplands*. As such, this methodology is covered in detail in section 6.7.1.

The activity data for the *forest land converted to grassland* classification is drawn from the remote sensing program (see Appendix 6.A), and that for the *wetlands converted to grassland* classification comes from the 1996 and 2010 Land use of Australia surveys, to which extrapolation and interpolation methods were applied to calculate an average annual rate of conversion (see Section 6.7.1). Table 6.50 shows cumulative areas for *land converted to grassland* over the period 1990-2015.

Table 6.50 Cumulative area of *land converted to grassland* 1990–2015 (ha)

Year	Forest land converted to grassland	Wetlands converted to grassland	Total
1990	8,207,166	48,877	8,256,043
1995	10,600,597	48,877	10,649,474
2000	12,390,294	48,877	12,439,171
2005	14,377,448	48,877	14,426,325
2006	14,767,462	48,877	14,816,339
2007	15,088,259	48,877	15,137,136
2008	15,310,061	48,877	15,358,938
2009	15,486,569	48,877	15,535,446
2010	15,629,486	48,877	15,678,363
2011	15,745,549	48,877	15,794,426
2012	15,863,938	48,877	15,912,815
2013	16,006,292	48,877	16,055,169
2014	16,130,588	48,877	16,179,465
2015	16,241,364	48,877	16,290,241

6.9.2 Emission estimates

Emission estimates for the components of *land converted to grassland* are reported in Table 6.51.

Table 6.51 Net emissions and removals from *land converted to grassland* sub-categories 1990–2015 (Gg CO_2-e)

Year	Forest land converted to grassland	Wetlands converted to grassland	All
1990	152,318	896	153,214
1995	65,400	896	66,296
2000	62,362	896	63,258
2005	74,116	896	75,012
2006	76,238	896	77,134
2007	68,276	896	69,172
2008	56,437	896	57,332
2009	51,968	896	52,864
2010	45,882	896	46,778
2011	42,008	896	42,904
2012	40,101	896	40,997
2013	40,921	896	41,816
2014	34,900	896	35,796
2015	28,968	896	29,864

6.9.3 Uncertainties and time series consistency

Uncertainties for *forest land converted to grassland* at the national scale were estimated to be ±27.9% for CO_2. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

Emissions estimated against *wetlands converted to grassland* are reported for the period 1990 to 2015. The current Tier 1 method relies on interpolation and extrapolation with respect to two observational years. ABARES does not report on uncertainty about the land use estimates. However, these are likely fall in the medium to high range.

While there is a higher uncertainty in *wetlands converted to grassland* than in *forest land converted to grassland,* the former category makes only a small contribution to the overall uncertainty of *land converted to grassland* due to its lower emissions.

6.9.4 Source specific QA/QC

Verification of area of forest clearing estimates

The Department has undertaken a detailed quality control verification exercise, in consultation with the Queensland Department of Science, Information Technology and Innovation (Queensland DSITI), to address recommendations contained in Federici (2016b) designed to test the quality of the estimates of areas of forest conversion used for the national inventory.

The analysis showed a high level of agreement between the monitoring systems implemented by the Department of the Environment and Energy for the national inventory system and the Queensland DSITI system implemented for the *Vegetation Management Act 1999* for the state of Queensland.

Over the available time series (1988-2014), the Department of the Environment and Energy estimates of the area of the conversion of forest lands were within ±10% of Queensland DSITI datasets (see section 6.A.7) providing assurance that national inventory estimates of forest conversion are complete and unbiased.

One area of difference between the two systems related to the identification of the area of *forest lands.* Some clearing of woody vegetation identified in both systems is reported in the national inventory in the *grasslands remaining grasslands* classification (and is treated as loss of shrub or sparse woody vegetation).

An additional 16,839,196 hectares of shrub or sparse woody vegetation not classified as *forest lands* was also identified in the national inventory system as having been lost since 1988, ensuring that the national inventory is complete in estimated losses of sparse woody vegetation (note that a similar amount of sparse woody vegetation was gained during this period).

In around 6% of cases, the Queensland DSITI identified clearing activity by landowners on national inventory grasslands predominantly consisting of native or improved pastures - which may be interpreted in large part as actions by landowners to prevent the emergence of woody species or to remove isolated woody vegetation in pasture which, while having significant long term implications for the nature of the landscape, does not generate material net emissions at the time of the event and is not recorded in the national inventory. Validation/fine tuning of biomass estimates using empirical data

Following on from a verification study undertaken in 2016 (Roxburgh et el., 2016), CSIRO scientists have utilised a recent collation of approximately 6,000 new empirical biomass datapoints to update *FullCAM*'s *M* layer to fine tune the accuracy of predicting biomass, particularly in tall temperate forests (Roxburgh *et al.* 2017) forthcoming). The simulation of above-ground forest biomass in FullCAM is based on an empirical relationship between model-predicted forest growth (the Forest Productivity Index or FPI) and observations of biomass collected from minimally disturbed stands. This relationship is used to predict '*M*' - the maximum attainable site above-ground biomass. In the update by Roxburgh *et al.* (2014), the original calibration database was augmented with forest biomass observations from the TERN/AusCover National Biomass Library (See Appendix 6.D for details the latest validation and fine-tuning of the *FullCAM* model).

Further information on the *FullCAM* model, along with the associated quality assurance and quality control program, are in Appendices 6.B, 6.C, 6.D and 6.F.

Verification using Tier 2 model

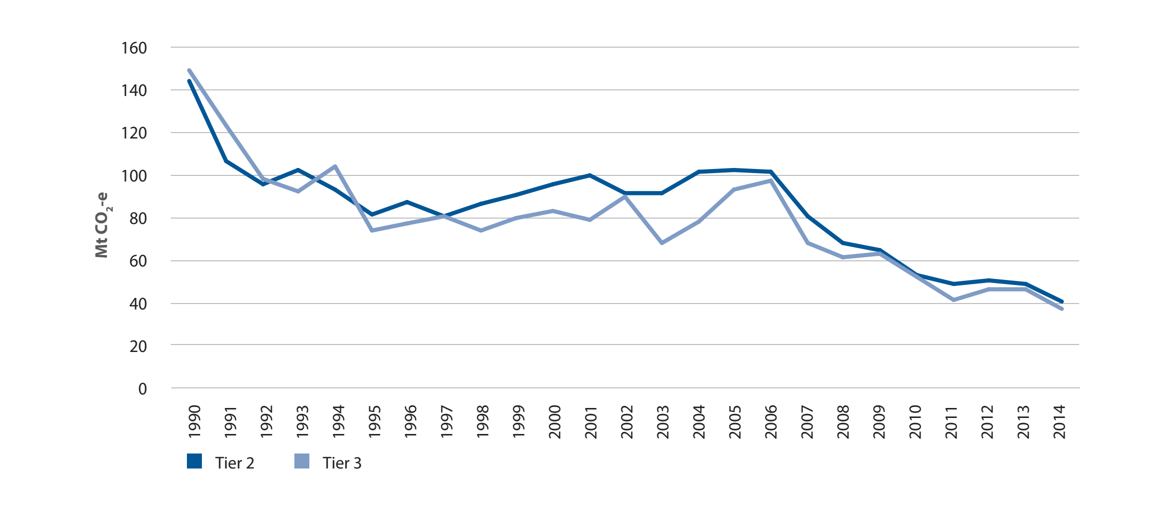
Up until the 2016_14 NIR, verification of the Tier 3 based emission estimates from this sub-category was performed through comparison with a Tier 2, Approach 2 method (described in Appendix 6.H). The Tier 2 method is a spreadsheet model based on country specific biomass data for three broad ecosystem types and uses the areas from the remote sensing analysis, applied using an Approach 2 method (i.e., not fully spatially explicit). The model includes all carbon pools (living biomass, DOM and soil) and emissions from fire.

The results from the two models have been largely consistent and have followed a similar trend since 1990 (Figure 6.26). By and large, the emissions output has not varied substantially between the Tier 2 and Tier 3 models; however, the discrepancies between the two model approaches can be explained further.

The Tier 2 method uses country-specific coefficients for three regions differentiated by vegetation class to estimate emissions and removals from deforestation (land use change). It standardises the biophysical (soil, climate, etc.) environment, and hence forest productivity, across Australia. That is, the Tier 2 model does not encompass the finely disaggregated spatial variability relating to soil types (and their characteristics) and climate variability (particularly rainfall) which would have an effect on emission levels. As such, CO_2 emissions and removals could be overestimated or underestimated. The Tier 3, Approach 3 method is spatially explicit, operates at a fine scale (25 m) and incorporates the variability of the biophysical environment (climate and soil) across Australia. This therefore includes the effects of climate, better represents regrowth and reclearing cycles and varies emissions based on the site characteristics of the land subject to clearing.

Due to the significant updates and improvements to activity data collection and estimation methods (see section 6.9.5 below), comparison with the Tier 2 model as described above is no longer strictly valid. However, historical use of the model as described above remains valid, and the factors driving the changes between the 2016-14 and 2017-15 NIRs are well understood and explained, along with their impacts, in section 6.5.5 below. As part of our improvement plan, we will review and update the current Tier 2 model to ensure it remains a valid QA check for future inventories.

Figure 6.26 Emissions from *forest land converted to cropland* and *grassland* output from Tier 2 and Tier 3 methodology from 1990–2014

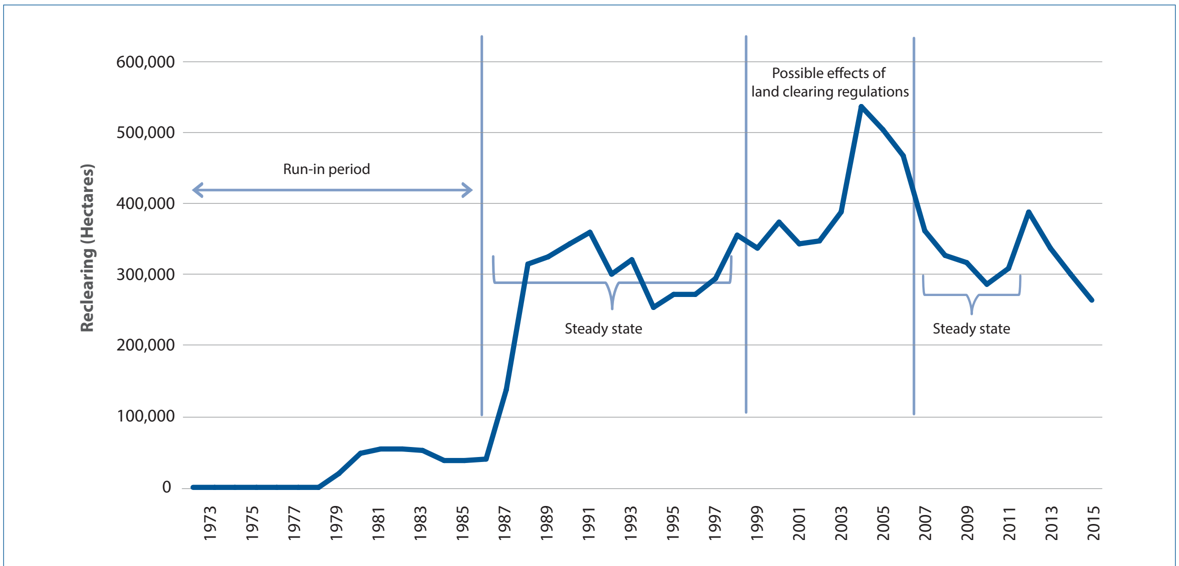


Testing sensitivity of emissions in 1990 to re-clearing prior to 1990

The Tier 2 forest conversion model described in Appendix 6.H has been further used to test the sensitivity of the 1990 estimate of emissions from *forest land converted to other land uses* to the amount of re-clearing prior to 1990.

Re-clearing is the observation of forest clearing on land which has been observed to be cleared previously. Observations of re-clearing are constrained by the availability of Landsat data from 1972 (see Appendix 6.A). Despite this constraint, by 1990, observed re-clearing reaches a level that is consistent with the amount of re-clearing observed subsequently – a steady-state of re-clearing of observed (Figure 6.27). From 2004 re-clearing rates increase from the steady-state and then decline in the period 2007 to 2015. Aside from the effects of economic drivers, the recent declines may be due to the more restrictive land clearing policy changes implemented in 2007. The current decline may also reflect land managers bringing forward decisions to clear land in the period 2004 and 2006 – the period between the passage of the new laws and before they came into force.

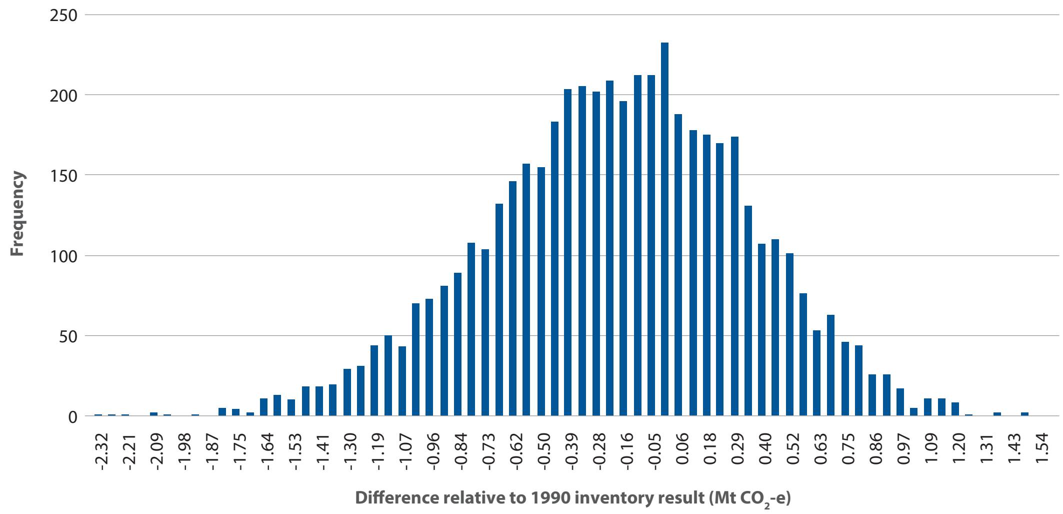
Figure 6.27 Observed re-clearing 1975–2015



While by 1990 re-clearing had reached a steady state, the observed re-clearing during the run-in period 1972-1989 (Figure 6.27) are less certain. To test the potential impact of varying levels of re-clearing prior to 1990 on estimated emissions in 1990 a simulation with 5,000 iterations was undertaken using the tier 2 forest conversion model (see Appendix 6.H for a description of this model).

The impact of varying re-clearing prior to 1990 on emissions in 1990 was tested using a Monte Carlo simulation through 5,000 iterations. The simulations were set to randomly select an amount of re-clearing within the range of approximately 0-500,000 hectares per year in the period 1972-1989. The results of this analysis are presented in Figure 6.28.

Figure 6.28 Sensitivity of 1990 emissions estimate (*Forest land converted to other land uses*) to Monte Carlo simulations of re-clearing scenarios prior to 1990



The results of this sensitivity analysis show that the estimate of emissions in 1990 is relatively insensitive to re-clearing prior to 1990 (Figure 6.28). The results of the 5,000 iterations of the model fell within the range of approximately -2.5 Mt CO_2-e to 1.5 Mt CO_2-e relative to the inventory estimate. To simulate re-clearing rates higher than those observed (Figure 6.27), it was necessary to simulate a corresponding first time clearing event further in the past[7]. When the re-clearing simulated was higher than the observed rate of re-clearing, emissions are estimated to be lower in 1990 under these scenarios because of the additional time available for the decay of soil carbon and forest debris prior to 1990.

The estimates of *forest conversion* for 1990 are based on a limited dataset on estimated land use change extending only from 1973-1990. Extending the observed dataset on land use change to include estimates for the missing data on land use change for the period 1940-1972 could be implemented using a range of techniques identified in IPCC 2006.

The implementation of an extended dataset on land use change to 1940 would lead to higher emissions estimates for *forest conversion* for the entire time series, with larger impacts at the start of the time series, 1990, than for later periods of the time series. It is assessed that the estimate for net emissions for *forest conversion* categories would be 13 Mt CO_2-e higher in 1990 if the land clearing trend is back cast with an assumed clearing peak in 1974 and is applied in the *FullCAM* Tier 2 model (see Appendix 6.A). This step has not yet been implemented.

7 Where regrowth (prior re-clearing) was simulated to occur between 5-10 years after first time clearing, which in-turn was simulated to occur between 10-15 year prior to regrowth. As a result the simulation included scenarios where first-time clearing was modelled to occurs as far in the past as 1947 (1972 minus (10+15).

A related question, that of the appropriate length of the transition process, remains open. While the Department of the Environment and Energy assumes a 50-year period for the reporting of land in a land use change category, the IPCC assumes a default length of transition to a new carbon stock level of 20 years.

Quality assurance/quality control measures for *wetlands converted to grassland* involve internal reviews of data entry and model outputs, including a check on the consistency of land use statistics across Australian jurisdictions.

6.9.5 Recalculations since the 2014 Inventory

6.9.5.1 Forest land converted to grassland

Table 6.52 shows the overall size of the recalculations applicable to *forest land converted to grassland* each year since 1990, and includes a break-down of the contributions by the main factors influencing these changes.

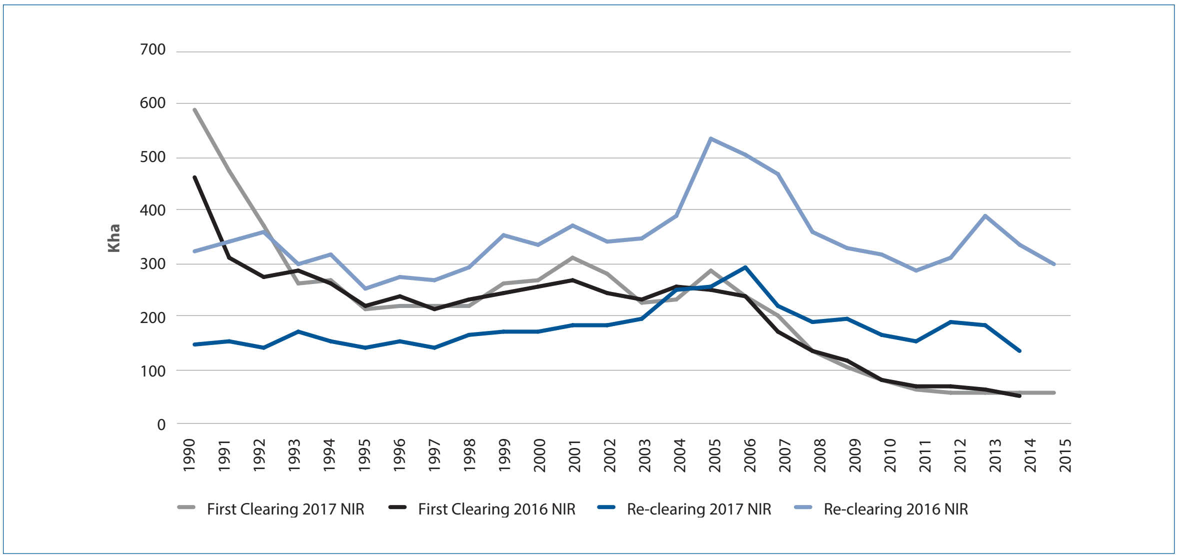
The key factors are: enhancements in geospatial monitoring of land clearing; a range of updates to key parameters used in the FullCAM modeling suite, and changing the reporting cycle from calendar to financial years for consistency with other sectors.

A. Enhanced Geospatial monitoring

A key factor in annual recalculations for the forest conversions sub-categories is revisions to the area of forest conversions identified using satellite imagery. These revisions are due to expansion of the forest area monitored and improvements in the analysis of satellite imagery. In this NIR, a national mapping programme has been undertaken to assess both the extent, and changes in extent, of sub-forest forms of woody vegetation using the Landsat TM, ETM+ and OLI data from 1988 to 2016 (Caccetta and Furby, 2004). This method (3-class algorithm) builds on the 2-class (forest and non-forest) time series CPN classification technique, by incorporating an additional spatial measure to distinguish between sparse woody vegetation (5-7% to <20% canopy cover) and forest (≥ 20% canopy cover).The revisions can affect annual estimates throughout the historical monitoring period from 1972.

Land clearing has been recalculated in this NIR using the lastest land cover change data derived from the new 3-class algorithm (Figure 6.29). As shown in this figure, there is no significant difference in land clearing area estimates for the first time clearing of mature forests. However, reclearing of regrowth forests has increased using the 3-class time series data. Reclearing encompasses areas where clearing has previously occurred, vegetation has been allowed to regrow and is then cleared at a later date. The classification parameters in the 3-class algorithm have been modified in such a way that allows more area to be qualified as forest at the forest and sparse woody vegetation boundary. As a result, many areas of reclearing that were previously captured in the NIR as sparse clearing are now reclassified as forest clearing. Using the latest 3-class woody vegetation time series change data, these areas are now included in the deforestation account, which were previously reported as sparse woody vegetation clearing in grasslands. This is supported by the sharp decrease in sparse woody vegetation loss previously reported in grasslands as shown in Figure 6.30 below. Sparse woody vegetation is highly dependent on climatic conditions and fire history. In addition, it is more difficult to detect sparse woody vegetation using Landsat MSS imagery, hence sparse woody vegetation data is only available from 1988 using TM data. Given the fewer observations of TM sensor data during the early 1990s, it takes a few more years for the CPN algorithm to stabilise in order to provide more accurate detection of sparse woody vegetation. This explains the spikes seen during the early 1990s in the sparse woody vegetation change data.

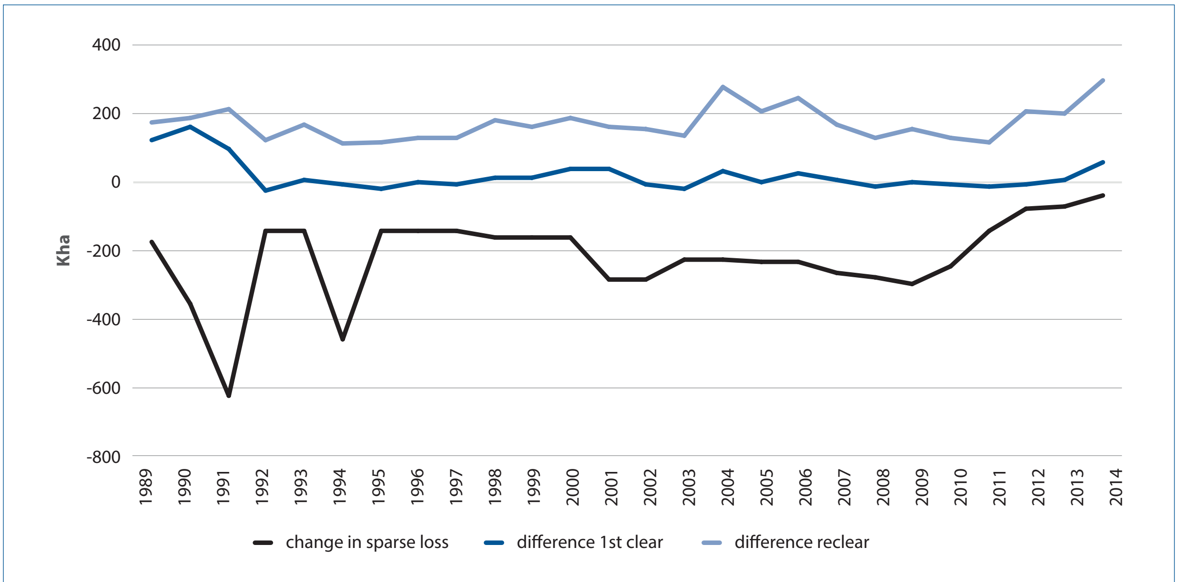
Figure 6.29 Revision of land clearing areas using the new 3-class woody vegetation monitoring system



Net emissions reported for a particular year comprise the immediate emissions associated with the clearing undertaken in that year and the lagged emissions and removals modeled for that year associated with land previously cleared. The inter-annual variations in net emissions are due to the differences in land area cleared from year to year, as well as variations in soil carbon loss and biomass gains across the accumulated area cleared since 1972.

Figure 6.29 shows a sharp increase in first time clearing of mature forests in 1990. This is likely to be a result of less clearing being reported in 1988-89, which is now confirmed as actual clearing and has been reported in 1990. These years also correspond to the dates of sensor change in the Landsat satellite, which resulted in corrections to the imagery. Some minor changes could also be due to historical clearing picked up with the 3-class algorithm.

Figure 6.30 Change in reported primary forest clearance and reclear, and change in sparse woody losses between the 2014 and 2015 national inventory reports. (kha)



For the 2017 submission, monitoring of forest conversions has been extended to new areas of Western Queensland, Northern Territory, Western Australia and South Australia (see Figure 6.A.1 of Appendix 6), given advances in monitoring capabilities that have permitted more timely and cost effective processing of data.

In addition, satellite imagery used in earlier inventories has been re-analysed to take account of independent datasets for vegetation clearing, including vegetation monitoring data prepared by the Queensland Department of Science, Information Technology and Innovation (DSITI) and NSW OEH (See Appendix 6.A for further details). Rule based processing and filtering of land cover change data is also being undertaken to improve accuracy and consistency of attribution, while new QA/QC reporting procedures have enhanced the transparency of the processes.

B. FullCAM maximum biomass 'M' parameter

Enhancements were made to the tier 3 FullCAM modeling suite that influenced emissions estimates for land conversions over the 1990-2014 time series. This included recalibrating the FullCAM spatial layer representing maximum biomass carrying capacity (M) across Australia to improve confidence in estimates of emissions/removals associated with forest cover changes (Appendix 6.D). The update confirmed the validity of the current FullCAM model performance for those forests subject to clearing and regrowth, particularly Queensland, but resulted in increases to predicted maximum biomass for temperate forests (Roxburgh *et al.* (2017)).

The effects of this improvement on emission estimates varies by region, however overall resulted in an increase in emissions from primary clearing, particular clearing of temperate forests with >50% canopy cover.

C. FullCAM Tree parameter updates

Recent empirical research has been used to update the parameters governing the allocation of biomass amongst tree components during growth, rates of turnover of these components to debris and subsequent decomposition (including turnover to the soil carbon pool and decay to atmosphere). These enhancements are described in Paul and Roxburgh *et al.* (2017) and Appendix 6.B, however the main changes are outlined below.

- A decrease in allocation to stem wood, an increased allocation to branch wood for most forest types and an increase to foliage for woodlands and shrublands. There was also generally a decrease in the root-to-shoot ratio for many woodlands and shrublands
- Turnover of all pools significantly increased for native systems
- Decomposition rates under native systems were reduced based on recent research and litter bag studies
- Turnover of all pools significantly increased, and the CO_2-C loss to atmosphere on decomposition was substantially decreased. The CO_2-C loss on decomposition was substantially decreased for all forest types, but particularly for native systems
- Resulting revisions to model initialisation resulted in decreased initial debris pool. Woodlands changes to initial pools of biomass resulted in less on-site C stocks post-clearing given the increased allocation to foliage at the expense of allocation to stem wood.

These data improvements resulted in a reduction of net emissions due to clearing and burning events, and an overall increase in sequestration from regeneration, particularly in soil due to a greater input of C. This has had the effect of significantly reducing emissions earlier in the time series when land clearing rates were higher, with smaller reductions to emissions in later years when primary clearing is reduced however rates of regeneration are increased (see Figure 6.5).

D. Alignment with sectoral estimation periods

Alignment of estimation periods for carbon stock estimates, consistent with Annex A sectors and other parts of LULUCF reporting.

E. Rounding policy and performance audit

There are minor recalculations due to corrections in data and implementation of a new rounding policy for emission factor precision.

Table 6.52 *Forest land converted to grassland*: recalculation of total CO_2-e emissions, 1990–2014

Year	Forest land converted to grassland				Reasons for Recalculations				
	2016 submission	2017 submission	Change		A. Enhanced Geospatial monitoring	B. FullCAM 'M' parameter update	C. FullCAM Tree parameter updates	D. Conversion to financial year basis	E. Recalculation due to rounding policy
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	%					
1990	130,645	152,318	21,673	17%	40,285	7,284	-30,796	4,892	8
1995	65,805	65,400	-405	-1%	8,298	2,831	-26,434	14,893	7
2000	69,699	62,362	-7,336	-10%	8,151	463	-11,630	-4,326	6
2005	79,975	74,116	-5,859	-7%	15,873	-2,268	-14,729	-4,741	5
2006	83,000	76,238	-6,762	-8%	3,992	193	-2,407	-8,543	3
2007	57,746	68,276	10,530	18%	16,813	1,014	-31,374	24,073	5
2008	53,121	56,437	3,315	6%	10,446	1,595	-11,741	3,012	4
2009	54,080	51,968	-2,112	-4%	584	2,285	6,700	-11,686	4
2010	44,522	45,882	1,360	3%	8,298	2,856	-29,611	19,799	17
2011	35,021	42,008	6,987	20%	8,732	1,935	2,564	-6,249	5
2012	38,887	40,101	1,215	3%	-1,045	1,436	7,164	-6,345	4
2013	39,774	40,921	1,147	3%	4,610	1,256	-5,937	1,211	8
2014	30,409	34,900	4,491	15%	7,706	826	-12,755	8,710	4

6.9.5.2 Wetlands converted to grassland

Table 6.53 below provides the recalculation results for *wetlands converted to grassland* over the period 1990 to 2014.

There is a minor change due to implementation of a new rounding policy for emission factor precision.

Table 6.53 *Wetlands converted to grassland:* Recalculation of CO_2-e emissions 1990–2014

Year	2016 submission (Gg CO_2-e)	2017 submission (Gg CO_2-e)	Change (Gg CO_2-e)	Change (%)
1990	896.1	895.5	-0.5	-0.1%
2000	896.1	895.5	-0.5	-0.1%
2005	896.1	895.5	-0.5	-0.1%
2006	896.1	895.5	-0.5	-0.1%
2007	896.1	895.5	-0.5	-0.1%
2008	896.1	895.5	-0.5	-0.1%
2009	896.1	895.5	-0.5	-0.1%
2010	896.1	895.5	-0.5	-0.1%
2011	896.1	895.5	-0.5	-0.1%
2012	896.1	895.5	-0.5	-0.1%
2013	896.1	895.5	-0.5	-0.1%
2014	896.1	895.5	-0.5	-0.1%

6.9.6 Source specific planned improvements

Systems for the estimation of areas of forest, forest conversion and related assessments of the gains and losses of sparse woody vegetation will continue to be updated to enable routine integration of information contained in datasets obtained from Queensland DSITI and similar products as they develop. The new systems will continue to build on experiences gained in the use of these datasets during the finalisation of the area estimates for this inventory.

Specifically, the remote sensing programme is further advancing the methods to identify:

- Ongoing improvements and development of rule based methods for change detection and attribution;
- Annual updating of Landsat time series data prior to 2004 subject to availability of data;
- Updating of pre-90 plantation database by combining remote sensing data with existing spatial data held by other agencies
- Review of land use datasets for improved reporting of time series land conversions
- Processing of remaining areas of sparse woody vegetation for parts of central Australia to complete the national coverage.

The planned improvements associated with the modelling of crops and grasslands will have impacts on forest conversion estimates. They are detailed in *cropland remaining cropland* and *grassland remaining grassland* sections below.

Improvements are also planned in relation to activity data collection and modelling of emissions and removals associated with conversons of conventional forest to wetlands (flooded lands) and of mangrove forest to settlements.

With respect to mangrove forest conversions and accounting more broadly for emissions and removals associated with wetlands , the Department of the Environment and Energy has established an informal expert advisory group of academic and government wetland specialists to provide advice on the development of methods and datasets for the coastal wetlands subsector.

Estimating changes in carbon pools and fluxes depends on data and model availability. Australian empirical data will continue to be developed to support future Tier 2 and Tier 3 models.

6.10 Wetlands Remaining Wetlands (Source Category 4.D.1)

Estimates are guided by the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement) (IPCC 2014b). The wetlands inventory focuses initially on coastal wetlands and will be extended in future inventory reports to include inland wetlands.

Net emissions for two subdivisions of *wetlands remaining wetlands* are reported in this submission:

- Gains and losses of sparse woody vegetation on wetlands (both coastal and inland); and
- Emissions from aquacultural production in Australia.

6.10.1 Methodology

Sparse woody vegetation gains/losses

Carbon stock-changes from gains and losses in sub-forest sparse woody vegetation on wetlands have been identified using the same monitoring systems used to identify areas of sparse woody vegetation for grassland systems (see Section 6.9.1.2).

Aquacultural production

The aquaculture (use) subdivision utilises the Australian production figures published annually by the Australian Bureau of Agriculture and Resource Economics (ABARES) in the Australian Fisheries and Aquaculture Statistics report. These statistics are available to the level of state or territory jurisdiction.

ABARES aquaculture production data are reported for various broad groups of animals, and the subgroups within those. The two groups of interest are “Fish” and “Crustaceans”, both of which contain sub-groups that represent marine and/or freshwater species. Only production figures involving sub-groups that are mostly cultured in coastal wetland based facilities are included in this analysis. Therefore fish production data for salmonids, tuna and barramundi are included from “Fish”, while prawns is the only sub-group reported from the “Crustacean” group. There are no other groups from the ABARES dataset reported here.

A Tier 1 method was developed for reporting N_2O emissions. Direct N_2O emissions were estimated using Equation 4.10 in the 2013 Wetlands Supplement. Note that quantities are expressed here in tonnes rather than kg, so that:

$$N_2O\text{-}N_{AQ} = F_F \bullet EF_F,$$

- $N_2O\text{-}N_{AQ}$ = annual direct N_2O-N emissions from aquaculture use; tonne N_2O-N yr^{-1}
- F_F = annual fish production; tonne fish yr^{-1}
- EF_F = emission factor for N_2O emissions from fish produced; 0.00169 tonne N_2O-N (tonne fish produced)$^{-1}$

6.10.2 Emission estimates

Sparse woody vegetation gains/losses

The key input data and estimated net emissions from changes in sparse woody vegetation on wetlands are presented in Table 6.54 below:

Table 6.54 Area and net emissions of sparse woody vegetation, UNFCCC Wetlands remaining wetlands

Year	Area gains	Area losses	Net emissions
	kha	kha	Gg CO_2
1990	61.4	62.1	204.7
1995	46.4	34.8	251.8
2000	62.1	53.0	200.0
2005	73.4	157.1	164.9
2006	50.4	98.9	206.0
2007	49.6	85.6	238.6
2008	67.9	73.5	173.4
2009	77.4	100.5	158.5
2010	60.2	87.3	182.7
2011	107.0	58.5	4.1
2012	111.1	79.6	-43.3
2013	68.8	89.3	-37.0
2014	69.1	103.4	-18.2
2015	130.0	89.8	-44.5

Aquacultural production

Annual emissions for aquaculture over the reporting period 1990–2015 are shown in Table 6.55 below.

Table 6.55 Annual emissions calculated for aquaculture (use) within the wetlands remaining wetlands category

Year	Emissions (Gg CO_2-e)
1990	2.4
1995	6.5
2000	12.2
2005	14.9
2006	17.9
2007	19.6
2008	21.0
2009	23.1
2010	24.3
2011	25.7
2012	30.1
2013	29.1
2014	28.5
2015	33.3

Land Use, Land Use Change and Forestry

The key drivers of variation over the time period are increased sparse transitions in wetlands due to climatic impacts that alter wetland hydrology, increased aquaculture production in tidal wetland areas, and an increase in water storage to meet both agriculture and community water demands.

6.10.3 Uncertainties and time series consistency

Based on a qualitative assessment, the uncertainties for sparse woody vegetation transitions on *wetlands remaining wetlands* is estimated to be medium. Further information is provided in Annex 2. Time series consistency is ensured by the use of consistent methods across the time series.

For the subdivision, N_2O from Aquaculture Use, ABARES aquaculture production data is available for the period 1991 to 2015 (ABARES: *Australian fisheries and aquaculture production publications*). These data are reported nationally and by state/territory, and represent live-weight quantity of aquaculture product that is produced and marketed by aquaculturists. The data generally excludes hatchery production. ABARES does not specify a level of uncertainty with its aquaculture and fisheries production figures. Uncertainty regarding annual finfish and crustacean production in coastal facilities is likely to be within the low to medium range.

6.10.4 Source specific QA/QC

The QA / QC of the activity data for detecting gains and losses of woody vegetation is described in Appendix 6.A.4.

Quality assurance/quality control measures for *wetlands remaining wetlands* (*Aquaculture Use*) involve internal reviews of data entry and model outputs, including a check on the consistency of aquaculture production statistics across Australian jurisdictions.

6.10.5 Recalculations

Recalculations for *wetlands remaining wetlands* for 1990 to 2014 are shown in table 6.56 below. Like for *grassland remaining grassland* (section 6.8.5), activity data for grass and shrub transitions has been revised due improvements in image classification for identifying changes in sparse cover. In addition, emissions from aquaculture production are being reported for the first time.

Table 6.56 *Wetlands remaining wetlands*: recalculation of total CO_2-e emissions, 1990–2014

Year	Wetlands remaining wetlands				Reasons for Recalculations (Gg CO_2 -e)	
	2016 submission	2017 submission	Change		A. Enhanced Geospatial monitoring	B.First estimate of emissions from aquaculture production
	(Gg CO_2 -e)	(Gg CO_2 -e)	(Gg CO_2 -e)	%		
1990	238	207	-30	-13%	-33	2
1995	336	258	-77	-23%	-84	6
2000	265	212	-53	-20%	-65	12
2005	120	180	60	50%	45	15
2006	182	224	42	23%	24	18
2007	228	258	30	13%	10	20
2008	254	194	-59	-23%	-80	21
2009	150	182	32	21%	9	23
2010	138	207	69	50%	45	24

Year	Wetlands remaining wetlands				Reasons for Recalculations (Gg CO_2-e)	
	2016 submission	2017 submission	Change		A. Enhanced Geospatial monitoring	B.First estimate of emissions from aquaculture production
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	%		
2011	133	30	-103	-78%	-129	26
2012	-31	-13	18	57%	-12	30
2013	-51	-8	43	84%	14	29
2014	-47	10	57	122%	29	29

6.10.6 Source specific planned improvements

As indicated for *grassland remaining grassland* (section 6.8.6), further development of the sparse transitions model is planned. For example, growth and decay models will be further developed, exploring options of non-linear transitions and region-specific biomass volumes, and including eventual integration into the tier 3 FullCAM model.

Ongoing improvements include extension of reporting to cover seagrass; specifically accounting for the impacts of capital dredging in Australian coastal waters and estuaries.

6.11 Land converted to wetlands (Source category 4.D.2)

This category comprises the subcategory *forest land converted to wetlands* (flooded land). Forest conversion occurs where forests are cleared as part of the construction of reservoirs and other land categorized in the IPCC 2006 Guidelines as 'flooded lands' under *forest land converted to wetlands*, within the broader *land converted to wetlands source category* (4.D.2).

Where mangrove forests are cleared for commercial developments such as marinas, these conversions are categorised as *forest land converted to settlements* within the broader *land converted to settlements* source category (4.E.2 – see section 6.12 below).

6.11.1 Methodology

Like for areas of forest conversions for cropping and grazing, areas of forest converted to wetland are identified at fine spatial resolution via Australia's Approach 3 remote sensing programme. In this case, the satellite imagery is analysed to identify where forest is cleared for construction of perennial water bodies such as reservoirs.

The method for estimating net emissions is taken from the 2006 IPCC Guidelines, Volume 4.1, Chapter 7, page 7.20, since the conversion to wetlands is a conversion of land to flooded land. Only carbon dioxide is estimated and it is assumed that emissions from the lost biomass occur in the year of conversion. This model is implementated in FullCAM in fully spatial tier 3 mode considering only fluxes in living biomass.

The methodology for activity data collection and modelling of emissions and removals for forest land converted to wetlands has been detailed as part of the earlier section 6.8.1 which covers forest conversion to grassland and cropland subcategories.

6.11.2 Emission estimates

The annual area identified, and associated net emissions are in table 6.57 below.

Table 6.57 Cumulative areas of *forest land converted to wetlands (flooded land), and associated net annual emissions* 1990–2015

Year	Cumulative National Area (kha)	Net Annual Emissions (Gg CO_2-e)
1990	17	610
1995	22	168
2000	24	21
2005	26	23
2006	26	55
2007	26	19
2008	27	35
2009	27	9
2010	28	250
2011	30	455
2012	30	-15
2013	30	19
2014	30	17
2015	30	-7

6.11.3 Uncertainties and time series consistency

Uncertainties for *land converted to wetland* at the national scale were estimated to be ±27.3% for CO_2. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

6.11.4 Source specific QA/QC

The source specific QA/QC for the subcategory *forest land converted to wetland* is covered in detail under *forest land converted to grassland* (Section 6.9).

6.11.5 Recalculations

Recalculations for *land converted to wetlands* for 1990 to 2014 are shown in table 6.58 below.

The recalculations are due to refinement of the preliminary methods used to estimate forest converted to flooded land in the 2016 NIR.

Table 6.58 Recalculation of total CO_2-e emissions, 1990–2014

Year	Forest land converted to flooded land			
	2016 submission	2017 submission	Change	
	(Gg CO_2 -e)	(Gg CO_2 -e)	(Gg CO_2 -e)	%
1990	975	610	-365	-37%
1995	438	168	-270	-62%
2000	490	21	-468	-96%
2005	572	23	-548	-96%
2006	538	55	-483	-90%
2007	362	19	-344	-95%
2008	278	35	-243	-87.5%
2009	257	9	-248	-97%
2010	131	250	119	91%
2011	113	455	342	303%
2012	156	- 15	-171	-109%
2013	137	19	-118	-86%
2014	78	17	-61	-78%

6.11.6 Source specific planned improvements

The source specific planned improvements for the subcategory *forest land converted to wetland* are covered in detail under *forest land converted to grassland* (Section 6.9).

6.12 Settlements Remaining Settlements (Source Category 4.E.1)

The *settlements remaining settlements* subcategory does not include areas of woody vegetation that constitute a forest. This subcategory includes only estimates of net emissions from changes in sparse woody vegetation.

6.12.1 Methodology

Carbon stock-changes from gains and losses in sub-forest sparse woody vegetation on settlements have been identified using the same monitoring and modelling systems used to identify areas of sparse woody vegetation for *grassland remaining grassland* and estimate the associated emissions and removals (see Section 6.8.1).

6.12.2 Emission estimates

The key input data and estimated net emissions are presented in Table 6.59.

Table 6.59 Area and net emissions of sparse woody vegetation, *settlements remaining settlements*

Year	Area gains	Area losses	Net emissions
	kha	kha	kt CO_2
1990	7.5	6.9	-101.4
1995	6.4	4.5	-54.7
2000	6.1	6.6	-22.1
2005	12.6	13.0	-3.6
2006	14.8	11.3	-5.6
2007	11.8	12.1	-1.1
2008	11.7	12.9	6.0
2009	18.0	12.8	-8.7
2010	21.2	12.7	-16.0
2011	18.8	11.0	-25.0
2012	32.5	7.1	-50.9
2013	24.8	8.4	-63.8
2014	22.0	14.9	-68.0
2015	13.7	12.5	-67.4

6.12.3 Uncertainties and time series consistency

Based on a qualitative assessment, the uncertainty for *settlements remaining settlements* is estimated to be medium. Further information is provided in Annex 2. Time series consistency is ensured by the use of consistent methods across the time series.

6.12.4 Source specific QA/QC

The QA / QC of the activity data for detecting gains and losses of woody vegetation is described in Annex 6.A.4.

6.12.5 Recalculations

Recalculations for *settlements remaining settlements* for 1990 to 2014 are shown in Table 6.60 below. Like for *grassland remaining grassland* (section 6.8.5), activity data for grass and shrub transitions has been revised due improvements in image classification for identifying changes in sparse cover.

Table 6.60 Settlements remaining settlements: recalculation of total CO_2-e emissions, 1990–2014

Year	Settlements remaining settlements			
	2016 submission	2017 submission	Change	
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	%
1990	-132	-101	31	-23%
1995	-76	-55	22	-29%
2000	-29	-22	7	-23%
2005	-1	-4	-3	-469%
2006	-4	-6	-2	54%
2007	-2	-1	1	-46%

Year	Settlements remaining settlements			
	2016 submission	2017 submission	Change	
	(Gg CO_2 -e)	(Gg CO_2 -e)	(Gg CO_2 -e)	%
2008	10	6	-4	-43%
2009	-2	-9	-6	-254%
2010	-9	-16	-7	-69%
2011	-23	-25	-2	-11%
2012	-58	-51	8	13%
2013	-65	-64	2	3%
2014	-75	-68	7	10%

6.12.6 Source specific planned improvements

As indicated for *grassland remaining grassland* (section 6.8.6), further development of the sparse transitions model is planned. For example, growth and decay models will be further developed, exploring options of non-linear transitions and region-specific biomass volumes, and including eventual integration into the tier 3 FullCAM model.

6.13 Land Converted to Settlements (Source category 4.E.2)

The land converted to settlements category includes forest land converted to settlements and wetlands converted to settlements sub-categories.

In reporting net emissions from conversion of forest land to settlements, the emissions and removals from the clearance of terrestrial forests estimated separately from mangrove forests.

6.13.1 Methodology

6.13.1.1 Forest land converted to settlements

While activity data is collected via satellite imagery for both types of clearance, the modelling methods differ, reflecting the significant differences between mangrove and terrestrial forests in terms of their allometrics and carbon fluxes.

Clearance of terrestrial forests for settlement development is modelled using the Tier 3 FullCAM model, considering fluxes between all five carbon pools in the same way that conversions from forest land to grassland are modelled. See section 6.9.1 above.

It is assumed that Australian mangrove forest is cleared for the purpose of development only. As such, emissions from mangrove forest loss are reported under *forest land converted to settlements*. The Tier 2 method employed assumes that the biomass, dead organic matter and soil (to a depth of one meter) are all removed under aerobic conditions, and that all carbon from these pools is emitted as CO_2 during the year of extraction with no subsequent changes (Hiraishi, *et al.*, 2013).

The Tier 1 IPCC default values for above ground biomass (AGB), below ground biomass (BGB), dead organic matter (as woody and non-woody litter), and soil organic carbon (SOC), were replaced with values relevant to Australia's varied coastal regions (See Appendix J, Table 6.J.1). This followed a review of the available empirical data reported in the national and international scientific literature with the Australian-based estimates then distributed across an Australian coastline divided into seven broad regions (See Appendix J, Figure 6.J.1).

Values are weighted averages of values reported for common regional species, with the weighting based on estimates of the relative abundance of each species within each region. See discussion below and Tables 6.J.2 and 6.J.3 in Appendix J for more information on which species were included and their relative abundance within the coastal regions.

Activity data (forest cleared) was acquired by overlaying the mangrove major vegetation group (MVG) spatial layer (DoEE. *NVIS data products*. 2017) over Landsat imagery analysed for deforestation activity, as described in section 6.9.1 above and accounting for those areas of deforestation that overlap into the mangrove MVG layer.

The seven coastal regions defined are constructs that correspond approximately to combinations of mangrove biogeographical regions defined in Cresswell (2012), and also fully incorporate sets of spatial tiles that return areas of vegetation clearance and revegetation (Appendix 6J). Mangrove species common to and across several coastal regions were identified and their relative abundances within each coastal region estimated from surveys undertaken in Australian states and territpories (Appendix 6J). Only one species of mangrove (*Avicennia marina*) exists in Victoria and South Australia so that this species had a relative abundance score of 1 in these states.

Differences in regional coastal biogeomorphology are captured by employing species in this analysis that represent a range of intertidal habitats. Therefore the choice of species used in the analysis of regional mangrove mangal characteristics is based on a combination of their relative abundance within and across regions, as well as their place within the intertidal zone. The latter is determined by each species adaption to a combination of factors, particularly frequency and period of tidal inundation, soil pore water salinity and access to freshwater.

6.13.1.2 Wetlands converted to settlements

The *wetlands converted to settlements* sub-category comprises areas of tidal marsh that have been cleared and converted to some form of commercial or residential use. Tidal marsh incorporates all the vegetated, non-forested intertidal habitats that comprise combinations of sparse vegetation (salt marsh mixed with individual mangrove plants), herbs, saline grasses, sedges and rushes. Because tidal marshes form neighbouring and ecotone communities with mangroves any conversion of mangroves to settlement will also result in the clearance of tidal marsh. An estimate of emissions due to this associated clearance of tidal marsh is provided in this inventory.

Whereas mangrove clearance can be detected in Landsat imagery, the same images cannot distinguish between vegetated tidal marsh and un-vegetated saltpan and tidal flat. Therefore the normal spatial analysis framework employed in the Land Sector cannot be used to evaluate the areas of tidal marsh cleared. However the surveys listed in Appendix.J quantify the areas of tidal marsh present, as well as that of mangroves. Therefore the area of tidal marsh cleared is based on their proportional representation (by area) with respect to mangroves within each coastal region (Table 6.J.2).

The methodology for estimating net emissions from conversion of tidal marsh involves a similar tier 1 model to that used for mangrove forest to settlements, using carbon pool parameters relevant to Australia's coastal region. The parameters were derived through a review of the available empirical data reported in the national and international scientific literature with the Australian-based estimates then distributed across an Australian coastline divided into the same seven broad regions used for mangrove forest conversions. Details of the model and parameters are in section 6.13.1.1 and Appendix 6.J

Table 6.61 Cumulative area of *land converted to settlements* 1990–2015 (ha)

Year	Terrestrial forest converted to settlements	Mangrove forest converted to settlements	Wetlands converted to settlements	Total
1990	143,606	1,355	1,567	145,173
1995	212,412	1,828	2,150	214,562
2000	262,053	2,130	2,520	264,573
2005	307,198	2,467	2,952	310,150
2010	330,526	2,826	3,487	334,014
2011	333,558	2,881	3,558	337,116
2012	335,678	2,937	3,633	339,311
2013	338,176	3,008	3,728	341,904
2014	340,364	3,106	3,816	344,180
2015	342,500	3,148	3,863	346,362

6.13.2 Emission estimates

Annual areas identified and associated emissions are in table 6.62 below.

Table 6.62 Net emissions from *land converted to settlements* 1990–2015 (Gg CO_2-e)

Year	Land converted to settlements			
	Mangrove forest	Terrestrial forest	Wetlands (tidal marsh)	All
1990	210	4,714	85	5,009
1995	97	2,336	48	2,482
2000	92	1,793	55	1,940
2005	162	1,983	60	2,205
2006	173	2,160	70	2,403
2007	118	1,555	62	1,735
2008	100	1,312	87	1,499
2009	60	1,131	66	1,257
2010	94	1,161	52	1,307
2011	98	1,377	44	1,519
2012	94	1,182	55	1,330
2013	132	1,105	101	1,338
2014	158	972	67	1,198
2015	74	750	31	855

6.13.3 Uncertainties and time series consistency

Uncertainties for *forest land converted to settlements* at the national scale were estimated to be ±28.4% for CO_2. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

Under *mangrove forests converted to settlements* and *wetlands converted to settlements* the confidence intervals associated with 2013 IPCC guidance values for parameters associated with land use, land use change involving coastal wetlands range from 24% to over 200%. This inventory applies available country-specific values, sourced from the scientific literature, to reduce that level of uncertainty. Although a formal uncertainty analysis is not yet available, the level of uncertainty is anticipated to be towards the lower end of the guidance values, and is considered to be within the medium range.

6.13.4 Source specific QA/QC

The source specific QA/QC for the subcategory *forest land converted to settlements* is covered in detail under *forest land converted to grassland* (Section 6.9).

Quality control of the Excel-based Tier 2 coastal wetland models is based on the comparison of model outcomes against expected outcomes from test data sets used as model inputs. In addition, the area of mangrove forest is determined from the land sector remote sensing program and is subject to the associated quality control and quality assurance protocols described in Appendix 6A. Initial quality assurance of the coastal wetland models is based on in-house reviews of the models, underlying assumptions, and parameter and emission factor values, and is informed by the latest scientific literature published by members of the wetland advisory group, an external and independent advisory panel to the department.

6.13.5 Recalculations

Recalculations for land converted to settlement are reported in Table 6.63 below.

These include

A. Forest converted to settlements, from refinement of the preliminary methods used to estimate forest converted to flooded land in the 2016 NIR.

B. Implementation of new rounding policy for emission factor precision. This resulted in change to the precision of the emission factor used for direct emissions from nitrogen mineralisation in mineral soils

C. Separate reporting of mangroves converted to settlements

D. First time reporting of wetlands converted to settlements, according to the methodology described in section section 6.13.1.

Table 6.63 Land converted to settlements: recalculation of total CO_2-e emissions, 1990–2014

Year	Land converted to settlements							
	2016 submission	2017 submission	Change		Reasons for change			
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	%	A. Refinements to terrestrial forest modelling method	B. Rounding policy	C. Separate modelling of mangrove converted to settlements	D. New estimates of wetlands converted to settlements
1990	1,301	5,009	3,708	285%	3,413	0.1	210	85
1995	657	2,482	1,825	278%	1,680	0.1	97	48
2000	702	1,940	1,238	176%	1,092	0.1	92	55
2005	787	2,205	1,418	180%	1,196	0.1	162	60
2006	809	2,403	1,594	197%	1,351	0.1	173	70
2007	559	1,735	1,177	211%	997	0.1	118	62
2008	510	1,499	989	194%	802	0.1	100	87
2009	521	1,257	737	141%	610	0.1	60	66
2010	424	1,307	884	209%	737	0.2	94	52
2011	325	1,519	1,194	367%	1,052	0.1	98	44
2012	364	1,330	966	265%	817	0.1	94	55
2013	371	1,338	966	260%	734	0.1	132	101
2014	274	1,198	924	338%	699	0.1	158	67

6.13.6 Source specific planned improvements

Grassland and cropland converted to settlements are included within settlements remaining settlements, based on land representation Approach 1 (IPCC 2006 Guidelines, Volume 4, page 3.10). Work is underway to assess the feasibility of reporting of all conversions to settlements using land representation Approach 3 (spatially explicit land-use conversion data) in future inventory submissions.

The source specific planned improvements for the subcategory of terrestrial *forest land converted to settlements* is covered in detail under *forest land converted to grassland* (Section 6.9)

The following improvements are planned for the mangrove forest and tidal marsh wetlands conversions methodologies:

- Continuous improvement of parameter values within the seven coastal region
- Further assessment of the seven coastal regions regarding their adequacy in representing regional differences in tidal wetland characteristics around Australia
- Assessing model outcomes against outcomes reported in the scientific literature on natural or anthropogenic disturbances in Australian tidal wetlands
- A full uncertainty analysis of model parameter values, and model outputs

6.14 Other Lands (Source Category 4.F)

All *other lands* are considered unmanaged, and as such, Australia does not report emissions and removals from this voluntary reporting category. *Other lands* typically occur in unmanaged regions of central Australia, e.g., deserts.

Other land, by definition, cannot include any land on which a forest has been observed in the Landsat time series since 1972. As a consequence of this definition land converted to *other land* is not observed.

6.15 Harvested Wood Products (Source Category 4.G)

For *harvested wood products*, the carbon pool considered is defined as the wood products in service life within Australia- that is, products consumed in Australia and not yet disposed to a waste stream, plus those that remain in solid waste disposal sites (SWDS). The stock of HWP in service is estimated as the national production (including transfers from *forest land* after harvest that are recorded as a carbon stock reduction in *forest land remaining forest land* and *grassland converted to forest land*) plus the imported material, minus exported material and product disposed to the waste system.

Transfer of carbon from in service HWP to landfill is recorded as a loss of carbon stock from the in-use HWP pools and as a gain in the HWP in SWDS pool. As material in SWDS decays, one half of the losses are recorded as an emission of CO_2 from HWP in SWDS and, reflecting the assumption that landfill gas is 50:50 carbon dioxide and methane, one half of the decaying carbon is emitted as methane.

6.15.1 Methodology

A national database of domestic wood production, including import and export quantities, has been maintained in Australia since the 1940s. It is currently maintained as the Australian forest and wood products statistics by the Australian Bureau of Agricultural and Resource Economics and Sciences within the Department of Agriculture and Water Resources (ABARES, 2015a). This consistent and detailed collection of time-series data provides a sound basis for the development of a national wood products model.

Model components

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

- log flow from the forest: current annual production data were obtained by species groupings, and product classes, e.g., sawlogs, veneer logs, pulp logs, roundwood and other, e.g., sleepers;
- 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 and decomposition in landfill;
- use for bioenergy; and
- other losses to atmosphere.

Wood flow

The model develops wood flows separately for each pool of wood products within the overall HWP pool and these are integrated to account for cross-linkages. This is particularly important in the accounting for waste or by-products, which are themselves used as resources in production for other wood product pools. In conjunction with the opening carbon stock and life cycle of timber products, this model enables the total and projected carbon stocks in HWP to be estimated.

In broad terms, the components of the models developed for each pool of HWP 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, e.g., "x" percentage sawdust, shavings or sander dust for on-site energy generation or compost, "y" percentage woodchips for other manufacturing processes, "z" of sawn timber products, panel products and paper;
- an estimate of the proportion of products by product categories, depending on whether their expected end use is long-term or short-term; e.g., framing timber, dry dressed boards, cases and pallet stock, panel products for use in house construction, panel boards for use in furniture and cabinets, newsprint paper, and writing and printing paper;
- a final figure for total Australian consumption by end use categories, converted to wood fibre content (oven-dry weight) and to tonnes of carbon; and
- import and export data obtained via the ABARES (2015a) source data by end use categories.

Details of the flows are shown in Appendix 6.I.

Treatment of bark

There has been no accounting for bark. All bark is regarded as being a component of logging slash (harvesting residue) and accounted for under in-forest logging operations.

Basic density and carbon content

Basic wood density and carbon content estimates (Table 6.64) are relevant to all processing options, and the choice of values adopted has a significant bearing on the final outcome. In the case of all sawn timber, and treated softwood and hardwood poles, weighted basic densities for the species involved have been applied across each category and the values adopted based on Ilic *et al.* (2000). For board products and paper, which have been subjected to varying amounts of compression during manufacture, their basic densities have been adjusted to that of the finished products.

Carbon content is defined variably throughout the literature, with values ranging from 0.4 to 0.53 of the oven dry (bone dry) weight. A figure of 0.5 has been adopted for use in the model as a median value extracted from Gifford (2000a).

Apart from the assumptions concerning basic density and carbon content, the other manufacturing assumptions were developed from interviews with representatives from the various industry associations and individual sawmilling companies.

Table 6.64 Basic densities, moisture and carbon contents

Carbon Fractions	
Description	**Value**
Fraction of softwood sawmilling dry matter that is carbon, by weight	0.50
Fraction of particleboard dry matter that is carbon, by weight	0.40
Fraction of MDF dry matter that is carbon, by weight	0.40
Basic Densities [(a)]	
Description	**Value kg m-3**
Density of softwood sawmilling	460
Density of hardwood sawmilling	630
Density of cypress sawmilling	600
Density of plywood (softwood and hardwood) and veneer	540
Density of particleboard	520
Density of MDF	600
Density of hardboard	930
Density of softboard	230
Density of pulp and paper: Paper	1,000
Density of pulp and paper: Softwood	430
Density of pulp and paper: Hardwood	500
Density of pulp and paper: Waste paper	1,000
Density of pulp and paper: Pulp	1,000
Density of paper and paperboard imports and exports, on average	1,000
Density of chips and logs for export: Softwood logs	415
Density of chips and logs for export: Hardwood logs	630
Density of hardwood poles, sleepers and miscellaneous	790
Moisture Content of Green Wood	
Description	**Value**
Ratio of weight of water to weight of wood substance in softwood chips	1.10
Ratio of weight of water to weight of wood substance in hardwood chips	0.90

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

Wood flows from processing

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

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

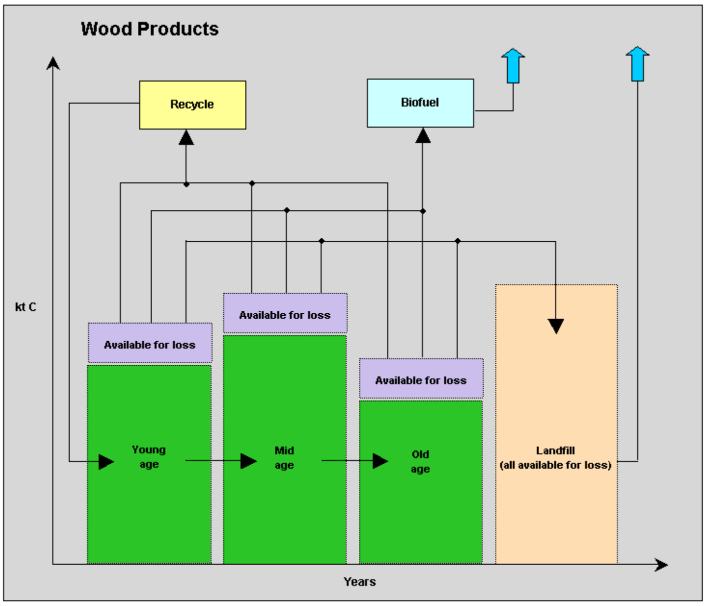
Life span of timber products (recycling and landfill)

The life span of wood products must be taken into account when ascertaining the quantity of carbon stored in timber products. Considerable attention has been given 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 life 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 proportion of material lost from each pool may vary (e.g., 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 (e.g., burnt with no energy capture) (Figure 6.31). The destination of material lost from service life is shown in Table 6.65.

Table 6.65 Destination of material lost from service life (kt C)

Year	Disposed to Landfill	Recycling and recovery of residues	Fuelwood consumed	Emissions from other processes (e.g. Aerobic decay)
1990	1,215	1,726	461	616
1995	1,265	1,998	531	473
2000	1,228	2,453	550	612
2005	1,294	2,551	544	768
2006	1,145	2,620	536	881
2007	1,056	2,674	546	1,034
2008	991	2,704	570	1,168
2009	956	2,748	418	1,230
2010	726	2,802	390	1,443
2011	760	2,833	370	1,414
2012	657	2,851	393	1,324
2013	611	2,812	312	1,432
2014	564	2,856	346	1,368
2015	573	2,905	361	1,308

Figure 6.31 Structure of the Wood Products Model



For shorter-term products, the impact of the size of previous stocks is fairly slight, as the recent additions to the pools have the major impact. For long-term products, an estimate of the size of the initial pool is essential, but difficult. The size of the longest-lived pool representing housing products uses housing starts data.

Life span pools assumed for the Carbon Model

Very short-term products – Pool 1

- Paper and paper products.
- Woodchips and pulplogs for export.
- Age: young = 1; medium = 2; old = 3

Short-term products – Pool 2

- Hardwood – pallets and palings.
- Particleboard and MDF – shop fitting, DIY, miscellaneous.
- Plywood – form board.
- Hardboard – packaging.
- Age: young = 2; medium = 6; old = 10

Medium-term products – Pool 3

- Softwood – pallets and cases
- Plywood – other (noise barriers).
- Particleboard and MDF – kitchen and bathroom cabinets, furniture.
- Preservative treated softwood – decking and palings.
- Age: young = 10; medium = 20; old = 30

Long-term products – Pool 4

- Preservative treated softwood – poles and roundwood.
- Softwood – furniture.
- Roundwood logs for export.
- Age: 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, poles, piles, girders, sleepers and other miscellaneous products.
- Plywood – structural, LVL, flooring, bracing, lining.
- Particleboard and MDF – flooring and lining.
- Softboard and Hardboard – weathertex, lining, bracing, underlay.
- Preservative treated softwood – sawn structural timber.
- Age: young = 30; medium = 50; old =90

A specified proportion of material is lost annually (an exponential loss) from each age class of each in-use product pool. The amount lost from each age class for each product pool can be capped and different proportions can be lost according to age. This feature of the model provides for 'steps' in product loss rather than functioning on 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 is available for the model since 1940. This has the benefit of allowing the model to establish new equilibrium pools, as the input material may be 'turned-over' several times prior to an equilibrium stock being reached for recent years. Initial stock estimation (for 1940) is more important for Pool 5 as this material may remain in use in housing assets.

Model calibration

Once the data on production inputs, processing flows and initial stocks is determined, other model calibration requirements include:

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

The model estimates used are presented in Tables 6.66 and 7.5 (in Chapter 7).

Table 6.66 Decomposition rates and maximum possible loss

Pool	YOUNG		MEDIUM		OLD	
	Loss Yr^{-1}	Proportion of in use Pool exposed to decay	Loss Yr^{-1}	Proportion of in use Pool exposed to decay	Loss Yr^{-1}	Proportion of in use Pool exposed to decay
1	1.0	0.60	1.0	0.65	1.0	0.90
2	0.50	0.30	0.25	0.50	0.25	0.90
3	0.10	0.15	0.1	0.65	0.1	0.45
4	0.05	0.25	0.1	0.65	0.05	0.80
5	0.033	0.20	0.05	0.55	0.025	0.95

Model results

By integrating the carbon pools and life cycles of wood products, the model enables the total carbon pools and emissions to be estimated (Table 6.67).

Table 6.67 Carbon stock and emissions outcomes (kt C)

Year	Domestic Production of Wood Products	Imports of Wood Products	Exports of Wood Products	Increase Due to Wood Products	Carbon Pool (excl. landfill)
	kt C	kt C	kt C	kt C	kt C
1990	2,892	817	781	2,927	74,332
1995	3,585	989	1,206	3,368	80,204
2000	4,464	1,071	1,808	3,727	86,108
2005	5,046	1,178	2,210	4,014	92,772
2006	5,005	1,135	2,172	3,968	94,133
2007	5,166	1,169	2,389	3,946	95,446
2008	5,236	1,235	2,387	4,085	96,834
2009	4,821	1,079	2,150	3,750	97,900
2010	4,687	1,162	2,172	3,678	99,037
2011	4,816	1,277	2,367	3,726	100,229
2012	4,486	1,214	2,164	3,536	101,308
2013	4,234	1,212	1,991	3,455	102,377
2014	4,718	1,206	2,532	3,391	103,448
2015	5,132	1,228	2,851	3,509	104,637

6.15.2 Emission estimates

Table 6.68 Net emissions from *harvested wood productss* 1990–2015 (Gg CO_2-e)

Year	Emissions
1990	-7,157
1995	-7,765
2000	-7,699
2005	-8,061
2006	-7,277
2007	-6,767
2008	-6,812
2009	-5,459
2010	-4,982
2011	-5,326
2012	-4,567
2013	-4,398
2014	-4,284
2015	-4,800

6.15.3 Uncertainties and time series consistency

A qualitative assessment of uncertainty was undertaken and uncertainties for *harvested wood products* were estimated to be medium. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

6.15.4 Source specific QA/QC

Wood product data are available through the Australian Forests Products Statistics published quarterly by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES, 2015a). Economic data from the Australian Bureau of Statistics on the wood and paper products manufacturing industry is also used as a confrontational data source.

Original development of the models used to estimate emissions in the wood products category was undertaken by Jaakko Pöyry Consulting in 1999.

6.15.5 Recalculations since the 2014 inventory

Table 6.69 Recalculations of the HWP inventory

Year	2016 submission	2017 submission	Change		A. HWP in SWDS	B. Minor data changes
	(Gg CO_2-e)	(Gg CO_2-e)	Change (Gg CO_2-e)	Change (%)	(Gg CO_2-e)	(Gg CO_2-e)
1990	-7,157.24	-7,157.16	0.08	< 0.01%	0.08	0.00
1995	-7,764.72	-7,764.66	0.06	< 0.01%	0.06	0.00
2000	-7,699.42	-7,699.39	0.03	< 0.01%	0.03	0.00
2005	-8,060.51	-8,060.51	0.00	0.0%	0.00	0.00
2006	-7,276.54	-7,276.55	-0.01	< 0.01%	-0.01	0.00
2007	-6,767.06	-6,767.07	-0.02	0.01%	-0.02	0.00
2008	-6,812.21	-6,812.24	-0.03	< 0.01%	-0.03	0.00
2009	-5,517.61	-5,458.98	58.63	1.1%	58.63	0.00
2010	-4,951.31	-4,982.14	-30.83	0.6%	-31.07	0.24
2011	-5,319.62	-5,325.51	-5.89	0.1%	-5.66	-0.23
2012	-4,566.75	-4,567.38	-0.63	0.01%	-0.67	0.05
2013	-4,397.42	-4,398.20	-0.78	0.02%	-0.74	-0.03
2014	-2,879.84	-4,283.64	-1,403.80	49%	-1,328.76	-75.03

Recalculations as shown in table 6.69 are due to:

A. HWP in SWDS – revisions as described for the Waste sector;

B. Revised estimates in the Australian Forest and Wood Products Statistics (ABARES, 2016) and minor data changes.

6.15.6 Source specific planned improvements

A review will be undertaken into the interactions of the harvested wood product model with the *forest land* classification (the source of biomass gains), and the *energy* sector (source of loss). The purpose of the review is to ensure that any improved understanding in scientific and technical literature of these interactions is reflected in the operation of the model.

An investigation will be made into improving the interactions between the wood products and waste models with respect to the disposal of woodwaste and paper to solid waste disposal sites.

A planned improvement is underway to enable AD and carbon stock changes to be included for the period 1960-1989 in CRF table 4.Gs.2.

6.16 N_2O emissions from N fertilisation 4(I)

Nitrous oxide emissions, associated with nitrogen fertilisers, are reported under the *Agriculture* sector (3D). N_2O released from the application of N fertiliser on forests is reported as IE (agriculture). The amount of N applied to lands in Australia is obtained from national statistics of the amount of N purchased. It is not possible to split the use of N fertiliser between agriculture and forests.

N fertilisation of native forests is very rare, if occurring at all. There is a limited amount of N fertiliser applied to forest plantations in Australia. Fertiliser application in plantations is typically done to correct for nutrient deficiencies and trace element correction at establishment. N may be applied on sites where it is shown that it is a significant limiting nutrient, but as most establishments are on pasture systems, background nutrient levels are typically sufficient.

6.17 Emissions and removals from drainage and rewetting and other management of organic and mineral soils 4(II)

Australia does not estimate emissions and removals from this voluntary reporting category.

6.18 Direct and Indirect N_2O emissions from managed soils – 4(III) and 4(IV)

6.18.1 Methodology – N_2O emissions from N mineralisation associated with loss of soil organic matters

An increase in N_2O emissions can be expected following a decline in soil organic carbon stocks. This is a consequence of enhanced mineralisation of soil organic matter that takes place as a result of soil disturbance. The conversion not only results in the net loss of soil organic carbon, but the corresponding effects on mineralised nitrogen can result in N_2O emissions from the process of nitrification and denitrification.

The IPCC (2006) methods are used to calculate N_2O emissions from this source. The amount of nitrogen mineralised is calculated from the C:N ratio of soil. The C:N values used are 18 for *forest land* and forest conversion categories and 10 for *grassland remaining grassland*, reflecting the approximate median value extracted from a survey of national estimates (Snowdon *et al.* 2005). The country specific emission factor for fertiliser additions to non-irrigated crops and pastures (0.002 (Gg N_2O-N/Gg N)) is then applied.

Emissions associated with N mineralisation in *cropland remaining cropland* soils are reported in the Agriculture sector (3.D).

6.18.2 Leaching and run-off

In accordance with the IPCC Guidelines, estimates are made of emissions associated with leaching and run-off of the N mineralised through loss of soil carbon. The CS method used for estimating leaching and run-off from agricultural N sources is used.

Annual nitrous oxide production from leaching and runoff is calculated as:

$$E_{ij} = M_{ij} \times FracWET_{ij} \times FracLEACH \times EF \times C_g \quad (4IV\_1)$$

Where M_{ij} = mass of N mineralised due to a loss of soil carbon (Gg N)

$FracWET_{ik}$ = fraction of N available for leaching and runoff (Appendix 5.J.I)

FracLEACH = 0.3 (Gg N/Gg applied) IPCC default fraction of N lost through leaching and runoff

EF = 0.0075 (Gg N_2O-N/Gg N) IPCC (2006) default EF

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

6.18.3 Uncertainties and time series consistency

Further details are provided in Annex 2

6.18.4 Source specific planned improvements

All data and methodologies are kept under review and development.

6.19 Source Category 4(v) Biomass Burning

The methods applied to estimate emissions and removals associated with biomass burnt are described under 4.A *forest land* and 4.C *grassland*.

Appendix 6 A Land cover change

6.A.1 Introduction

The estimation of net emissions for the land sector is supported by the use of remote sensing imagery to determine a time series consistent assessment of land use change in Australia.

The Department of the Environment and Energy has assembled a series of national coverages of Landsat satellite data (MSS, TM, ETM+ and OLI) across 25 time epochs from 1972 to 2016 which are analysed to identify both where and when land use change occurs.

The archive of time series of historic cover and cover change information managed by the Department extends as far as possible given the importance of time series consistent data from 1990 to the present. The effects on emissions from land cover change are typically long lasting, and estimates of emissions from current activities will be affected by the site history. A current conversion event, for example, will likely generate fewer emissions if the forest cleared is secondary forest (regrowth after a previous deforestation) rather than a primary (mature) forest. Consequently, an extensive record of past land management history is a critical input into the preparation of accurate emission estimates.

6. A.2 Monitoring change with remote sensing imagery

Satellite Data Processing

A detailed protocol of remote sensing specifications for land cover change was developed by Furby (2002) through extensive pilot testing (Furby and Woodgate, 2002) to ensure time series consistency of methods, and the provision of spatially accurate land cover change data through time. These specifications determine the exact way that images are acquired, processed and classified.

The sequence of processing stages have been streamlined since the development of the Australian Geoscience Data Cube (previously referred as ARG25) in 2014. The process to produce the assessment of Australia-wide land cover change is:

- selecting highest quality cloud free pixels acquired during the summer season for the southern tiles and the winter season for the northern tiles, from the Data Cube;
- mosaicing[8] of multiple images to the individual map tiles for each time sequence;
- thresholding[9] through all time sequences;
- conditional probability network (CPN) analysis (Kiiveri *et al.*, 2001), each year over the entire time series; and
- attribution[10] of change to direct human-induced change.

8 Mosaicing aggregates images into the map tiles shown in red in Figure 6.A.1, removing overlaps in the original 185 km*185 km images and optimising cloud removal.

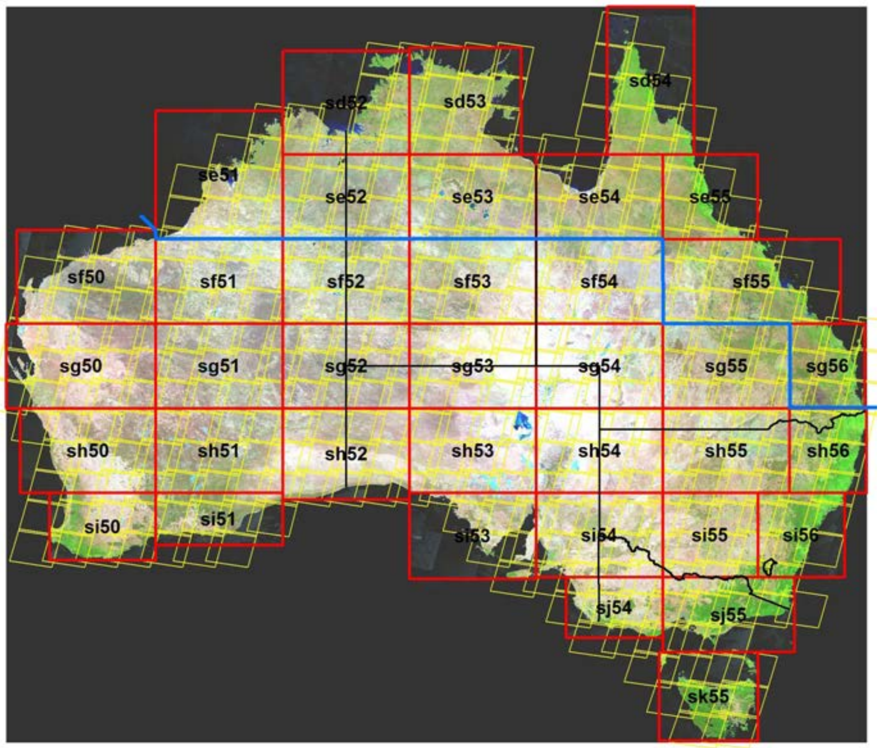
9 Thresholding compares each image pixel to a reference set of spectral characteristics formed by specific band mixes (indices) that represent forest and non-forest conditions.

10 Attribution uses a combination of automation and visual inspection of the image sequence to determine the cause of land cover change and determine subsequent/existing land use.

Image acquisition and selection

The time series of available Landsat images extends from 1972 to 2016. The selection of periods for analysis, shown in Table 6.A.1, was designed to give maximum temporal resolution immediately before and after 1990 and for the period from 2004 onwards to maximise accurate detection of trends in land cover change over time. Since 2005 imagery has been delivered on an annual basis. Figure 6.A.1 shows the 37 map tiles used in the remote sensing programme (red), the north-south seasonal divide used for image capture (blue line) and the paths/rows of Landsat imagery (yellow).

Figure 6.A.1 The 37 1:1 million scale map tiles used in the remote sensing programme



Selection of suitable Landsat scenes from the Data Cube is fully automated. For a given location, the season from which the scene should be selected is identified and the best (cloud-free) image is automatically allocated from the stack within the Data Cube. The image selection criteria (Furby, 2002) require the images to be within three months of the nominated target date. The target dates vary between the north (winter or dry season) and south (summer) of the country and aim to provide the best possible forest discrimination (see Figure 6.A.1). The precise date allocated to each land cover change (clearing and regrowth) pixel is randomly generated by *FullCAM*, within the sequence of coverage dates for the relevant map tile. This method provides a random (unbiased over a large sample) distribution of initialisation dates (timing of land cover change event) for the carbon model, within the constraint of the two dates in the overall interval of the image sequence.

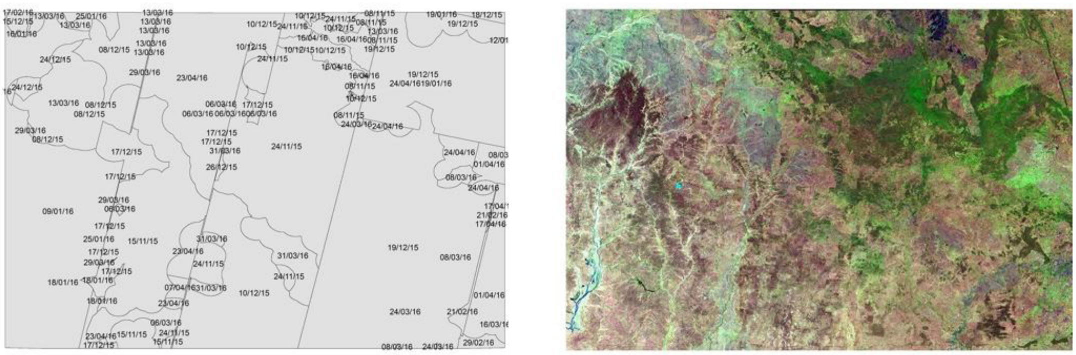
Table 6.A.1 Landsat Image sequence

Year	Resolution (m)	Time since previous image (yrs)
1972	50	-
1977	50	5
1980	50	3
1985	50	5
1988 (early)	25/50	3
1989 (end)	25/50	2
1991 (early)	25	1
1992	25	2
1995, 1998	25	3
2000, 2002, 2004	25	2
2005-2016	25	1

Mosaicing

Scene selection and compositing is automated so multiple images can be combined within each path/row to create a cloud free composite (Furby, 2016). Figure 6.A.2 shows how a mosaic is constructed using multiple images within each path and row, resulting in a composite cloud free image. However, in inherently cloudy locations, some gap filling from earlier imagery may be required.

Figure 6.A.2 Image selection procedure, to create composite cloud free imagery mosaics



Unit of analysis – spatial resolution of the imagery

The 'natural' pixel size of the 1972 to 1985 Landsat MSS (57 m × 79 m) is re-sampled to a 50 × 50 m pixel. The 30 × 30 m native resolution of the Landsat TM, ETM+ and OLI data available after 1985 is produced as 25 × 25 m pixels. This approach deals with the change in pixel size of the various Landsat sensors over time and supports the need for spatially and temporally consistent integration with other spatial data used in *FullCAM*.

To apply the pixel-by-pixel analysis over the period where the pixel size changed from 50 m to 25 m, a 50 m MSS equivalent (in both spatial and spectral resolution) is derived from the 1989 TM (25 m) data, and then forest extent is calculated separately from both the 50 and 25 m data sets. Differences in the extents of forest between these two outputs are due to "sensor change". An overlap technique is used to ensure time-series consistency such that the assessment of land cover change for 1988-89 is then based on a 50 m to 50 m comparison, while the 1989-1991 data is a 25 m to 25 m comparison. As part of continuous improvement, processing of 1988 Landsat TM data at 25m spatial resolution has been completed replacing the 50 m resolution MSS data for 1988. Consequently the entire land cover time series data has been recalculated making use of best available data while maintaining time series consistency. This approach is consistent with good practice for ensuring time-series consistency where the instruments used to collect activity data change or degrade through time (IPCC, 2003 page 5.58).

All Landsat derived data are used at a consistent 25 m resolution for the full time series analysis by re-sampling the 50 m pixels (1972-1985 products) into four 25 m pixels. A spatial-temporal model (see the Conditional Probability Network section below) is used to reduce the effect of "mixed" isolated and edge pixels in the overlap period. The ability to determine, from 1988 onwards, the effects of land use change to 0.2 ha minimum areas is robust, given that this area is greater than the pixel resolution and the approach used removes mixed and other pixels which are temporally and spatially inconsistent.

Re-sampling Landsat TM, ETM+ and OLI sensor data to 25 m pixels is a common practice and provides consistency over the multiple resolutions of Landsat sensors while ensuring uniformity across the time series. Quality assurance and validation processes confirm that accurate results are achieved with this re-sampled data.

Use of Landsat 8 Data

Observations of recent land cover change have been derived from the latest sensor on-board the Landsat 8 satellite, Operational Land Imager (OLI). OLI is an advanced sensor designed to collect improved quality data, ensuring continuity of previous instruments – Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors. Landsat 8 products supplied through the Australian Geoscience Data Cube are in a new format known as the Australian Reflectance Grid (ARG25). ARG25 is a pre-processed product corrected for geometric distortions and calibrated as absolute surface reflectance, hence the specifications of this new product are quite different to the previous Landsat 5 and 7 data products used for the national inventory Land Cover Change Programme (LCCP). To ensure time series consistency and compatibility with the existing LCCP, a detailed technical assessment of the geometric and radiometric consistency and interoperability between these two products was undertaken.

First, geometric consistency was assessed by matching about 13,300 ground control points (GCP) drawn from the LCCP scenes held in the national inventory data library and the corresponding ARG25 scenes. Assuming that the correlation matching succeeds in correctly registering each point, the position residuals provide a measure of the accuracy of co-registration of the two datasets. This analysis showed that whilst the temporal geometric accuracy of ARG25 products is highly consistent, several GCPs had residual matching errors ranging from 1, 2 and greater than 2 pixels compared to the LCCP products. The mis-registration, if not accounted for, would result in false change being reported. To resolve this, the mean residual vector for each ground control point (GCP) was calculated and applied to the LCCP scenes to align with the ARG25 product base. The scene specific transformation coefficients ensure that the two products are aligned and consistent to within a pixel for the entire country.

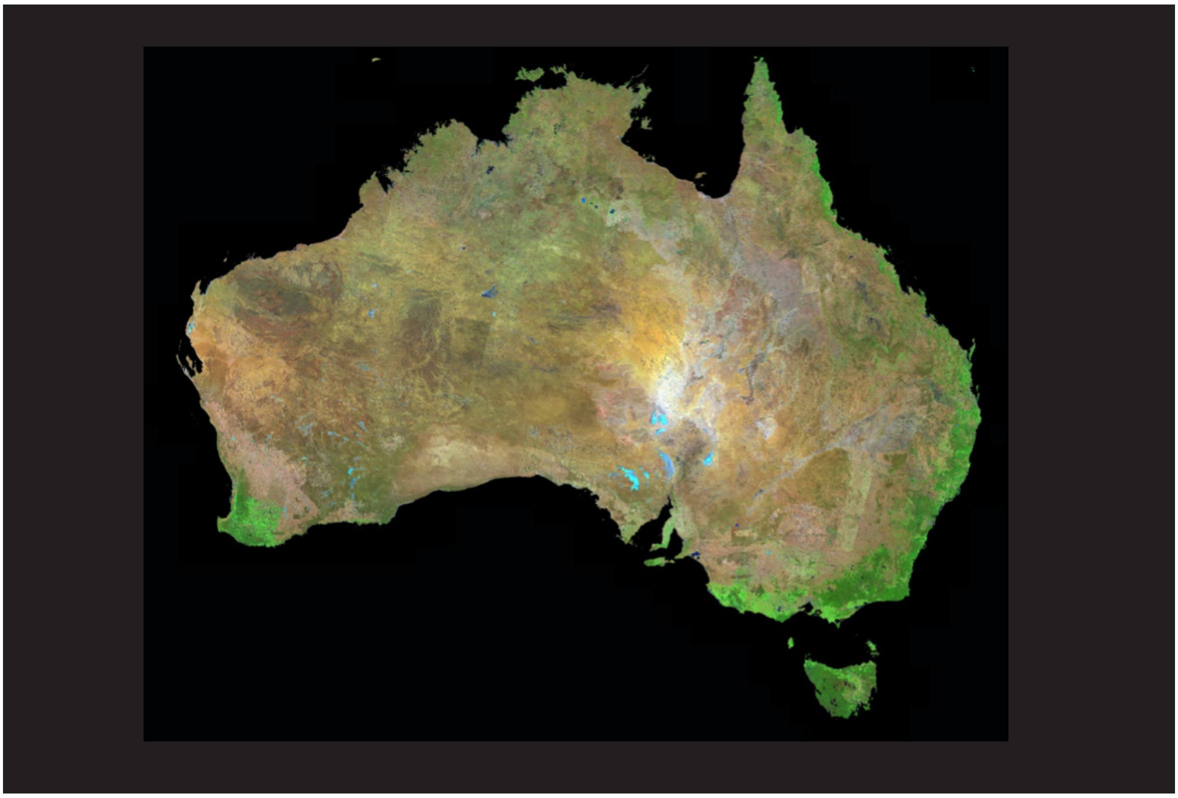
The second step in the process was to assess the radiometric consistency between the ARG25 and LCCP products using a total of 339 image pairs from the 2005 continental coverage. The two products were paired up based on the Landsat path and row, and image acquisition date. Null pixels in either image were discarded. Pixels located in very dark or very bright regions in the LCCP images were also excluded from the analysis, since such values may have potentially saturated during the pre-processing. The remaining pixels were linearly regressed against each other, assuming that the relationship will be strongly linear if both products are internally consistent in relation to radiometric characteristics. Correlation values were calculated for each band, gain, and offset combination. The gain and offset values for converting LCCP pixel values into ARG25 pixel values can be expressed as –

ARG25 = gain × LCCP pixel value + offset

The relatively high correlations found in the 2005 coverage confirm that there is a strong linear relationship, across all bands, between the LCCP values and the equivalent ARG25 image values. Based on this study a scene specific, linear transformation coefficient for each band was calculated to convert the LCCP calibrated pixel values to be consistent with the ARG25 surface reflectance values (Devereux, *et al.* 2013). The time series consistency of this method was also assessed for selected sites using eight years of surface reflectance data.

Based on this study, the 2015 and 2016 ARG25 Landsat 8 datasets (Figure 6.A.3) have been processed to a consistent quality, LCCP compatible tile based mosaic which are then subjected to image classification to derive forest probability maps.

Figure 6.A.3 2016 Landsat 8 surface reflectance image of Australia



Thresholding (forest extent >20% canopy cover)

Thresholding is the process through which pixels in the land cover image sequence are identified as either forest or non-forest. Pixel identification involves comparing the spectral indices of each pixel in the land cover image sequence with reference indices that identify areas of forest in selected strata. Reference indices were established through the use of air photographs, ground data and very high resolution satellite data. Air photographs with known forested areas were interpreted and compared with the Landsat data of the same area and around the same time. The Landsat data spectral bands of the forested area were then identified as reference indices for a given forest and soil type. The air photograph interpretation was undertaken centrally by appropriately qualified and experienced air photograph interpreters. The interpreters provided brief descriptions of forest or non-forest areas at a set of known locations. These descriptions were then used in the selection of reference indices from the Landsat data.

The final reference indices allow for variability in both forest and soil type by selecting indices within homogeneous strata. The stratification to deal with this variability was achieved largely through vegetation and soils mapping. The final reference indices used to identify areas of forest/non-forest are consistent with the definition of a forest, i.e., a minimum of 20% canopy cover and a minimum potential height of 2 m.

Thresholding (Sparse Woody Vegetation <20% canopy cover)

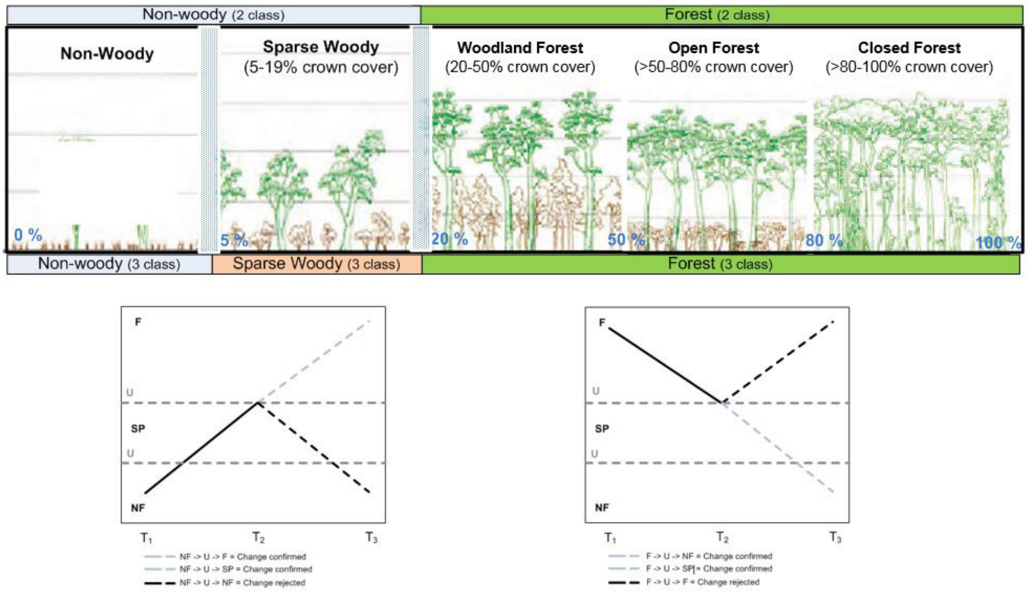
A national mapping programme has been undertaken to assess both the extent, and changes in extent, of sub-forest forms of woody vegetation using the Landsat TM, ETM+ and OLI data from 1988 to 2016 (Caccetta and Furby, 2004). This method builds on the 2-class (forest and non-forest) time series CPN classification technique, by incorporating an additional spatial measure to distinguish between sparse woody vegetation (5-7% to <20% canopy cover) and forest (≥ 20% canopy cover). The 3-class classification better reflects the different types of woody vegetation across the Australian landscape.

The 3-class algorithm provides increased confidence and certainty in the identification of woody vegetation change. As the entire range of woody vegetation needs to be monitored for reporting under the Kyoto Protocol second commitment period and the Paris Agreement, it is essential to create a product that better encompasses all woody vegetation. In the traditional 2-class product, uncertain pixels near the 20% canopy boundary were classified as uncertain forest (see Figure 6.A.4). These pixels had a lower probability of being forest and unless confirmed as forest after the CPN application, ended up being classified as non-forest. Using the 3-class algorithm, forest sites are identified using the same decision boundaries as the previous 2-class product, but a further set of decision boundaries are applied to separate the sparse and non-woody sites using a texture index and two spectral indices. This is a less conservative approach that ensures transitions between woody vegetation types are captured and allows pixels that fall in the uncertain zone to be classified as woody vegetation. Figure 6.A.5 compares the previous 2-class (forest and non-forest) product with the current 3-class ouputs. Background image is from UrbanMonitor™ 2014 (Figure 6.A.5 (A)), and a Landsat false colour composite 2014 (B). Forest is highlighted green and Figure 6.A.5 (D) shows sparse vegetation (in orange) that was detected using the 3-class algorithm.

The extent of sparse woody vegetation covers the period from 1988 to 2016, except for a few interior rangeland areas, for which current sparse woody coverage is limited to 2006. As sparse vegetation has now been incorporated into the 3-class woody vegetation classification, the forest extent and change data has been regenerated for the entire time series to ensure consistency from 1972 to present for all tiles.

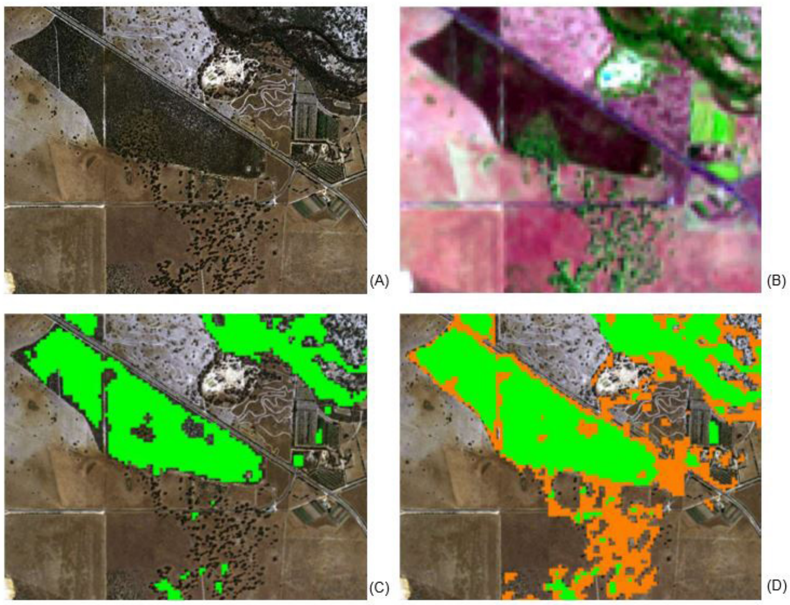
Processing for sparse includes setting woodiness thresholds to identify certain forest, certain non-forest and the uncertain region that could be classified as sparse. The thresholds vary across the landscape according to factors such as soil type, geology and rainfall (Furby, 2016). The conditional probability assigned to each pixel is a result of threshold values being compared to training regions of known vegetation classifications, and also compared to the probability values from the previous epoch at a given location. The forest cover probability images output from this process are reviewed to assess the adequacy of the thresholds and revised accordingly.

Figure 6.A.4. 3-class algorithm to detect entire range of woody vegetation.



Source: Adapted from *Australia's State of the Forests Report 2013*

Figure 6.A.5. Comparison of traditional 2-class forest and non-forest product with the new 3-class product



Conditional Probability Network analysis

Remote sensing pilot testing demonstrated the need for time-series consistency in image data pre-processing, analysis and subsequent formation of time-series woody/sparse/non-woody labels. The operational standards (Furby, 2002) give explicit emphasis through documented rule sets to each of these areas. For time-series classification, these standards also include the use of a joint spatial-temporal model, in this case a Conditional Probability Network (CPN) (Caccetta, 1997; Caccetta *et al.* 2003; Kiiveri *et al.* 2001, 2003), for determining a time-series of woody/sparse/non-woody classes. This process produces superior woody extent and change results compared to a process reliant on pair-wise differencing of image pairs. The use of pair-wise differencing methods can lead to change estimates that are affected by errors due to seasonally changing land management effects (introducing large contiguous areas of false change), or by subtle sampling differences where mixed pixels have varying composition of woody/non-woody from year to year (producing many isolated false change pixels or edge effects at woody boundaries).

The land cover change programme uses Conditional Probability Network (CPN) analysis to strengthen confidence in the 'woody', 'sparse woody' and 'non-woody' classification of a pixel (previously 'forest' or 'non-forest'). This is achieved using a series of spatial and temporal rules to create woody vegetation and land cover conversion datasets. The temporal rules bias against unlikely events such as multiple one year conversions between woody and non-woody, as the CPN empirically assesses the logic of vegetation cover status of a pixel at a point in time, compared to the previous and subsequent images. This helps to eliminate false change from a single image that may be due to anomalies in the data such as unseasonal greenness, wetness or flooding, or missing data. The rules are particularly effective when the time between observations is less than that of a forest growth and harvest cycle.

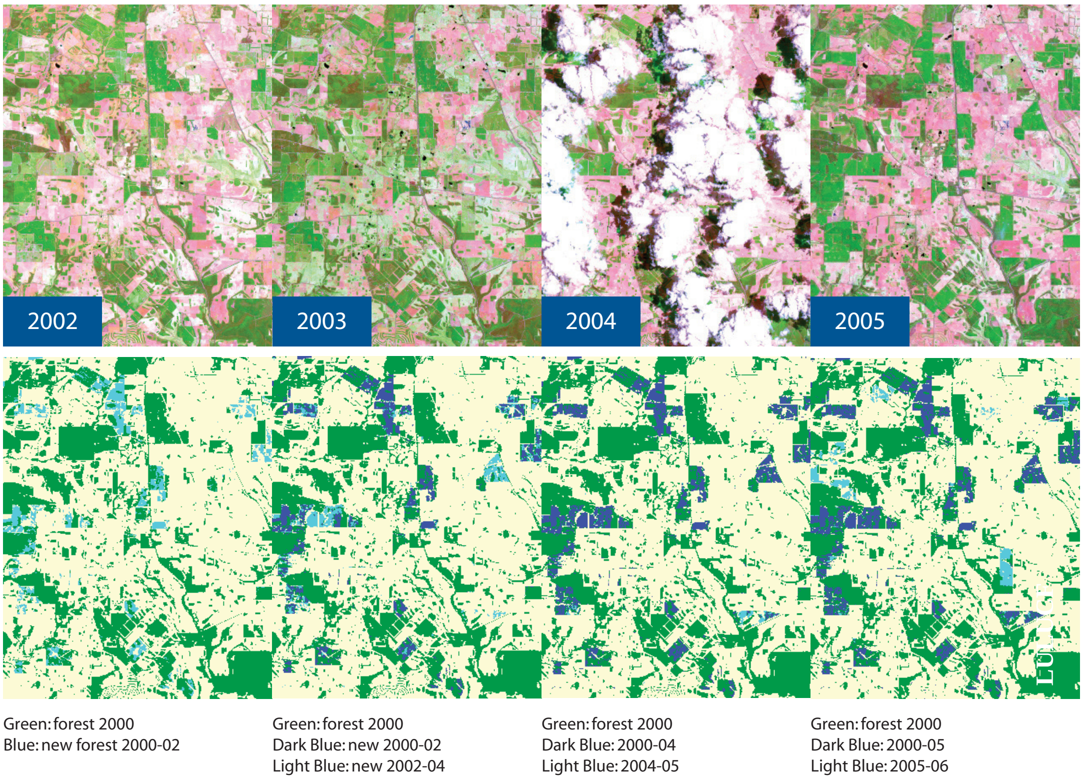
The spatial rules consider the labelling of a pixel in the context of its spatial surroundings, where labels that are consistent with the neighbouring labels are reinforced as opposed to those that are inconsistent (e.g., isolated pixels). This method evaluates the status of adjoining pixels as well as the pixel of interest, which has the effect of reducing 'flickering' false change in scattered and edge woody pixels. It also ensures that individual and small clusters of forest pixels have a high classification certainty in relation to their neighbouring pixels and through time, minimising false detection of individual woody pixels and minimising false change in woody classification that would otherwise occur as a result of small changes in the crown cover of isolated pixels. The spatial and temporal rules work together providing spatial and temporal consistency, minimising temporally varying "mixed pixel" effects (due to spatially varying sampling from independent satellite overpass from year to year) and subsequent error in pixel and change labelling.

This comparative analysis of the same land unit over time was made possible by the accurate and consistent geographic registration and spectral calibration of the image sequences, providing the ability to 'drill' through time on a pixel-by-pixel basis. Geographic registration ensures that the same pixel is being looked at through the time sequence. It also avoids incorrect change status determination due to substitution of neighbouring pixels having potentially different forest cover status, relative to the correct pixel for that location. Spectral inconsistency can also potentially increase the area attributed to clearing and regrowth events by variable status determination due to image calibration difference. This is addressed by consistent (spectral) calibration, thereby preventing the identification of false clearing or regrowth events and results in a more accurate land cover change map. Consistent registration and calibration are both required to ensure robust multi-temporal change analyses.

The CPN allows areas of missing data, such as those due to cloud cover in the Landsat imagery, to be filled in based on the cover status of the earlier and later images (see Figure 6.A.6). With the advent of optimal cloud free image selection from the Data Cube, the amount of missing data is reduced. However gap filling is still necessary in places due to imperfect automated cloud masks and the lack of available data for locations that are inherently cloudy.

There is also potential for sub-pixel shifts to change the forest/non-forest status on the edges of forest systems where a small edge portion of the pixel may have previously been just over the forest area, but a small shift in geographical registration (e.g., 10 m) would be enough to move the pixel out of the forest area. The spatial rules take the status of adjoining pixels into account and so reduce false change in isolated and edge woody pixels.

Figure 6.A.6 Images of forest extent and change, showing how the CPN gap-fills missing data due to cloudy imagery



Forest extent and change analysis

Once the change in forest cover status has been determined for each pixel for a point in time, the spatial relationship of each change pixel to other surrounding or nearby change pixels is assessed to identify isolated pixels with forest cover that do not form part of a forest system. This allows for the identification of pixels that are isolated trees not meeting the minimum canopy criterion defining a forest, as opposed to those pixels that may be part of sparse linear features such as roadsides and riparian zones which do meet the canopy criterion. A minimum mapping unit filter is applied to remove the isolated pixels from the data to be used for attribution.

The area of land cover change is determined as the sum of the changed pixels through time. This approach avoids inclusion of pixels that represent gaps in the forest canopy. An independent study which looked at the implication of the inclusion or exclusion of forest canopy gaps in this way found that the resultant area estimate could vary significantly between approaches (ERIC, 2001). The approach used only includes the area of forest canopy loss and not 'gaps' in the forest canopy. This provides a much lower estimate of area cleared than specified in clearing permits, which usually define the area bounded by the clearing, including gaps in forest canopy cover. Subsequent carbon stock and emissions estimates are computed consistently with the spatial area calculation method. That is, the carbon stock values should reflect the area under canopy, and are not an average that includes 'gaps' between areas of tree canopy.

Using the 3-class product allows us to identify six types of land cover changes in the landscape, namely:

- non-forest to sparse
- non-forest to forest
- sparse to forest
- sparse to non-forest
- forest to non-forest, and
- forest to sparse

Land cover changes related to forest cover gain and loss are reported as *land converted to forest* and conversions of forest land to other land classifications (sections 6.5, 6.7, 6.9, 6.11 and 6.13), whereas changes in sparse woody cover are reported in the *grassland remaining grassland*, *wetlands remaining wetlands* and *settlements remaining settlements* categories (sections 6.8, 6.10 and 6.12) consistent with the 2006 IPCC guidelines.

Attribution of change

The high resolution spatial assessment across the continent identifies land cover change resulting from many causes. For unique identification of conversion to another land use it is necessary to attribute the change event as either direct human-induced and permanent or due to natural temporary effects or methodological artefacts. Land cover change due to temporary tree dieback, natural dynamics of tree mortality and recruitment, drought and both seasonal and inter-annual variability (causing green 'flushes' of growth with similar spectral signals to regrowth) are also identified and excluded by means of an automated, rule based monitoring system, that monitors the temporary loss of forest cover for x number of years to determine if a permanent change in land use or deforestation has occurred. Qualified technical staff use visual image backdrops such as Landsat, Google Earth™ and DigitalGlobe™ via Terraserver™ to differentiate permanent land use change events from those of temporary forest cover loss events such as harvesting or forest fire.

This attribution is achieved by the development of a second series of 'masks' that are derived via visual interpretation of the sequences of images against change mapping. Masks are designed to exclude change due to:

- intermittent water features and irrigation areas that may give a false change signal;
- drought and growth flushes; and,
- terrain illumination.

In each national inventory cycle, the method of attribution is continually updated and improved to increase efficiency and reduce the subjectivity of visual attribution of change.

6.A.3 Plantation typing

To allow for more accurate modelling of emissions and removals from newly established forests (under *Grassland converted to Forest Land*), new plantings (reforestation) identified in the remote sensing imagery are mapped into three classes; native forest (environmental type plantings), hardwood plantation and softwood plantation. Plantation forests are those that are identified as being due to deliberate human action and are identified by type (e.g., introduction of non-endemic species), evidence of establishment practices (e.g., rip lines) and planting patterns (e.g., rows and stand geometry). The identification of conversion between forest and non-forest condition follows the same general approach described above. Plantation classes are identified by discrimination against regionally specific ground training data. The method uses an automated spectral discrimination and is described in Caccetta and Chia (2004). Currently, only Landsat TM, ETM+ and OLI data is used for plantation classification. The 3-class method has also been applied to plantation typing.

6.A.4 Quality Assurance and Quality Control

Programme implementation

During the initial implementation of the remote sensing programme, pilot tests were used to train and develop industry capacity, refine methods and software and to develop logistical systems to maximise both output and opportunity for quality assurance and quality control (QA/QC). The results of the pilot studies are published in Furby and Woodgate (2002).

The approach to programme administration provides for centralised progress monitoring and QA/QC at each stage in the processing of the Landsat data. Each processing stage is a regionally defined package of work based on 37 1:1,000,000 (1:1 M) map tiles of Australia (Figure 6.A 1).

The QA/QC and data validation procedures for each of these items in the Australia's land cover change methods are summarised below – see also Furby (2002). Some of the resource intensive processes undertaken in previous years are no longer valid as multiple steps have been integrated and automated. As a result, QA/QC procedures have also been streamlined, resulting in significant savings and efficiency.

Mosaicing

All mosaiced images (quadrants and time slices) for a particular map sheet tile are assessed at the same time. Due to the automated processing of imagery in the Data Cube, QA/QC of the mosaiced imagery has been streamlined to a single step in this NIR. Each data set is checked to ensure completeness and consistency of the composite images (Furby, 2016).

Thresholding

QA review processes are applied to the thresholding products, during and at the end of the process. The aim is to ensure that a standard methodology has been correctly applied and that the intermediate and final products are consistent with the supplied ground data and with each other, across stratification zone and map sheet boundaries. The assessment of the thresholding products is performed in several stages:

Results of the thresholding analyses are reviewed prior to mosaicing into a single forest cover probability image for each map sheet (Furby, 2016). An initial assessment report is produced, detailing the adequacy and consistency of the analyses and the accuracy of the probability images. The assessment reports advise on actions required. If the analyses or probability images appear inaccurate or inconsistent, further investigations are carried out so that the exact nature of any problem is identified, reported and fixed.

Once any required actions have been undertaken, the results are reviewed again to ensure that an adequate standard has been reached.

When the probability images have passed assessment and are mosaiced, the resultant images and key intermediate products are assessed for mosaicing accuracy, completeness and standardised formatting.

A final assessment report is completed, detailing the results of the assessment and whether any further data review is required.

CPN products

When the CPN datasets are supplied to the Geospatial team, they undergo a supplementary QA review process. The purpose of this review is to provide an independent logic check to identify any issues which may have impacts on future geospatial processing and modelling, before there is a significant impact on resource allocation.

The review assesses the following components of the CPN products:

- An initial contents check is conducted to ensure the correct number of CPN dataset components have been supplied per tile.
- Check that designated change transitions between neighbouring epoch woody definitions are logical and correct across the time series on a pixel by pixel basis.
- Ensure that each tile CPN dataset's individual components for the time series contain pixel values that are within the acceptable range for that component.
- Check that each tile CPN dataset's individual components for the time series have correct spatial extents, geographic projection, pixel resolution and no null pixel entries.
- Produce a summary of percentage difference between the previous NIRs CPN run with the updated CPN run, to determine any variations which would be considered extreme and should be investigated further.
- A sample visual review is undertaken of the distribution of pixels values within the CPN dataset's individual components to ensure they are consistent with the previous NIR and with satellite imagery (e.g., forest classification is consistent with forest shown in associated Landsat imagery for the same year).
- For plant type designations, check they occur over the expected spatial extent when related to the associated forest cover datasets for 1990.

If any issues are found from the above assessment the dataset is returned to the Remote Sensing Specialists for investigation. Only when all aspects of the review are satisfactorily resolved are the CPN datasets available for spatial attribution and *FullCAM* modelling.

Verification

The verification of the remotely sensed land cover mapping is conducted within a continuous improvement programme. An independent programme of checking the Landsat results is conducted by external agencies, both to verify the method (and hence the accuracy of the product) and to identify areas for improvement. This programme involves checking the results of the land cover mapping against high resolution satellite and air photograph interpretation using a stratified sampling technique.

The first verification considered the initial time-series of change data from 1972-2000 and was done using air photograph comparisons (Lowell *et al.* 2003; Jones *et al.* 2004; Lowell *et al.* 2005).

The initial independent assessment of the "raw" accuracy of the classification of forest and non-forest areas across the continent and over the period of 1972 – 2000 indicated that 94-98% of forest and 85-96% of non-forest vegetation was correctly classified (Jones *et al.* 2004). Accuracy in the data used for estimated rates of change (afforestation/regrowth or deforestation) was higher than the above, because the process of manual attribution, described previously, was used to confirm or reject changes in cover in the final dataset.

A second verification programme assessed the accuracy of forest/non-forest classification for the period from 2002-2010 using the same methodology that was used previously (Lowell *et al.* 2012). This involved establishing four hundred points selected in accordance with a temporally stratified random sample across each mapsheet, followed by human interpretation of the likelihood of forest for each point using very high resolution imagery and cross tabulating the interpretation against the CPN classification.

The study concluded that 92% of points were definitely or probably correct. A relatively small 3% of points were incorrectly classified and 7% were probably incorrect. About 81% of interpretations are consistent with the change for points that underwent land cover change at some point between 2002 and 2010.

In response to an ERT recommendation[11], the above study has been extended to assess the commission and omission errors resulting from application of the CPN algorithm. The CPN algorithm is designed to contribute to the process of minimising false changes as the entire time series data is reprocessed each year taking into account of both spatial and temporal history of each Landsat pixel. The resulting change product is subjected to a two-step attribution process, described above, to detect human induced land cover changes.

The following assessment relates to the verification of the raw CPN land cover change product (not the attributed product) using high resolution satellite imagery acquired between 2001 and 2012. The methodology developed for this project (Lowell, *et al.* 2014) enables the mapping of the 7680 sample points from the second verification program in 2012 to the multi-temporal confusion matrix in Table 6.A 2. This matrix shows all possibilities for a point correctly or erroneously classified as forest or non-forest at the start or end of the time interval – Time 1 (t_1; columns) or Time 2 (t_2; rows) respectively.

Table 6.A.2 Sample point distribution in a confusion matrix for temporal land cover change

			Time 1		
		Erroneously labelled Forest	Erroneously labelled Non-forest	Correctly labelled Forest	Correctly labelled Non-forest
Time 2	Erroneously labelled Forest	*Correctly detected No Change (although t1 and t2 classifications are both erroneous)*	*Undetected Deforestation*	*Undetected Deforestation*	*Erroneously detected Regeneration*
	Erroneously labelled Non-forest	*Undetected Regeneration*	*Correctly detected No Change (although t1 and t2 classifications are both erroneous)*	*Erroneously detected Deforestation*	*Undetected Regeneration*
	Correctly labelled Forest	*Undetected Regeneration*	*Erroneously detected Regeneration*	*Correctly detected No Change*	*Correctly detected Regeneration*
	Correctly labelled Non-forest	*Erroneously detected Deforestation*	*Undetected Deforestation*	*Correctly detected Deforestation*	*Correctly detected No Change*

Green cells are those that are correct on the change map. The four cells in the lower right are self-evident: points were correctly labelled at both t_1 and t_2 and therefore correctly identify No Change (NC), Deforestation (DEF)[12], and Regeneration (REG). The two green cells on the upper left diagonal are correctly labelled NC even though the classifications at both *t1* and *t2* are incorrect.

Red cells are errors of commission for change – DEF or REG. Two possibilities exist for both DEF and REG. DEF will be erroneously detected if a point is 1) erroneously identified as forest at t_1 and correctly identified as non-forest at t_2 and 2) correctly identified as forest at t_1 but erroneously identified as non-forest at t_2. The same is true for REG

Lavender cells are errors of omission for DEF while blue cells are errors of omission for REG. For each of DEF and REG there are three possible interpretation combinations that yield errors of omission.

11 FCCC/ARR/2013/AUS, paragraph 84; FCCC/ARR/2014/AUS, paragraph 54

12 Deforestation (DEF), in this section, refers to raw clearing pixels from the image processing and CPN procedures. This should not be confused with deforestation as used in the Kyoto Protocol context.

Out of the 7680 total sample points re-analysed, 7213 points had no change and the remaining 467 change points were further analysed to generate the confusion matrix shown in Table 6.A.3. To map a verification point to the temporal confusion matrix, multiple sources of information including GoogleEarth™, Google Streetview™, IKONOS and SPOT imagery acquired before and/or a change event, were visually interpreted as "ground truth" to assess the accuracy of a change class.

Over the entire study area and for all land cover change from 1998 to 2012, errors of commission for REG and DEF were 223 or 3% of the total 7680 points; the total of the lavender and blue cells (errors of omission for REG and DEF) is 23 or 0.3% of the total. These low numbers reflect the relative rarity of change in the area examined and the high classification accuracy of time series land cover classification using CPN.

Table 6.A.3 Collapsed confusion matrix showing the distribution of sample points (NC – No Change, DEF – Deforestation, REG – Regrowth)

All Periods summary – Definite + Probable					
		"Truth			
		NC	DEF	REG	Total Est.
	NC	7213	11	12	7236
NCAS	DEF	136	124	0	260
	REG	87	0	97	184
	Total	7436	135	109	7680

Colours equate to colours in the temporal change matrix shown in Table 6.A.2.

The temporal confusion matrix not only indicates correctly classified pixels at any given time but also accuracy of land cover change pixels which is of equal interest that the total national amount of land cover change is accurately estimated. This is indicated by the gross over- or under-estimate for each class. For example, there were 135 "true" deforestation points but the CPN estimates 260 deforestation points as shown in Table 6.A.3 – an overestimate of 1.6% of the total sample points. Similarly, about 75 points or 1.0% of the total number of points were overestimated as regrowth. This means that an area equivalent to 2.6% of the total area evaluated were erroneously mapped as land cover change.

Table 6.A.4 Summary statistics for the information in the temporal confusion matrix (Table 6.A.3)

Time Intervals	Error Strength	Global Accuracy (%)	Global Kappa[1]	Change Classes:	No Change	Deforest	Regrowth
All	Definite and Probable	96.8	0.63**	User's Accuracy(%)	99.7	47.7	52.7
				Producer's Accuracy(%)	97.0	91.9	89.0
				Conditional Kappa[1]	0.90**	0.47**	0.52**
				Gross Over/Under-estimate(%)	2.6	1.6	1.0
				Net Over/Under-estimate(%)		0.7	0.7
	Definite Only	97.6	0.63**	User's Accuracy(%)	99.9	50.3	45.2
				Producer's Accuracy(%)	97.7	91.4	100.0
				Conditional Kappa[1]	0.94**	0.50**	0.45**
				Gross Over/Under-estimate(%)	2.1	1.3	0.9
				Net Over/Under-estimate(%)		0.4	0.4

[1]** Indicates that the CPN classification is significantly better than random ($p<0.01$).

As shown in Table 6.A.4, over all time intervals, global accuracy is high (approximately 97%) and *kappa* is statistically significant. Class-based statistics show a high user's accuracy which is reflected in the statistical significance of the conditional *kappa*. However, user's accuracy for DEF and REG change classes is roughly 50%. Combined with the producer's accuracy for these classes, this indicates that the CPN classification has identified more change than is the case. That is, errors of commission were more than the omission errors. However, the high producer's accuracy for these classes indicates that most of the real change was identified by the classification, but at an "accuracy cost" of having many false positives.

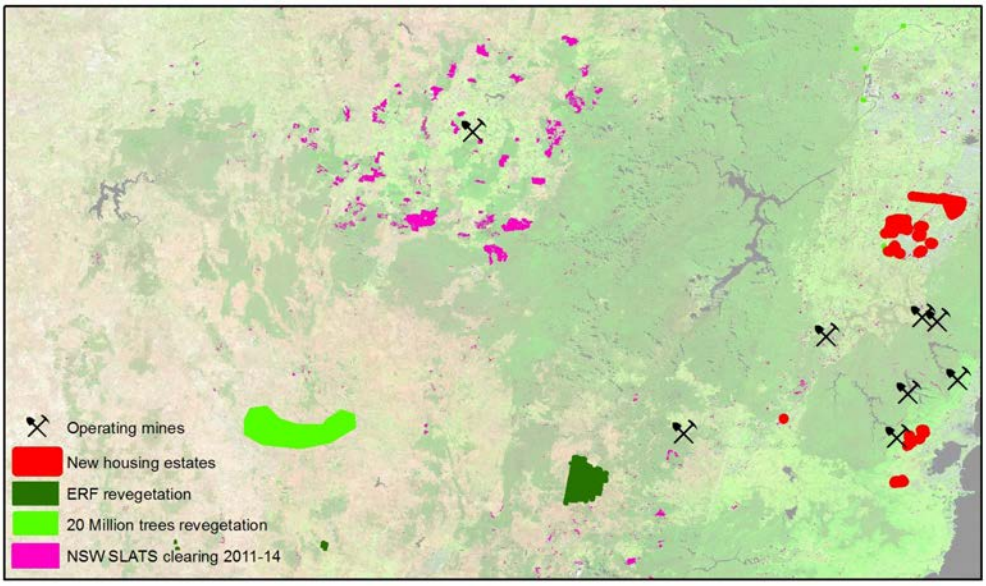
It is important to note that the subsequent step in the data processing, which is visual inspection of all change pixels for each epoch through an attribution process, discussed in Section 6.A.2 and below, was essentially designed to control for remaining false positive pixels.

Attribution

The final quality control requires attribution of changes identified in cover change maps by the CPN as either direct human-induced, temporary change or methodological artifacts such as false positive change. The latter effects are well understood and include green flushing in images due to climate, terrain illumination variability, irrigation, water bodies and fire scars. The Department of the Environment and Energy staff use visual image backdrops such as Landsat imagery, Google Earth™ or DigitalGlobe™ via TerraServer™ data for this discrimination. Results of this discrimination are then quality controlled. This attribution step provides a final quality control process designed to mitigate the risks of errors identified in the confusion matrix in Table 6.A.3.

A recent innovation to the attribution process is the development of an Attribution Reference Database (ARD) that captures published information and anecdotal evidence of clearing, land development or reforestation activities such as those funded by state and federal government programmes (see Figure 6.A.7). This information is being used for attribution and QA/QC of satellite derived activity data. The Department has formalised co-operative arrangements with Queensland and NSW state government agencies to gain access to vegetation monitoring data used to support the current inventory cycle. It is intended that these types of arrangements will be developed with other states and become an integral part of the quality control plan for future national inventories. The use of this information provides further assurance that high quality estimates of areas of land cover change are used for the national inventory and confirms that the national inventory accounts are complete and unbiased.

Figure 6.A.7 Example of ancillary datasets in the Attribution Reference Database that were used to confirm human induced changes.



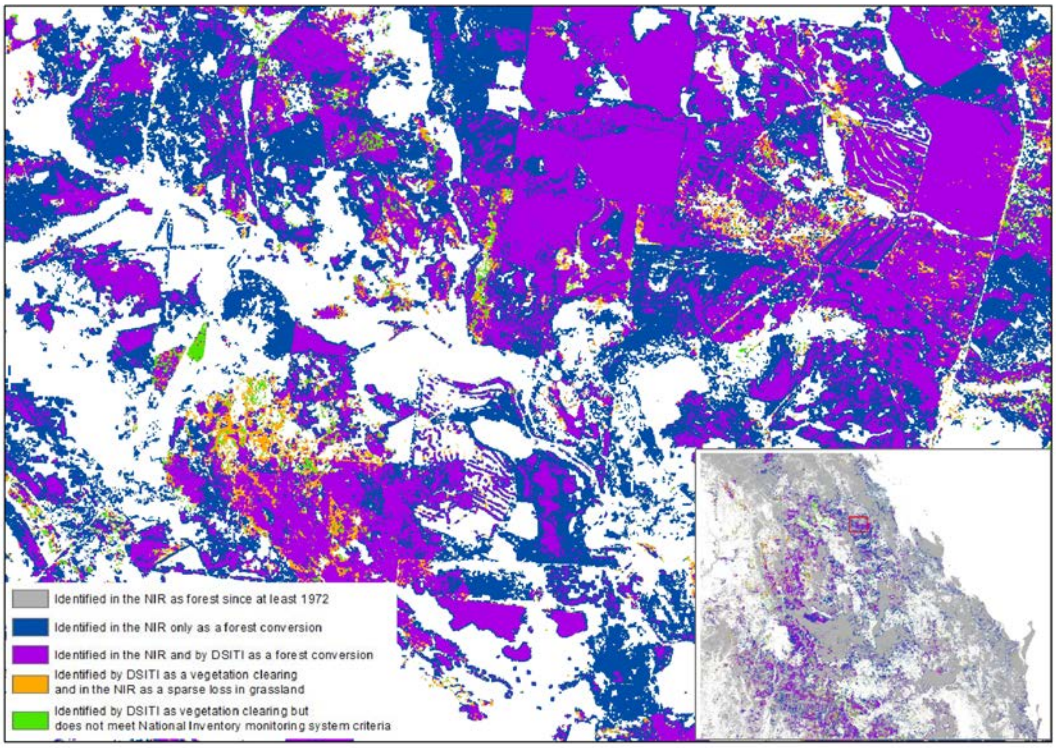
Examples of the QA/QC undertaken using external datasets are outlined below.

Pixel level comparisons were undertaken of woody vegetation loss between the national inventory data and the Queensland Department of Science, Information Technology and Innovation (Queensland DSITI) vegetation monitoring system. An assessment was made of the level of agreement between the two datasets for the period 1988 to 2015 (see Figure 6.A.8). Using the improved 3-class change data, there is high level of agreement (within 5%) between the two systems, although at a few places the clearing pattern does not match. The areas reported only in the NIR are mostly pre-1990 clearing, whilst most of the Queensland DSITI clearing is post-1990. At few places, clearing is detected only in the DSITI dataset which is mostly picked up for the National Inventory Report as sparse woody loss reported under the *grassland remaining grassland*, *wetlands remaining wetlands* and *settlements remaining settlements* accounts.

The main difference between the systems is related to vegetation classification - the national inventory distinguishes between reporting on forest conversion (i.e. clearing in areas where woody vegetation cover meets or exceeds a canopy cover of 20 per cent and a height of 2m); and sparse woody vegetation changes reported under grasslands, whereas the Queensland system reports clearing in all woody vegetation types, independent of tree height, in a single classification. This is a significant factor that explains the majority of the difference in "land clearing" estimates reported by the two systems.

Nevertheless, the analysis showed a high level of agreement between the two systems in the detection of changes in vegetation on forest lands and sparse woody vegetation over the time series. Each area of disagreement was reviewed carefully and the national inventory revised accordingly, where appropriate, using the improved 3-class change product.

Figure 6. A. 8 Pixel level comparison of the clearing data of the two systems - national inventory (1972-) and Queensland DSITI (1988-)

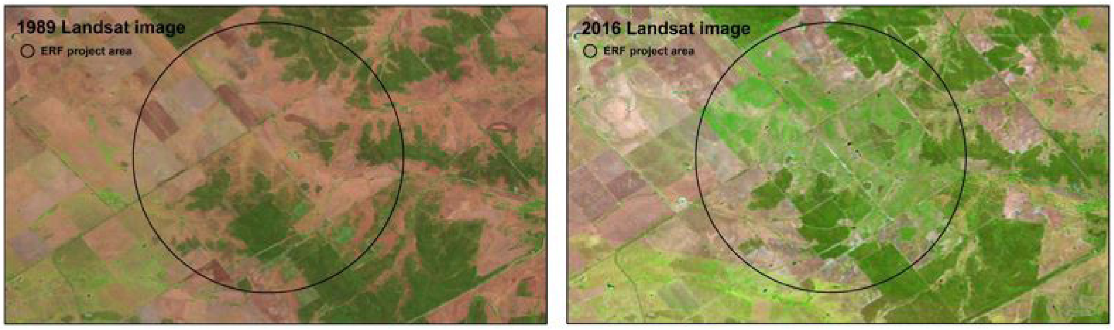


A similar process was also undertaken using vegetation monitoring data for NSW from 1988 to 2014. All areas identified by NSW Office of Environment and Heritage (OEH) as cleared in the past were checked to determine if they were already part of the national inventory. This analysis showed a high level of agreement, and areas of disagreement were carefully reviewed and the inventory revised if appropriate. Comparisons show that the National Inventory Report estimates of primary forest clearing are within 7,000 hectares of clearing reported by NSW OEH.

Additional verification of land clearing has been undertaken using data reported in the media and other published reports. 2014 NIR data were compared with published information on high value agricultural clearing approvals in Queensland reported by Taylor (2015), for the period from 2012 to 2015. The analysis undertaken in 2015 indicated that, of the 94 approved sites, 75% were already included in the national inventory while the remaining 25% were being monitored for clearing in the future or were included in a different part of the account such as timber harvesting. In cases where clearing is not yet evident at the time of image acquisition, the national system continues to monitor potential areas and captures any confirmed clearing in subsequent years. A follow-up check during 2017 confirmed that five sites were now confirmed as cleared and added to the inventory.

Reforestation attribution also undergoes a series of QA/QC checks using data collected for the ARD. Figure 6.A.9 shows an area reforested under the Department's Emissions Reduction Fund (ERF). Landsat imagery shows how the area was cleared in 1989, and a revegetation signal is visible in the 2016 image.

Figure 6.A.9 ERF data used to identify reforestation across the time series.



6.A.5 Plantation typing

Validation of plantation type mapping accuracy was carried out against specifically collected field data showing plantation species, stocking, condition, age and extent. This validation data was collected during a national programme of site visits. Plantation mapping achieved an accuracy of 91% in terms of both species and spatial referencing for plantations identified as post-1990 plantations. Incorrect forest typing (e.g., labelling hardwood as softwood and vice versa) contributed 5% of the error, with only 4% being incorrect for both location and type. Methods for plantation typing of pre-1990 plantations are being developed. Similar to post-1990 plantation typing (into hardwood and softwood plantations), pre-1990 softwood plantations are being distinguished from native forests using the Landsat MSS/TM data from 1972-88. Validation of softwood plantation type mapping pre-1990 is currently being carried out by validating (and calibrating) against ancillary field data.

6.A.6 Forest conversion prior to 1972

Forest land converted to cropland or grassland remains in the *converted* category for 50 years.

Estimates of *forest land converted to cropland or grassland* since 1972 are derived from observations of forest cover loss using Landsat satellite data.

Estimates of the area of *forest land converted to cropland* or *grassland* for the period 1940-1972 is a gap in the activity data used to prepare the estimates for the *forest conversion* categories. Approaches to the estimation of these missing data have been explored, in line with recommendations in the ARR 2010, ARR 2011 and ARR 2012 reviews of the Australian inventory. Estimates have been produced using extrapolation techniques provided in IPCC 2006 Volume 1, chapter 6. The results are compared below.

Previous studies

Graetz *et al.* (1995) estimated that 102.964 million hectares of forest were cleared between 1788 and 1990, or an average of 514,820 ha per year. Similar conclusions have been reached in the *State of the Environment Report* for Australia[13], with the area of forest cover cleared since 1788 estimated to be around 100 million hectares. A study by Barson *et al.* (2000)[14] found that approximately 92.5 million hectares of forest had been cleared since 1788.

If extrapolated to the period 1940-1972, the Graetz *et al.* estimate translates into a cumulative area cleared over the period of 16.4 million hectares.

13 State of the Environment 2011 Committee. Australia state of the environment 2011. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. Canberra: DSEWPaC, 2011.

14 Barson, M., Randall, L. And Bordas, V. (2000) Land cover change in Australia, Bureau of Rural Sciences, Australian Government, Canberra.

Forest conversion required to meet additional crop and livestock activity 1940-1972

The demand for additional pasture or cropland was high in the period 1940-72, reflecting relatively high prices paid for agricultural commodities. Cropping lands increased by 50 per cent, or around 6 million hectares in the period 1940-1972. For grazing activity, demand for land increased by the equivalent of 60-100 million hectares (based on agricultural activity data published by the Australian Bureau of Statistics).

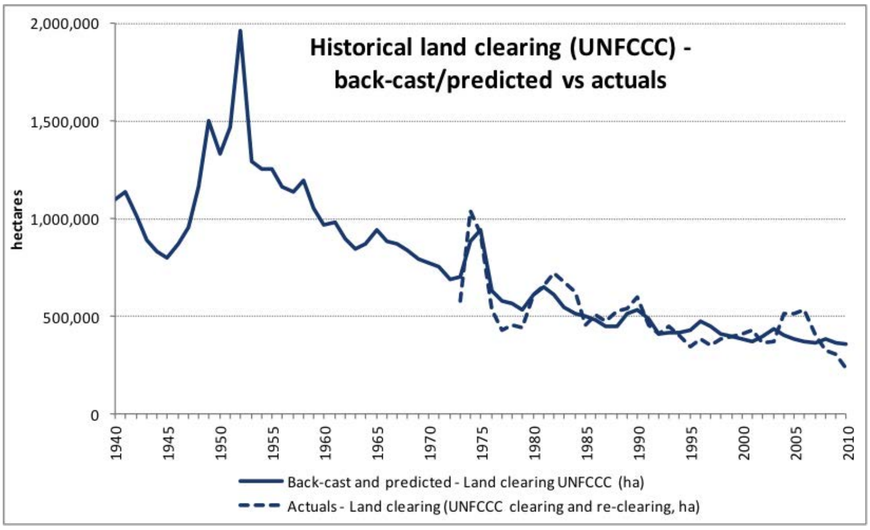
The estimated demand for grazing lands was derived from the increment in cattle and sheep numbers over the period 1940-1972. These data were converted into a demand for cleared land. The conversion was based on assumptions regarding the amount of grazing land needed to support the number of sheep and cattle indicated in the national statistics (1-2 sheep per hectare, 1 cow equal to 10 sheep based on data provided in Hamblin (2001)[15] and Henzell (2007)[16].

Not all of the additional demand for pastures would have required a clearing event. With a discount of 50 per cent, the cumulative increase in area of land needed to support the increment in livestock activity was estimated to be 60-100 million hectares in the period since 1940-1972.

Back cast regression of observed clearing on the farmers' terms of trade 1940-1972

Observed land clearing activity has also been established to respond to the farmers' terms of trade index of prices received to prices paid. A linear regression linking area cleared to the farmers' terms of trade was performed for the period where satellite-based land clearing estimates are available (1973 to 2010). The coefficients from this regression were used to back-cast land clearing activity to 1940 (Figure 6.A.10).

Figure 6.A.10 Estimated area of land clearing and actual land clearing (Source: ABARES various)



Inverted back-cast of 1973-2010 trend

Trends in area under cropland and cattle and sheep numbers indicate a peak of agricultural activity in the early 1970s. The Landsat time series indicates that the peak in land clearing in the period 1972-2013 occurred in 1974. Under this scenario it is assumed that land clearing gradually increased in the period 1940-1970 and peaked in 1974. This estimation of the historical trend was made by inverting the trend observed in the period 1973-2013.

15 Hamblin, A.P. (2001) *Land, Department of the Environment and Heritage, Canberra.*

16 Henzell, T. (2007) Australian agriculture: Its history and challenges, CSIRO publishing, Collingwood.

Table 6.A.5 Estimated land clearing 1940-1972: comparison of extrapolation methods

Extrapolation method	1940-1972		1973-1990
	Extrapolation		Landsat imagery
	Cumulative land clearing (ha)	Annual clearing (ha)	Annual clearing (ha)
Graetz *et al*. average annual forest conversion 1788-1972	16,474,240	514, 820	547,222
Forest conversion required to meet additional crop and livestock activity 1940-1972	60,000,000	1,875,000	547,222
Back cast regression of observed clearing on the farmer's terms of trade 1940-1972	34,200,000	1,069,000	547,222
Back cast of 1960-1990 trend in farmers' terms of trade model with clearing peak in 1974	25,200,000	763,636	547,222

The data in Table 6.A.5 indicates that the rates of land use change observed from the Landsat record, at 547,222 hectares a year for the period 1973-1990, are similar to the long run average rate of change calculated by Graetz *et al.* (1995) of 514,820 hectares a year. Independent data on a range of economic forces, including higher prices for agricultural products and reduced costs of forest conversion for this period compared with earlier periods, anecdotal country histories and observed increases in national livestock numbers and cropping areas all indicate that the period 1940-1972 was a period of strong land use change in Australia.

The estimates of *Forest Conversion* presented in Sections 6.7 and 6.9 for 1990 are based on a limited dataset on land use change extending only from 1973-1990. Extending the observed dataset to include estimates for the missing data on land use change for the period 1940-1972 could be implemented using a range of techniques identified in IPCC 2006 based on the data presented in Table 6.A.5.

The implementation of an extended dataset on land use change to 1940 would lead to higher emissions estimates for *Forest Conversion* for the entire time series, with larger impacts at the start of the time series, 1990, than for later periods of the time series. It is assessed that the estimate for net emissions for *Forest Conversion* categories would be 13 Mt CO_2-e higher in 1990, if the land clearing trend is back cast with an assumed clearing peak in 1974 and is applied in the *FullCAM* Tier 2 model. As indicated in section 6.9.4, this step has not yet been implemented in the estimates.

Appendix 6.B *FullCAM* framework

Land sector reporting within Australia's National Inventory System integrates a wide range of spatially referenced data through a process based empirical model (Tier 3) to estimate carbon stock change and greenhouse gas emissions at fine spatial and temporal scales. Analysis and reporting includes all carbon pools (biomass, dead organic matter (DOM) and soil), all principal greenhouse gases (CO_2, CH_4 and N_2O), and covers both forest and non-forest land uses A Tier 3 method is used to estimate carbon stock changes for agricultural soils, living woody biomass (excluding perennial woody horticulture) and dead organic matter. This approach has several advantages over an IPCC Tier 1 or 2 method:

- Models have the potential to improve coverage and completeness as they can extend beyond existing data to improve geographic coverage/distribution and coverage of source/sink categories by filling in gaps in data.
- Measured climate data are interpolated using a mathematical (multivariate spline) function at the 1 km scale (Appendix 6.E.3) rather than broad climatic region classification. This enables quantification of carbon stock changes at finer spatial scales.
- The method includes detailed characterisation of spatially mapped soil properties (Appendix 6.E.1) that influence soil carbon dynamics as opposed to broad soil taxonomic classification of the IPCC methodology
- The method provides a more detailed representation of management influences and their interactions. This increases the spatial and temporal resolution of estimates compared to those that are represented by a discrete factor-based approach.
- Soil carbon stock changes are estimated on a more continuous, non-linear and dynamic, monthly basis as a function of the interaction of climate, soil, and land management compared with the linear averaging as applied in tiers 1 and 2.

6.B.1 Overview of the *FullCAM* Model Framework

FullCAM is a process based ecosystem model that calculates greenhouse gas emissions and removals in both forest and agricultural lands using a mass balance approach to carbon cycling. The *FullCAM* framework and its development are described in Richards (2001) and Richards and Evans (2004).

FullCAM has been selected for the Tier 3 method based on several criteria:

- The model has been developed in Australia and extensively tested and verified for Australian conditions (Appendix 6.B.1.3 and 6.B.5.1). In addition, the model has been widely used for simulating soil and biomass carbon dynamics at project level (Australian Government Carbon Farming Initiative and Emission Reduction Fund) and nationally.
- *FullCAM* is capable of simulating, cropland, grassland, and forest eco-systems and land-use transitions between these different land uses at the 25m pixel level. As most emissions and removals of greenhouse gases occur on transitions between forest and agricultural land use, integration of agricultural and forestry modelling was essential.
- The model is designed to simulate management practices that influence soil carbon dynamics including quantification of inter-annual variability. The *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* (IPCC 2014) (KP Supplement) have provision to reduce interannual variability and isolate the impacts of changes in human activities by calculating two time series of emissions and removals in which only the rate of human activities differ. This provision, in conjunction with new modelling techniques allows for emissions and removals due to the 'signal' of the impact of human activities, including mitigation measures, to be estimated using *FullCAM*.

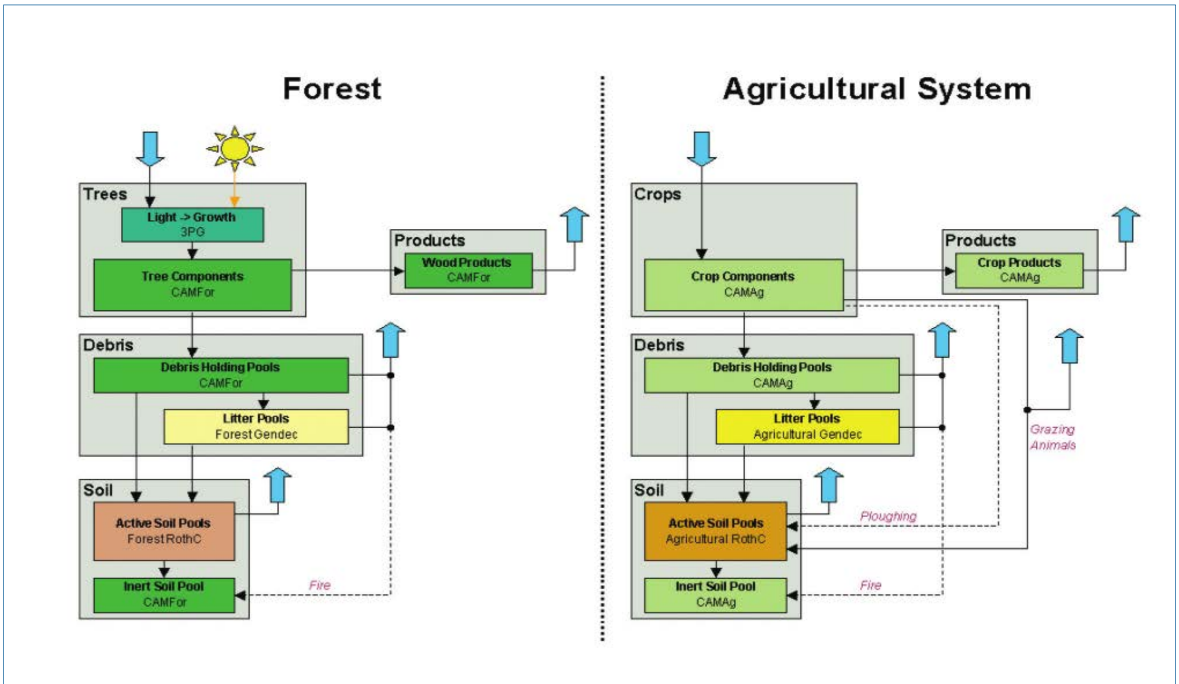
- *FullCAM* has components that deal with both the biological and management processes which affect carbon pools and the transfers between pools in forest, agricultural and transitional systems. The exchanges of carbon, loss and uptake between the terrestrial biological system and the atmosphere are accounted for in the full/closed cycle (mass balance) model which includes all biomass, litter and soil pools (Table 6.B 2).
  - The data required for *FullCAM* to simulate is available nationally at appropriate scales for the data in a spatially and temporally time series consistent format.

6.B.1.1 *FullCAM* Sub-Models

FullCAM has been developed as an integrated compendium model that provides the linkage between various sub-models. The three sub-models integrated to form *FullCAM* as used in the National Inventory are:

- *CAMFor* (Richards and Evans, 2000a), the carbon accounting model for forests (Figure 6.B1). *CAMFor* is used to model carbon mass and transfers between the living tree and debris pools of forest lands.*CAMFor* has its origins in the 1990 CO_2 Fix model of Mohren and Goldewijk (1990);
- *CAMAg* (Richards and Evans, 2000b), the carbon accounting model for cropping and grazing systems (Figure 6.B1).
  - The *CAMAg* model reflects the impacts of management on carbon accumulation and allocates masses to various plant, debris and soil pools. Yields need to be prescribed in the model;
- Rothamsted Soil Carbon Model, *Roth-C* (Jenkinson, *et al.* 1987, Jenkinson *et al.* 1991).
  - *Roth-C* models changes in soil carbon based on the inputs of organic matter from dead plant material and soil carbon decomposition rates. It is used in conjunction with both *CAMFor* and *CAMAg*.

Figure 6.B.1 The *FullCAM* model pool structure



Appendix

6.B.1.2 Sub-model integration

The sub-models described above are integrated into *FullCAM* which was developed in the programming language C++ with a graphical user interface (Richards, 2001; Richards and Evans, 2004). The individual sub-models can be applied independently or in various combinations within the *FullCAM* framework. By embedding both the forest and agricultural models within *FullCAM*, it is possible to represent transitional activities – afforestation, reforestation and deforestation (change at one site) – or a mix of agricultural and forest systems (e.g., agroforestry, discrete activities at separate sites) in a single, mass-balance model framework.

6.B.1.3 Quality assurance and quality control

Sub-model integration

The integration of the sub-models into a single compendium model was initially undertaken in Excel as a test version. The prototype forest model derived (Richards and Evans, 2000c) was subsequently tested by CSIRO (Paul *et al.* 2002a). Several independent studies to test and calibrate the model were completed on various parts, integrations and applications of the models. When there was confidence that the Excel developmental models were giving the same results as the original source code versions, the Excel models were fully documented and returned for verification to the original authors or host organisations. Modifications were only considered subsequent to this initial review. These modifications were made for a variety of reasons including efficiency in code (computational speed and resources) and in recognition of Australia's different biophysical conditions.

Model coherence and validation

Testing for coherence in a Tier 3 (Approach 3) model-based pixel by pixel inventory method requires very different techniques to those applied to checks on trends and emissions factors in Tier 1 and Tier 2 models[17]. Tests of model coherence and validation can only be meaningfully undertaken at the pixel level. This is the approach taken and is consistent with the good practice recommendations of the *2006 IPCC Guidelines*. As the robustness of the national account simply flows from the correct summing of the outputs of the individual pixels, testing the results at the individual pixel scale will validate the national results. Therefore, programmes to test model cohesion operate in two realms. The first is coherence testing by time series to validate model calibrations and verify the results at the pixel level. The second is quality control to ensure robust summation of the pixels to an aggregate national account.

Representative individual pixels in *FullCAM* simulations have been validated against field data. These validations have been undertaken by independent agencies. The results of these studies have shown that the model is robust. Examples of the independent initial biomass, debris and soil carbon validation results are shown in Appendix 6.D, section 6.B.3, and section 6.B.5, respectively.

Individual pixel models are internally checked to ensure that all emissions, removals and transfers of carbon between pools are accounted for. At each monthly time-step *FullCAM* reconciles removals due to growth, transfers between carbon stocks in pools, and emissions from pools for every pixel modelled. Taking a mass balance, full carbon-cycle approach for each pixel, and running this over an extended period, is a very rigorous way of testing the model's ability to appropriately reflect transfers between carbon pools, and hence the balance of emissions and removals. When multiple pixels are simulated, pixel results are consolidated and then reported at an aggregate level. These aggregate outputs are cross checked by both internal and external processes to ensure that

17 The change in pixel output is also strongly affected by the amount of time since the land was cleared and climate variability. As there are multiple variable factors, the implied emissions factors from the overall inventory cannot be used to test the model's coherence as the model processes can no longer be observed in anything like their original analytic unit. Analysis of IEFs in the LULUCF sector is further complicated by reporting of accumulating land areas.

the consolidation process accurately reports all spatial simulation results. The correct summing of model outputs is also critical to model performance and therefore internal and external quality control checks are made on this aspect of the model. The results from the Tier 3 model have also been compared with the results using Tier 2 methods (see section 6.3.3 and 6.7.3) and were found to be broadly consistent.

Transparency and peer review

For the complex Tier 3 methods, which incorporate models and large datasets, different approaches to transparency and peer review are required. Transparency and review of the land sector accounts is founded on:

- published specifications, protocols and methods;
- published verification results;
- public release of models, tools and data ; and,
- publication in peer reviewed journals or other literature.

Australia has published six series of strategic and technical reports which document the development of *FullCAM*, the specifications, protocols and methods used, and the results of verification, validation and calibration of *FullCAM*. All reports are accessible by the public via the DE website (http://pandora.nla.gov.au/pan/102841/20090728-0000/www.climatechange.gov.au/publications/index.html). The methods and data used as part of the land sector accounts have also been extensively published in peer-reviewed papers in scientific journals.

The Australian Centre for Ecological Analysis & Synthesis undertook a modelling workshop in 2011 on Improving long-term predictions of carbon and nutrient dynamics in Australia's agro-ecosystems (http://aceas.org.au/index.php?option=com_content&view=article&id=74&Itemid=76). In the workshop *FullCAM* soil carbon outputs were compared with those from DayCENT, Century and a Microsoft Excel version of RothC, initially for two sites, Hermitage and Wambiana. Preliminary results suggested little difference between outputs of the four models over the study period. Further, if input data were the same or very similar then all models appeared to simulate soil carbon stocks to within 10 t C/ha (0-30 cm soil profile) of the final result based on a measured value of soil carbon stock (2010 site data).

6.B.2 Estimating changes in forest biomass

6.B.2.1 Forest growth

Forest growth in *FullCAM* is controlled through two separate biomass increment components of the model:

- the tree yield formula (Richards and Brack (2004a), Brack *et al. (2006) and Waterworth et al. (2007);* and
- direct entry of biomass increment data.

Tree yield formula

The tree yield formula is embedded into the *FullCAM* code and when applied within the National Inventory System provides an empirically constrained process model for the calculation of biomass increment in the living components of *forest land*. The tree yield formula allows for responses to climatic variability while empirical data and parameters constrain initial aboveground biomass, forest growth, and relative movements between pools. It is the empirical data that constrains the model to reflect extensive field data (both existing and specifically collected).

The tree yield formula is applied to estimate the forest biomass increment in the following sub-categories:

- Forest land converted to cropland;
- Forest land converted to grassland;
- Forest land converted to wetlands;
- Forest land converted to settlements; and
- Grassland converted to forest land.

The tree yield formula is provided in Equation 6B_1:

$$\text{Aboveground Tree Mass at age a} = M \times e^{(-k/a)} \quad \text{(6B\_1)}$$

Where a = age of the tree stand

M = biomass predicted by the assumed initial biomass model (Appendix 4.D), and

k =estimated constant that determines the rate of approach towards M.

The value of k sets the rate of growth, where $k = 2 \times BI_a - 1.25$, and BI_a is the age (in years) of maximum aboveground biomass increment.

The long-term average annual increment between a and $a + 1$ years (I_a) for a stand can be estimated from the long-term average productivity (P) (see Appendix 6.C):

$$I_a = M \times (e^{(-k/a)} - e^{(-k/(a-1))}) \quad \text{(6B\_2)}$$

However, as productivity in any given year may vary around the average due to non-average weather or other factors, the actual annual increment (I_a is adjusted by the productivity in a given year (Pa) as a ratio with the long-term average productivity (P):

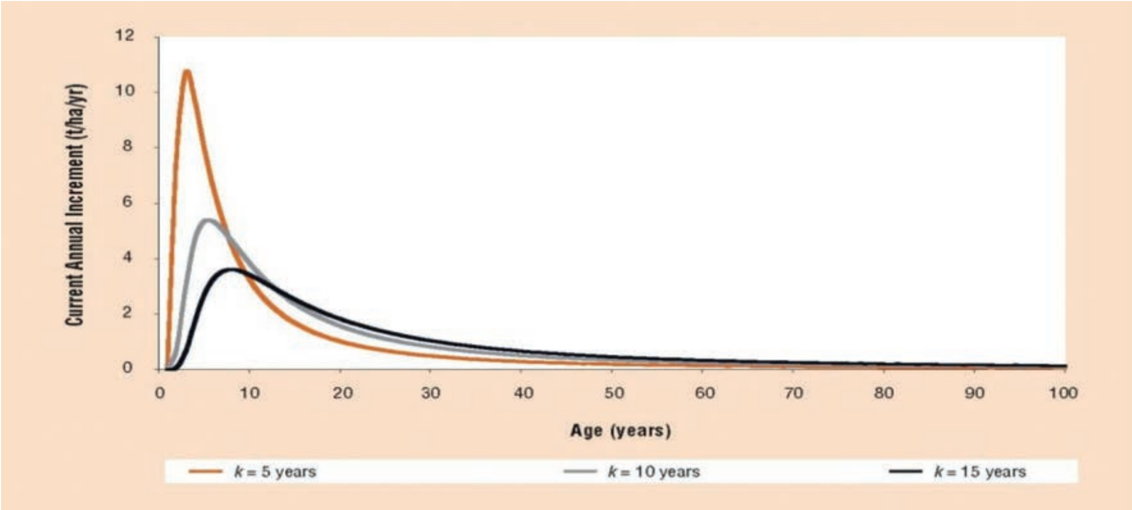
$$I_a = I_a \times P_a/P \quad \text{(6B\_3)}$$

This approach provides biomass stock estimates for a given land unit at any point in time that recognises prior forest disturbance, and the rates of growth for a land unit at any point in time, specific to site condition and age. The patterns of growth will show variability according to the spatial and temporal patterns of the main process drivers, e.g., water balance, captured in the productivity modelling. This ensures that the estimates of biomass in areas of regrowth are then both spatially and temporally relevant.

Maximum aboveground biomass increment

One of the key parameters in the tree yield formula is the age of maximum aboveground biomass increment (BI_a). Figure 6.B.2 presents the results of an analysis of the effects of varying age of maximum aboveground biomass increment over the range of three to eight years. While the early age growth increments are very sensitive to BI_a, even by age 18 there is little difference in the annual aboveground biomass growth increment (Figure 6.B.2).

Figure 6.B.2 Effects of varying age of maximum current annual increment for three values of parameter k (5, 10 and 15 years), corresponding to BL_a = 3.1, 5.6 and 8.1 years, respectively.



Available national data and literature sources were analysed to estimate BI_a for regrowth forests (i.e., those identified by remote sensing as recovering from clearing since 1972). This analysis was based largely on the work of West and Mattay (1993). This was a challenging task due to the lack of growth data for Australia's native forests, in particular for the drier woodlands. Available data, such as that reported by West and Mattay (1993), suggest that the age of maximum current annual increment (CAI) for stem volume is within a small range (12-20 years) for most species and is largely independent of site productivity. For the *forest land converted to cropland, forest land converted to grassland, forest converted to wetlands and forest land converted to settlements* sub-categories the age of maximum aboveground biomass increment is set to 10 for all species based on the following:

- available data for production native forests which yields a central estimate of 14 years for maximum volume increment (range 12-20);
- the age of maximum volume increment is reduced by one to two years to account for increased allocation of biomass growth to non-stem (wood volume) components as trees are establishing, in particular just before canopy closure;
- the age of maximum volume increment is further reduced by one to two years to allow for the lag in detection of regrowth by remote sensing data (i.e., accounting for the time until detection of trees becomes possible); and,
- a final reduction is applied to account for the rapid site occupancy of woodland species which regenerate from root stock left after clearing, allowing more rapid growth following the removal of grazing pressures.

The effect of these adjustments is that a BI_a of ten is equivalent to an effective age of maximum current annual increment in stemwood volume of around 14 years. A BIa of ten is higher than that found in most eucalypt plantations, which reach this peak between two to seven years. Plantation management aims to achieve maximum growth rates as quickly as possible and probably represent the best achievable early age growth rates when compared to natural forests.

Direct entry of biomass increment data

When the direct entry of biomass increment data component of *FullCAM* is in use, the model uses these data in calculations and so there is no calculation of biomass increment within *FullCAM*. The direct entry of biomass increment data component of *FullCAM* is applied in the source category *forest land remaining forest land*.

6.B.2.2 Partitoning of biomass

FullCAM applies allocation scaling parameters to predict the partitioning of biomass to stem wood, branches, bark, foliage and coarse and fine roots. This time-series input table specifies biomass allocation for each year of growth, thereby enabling the prediction of how growth is attributed to the six components of biomass over time. Generally, the units used in the allocation input table are growth increments of branches, bark, foliage, coarse roots and fine roots components relative to that of the stem, with the input for stem thereby being 1.00 at each time step.

For aboveground biomass, allocation input tables adjust the relative allocation to wood, branches, bark and foliage, with the total aboveground biomass (AGB) being set by FullCAM's TYF (Eq. 6B.a). In contrast, predicted belowground biomass (BGB) is determined by allocation to coarse roots (BGB_C) and fine roots (BGB_F) as defined in the allocation input table. The allocation of biomass in FullCAM also determines the management- or disturbance-induced impacts on C stocks. Accurate biomass allocation predictions are important when predicting changes in on-site C stocks following events such as fire, pruning, thinning or harvesting. This is because these events affect the different pools of biomass in different ways.

Calibration of partitioning parameters

As outlined in detail by Paul and Roxburgh (2017), a large dataset on biomass partitioning of tree or shrubs has recently been collated for Australia. These data provided a useful means to revise FullCAM input tables of allocation of biomass. This database included a total of 3,005 individual trees or shrubs with measurement of partitioning of AGB, and 1,115 individuals with measurements of the relative allocation of BGB_C to AGB, where BGB_C is the biomass of coarse roots (>2 mm diameter). For all forest type, BGB_F were predicted from AGB using a global empirical model (Mokany *et al.* 2006).

Previously, FullCAM allocation inputs varied with stand age only. But the new expanded datasets on biomass partitioning facilitated the development of new empirical models that demonstrated that, at least for some types of forests, AGB partitioning and R:S varies not just with stand age, but also with the stands total AGB, average rainfall, density, and species or species-mix.

These empirical models were incorporated into an Allocation Calculator that was then used to generate the time-series allocation inputs tables required by FullCAM. This was done for the 51 forest types, each utilising specific empirical models within the Calculator based on their categorisation into either: environmental or mallee plantings; hardwood plantation; softwood plantation; native forest, or; woodand and shrublands. The mean site quality and typical rainfall in their regions of growth were inputs into the Calculator.

.An example of the how the revised predictions of biomass partitioning compare to that observed is given below (Table 6.B.1) for native forests systems, where datasets were collated from 46-168 different souces as described by Paul and Roxburgh (2017). Datasets were collated from 46-168 different souces. Predictions were for the relevant 20-100 year old stands. Further details, and results for other forest types, are described by Paul and Roxburgh (2017).

Table 6.B.1 Mean (± SD) observed and predicted biomass ratios for native forest

Crop	Observed	Predicted
Wood:AGB	0.65 ± 0.12	0.52-0.54
Bark:AGB	0.12 ± 0.06	0.14-0.15
Branch: AGB	0.14 ± 0.09	0.25-0.26
Foliage: AGB	0.05 ± 0.06	0.06-0.09
BGBC: AGB	0.33 ± 0.14	0.06-0.09

6.B.3 Estimating changes in forest debris

FullCAM allows for the modelling of debris accumulation and decay based on forest growth and management. Debris accumulates from the turnover of live plant material (e.g., branches, bark, leaves, and roots) to dead organic matter (DOM) (e.g. litter, coarse woody debris and dead roots). The turnover rates determine the amount of material being added to the debris pool. Decomposition rates determine the rates of loss of carbon back to the atmosphere and soil as the debris breaks down. The balance of these two factors determines the amount of debris on site excluding the effects of management.

In the absence of forest disturbances such as harvest or fire, debris mass increases with age to a steady state where the addition of forest material to the debris pools and loss from decomposition is in balance. Debris pools are also increased by the addition of slash material following harvest and decreased by any residue management techniques, in particular residue burning.

6.B.3.1 Calibration of rates of turnover and decomposition

Recent work on reviewing field studies with litter traps (Paul and Roxburgh, 2017) has greatly expanded the Australian database of forest turnover rates based on that previously available. Measurements of litterfall via litter trap studies were collated from across a range of forest types:

- Environmental plantings: 4
- Hardwood and softwood plantations: 16 and 29, respectively.
- Native forests and woodlands: 83 and 24, respectively.

As described by Paul and Roxburgh (2017), these 156 litter trap studies were used to determine average rates of litterfall of foliage, twigs and bark from different forest types. Where required, average %Foliage, %Twig and %Bark observed for the different forest types were used to 'fill-gaps' for studies where the total litterfall was not partitioned into these components. Similarly, where the stand-based mass of foliage, twigs and bark were not measured, these were predicted using FullCAM and the revised allocation input tables. Average rates of foliage turnover were then calculated to refine foliage turnover for each for environmental or mallee plantings, hardwood plantations, softwood plantations, native forests and woodlands/shrublands. As there was insufficient evidence to justify different rates of turnover of twigs and bark based on forest type, a single rate of twig litterfall, and a single rate of bark litterfall, were calculated to refine the inputs of branch and bark turnover. These values were applied across all forest types.

Recent work on reviewing litter bag studies (Paul and Roxburgh, 2017) has also greatly expanded the Australian database of forest decomposition rates. Measurements of litter decomposition were available from litter bag studies installed under a range of forests, including:

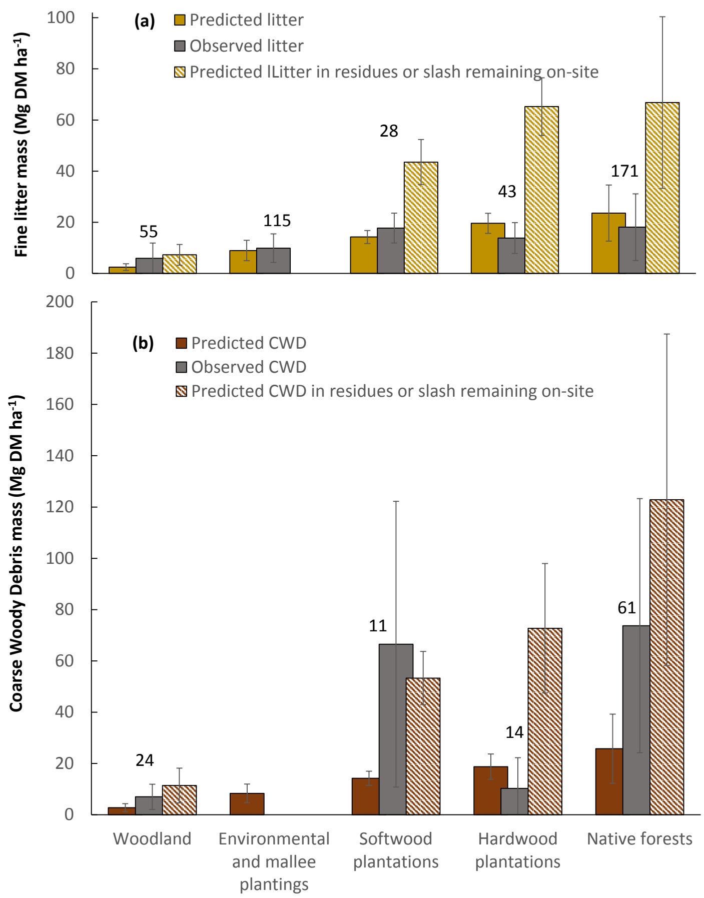
- Eucalypt-dominant stands; 23, 13 and 59 measurements of decomposition of deadwood, bark litter and foliage litter, respectively.
- Softwood plantations; 28 measurements of decomposition of needle litter.

Simple double- or single-pool decay functions are commonly calibrated to datasets obtained from litterbag studies. On review of these, it was found that single-pool models were justified for deadwood and bark litter, while a two-pool double models were justified for foliage litter. Hence for all forest types, FullCAM inputs of the fraction of debris that was resistant was set to 100% for deadwood and bark, while for foliage it was set to the average values observed from the fitting of the double-pool decay function to litterbag studies of foliage. On average, the resistant fraction of pine needle litter was higher than that of eucalypt leaves, and so the revised FullCAM parameter for resistant fraction of foliage debris was higher (set at 83%) for softwood plantaitons than all other forest types (set at 77%). These proportions, as well as the rate parameters, derived from calibration of the decay functions were used as inputs into FullCAM as described by Paul and Roxburgh (2017).

Rates of decomposition in FullCAM are influenced by temperature and rainfall using the options of either 'Mulch-style' or 'Soil-style' sensitivity. Decomposition was particularly sensitive to climate using a 'Soil-style' approach. Given the lack of data on how climate impacts rates of decomposition, the more conservative approach of using 'Mulch-style' sensitivity was applied; with sensitivitie values of 1 being used as per previous NIRs.

As a result of revising the parameters for rates of turnover and decomposition, predictions of inputs and outputs from the debris pool were changed. Figure 6.B.3 below (taken from Paul and Roxburgh, 2017) shows that, for the various forest types, using these revised parameters, prediction of litter mass and coarse woody debris was generally within the bounds on one standard deviation in the average observed stocks of these pools. Both the observed and predicted masses of debris will be strongly influenced by the management regime (e.g. harvesting or fire).

Figure 6.B.3 Predicted and observed (a) litter mass, and (b) coarse woody debris (CWD) under various forest types, including: mature (100 year) woodlands; relatively young (20 year) environmental and mallee plantings; softwood plantations of multiple rotations; hardwood plantations of multiple rotations, and; mature (100 year) native forest



For woodlands and native forests, predictions are at 100 years when left uncleared, and when assumed to be cleared, the year 99 of simulation. For plantations, predictions the average observed across multiple rotations simulated over a 100 year period, or that predicted in the year post the final clearing event. Number labels represent the number of observations that were used to calculated the average observed litter or CWD. Error bars represent the standard deviations of the means. Predicted means were based on the simulation of 5 woodlands, 21 environmental or mallee plantings, 5 softwood plantations, 6 hardwood plantations, and 4 native forests (Paul and Roxburgh 2017).

Appendix

6.B.4 Estimating changes in forest soils

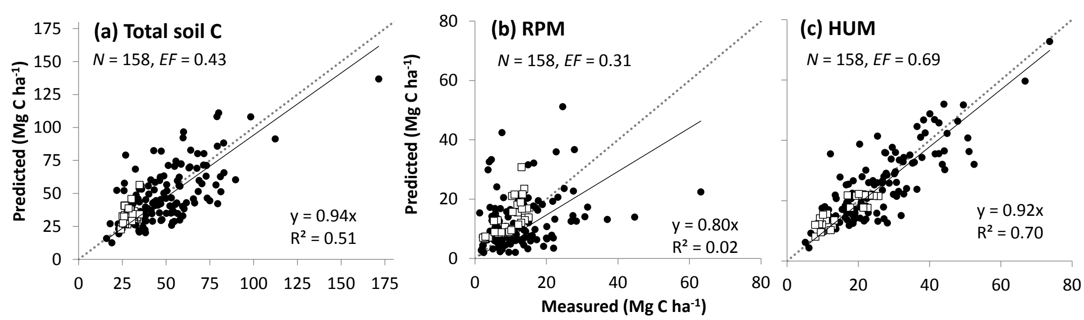
Soil can often be the largest storage of C in forests, and many pools of soil C significantly change in response to land use change, or changes in management. However, the modelling of stocks of soil C is complicated given: (i) stocks are the balance of C inputs from debris decomposition, and outputs from turnover of soil pools, and; (ii) many of the important processes influencing soil C are difficult to measure. Hence, there is a paucity of data for inputs such as root turnover and decomposition, the fraction of C lost as CO_2 on decomposition, and turnover rates of the soil pools. Having measurements of the various pools of soil C simulated by FullCAMs RothC sub-model (e.g. RPM, HUM etc., Baldock *et al.* 2013a,b), together with measurements of biomass, and litter mass, have has been useful to constrain the calibration of some of these parameters (e.g. Paul and Polglase 2004b; Paul *et al.* 2017b).

6.B.4.1 Calibration of key parameters influencing predictions of pools of soil C under forests

Recent datasets of measurement of biomass, litter and pools of soil C were collated from a wide range of forest types across Australia (Paul and Roxburgh 2017). This included 124 paired environmental planting sites (Paul *et al.* 2017b) and 20 fertiliser and irrigation treatment plots under hardwood and softwood plantations (Paul and Polgase 2004a).

As described in detail by Paul and Roxburgh (2017), these studies found no justification to adjust any of the RothC parameters calibrated for agricultural soils (Table 6.B.5). The approach used was to effectively 'tune' rates of root turnover and decomposition, and the fraction of CO_2-C loss on debris decomposition, to ensure that predicted pools of soil C match that observed, while at the same time constraining predictions of biomass, litterfall and litter mass to that observed. In the absence of any justification to assume otherwise, the values of the parameters for root turnover and decomposition, and the fraction of CO_2-C loss on debris decomposition, were assumed to be the same, regardless of forest type. With such constaints, obtaining high efficiencies of calibration of pools of soil C was challenging. Nonetheless, efficiencies of prediction of total soil C pools was still 43% (and 31% for RPM and 69% for HUM) (Figure 6.B.4).

Figure 6.B.4 Relationship between observed and predicted carbon stocks (Mg C ha^{-1}) in surface soil (0-30 cm) for: (a) total soil organic carbon; (b) RPM pool of soil C; and (c) HUM pool of soil C



Datasets used in figure 6.B.4 are described by Paul and Polgase (2004a) and Paul *et al.* (2017b). Black circles represent the paired-site environmental plantings. White squares represent the hardwood and softwood repeated-measured forestry trials.

6.B.5 Estimating changes in crop and pasture biomass and debris

6.B.5.1 Biomass

The model uses crop and pasture yield data and the proportional allocation of dry matter to different plant components to estimate annual dry matter accumulation in agricultural ecosystems.

An earlier analysis (Unkovich *et al.* 2009) defined the relevant crops for carbon accounting purposes (Table 6.B.2) at the Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (Pink 2010).

Table 6.B.2 Field crops accounting for ≥95% (●), and additional crops for ≥99% (O) of field crop sowings for Australia as a whole, and in each Australian State in 2006 (from Unkovich *et al.* 2009)

Crop	Aust.	NSW	Vic.	Qld	SA	WA	Tas.
Wheat (*Triticum spp*)	●	●	●	●	●	●	●
Barley (*Hordeum vulgare*)	●	●	●	●	●	●	●
Narrow-leaf lupin (*Lupinus angustifolius*)	●	O	O		O	●	
Canola (*Brassica napus*)	●	●	●		●	●	
Oat (*Avena sativa*)	●	●	●	O	●	O	●
Sorghum (Sorghum vulgare)	●	●		●			
Sugarcane (*Saccarum officinarum*)	●	O		●			
Cotton (*Gossypium hirsutum*)	●			●			
Triticale (*Triticum durum x Secale cereale*)	●	●	●		●		●
Chickpea (*Cicer arietinum*)	O	O	O	●			
Field Pea (*Pisum sativum*)	O		●		●	O	
Faba bean (*Vicia faba*)	O	O	O		O		
Rice (*Oryza sativa*)	O	●					
Sunflower (*Heliantus annus*)	O	O		●			
Lentil (*Lens culinaris*)	O		●				
Maize (Zea mays)		O		O			
Vetch (*Vicia sativa*)			O		O		
Mung bean (*Phaseolus aureus*)				O			
Peanut (*Arachis hypogaea*)				O			
Soybean (*Glycine max*)				O			
Millet (*Pennisetum spp*)				O			
Oil Poppies (*Papaver somniferum*)							●

The available data have been reviewed to develop appropriate harvest indices for each plant type to enable conversion from mass of saleable product to total plant mass (Unkovich *et al.* 2010). The proportional allocation of dry matter to plant components were determined from estimates by expert field agronomists and include allocation to roots, GBF (grains, buds and fruit), stalks and leaves, coarse roots and fine roots. The crop types and plant partitioning used in the model are shown in Table 6.B.3.

The crop and pasture yield data for each cropping system, SA2 region and soil type are estimated in *FullCAM* (see Appendix 6.E.3)

Table 6.B.3 Plant partitioning by crop and pasture type

Species Name	Yield Allocation to Grains, Buds or Fruit (fraction)	Yield Allocation to Stalks (fraction)	Yield Allocation to Leaves (fraction)	Yield Allocation to Coarse Roots (fraction)	Yield Allocation to Fine Roots (fraction)
Annual & perennial (incl. Mulga)	0.00	0.00	0.50	0.00	0.50
Annual grass	0.00	0.00	0.50	0.00	0.50
Annual legume	0.00	0.00	0.50	0.00	0.50
Annual legume irrigated	0.00	0.00	0.50	0.00	0.50
Annual weeds	0.00	0.00	0.50	0.00	0.50
Aristida-Bothriochloa	0.00	0.00	0.50	0.00	0.50
Barley	0.00	0.30	0.40	0.00	0.30
Black speargrass	0.00	0.00	0.50	0.00	0.50
Blady grass	0.00	0.00	0.50	0.00	0.50
Blue lupin	0.00	0.23	0.55	0.00	0.22
Bluebush/Saltbush	0.00	0.00	0.50	0.00	0.50
Bluegrass-browntop	0.00	0.00	0.50	0.00	0.50
Canola	0.00	0.27	0.51	0.00	0.22
Chickpea	0.00	0.30	0.48	0.00	0.22
Cotton – irrigated	0.25	0.25	0.30	0.10	0.10
Cotton – rainfed	0.25	0.25	0.30	0.10	0.10
Faba bean	0.00	0.30	0.48	0.00	0.22
Field pea	0.00	0.30	0.48	0.00	0.22
Grass only – brigalow/gidyea	0.00	0.00	0.50	0.00	0.50
Grazed cereal	0.00	0.00	0.60	0.00	0.40
Grazed cereal – irrigated	0.00	0.26	0.44	0.00	0.30
Grazed vetch	0.00	0.30	0.48	0.00	0.22
Lentil	0.00	0.30	0.48	0.00	0.22
Lucerne	0.00	0.00	0.50	0.00	0.50
Lucerne irrigated	0.00	0.00	0.50	0.00	0.50
Maize	0.32	0.34	0.09	0.00	0.25
Millet	0.00	0.26	0.43	0.00	0.31
Mitchell grass	0.00	0.00	0.50	0.00	0.50
Monsoonal annual	0.00	0.00	0.50	0.00	0.50
Monsoonal perennial	0.00	0.00	0.50	0.00	0.50
Mung bean	0.00	0.30	0.48	0.00	0.22
Narrow-leaf lupin	0.00	0.23	0.55	0.00	0.22
Native annual	0.00	0.00	0.50	0.00	0.50
Native annual improved	0.00	0.00	0.50	0.00	0.50
Native perennial	0.00	0.00	0.50	0.00	0.50
Native perennial improved	0.00	0.00	0.50	0.00	0.50
Oat	0.00	0.26	0.43	0.00	0.31
Oil poppies	0.00	0.40	0.40	0.00	0.20
Peanut	0.00	0.35	0.35	0.00	0.30
Perennial grass	0.00	0.00	0.50	0.00	0.50

Species Name	Yield Allocation to Grains, Buds or Fruit (fraction)	Yield Allocation to Stalks (fraction)	Yield Allocation to Leaves (fraction)	Yield Allocation to Coarse Roots (fraction)	Yield Allocation to Fine Roots (fraction)
Perennial grass Irrigated	0.00	0.00	0.50	0.00	0.50
Perennial grass/clover	0.00	0.00	0.50	0.00	0.50
Perennial legume	0.00	0.00	0.50	0.00	0.50
Queensland bluegrass	0.00	0.00	0.50	0.00	0.50
Rice	0.00	0.26	0.43	0.00	0.31
Samphire	0.00	0.00	0.50	0.00	0.50
Sorghum	0.00	0.29	0.41	0.00	0.30
Soybean	0.00	0.30	0.48	0.00	0.22
Spinifex	0.00	0.00	0.50	0.00	0.50
Sugarcane	0.75	0.00	0.15	0.00	0.10
Sunflower	0.39	0.32	0.19	0.00	0.10
Triticale	0.00	0.26	0.43	0.00	0.31
Tropical grass	0.00	0.00	0.50	0.00	0.50
Vetch	0.00	0.30	0.48	0.00	0.22
Weeds annual	0.00	0.00	0.50	0.00	0.50
Weeds perennial	0.00	0.00	0.50	0.00	0.50
Wheat	0.00	0.26	0.44	0.00	0.30

Carbon contents of crop and grass species

Plant dry matter is converted to carbon using a crop carbon content value that is specific to the species in use, in the model. These average values for crop species were determined from an analysis of plant materials obtained from around the country, using a dry combustion method and published in the Technical Report series (http://www.pandora.nla.gov.au/tep/23322).

6.B.5.2 Debris

The amount of plant residue generated by a crop or grass species is dependent on both the plant growth and management practice. As well as containing the crop/pasture growth and species data, the relational database describes the agricultural management practices, (e.g., stubble management) applied to each crop/pasture (see section 6.E.3). These data are used to determine how much of the crop mass becomes residue for incorporation and decomposition to litter and soil carbon pools, how much is taken offsite and how much is burnt.

Initial crop litter mass and decomposition rates

The decomposition rates applied acknowledge that the crop residues that form the litter generally decompose within 12 months. The initial mass of litter assigned and their decomposition rates are shown in Table 6.B.4.

Table 6.B.4 Initial litter mass and decomposition rates for crop systems

Plant Component	Initial Mass t ha^{-1}	Decomposition Rate yr^{-1}
Grains, Buds, Fruit (Resistant)	0.10	1
Grains, Buds, Fruit (Decomposable)	0.00	1
Stalks (Resistant)	0.01	1
Stalks (Decomposable)	0.01	1
Leaves (Resistant)	0.01	1
Leaves (Decomposable)	0.01	1
Coarse Roots (Resistant)	0.01	1
Coarse Roots (Decomposable)	0.01	1
Fine Roots (Decomposable)	0.01	1

Crop turnover rates

Turnover (natural shedding of material) rates for crop and pasture species are generally low for each monthly simulation step given the sigmoidal growth response of agricultural plant species, including pastures (Table 6.B.5), perennial systems such as grazed pastures, root sloughing in response to grazing is included in the model which maintains the relative ratio of aboveground to belowground plant mass with grazing.

Table 6.B.5 Turnover rates applied to crop and pasture systems

Plant Component	Turnover Rates yr^{-1}	
	Pasture species	Annual crop species
Grains, Buds, Fruit	0.4	0.10
Stalks	0.4	0.10
Leaves	0.4	0.10
Coarse Roots	0.4	0.10
Fine Roots	0.4	0.10

6.B.6 Estimating changes in soil carbon

The Rothamsted soil carbon model (*Roth-C*) is a soil carbon model developed by Jenkinson *et al.* (1991). *Roth-C* models changes in soil carbon based on the inputs of organic matter from dead plant material and soil carbon decomposition rates. Within *Roth-C* there are five soil carbon pools generally defined by classes of resistance to decomposition. Plant residues are firstly split into decomposable and resistant plant material. Turnover rates for each soil pool are determined by rainfall, temperature, groundcover and evaporation other than decomposition rate constants specific to each soil carbon pool. *Roth-C* is used in conjunction with both *CAMFor* and *CAMAg* to model soil carbon stocks in the national account.

Model was initialised using measureable soil carbon fractions (see Appendix 6.E) by replacing the key conceptual pools namely DPM, RPM and HUM defined in the *Roth-C* model. *Roth-C* model also utlises clay content and the initial topsoil moisture deficit as inputs to carry out soil carbon simulations.

6.B.6.1 Model calibration, validation and verification

Calibration of *Roth-C* was undertaken using available long-term field trial data, which had sufficiently detailed and complete long-term data to enable calibration of the model against long-term field measurements. Only a minimum of data supplementation was accepted at these calibration sites. Other sites with incomplete long-term data, but providing a robust temporal pattern of carbon change under known management and climate, were used for model validation and verification (Skjemstad and Spouncer, 2002).

Calibration and validation

Two agricultural and seven forestry long term trial sites were selected for estimating changes in soil carbon. One agricultural site was located on a monsoonal subtropical environment with heavy clay soil and the other was located in a temperate Mediterranean climate with a light textured soil. At each agricultural site, archival soil samples (0-30 cm depth) collected throughout the life of the trials were fractionated into particulate organic carbon (POC), charcoal (char-C) and humic (HUM) pools (Skjemstad and Spouncer, 2003).

The soil carbon model (*Roth-C*) used to calculate changes in soil carbon stocks caused by shifts in agricultural practice was independently calibrated and validated (Skjemstad and Spouncer 2003). The results were found to be sensitive to the partitioning of carbon between the various soil fractions (Janik *et al.* 2002; Skjemstad *et al.* 2004; Paul and Polglase, 2004b).

Testing of the seven forestry sites and two agricultural sites confirmed the model calibrations for soil carbon pool allocations for both forestry and agricultural sites. Details of the calibration and testing of the model are provided in Paul *et al.* (2002b and 2003b).

Model validation used existing time-series data and new paired-site comparisons to test model predictions of change. Calibration of the model demonstrated that the measureable soil carbon fractions (POC, HUM and Char-C pools/ROC) fitted well with the modelled carbon pools (RPM, HUM and IOM) as defined in *Roth-C*, A full description of the model calibration and validation results for agriculture can be found in Skjemstad and Spouncer (2003).

In general terms the coefficient of variation for modelled outputs of soil carbon is around 5% (Janik *et al.* 2002), whereas the coefficient of variation for measured soil carbon is 15-40% (McKenzie *et al.* 2000a and b; Janik *et al.* 2002). Further details are provided in Murphy *et al.* (2002), Harms and Dalal, (2003) and Griffin *et al.* (2002).

More recently Chappell and Baldock (2013) were commissioned by the Department of the Environment and Energy to enhance the reliability of soil carbon change estimates provided by the *FullCAM* framework. A local optimisation was performed separately for each of the 103 plots of the calibration and verification sites (Skjemstad and Spouncer 2003) allowing optimisation of three initial stocks of SOC pools (RPM, HUM and IOM) and the decomposition rate constant parameters (RPM and HUM). The optimised values of the initial soil carbon pools were then used in a separate global optimisation of the same measurement data but with optimisation of only the decomposition parameters (RPM and HUM).

The results are shown in Table 6.B.6.

Table 6.B.6 Roth-C model including soil redistribution globally fitted decomposition rates and their goodness of fit

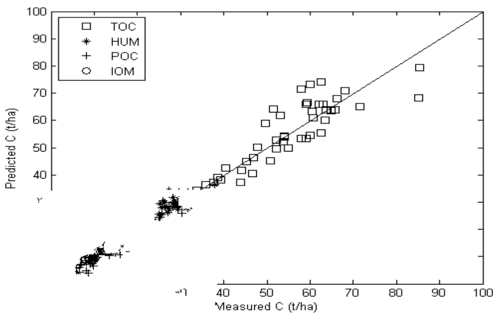
Global optimistation	RPM y^{-1}	HUM y^{-1}	RMSE (C t ha^{-1})
Calibration sites	0.207	0.021	0.234
Verification sites	0.149	0.029	0.095
All sites	0.173	0.028	0.090

Source: Chappell and Baldock (2013)

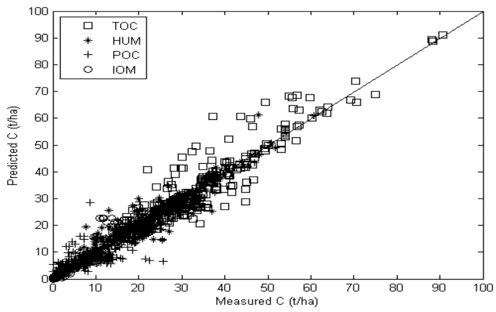
Figure 6.B.5a (below) shows a plot of measured C for all site data of Brigalow and Tarlee against Roth-C predicted C using the optimised values of the decomposition parameters RPM=0.207 y^{-1} and HUM=0.021 y^{-1}. The RMSE of the global model fitting was 0.234 (C t/ha) which describes the error associated with model predictions using the parameter values calibrated against these data.

Figure 6.B.5 Global optimisation of the *Roth-C* model (using decomposition parameters for RPM and HUM) against the measured C of the RPM (POC), HUM (HOC) and IOM (ROC) pools of the calibration site Brigalow and Tarlee (a), the verification sites only (b) and the calibration and verification sites combined (c)

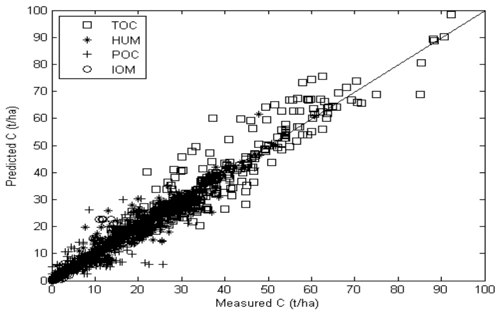
(a)



(b)



(c)

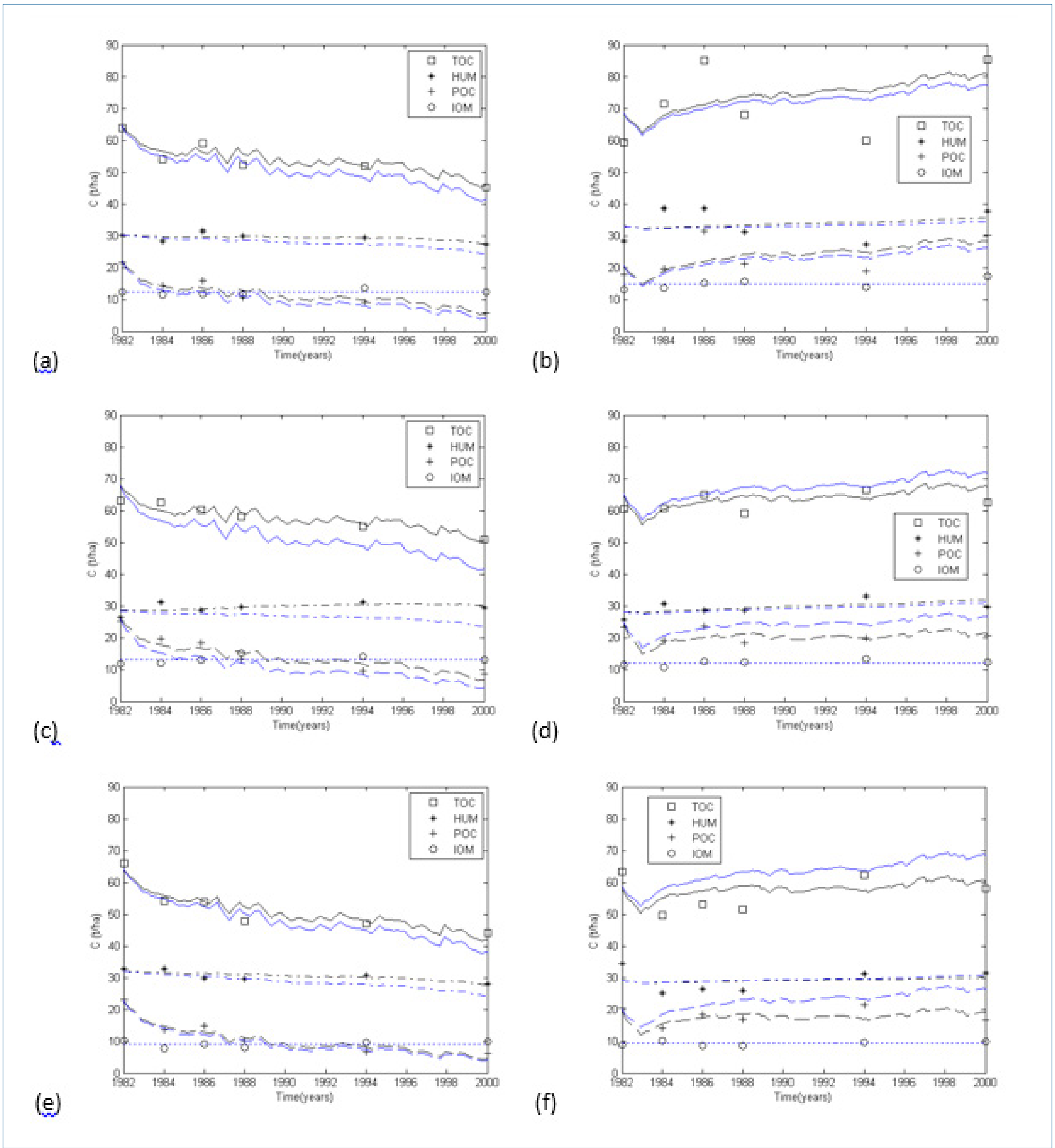


Source: Chappell and Baldock (2013).

Figure 6.B.5b shows a plot of measured C for all site verification data against *Roth-C* predicted C using the optimised values of the decomposition parameters RPM=0.149 y^{-1} and HUM=0.029 y^{-1}. The RMSE of the global model fitting was 0.095 (C t/ha). Figure 6.B.5c shows a plot of measured C for all sites (calibration and verification) data against *Roth-C* predicted C using the optimised values of the decomposition parameters RPM=0.173 y^{-1} and HUM=0.028 y^{-1}. The RMSE of the global model fitting was 0.090 (C t/ha). Evidently, the previously recommended values of RPM = 0.15 y^{-1} and HUM = 0.02 y^{-1} are within the variation found across the plots and sites around Australia but these values are smaller than the globally fitted decomposition rates. As such the decomposition parameters have been adjusted to reflect this latest research and provide the most robust calibration of *FullCAM*.

Figure 6.B.6 shows the behavior of *Roth-C* model temporal simulations for two sites in Brigalow with RPM and HUM soil decomposition rate constants values obtained from local and global optimization process. Even though the local optimise rate constant values mimic much closer representativeness with simulated data and measureable fractions, global optimise parameters also produced very similar pattern.

Figure 6.B.6 Brigalow continuous wheat (a, c & e) and Brigalow continuous pasture (b, d & f) with Roth-C local model fits (black line) and global model fits (blue line) using decomposition parameter values RPM=0.173 and HUM=0.028.



Verification

Subsequent to the implementation of the baseline map of organic carbon in Australian soil (Viscarra Rossel; *et al.*, 2014), the Australian three-dimensional soil grid (Clay) (Viscarra Rossel; *et al.*, 2015), updated species (Table 6.B.2) and management practices (section 6.E.4) as well as the optimisation of the decomposition rates (*Calibration and Validation*), the Department of Environment and Energy undertook a modelling exercise in which the *FullCAM* was used to simulate the effects on soil carbon of changes in practices to manage stubble, tillage and the amount of crop biomass as well as estimate the effects of a change in land use from a continuous cropping to a pasture system and a continuous pasture to rotational cropping system.

Given the impact of climate and soil properties on the technical potential of soil carbon enhancement and the uncertainty distribution around the technical potential, seven sites were selected to reflect four main temperature and moisture regimes (Cool-Wet; Cool-Dry; Warm-Wet; Warm-Dry) defined in accordance with the 2006 IPCC Guidelines. For each of the sites selected, the Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (Pink 2010) in which the site is located was identified.

For each of the seven selected sites, statistics (minimum, mean and maximum values and standard deviations of the values) for the percentage of soil that is clay by weight and total were determined for the SA2 in which the selected sites were located and regression analysis on the percentage of soil that is clay by weight and total soil carbon for the SA2s was carried out to determine the correlation coefficient between the two key soil properties.

The minimum, mean and maximum values, and standard deviations for the percentage of soil that is clay by weight and total soil carbon were applied as risk variables in the Monte-Carlo analysis using @Risk (Palisade Corporation, 2005). Parameterisation was designed to ensure that values that would not occur within the SA2 of the selected site were not used in the Monte-Carlo analysis. This approach ensures regional specificity by removing/reducing skew/bias and normalises the outputs according the input data so that the outcomes are truly reflective of that particular SA2, while allowing for the inherent variability in climate and soil type across the Australian landscape and, more specifically, the SA2.

The correlation between the percentage of soil that is clay by weight and total carbon, (including the 1:1 correlation between the soil fractions and the total soil carbon) was applied in the Monte-Carlo simulation correlation matrix to ensure proportionality of soil fractions and clay were observed.

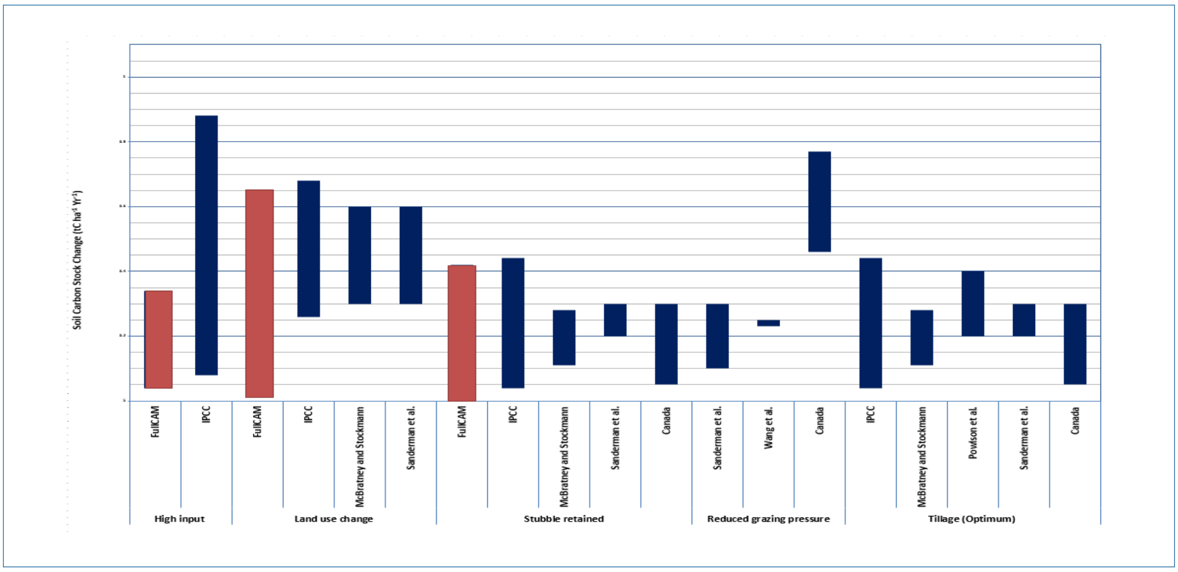
A truncated normal distribution was applied to the Monte-Carlo simulations to ensure the probability distribution of the output value for soil carbon stock is bounded above and below by the minimum and maximum values for the input risk variables.

The Monte-Carlo simulations were run for a full 1000 simulations as opposed to ceasing when convergence was met. This repeated sampling enabled the output value for soil carbon stock to converge on as close to the most probable technical potential value attainable for the SA2.

Factual (baseline) and counter-factual (scenario) simulations of selected activities identified in the 2006 IPCC Guidelines and the 2013 IPCC Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (KP) Supplement were run in *FullCAM*.

National values for the estimated response of soil carbon to changes in various management practices are presented in Figure 6.B.7. The results are within expected ranges and consistent with empirical literature and international practice. The model does not generate a single value, but a range of values where the distribution of values generated by the model is presented for each of the changes in management practices. The distribution of values demonstrates the variability in outcomes modeled by *FullCAM*, mainly reflecting spatial variations in soil quality, which is entirely expected from empirical experience across Australia. Figure 6.B.7 illustrates the variation in outcomes of differences in soil carbon sequestration and/or reduction in the rate of losses in a sensitivity scenario where the yields were increased by 20 per cent over a period of years.

Figure 6.B.7 Comparison for soil carbon response to changes in management practices for *FullCAM* and from domestic empirical literature and international practice



Soil carbon fractions

Fine spatial resolution continental maps of the soil carbon fractions (particulate organic carbon (POC), humic organic carbon (HOC) and resistant organic carbon (ROC)) are generated by CSIRO using a methodology that is similar to that used to derive the baseline map of organic carbon in Australian soil (Viscarra-Rossel *et al.* (2014).

There were 400 soil data with measurements of POC, HOC, ROC. Largely, these data originated from the Soil Carbon Research Program (SCaRP), and a small number are from two smaller projects that were funded under the Department of Agriculture (DA) Filling the Research Gap (FTRG) Programs. The data represented all Australian Soil Classification Orders but they were sparsely distributed across Australia and represented soil that is mostly under agriculture, but also forests. The spatial distribution of the data is shown in Figure 6.E.2.

The visible–near infrared and mid-infrared spectra of the 400 soil samples were recorded and spectroscopic calibrations were derived to predict POC, HOC and ROC of other soil samples for which data on the organic carbon fractions were not available. The calibrations were used to predict the fractions of around 4000 soil samples that cover the extent of Australia and represent all land use types, and all climatic and bio-geographical regions.

Once the spectroscopic predictions were made, the spatial modelling of the data was performed by combining the bootstrap, a decision tree with piecewise regression on environmental variables and geostatistical modelling of residuals. The spatial models were validated with an independent data set and the fine spatial resolution continental maps of the soil carbon fractions have been incorporated in *FullCAM* to ensure internal consistency of spatial soil inputs.

Appendix 6.C The forest productivity index

To derive the spatial and temporal patterns of forest growth the simplified form of the *3-PG* model (Landsberg≈and Waring 1997; Coops *et al.* 1998; Coops *et al.* 2001) was used to provide relative indices of growth potential (productivity indices[18]) at a 1 km grid scale on a monthly basis since 1970. The site-based, multi-temporal productivity indices are used to support a generalised empirical growth model. All modelling is done on the basis of aboveground biomass with subsequent factors to account for belowground (fine and coarse root) material.

A truncated version of the *3-PG* model (Landsberg and Waring 1997), retaining the essential features of biomass net primary production (*NPP*) estimation, without the carbon partitioning procedures is used to provides a site index of plant productivity that is independent of the type of forest present.

The essence of the model is the calculation of the amount of photosynthetically active radiation absorbed by plant canopies (*APAR*). *APAR* is calculated (Equation 6C_1) as half the amount of short-wave (global) incoming radiation (*SWRadn*) absorbed by plant canopies.

$$APAR = SWRadn \times 0.5 \times (1-e^{(-0.5 \times LAI)}) \times \text{days in month} \qquad (6C\_1)$$

Where *LAI* is the Leaf Area Index and the coefficient 0.5 is a general value for the extinction coefficient. *LAI* is derived by the expression *ln*(1-FPAR)/(-0.5) where FPAR is calculated by (NDVI * 1.0611) + 0.3431. *APAR* is multiplied by a factor that converts it to biomass.

This, in effect, amalgamates two steps, the conversion of absorbed CO_2 into initial carbon products (gross primary production) and the loss of a proportion of those products by respiration to give NPP. The value of the conversion factor (ε, gm Biomass MJ^{-1} APAR) used was obtained from literature (Potter *et al.* 1993; Ruimey *et al.* 1994; Landsberg and Waring 1997).

There is substantial variation in ε values, but no clear pattern in relation to plant type, so a value of *1.25 gm Biomass* MJ^{-1} APAR was used based on expert judgement. As the resultant output from the model is used as an index of 'productivity' (the Forest Productivity Index) and not as an absolute mass increase value, precision in the conversion factor is not critical. This NPP value assumes that there are no other constraints on growth. To account for the effects of other factors the potential NPP is reduced by modifiers reflecting non-optimal nutrition, soil water status, temperature and atmospheric vapour pressure deficits.

Calculation of growth modifying factors

Modifiers are dimensionless factors with values between zero (complete restriction of growth) and 1 (no limitation). Modifiers used in this way are discussed by Landsberg (1986), McMurtrie *et al.* (1992) and Landsberg and Waring (1997).

The modifying factors are:

Soil fertility: Because of natural variation and the considerable uncertainty surrounding soil fertility values, only three levels of soil fertility were used; high (effective modifier = 1), medium (effective modifier = 0.8) and low (effective modifier = 0.6), giving ε values of 1.25, 1 and 0.75, respectively. These were applied for each pixel, depending on soil type, before environmental modifiers were applied. Information on soils and their characteristics was obtained from McKenzie *et al.* (2000a).

18 A generic model of Net Primary Productivity derived a classification of productivity, on a scale of 1-30. Temporal and spatial variability is identified by a change in classification. This is not a linear relationship with biomass growth increment.

Vapour Pressure Deficit (VPD): VPD is a measure of atmospheric drought. VPD affects stomatal, and hence canopy conductance as trees regulate their water use. This can lead to reduced growth even where soil water content is high. The VPD modifier equation (6C_2) used is:

$$VPDmod = e^{(-0.05 \times VPD)} \quad (6C\_2)$$

This modifier essentially acts as a control on the rate of water loss and is conditional upon soil water content (see below).

Soil Water Content: This is derived from water balance calculations, which take into account the maximum soil water holding capacity (Equation 6C_6) in the root zone of plants. Plant water use (Equation 6C_4) is calculated from the equation for equilibrium evaporation (Equation 6C_3, see Landsberg and Gower 1997; p. 79), modified by feed-back from current soil water content, and a conventional water balance equation (Equation 6C_5):

$$EqEvapn = ((0.67 \times NetRadn * (1-0.05)) / 2.47) \times \text{days in month} \quad (6C\_3)$$
$$Transpiration = EqEvapn_j \times SWmod_{j-1} \quad (6C\_4)$$
$$WaterBal = (Rain \times (1\text{-}interception)) - Transpiration \quad (6C\_5)$$
$$SoilWaterContent_j = SoilWaterContent_{j-1} + WaterBal_j \quad (6C\_6)$$

Initial Soil Water Content was taken as 0.75 x SWcapacity. Soil Water Content carries over from one time step to the next. The soil moisture calculation sequence was run for 3 years, after which Soil Water Content had essentially equilibrated to stable monthly values. Soil Water Content values in year 3 were therefore used in the analysis. The soil water modifier (*Swmod*, Equation 6C_8) was calculated from the moisture ratio (*MoistRatio*, Equation 6C_7), which is Soil Water Content normalised to SWcapacity. The equation describes the variable effect of MoistRatio across the range from wet soil (MoistRatio ≈1) to dry soil (MoistRatio ≈0).

$$MoistRatio = SoilWaterContent/SWcapacity \quad (6C\_7)$$
$$SWmod = 1 / (1 + ((1\text{-}MoistRatio)/0.6)^{0.7}) \quad (6C\_8)$$

The soil water and VPD modifiers are not multiplicative; the lowest one applies. The argument is that if plant growth (conversion of radiant energy into biomass) is limited more by VPD than soil water (i.e., if VPDmod < SWmod) then soil water is not a limiting factor, even if soil water content is relatively low. The converse applies, that is, if SWmod < VPDmod, soil water is the limiting factor.

Temperature: The growth of any plant species is limited by temperatures outside the optimum range for that species. Since plants are dealt with in a generic way the assumption was made that, in any particular region, the plants are well-adapted to the temperature range. The equation (6C_9) describing the effect of temperature is:

$$T_{mod} = ((T_{av} - T_{low}) / (T_{opt} - T_{low})) \times ((T_{high} - T_{av}) / (T_{high} - T_{opt})) \quad (6C\_9)$$

T_{av} is the average monthly temperature, T_{min} is the monthly average temperature below which plant growth stops, T_{max} is the monthly average temperature above which plant growth stops and T_{opt} is the optimum temperature for growth $(T_{min} + T_{max})/2$. The temperature modifier (T_{mod}) is 1 when $T_{av} = T_{opt}$.

Equation (6C_9) gives a hyperbolic response curve, with $T_{mod} = 0$ when $T_{av} = T_{min}$ or T_{max}. T_{min} is set to ½ the minimum temperature of the coldest month (if the minimum temperature of the coldest month is greater than or equal to 0oC, T_{min} was set to the minimum temperature of the coldest month plus ½ the minimum temperature of the coldest month if the minimum temperature of the coldest month is less than 0oC). T_{max} is set to 5°C above the maximum temperature of the hottest month of the year and T_{opt} as equal to the average of T_{min} and Tmax. Consequently, T_{mod} generally had relatively small effects on the calculation of NPP.

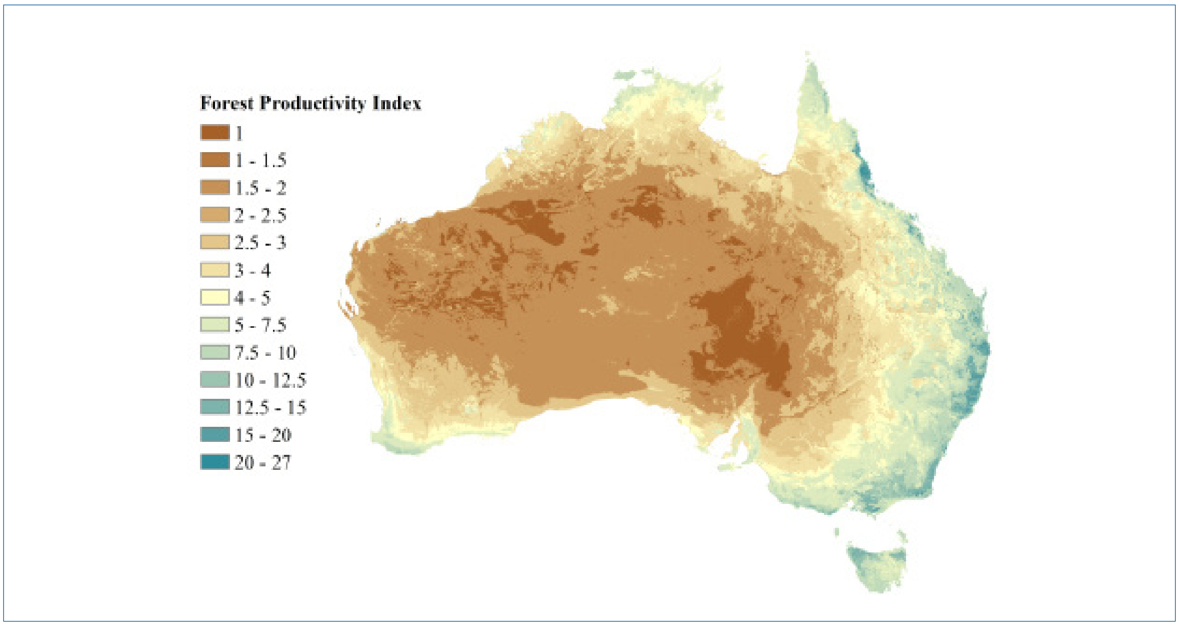
A frost modifier is included, using the simple assumption that frost temporarily inactivates the photosynthetic mechanism in foliage, so there is no growth on a frost day. The modifier is, therefore, simply the ratio of number of frost days/month to the number of days in the month.

Calculation of the forest productivity index

The Forest Productivity Index (FPI) is calculated both temporally and spatially using the monthly (since 1968) 1km grid climate and site information described in Appendix E. A further 250 m long-term average FPI is also calculated, using a slope and aspect corrected APAR calculation (Figure 6.C.1).

These productivity maps are used to describe the spatial and temporal variation in forest biomass and growth.

Figure 6.C.1 250m slope and aspect corrected productivity index map



Appendix 6.D Initial forest biomass

The initial forest biomass layer is used to estimate the initial biomass of forests on lands that is incremented in the following sub categories:

- Forest land converted to Cropland; and
- Forest land converted to Grassland.

An estimate of biomass (the assumed initial biomass) of mature forests is required to estimate emissions due to first time clearing events. The assumed initial biomass is applied to all first time clearing events whenever they occur. The assumed initial biomass for a pixel is calculated based on a regression model of the relationship between the Forest Productivity Index and measured biomass (Raison *et al.* 2003; Richards and Brack, 2004a), with subsequent modifications by Roxburgh *et al.* (2017) (described below).

Calibration data

Biomass measurements used in the calibration include all forest conditions except those with visible evidence of recent disturbance such as clearing, harvest or fire since 1970. The lands may, however, have an ongoing low level disturbance such as grazing and low intensity fires.

In the collection of the calibration plot data, caution was exercised to exclude forest 'gaps' contained in some field measurements. Plots taken as part of fixed-grid or transect systems could potentially fall in gaps in sparse forests. As the remote sensing programme at 25 m resolution is capable of separating such forest gaps from clearing events, the forest carbon mapping needs to represent the biomass of forested plots, not of that averaged over the gaps.

In the update by Roxburgh *et al.* (2017) the original calibration database was augmented with forest biomass observations from the TERN/AusCover National Biomass Library (http://www.auscover.org.au/purl/biomass-plot-library). This library is a collation of stem inventory and biomass estimates compiled from federal, state and local government departments, universities, private companies and other agencies. Of the approximately 14,500 site biomass records in the database, 5,739 were deemed consistent with the requirements for estimating initial mature biomass.

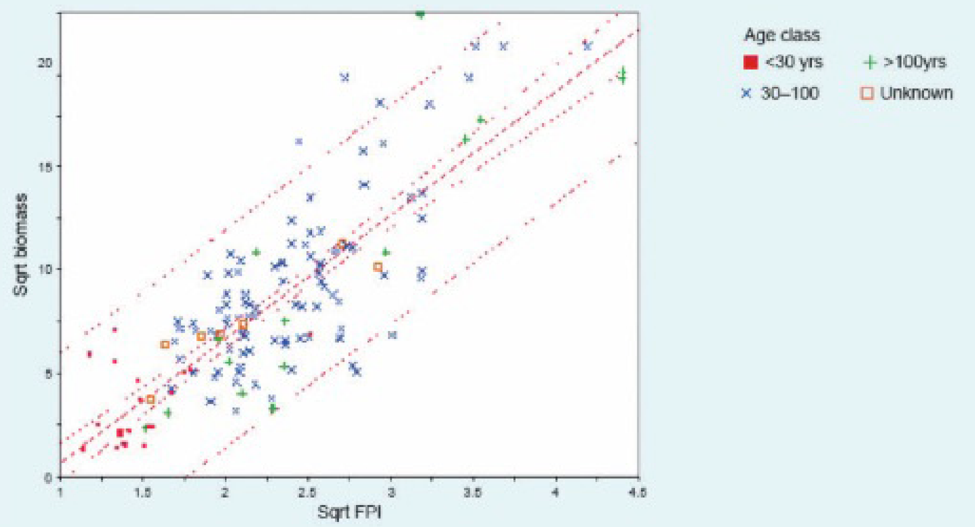
Assumed initial biomass relationship

For the original calibration of FullCAM the initial forest biomass for an individual forest site was fitted to the productivity map. The red line in Figure 6.D.1 represents the line of best fit for predicting the initial forest biomass of an individual forest site.

A regression found a significant relationship ($p < 0.01$, $r^2 = 0.68$) between the stand biomass measures (M) and the Long-Term Forest Productivity Index (P) (Equation 6D_1). A square root transformation was required to meet assumptions of normality and homogeneity (Figure 6.D.1).

$$M = (6.011 \times \sqrt{P} - 5.291)^2 \qquad \text{(6D\_1)}$$

Figure 6.D.1 The assumed initial biomass relationship



The goodness of fit of Equation (6D_1) to the measured data ($r^2 = 0.68$, $p < 0.01$) confirms that a robust relationship exists between the productivity mapping and measured aboveground biomass estimates although with some suggestion of under-prediction of high-biomass productive forests. The outer 95% confidence limits (outer pair of dotted lines) show the reliability for predicting biomass at any individual site, and the inner 95% confidence intervals (inner pair of dotted lines) show the confidence in the line of best fit being able to represent the variability in the field data at the national scale.

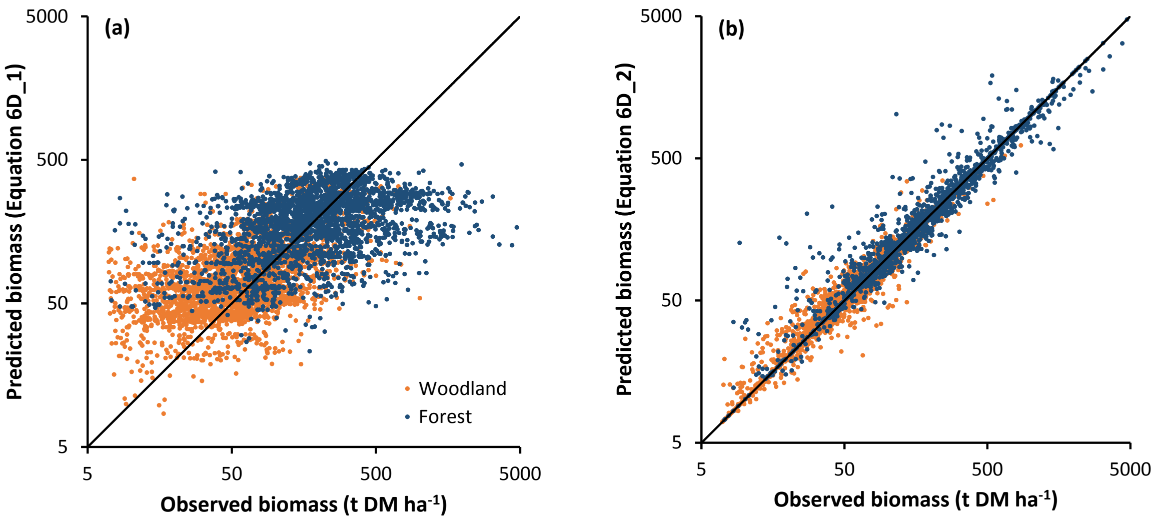
Applying Equation 6D_1 to the data from the TERN/AusCover National Biomass Library suggested the biomass predictions were accurate up to approximately 300-400 t DM ha^{-1}, after which point there was a strong tendency for the equation to under-predict actual biomass, such that all biomass observations greater than 500 t DM ha^{-1} are predicted to be less than 500 t DM ha^{-1} (Figure 6.D.3a). To correct for this bias, a spatially-explicit modifier (λ) was calculated based on the observed discrepancy between the observed and predicted biomass. Because of issues regarding non-normality and variability in the data, the non-parametric 'Random Forest' ensemble maching learning algorithm was used to estimate λ, using as predictor variables elevation, soil organic carbon content, and 21 climatic variables (Roxburgh *et al.* 2017). The revised model predictions, for pixel *i*, were therefore calculated as:

$$M_i = \lambda_i \times (6.011 \times \sqrt{P_i} - 5.291)^2 \qquad (6D\_2)$$

For regions in which the current model (Equation 6D_1) is consistent with the new data then λ is expected to be close to 1.0; for regions where biomas is being under-predicted then λ is expected to be >1, and for regions where biomas is being over-predicted then λ is expected to be <1.

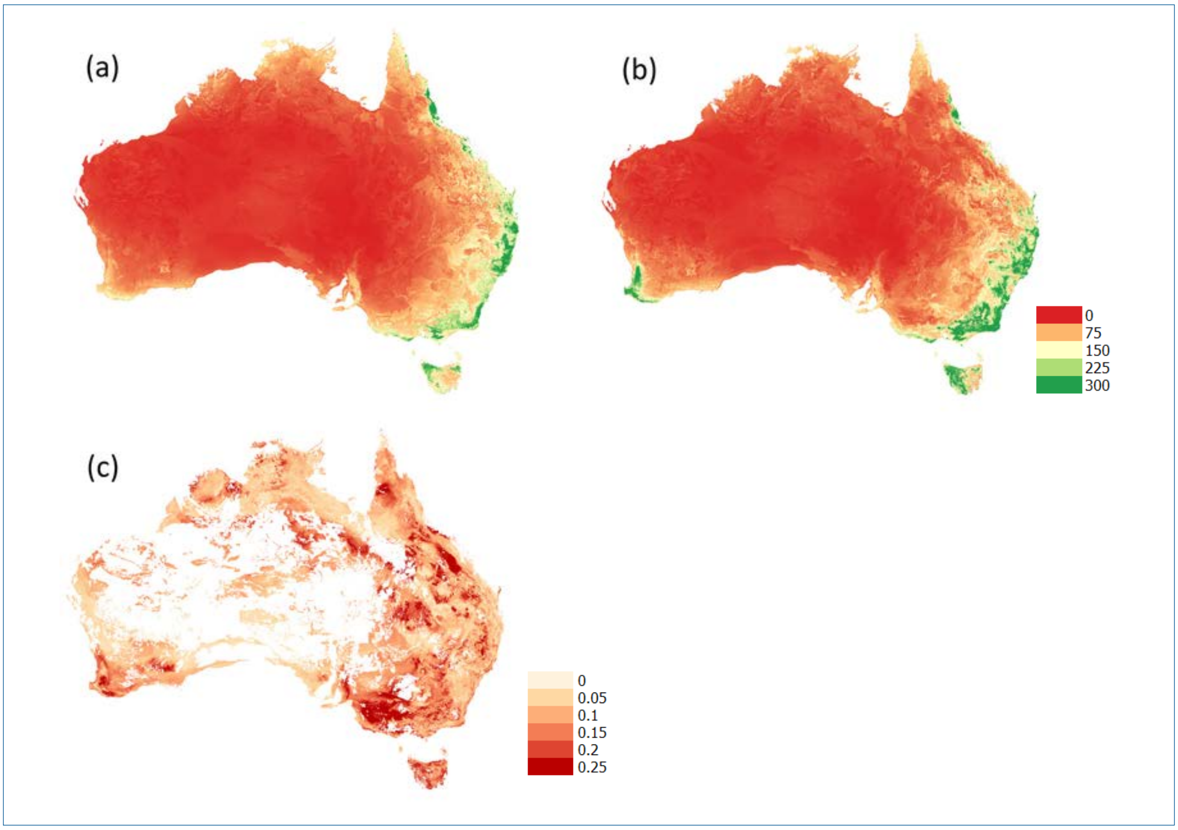
Under Equation 6D_1, and when applied to the full biomass database, the overall root mean square error (RMSE) was 239 t DM ha^{-1}, with a model efficiency (EF) of 0.14 and a mean absolute (ME) error confirming an overall bias of -35 t DM ha^{-1} (Figure 6.D.2a). Under Equation 6D_2, which includes the modifier λ, the model fit statistics all improved, with reductions in the RMSE and ME to 62 t DM ha^{-1} and -0.2 t DM ha^{-1} respectively, and a model efficiency (EF) of 0.94 (Figure 6.D.2b). The revised model is therefore characterized by a much closer fit to the 1:1 line, and negligible bias over the full range of forest biomass (equivalent statistics when observations were withheld as part of model validation testing are given in the next section).

Figure 6.D.2 (a) Observed vs. predicted biomass for the predictions using Equation 6D_1. (b) Observed vs. predicted biomass for the predictions using Equation 6D_2. 'Woodland' indicates sites with a canopy cover up to 50% (i.e. including some sites classified as sparse woody vegetation with canopy cover 5-20%). 'Forest' indicates sites with a conopy cover >50%. Lines are the 1:1 relationship, where observations equal predictions.



The initial assumed biomass at a chosen resolution for the entire continent can then be calculated by applying Equation (6D_2) to the FPI mapping (Appendix 6.C) and is shown in Figure 6.D.3a. The revised map of M (Figure 6.D.3b) differs from the original (Figure 6.D.3a) most obviously in the increased biomass density (i.e. darker green) in the taller forests of Western Australia, Tasmania, Victoria and New South Wales. Other regional-scale differences include declines in predicted initial biomass for the northern territory, and coastal queensland.

Figure 6.D.3 (a) Original FullCAM maximum biomass layer (t DM ha^{-1}). (b) Revised maximum biomass layer (t DM ha^{-1}). (c) Coefficient of variation (standard deviation / mean) of *M*, calculated over 100 replicate Random Forest model fits. White areas in (c) were excluded from analysis, and in (b) are filled with values from the original maximum biomass layer.



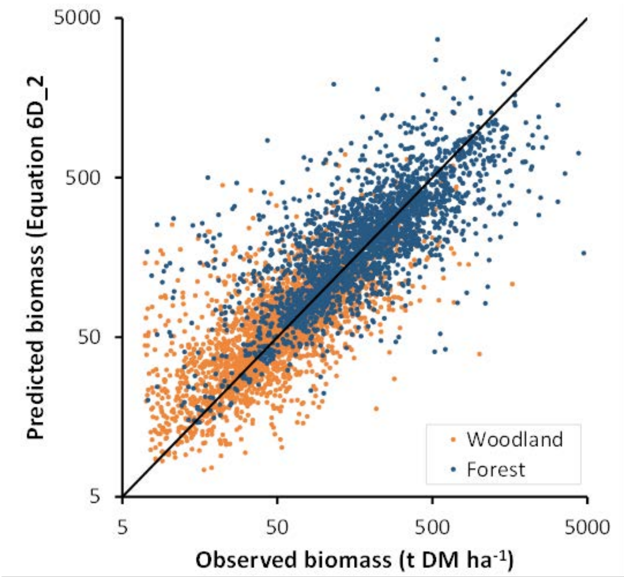
While the goodness of fit and lack of bias in error estimates (Figure 6.D.2b) provides confidence in the application of Equation (6D_2) as a model to predict biomass at maturity, there is an obvious scatter in the data which is somewhat masked by the logarithmic scales on which the figures are displayed. This is attributable to the range of age classes and forest histories used in the model, the differing methods used in the field estimation, an inherent variability between the 'plot' locations used to scale to one hectare mass estimates compared to the average condition reflected in the 250 m resolution productivity estimation, and to natural variability in forest biomass.

Validation and verification of assumed initial biomass

As part of the modeling procedure to predict λ the empirical database of 5,739 records was split at random into a 70% model fitting (calibration) subset and a 30% withheld (validation) subset. This was repeated 100 times as part of a Monte-Carlo estimation procedure, generating 100 separate models that were then used to estimate the mean and uncertainty of the predictions. Each observation therefore had the opportunity to be included both for model fitting (results shown in Figure 6.D.2b) and also for independent validation, where withheld observations are used to estimate the error associated with the prediction of 'new' observations not included in the model fitting procedure (Figure 6.D.4).

As expected, the scatter around the 1:1 line was larger when sites were used for independent validation (compare Figure 6.D.2b with Figure 6.D.4), with a RMSE of 201 t DM ha^{-1}, a model efficiency (EF) of 0.4, and a mean absolute (ME) error indicating a an overall bias of -8 t DM ha^{-1}, corresponding to an error of approximately 5% at the continental scale.

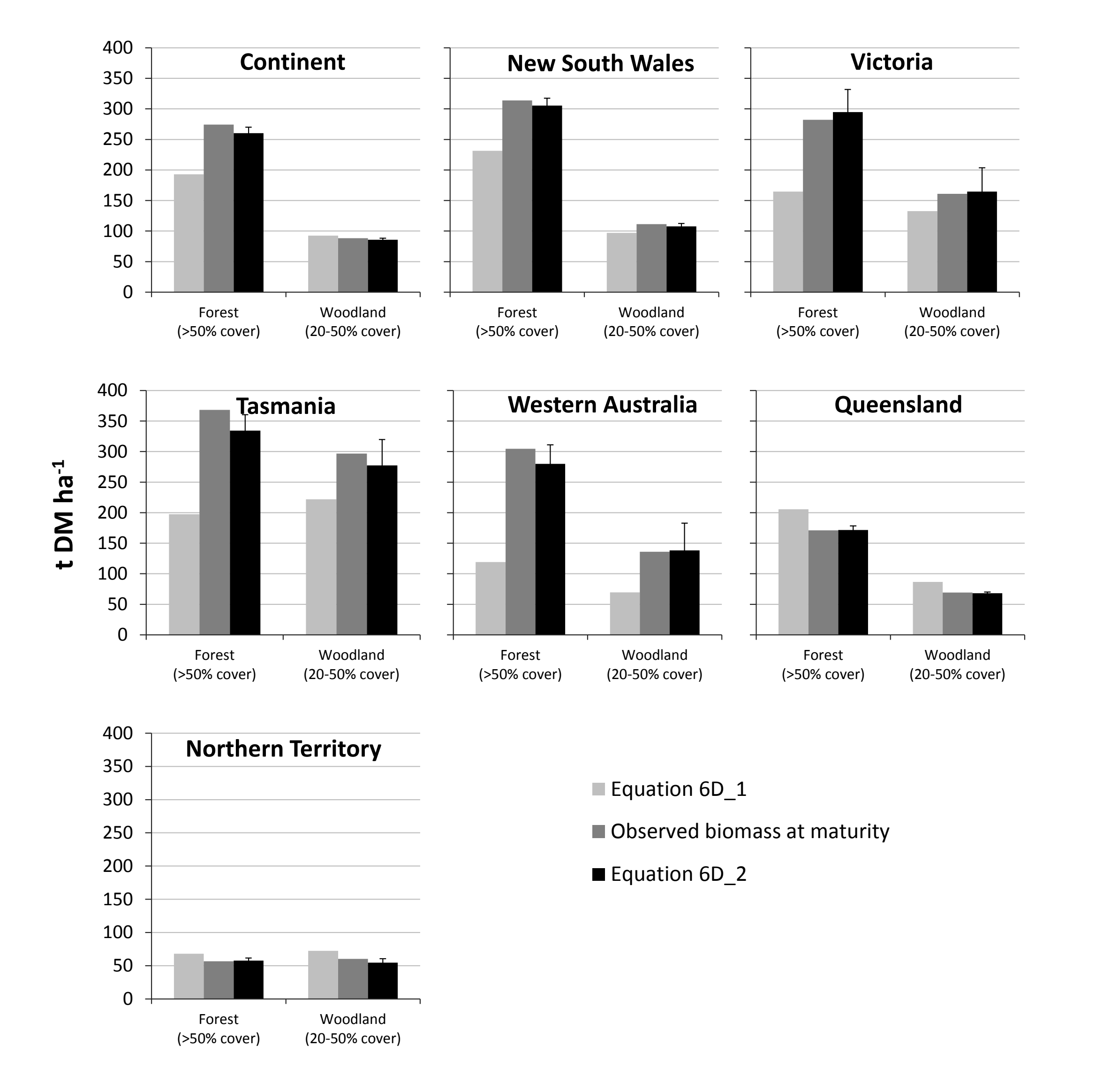
Figure 6.D.4 Observed vs. predicted biomass for the predictions using Equation 6D_2 when observations were withheld from model fitting and used for model validation. 'Woodland' indicates sites with a canopy cover up to 50% (i.e. including some sites classified as sparse woody vegetation with canopy cover 5-20%); 'Forest' indicates sites with a conopy cover >50%. Line is the 1:1 relationship, where observations equal predictions



The validation results can be more readily interpreted when the data is summarised regionally (Figure 6.D.5). At the continental scale, and for woodland forests with a canopy cover 20-50%, there was a slight decline in predicted biomass at maturity when comparing Equation 6D_1 (92 t DM ha^{-1}) to Equation 6D_2 (86 t DM ha^{-1}). In contrast, for forests with a canopy cover greater than 50%, the average biomass increased, from 193 to 260 t DM ha^{-1}. At the scale of individual states these forest increases were more pronounced; for example in Western Australia (119 to 280 t DM ha^{-1}), Tasmania (198 to 334 t DM ha^{-1}), Victoria (165 to 295 t DM ha^{-1}), and New South Wales (231 to 305 t DM ha^{-1}). Overall, comparison of the medium grey and dark grey bars in Figure 6.D.5 show that predictions from Equation 6D_2, for the validation subset, are all consistent with the observations.

When model predictions are averaged geographically then similar trends are apparent, with minor differences at the continental scale for woodland forersts (48 t DM ha^{-1} using Equation 6D_1 and 49 t DM ha^{-1} using Equation 6D_2), and increses in the >50% canopy cover forest class (172 t DM ha^{-1} using Equation 6D_1 and 234 t DM ha^{-1} using Equation 6D_2).

Figure 6.D.5 Comparison of mean above-ground biomass across the 5739 observed data points with the mean biomass from the original (Equation 6D_1) and revised (Equation 6D_2) predictions of above-ground biomass. South Australia is excluded due to lack of data. Error bars for Equation 6D_2 are the standard deviations of predictions across 100 replicate Monte-Carlo analyses



Appendix

Appendix 6.E Other *FullCAM* input data

6.E.1 Soil carbon input data

Initial soil carbon layer

To estimate soil carbon stock changes *FullCAM* requires spatial soil data including soil type, clay content and a pre-disturbance or initial soil carbon content. The soil data is used to derive water holding capacity which along with soil clay content determines the rate of decomposition of plant residues and the allocation of carbon to the different soil pools (Richards, 2001; Webb, 2002).

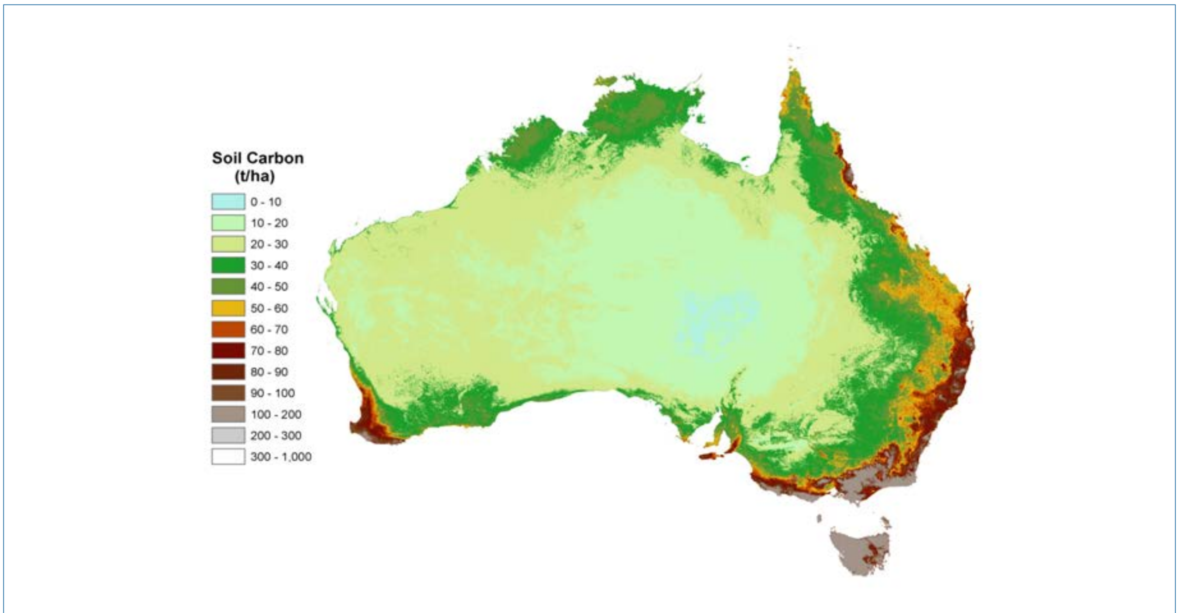
Viscarra-Rossel *et al.* (2014) has derived spatially explicit estimates, and their uncertainty, of the distribution and stock of organic carbon in the soil of Australia. This was achieved through the assembly and harmonisation of data from Australia's National Soil Carbon Research Program (SCaRP), the National Geochemical Survey of Australia (NGSA) and the Australian Soil Resource Information System (ASRIS) to produce the most comprehensive set of data on the current stock of organic carbon in soil of the continent.

A fine spatial resolution baseline map of organic carbon at the continental scale was produced by combining the bootstrap, a decision tree with piecewise regression on environmental variables, and geostatistical modelling of residuals. Values of stock were predicted at the nodes of a 3-arc-sec (approximately 90 m) grid and mapped together with their uncertainties. Baselines of soil organic carbon storage over the whole of Australia, its states and territories, and regions that define bioclimatic zones, vegetation classes and land use were then calculated.

Viscarra-Rossel *et al.* (2014) determined that the average amount of organic carbon in Australian topsoil is estimated to be 29.7 t ha^{-1} with 95% confidence limits of 22.6 and 37.9 t ha^{-1} The total stock of organic carbon in the 0–30 cm layer of soil for the continent is 24.97 Gt with 95% confidence limits of 19.04 and 31.83 Gt.

Figure 6.E.1 shows the baseline map of organic soil carbon in Australian soil to support national carbon accounting and monitoring under climate change. Soil carbon content was corrected to methodological standards where the initial method of measurement was known; otherwise the data were considered unusable and were not included in the final product.

Figure 6.E.1 Baseline map of organic carbon in Australian Soil (Viscarra-Rossel *et al.* 2014)



Soil carbon fractions

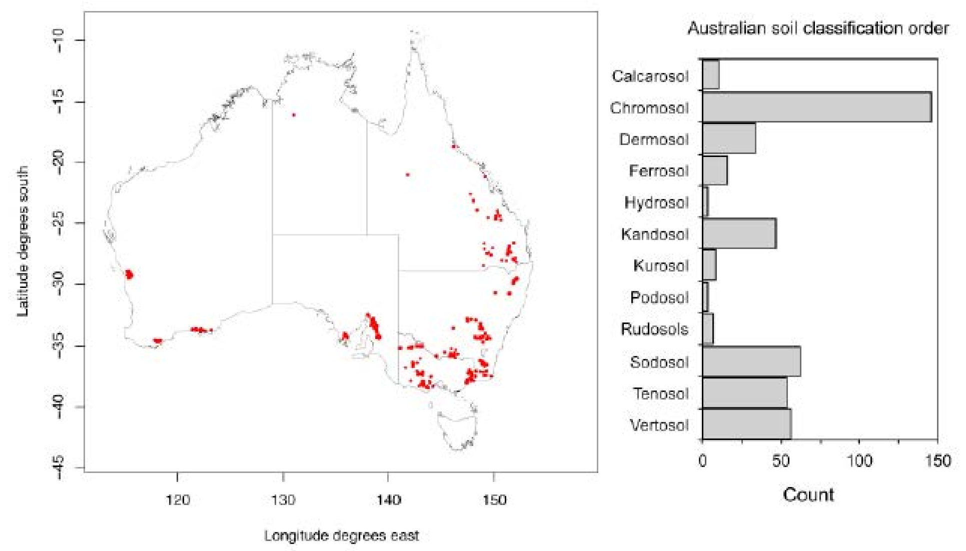
Measureable soil carbon fractions that can be replaced the conceptual pools of the Roth-C model which is used to simulate soil carbon changes within the FullCAM are used to initilise the FullCAM model. These fractions are defined by their differences in turnover times and biological significance (Baldock *et al.*, 2014).

Fine spatial resolution continental scale maps of the soil carbon fractions (particulate organic carbon (POC), humic organic carbon (HOC) and resistant organic carbon (ROC)) are generated by CSIRO Land and Water using a methodology that is similar to that used to derive the baseline map of organic carbon in Australian soil (Viscarra-Rossel *et al.* (2014).

There were 400 soil data points with measurements of POC, HOC, and ROC. Largely, these data originated from the Soil Carbon Research Program (SCaRP), and a small number are from two smaller projects that were funded under the Department of Agriculture (DA) Filling the Research Gap (FTRG) Programs. The data represented all Australian Soil Classification Orders but they were sparsely distributed across Australia and represented soil that is mostly under agriculture, but also forests. The spatial distribution of the data is shown in Figure 6.E.2.

The visible near-infrared and mid-infrared spectra of the 400 soil samples were recorded and spectroscopic calibrations were derived to predict POC, HOC and ROC of other soil samples for which data on the organic carbon fractions were not available. The calibrated models were used to predict the fractions of around 4,000 soil samples that cover the extent of Australia and represent all land use types, and all climatic and bio-geographical regions.

Figure 6.E.2 Spatial distribution of soil organic carbon fractions (POC, HOC, ROC) and the number of observations per Australian Soil Classification order.

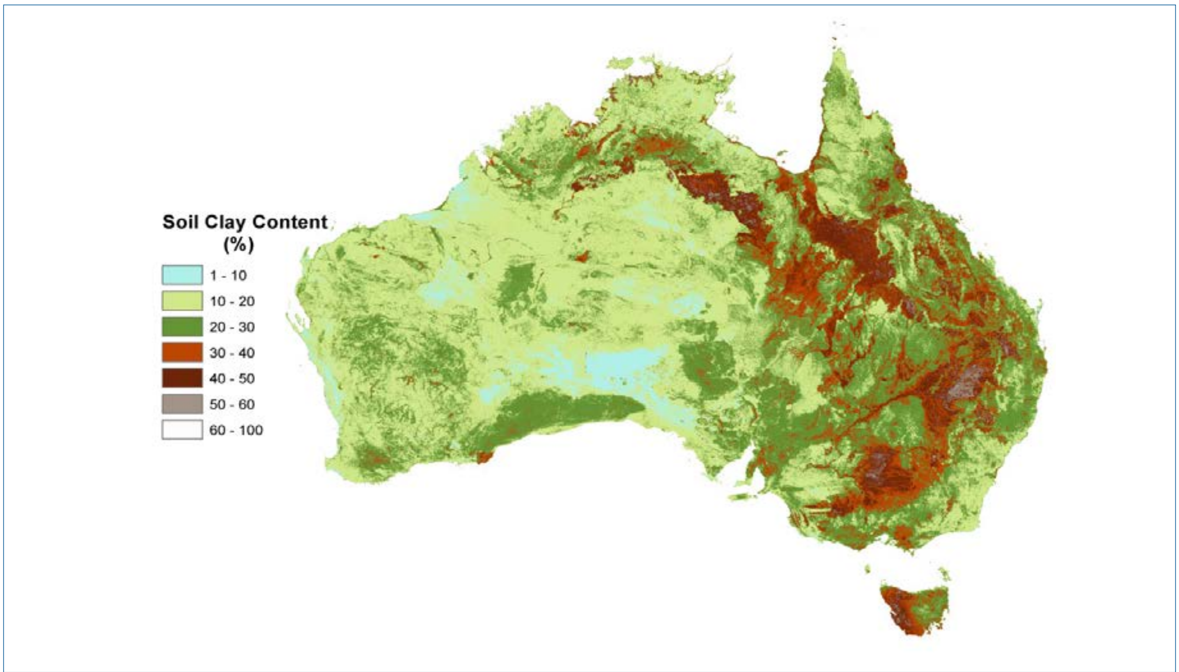


Once the spectroscopic predictions were made, the spatial modelling of the data was performed by combining the bootstrap, a decision tree with piecewise regression on environmental variables and geostatistical modelling of residuals. The spatial models were validated with an independent data set and the fine spatial resolution continental maps of the soil carbon fractions have been incorporated in *FullCAM* to ensure internal consistency of spatial soil inputs. In calculation of soil carbon fraction stocks for FullCAM, respective fractions were allocated based on the total soil carbon stock map produced by Viscarra Rossel *et al.* (2014) multiplied by the respective soil carbon fraction.

Soil clay content

A map of clay content was also developed (Figure 6.E.3) by Viscarra-Rosel *et al.* (2015). The Soil and Landscape Grid of Australia-wide Soil Attribute Maps were generated using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). The spatial modelling was performed using decision trees with piecewise linear models and kriging of residuals. Fifty environmental covariates that represent climate, biota, terrain, and soil and parent material were used in the modelling. Uncertainty was derived using a bootstrap (Monte Carlo-type) approach to derive for each pixel a probability density function (pdf), from which we derived 90% confidence limits. The approach is described in Viscarra Rossel *et al.* (2015a).

Figure 6.E.3 The Australian three-dimensional soil grid (Clay): Australia's contribution to the GlobalSoilMap project (Viscarra-Rossel, submitted)



6.E.2 Climate data

Model sensitivity testing identified that inter-annual climate variability has a significant effect on both soil (Janik *et al.* 2002) and forest (Brack and Richards, 2002) carbon stock change. The use of long-term (temporal) average and regionally (spatial) averaged climate data was shown to be inadequate to support spatially and temporally disaggregated carbon modelling, frequently generating spurious results when tested. To account for the effects of climate both spatially and temporally over the modelled period, 1970–2008, weather station data from the Bureau of Meteorology for rainfall, minimum and maximum temperature, evaporation and solar radiation were obtained. Monthly climate surfaces (maps) at 1 km resolution for each variable were then derived using the ANUCLIM (McMahon *et al.* 2000) techniques.

Raw data

Within the Bureau of Meteorology database there are approximately 1,200 weather stations recording temperature, 13,000 stations recording rainfall, 300 stations recording evaporation and 700 stations recording frost days. Precise location data were available for some 2,500 weather stations, providing a quality reference set of points from which to spatially interpolate climate surfaces. Version 2 of the 9 second (approximately 250 m resolution) national digital elevation model (AUSLIG, 2001) was used to provide terrain (elevation and aspect) mapping to support the spline functions used in the ANUCLIM software.

Derived outputs

The weather station climate data are interpolated (modelled) using mathematical (multivariate spline) functions that reflect influences on micro-climate such as elevation. Climate maps are derived at variable resolutions (grid sizes), again using the ANUCLIM software (Kesteven *et al.* 2004). The list of outputs and their resolution is shown in Table 6.E.1. Figures 6.E.4 and 6.E.5 illustrate national long-term average annual climate maps generated using the ANUCLIM software.

The surface interpolation from weather station data provides climate mapping which is both temporally (monthly) and spatially (at select resolution) relevant to the application of the *FullCAM* modelling.

Table 6.E.1 List of climate and productivity maps developed for land sector reporting in the National Inventory System

Climate Variable	Description
Rainfall	1 km resolution continentally, monthly 1968-2015
Temperature	1 km resolution min., max., and average continentally, monthly 1968-2015
Evaporation	1 km resolution continentally, monthly 1968-2015
Frost Days	1 km resolution continentally, monthly 1968-2015
Long-term productivity	250 m resolution
Annual productivity	(sum of monthly) 1 km resolution (1970–2015)

Figure 6.E.4 Long-term average annual evaporation

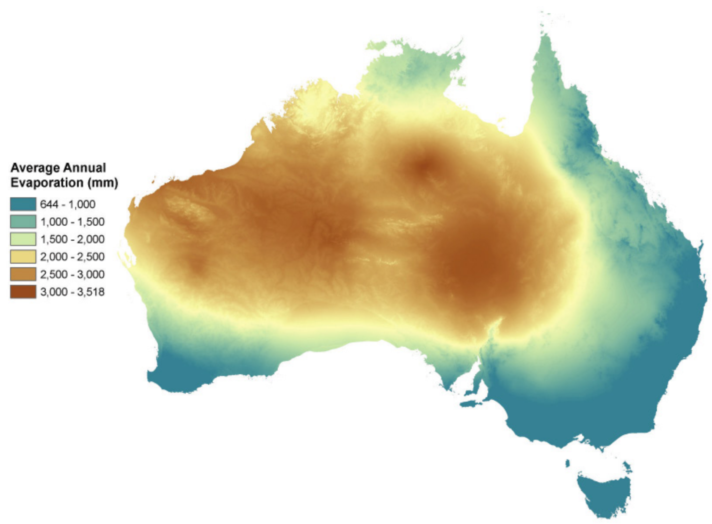
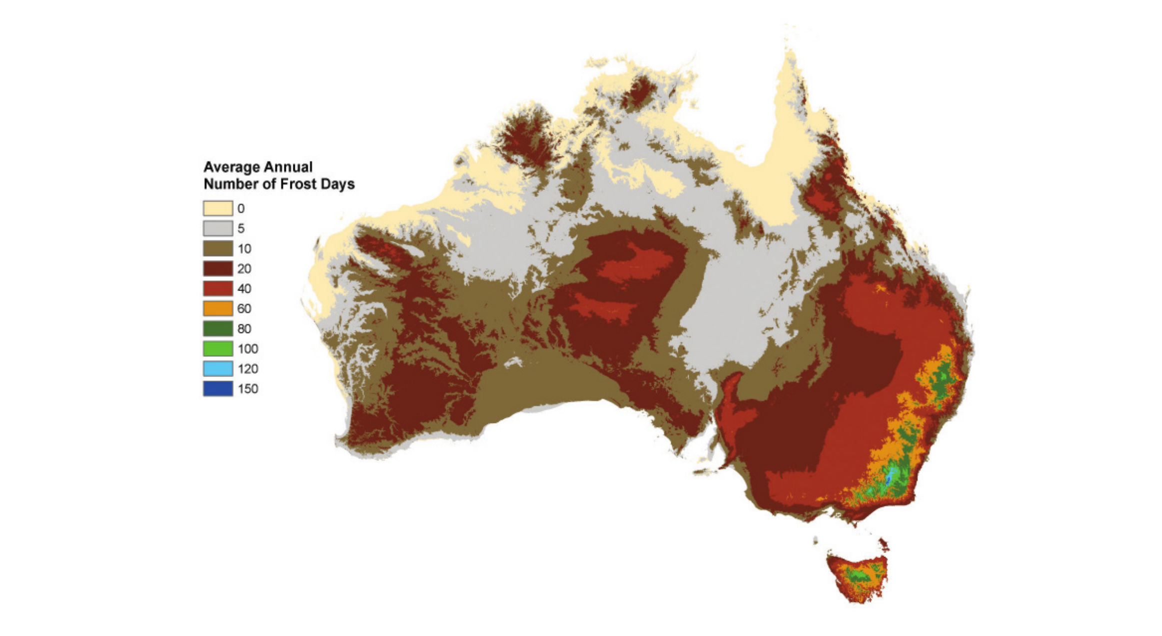


Figure 6.E.5 Long-term average number of frost days per year



6.E.3 Land use and land management

Land use and management data

Land management practices in both agriculture and forestry in Australia have varied considerably over time depending on species, region, desired products and site conditions. In 2014 the Department of Environment commissioned CSIRO to collate all available information regarding agricultural management systems to ensure a consistent, nationally available compilation of this information.

For the forest management data programme, a focus group was established comprising researchers and practitioners to give all management issues (e.g., forest and crop type, burning, harvesting and thinning) a jurisdictional (geographic) and temporal coverage. All available information was collated and supplemented with expert knowledge to give completeness where records were not available. The information gathered by these groups for use in the management databases is documented in Swift and Skjemstad (2002) and Raison and Squire (2008).

Cropping systems

For cropping systems the crop species identified by Unkovich *et al.* (2009) (section 6.B.5.1) were sourced from the Australian Bureau of Statistics agricultural census small area data in electronic format.

The collated datasets were concorded to the then new, Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (Pink 2010). All years between 1983 and 1997 were concorded to 1996 statistical local area boundaries (Australian Bureau of Statistics 2000), the 2001 at 2001 statistical local area boundaries (Australian Bureau of Statistics 2002), the 2006 at 2006 statistical local area boundaries (Australian Bureau of Statistics 2008) and for 2011 on 2011 statistical local area boundaries (Australian Bureau of Statistics 2013). This concordance ensured spatial consistency across the time series.

The datasets were used to extract the area of each of the crops listed in table 6.B.2 for each SA2 to construct a time series dataset from 1983 to 2011 to cover 99% of total crop sowing areas in each Australian State. Since the ABS has more recently (post 2001) changed from annual agricultural censuses to five yearly census, five yearly data blocks, in synchrony with the recent censuses were used to represent management epochs (Table 6.E.2).

Table 6.E.2 Agricultural census year data used to provide crop representation for five-year periods

Census Year	Applied to
1983	1970-1984
1986	1985-1989
1991	1990-1994
1996	1995-1999
2001	2000–2004
2006	2005-2009
2011	2010–2015

The year 1983 is the earliest time that data are available electronically and this is thus used to populate the time series back to the 1970 start point.

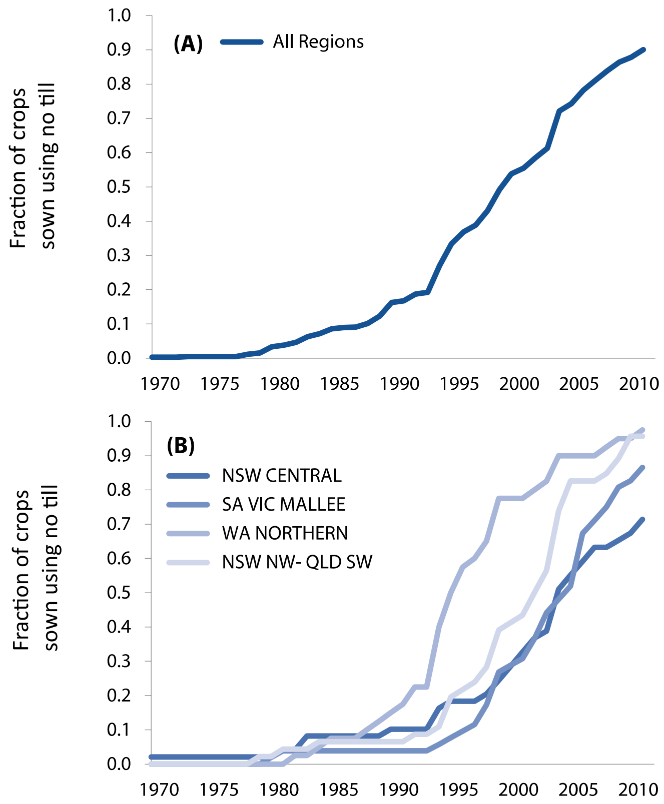
Cropping systems have evolved over time with the use herbicides to control weeds instead of tillage and sowing machinery adapted to sow into standing stubble of antecedent crops. This means that there has been a significant change over time in the extent of tillage and the incorporation of crop residues into soils which might influence carbon return to soils, carbon cycling and soil carbon stocks.

Two datasets assisted in informing these changes in management over time.

Time series data on the adoption of no till practices on a region by region basis is available through a survey in 2008 of the "Adoption of no-till cropping practices in Australian grain growing regions" (Llewellyn and D'Emden 2009; Llewellyn *et al.* 2012), and includes farmer estimates of the historical adoption of no-till seeding systems, back to 1960. This dataset is the only available resource describing the adoption of no till seeding systems across the Australian grain cropping zone on a temporal and spatial basis. This dataset, updated in 2014, provides opportunity to describe changes in the intensity of tillage on croplands over time. A second dataset, available from the Australian Bureau of Statistics, provides detailed information at SA2 scale on the management of crop stubbles in 2010–2011. Using these two data sources a time series dataset of tillage x stubble management at SA2 scale has been developed.

Details of the survey and the broad outcomes are given in Llewellyn and D'Emden (2009) and Llewellyn *et al.* (2012). The dataset provides information on the fraction crops established using "no till" seeding systems on a "regional" basis. In this case the regions were clusters of Statistical Local Areas (Trewin 2004). These regional data were used to populate an SA2 level dataset.

Figure 6.E.6 Adoption of changed tillage practices in Australia: 1970–2013

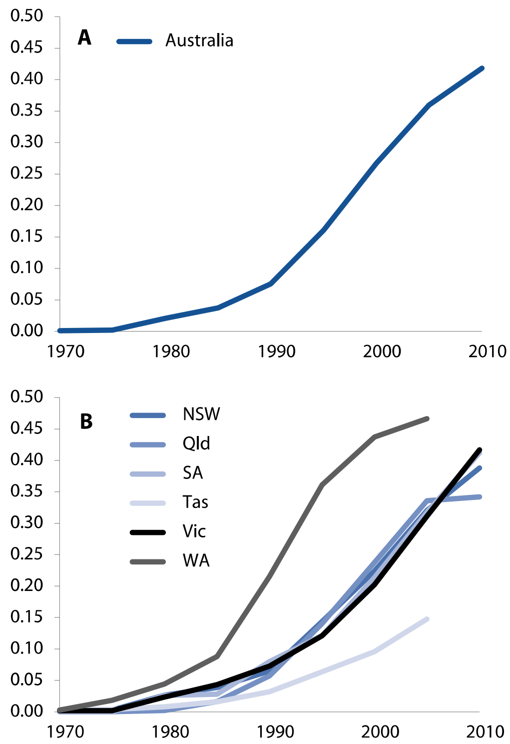


Note: Fraction of crops sown with no till (single pass) seeding technology across (A) the Australian grain belt, and (B) for four of thirteen regional areas Calculated from a revised dataset of Llewellyn *et al.* (2012).

The Llewellyn *et al.* (2012) dataset was used to produce regional scalars (0-1) describing the adoption of no till crop established from 1970 until 2010[19]. This was then applied against the 2011 ABS point census to created SA2 level data back in time. As a result the data of Figure 6.E.6 were normalised such that the value for 2010 was 1.0, and the preceding years scaled proportionately. These time series values were then applied to the 2011 ABS SA2 level census data to provide the historical no till fraction. The national and state level trends are shown to be about half that apparent in the Llewellyn *et al.* (2012) dataset.

19 When the data of Figure 6.E.6 and 6.E.7 were compared with the ABS survey of land management (2011) (ABS 2013b) it was found that the fraction of crops sown with "no till" were very much higher in the Llewellyn *et al.* (2012) dataset than that apparent in the ABS census of 2011 (ABS 2013a). This may be because the ABS census was for all cropping land, whereas the Llewellyn survey was very much skewed toward farmers who were primarily grain growers. It is likely that dedicated grain growers have larger cropping areas and invest in efficient no-till systems compared to mixed farmers or farmers with relatively small holdings. The ABS survey data was explicitly for the total area sown within an SA2.

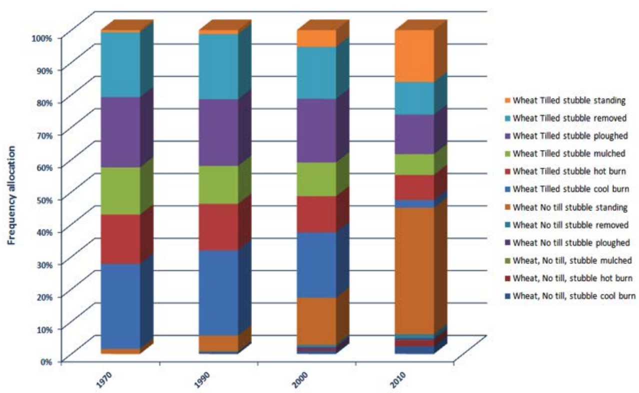
Figure 6.E.7 Adoption of changed tillage practices in Australia by state: 1970–2013



Note: Estimated fraction of crops sown with no till (single pass) seeding technology across (A) the Australian grain belt, and (B) for each of the primary Australian cropping States, calculated by scaling the 2011 ABS census data according to the data of Figure 6.E.6.

Changing management practices over time is one of the primary drivers for trends in emissions from Australian crop and pasture lands. Figure 6.E.8 illustrates the changing management practices for wheat crop species in Australia since 1970 for each epoch from Table 6.E.2. The benefit of changing management practices within the first 10 years, and diminishing returns afterwards, are a result of the soil carbon stock attempting to reach a new equilibrium. Peaks in net removals in Australia's emissions time series are attributed to changes in SOC and generally are experienced during drought conditions in which the net balance between C inputs and C losses are negatively altered.

Figure 6.E.8 Changing allocation of management practices for wheat since 1970 generated management crop management frequency database embedded in the FullCAM



One of the key operational challenges for any process-based model that simulates changes in carbon dynamics in spatio-temporal mode is to implement the changes occurring in the crop management practices over space and time related to tillage operations and stubble management within the simulation setup.

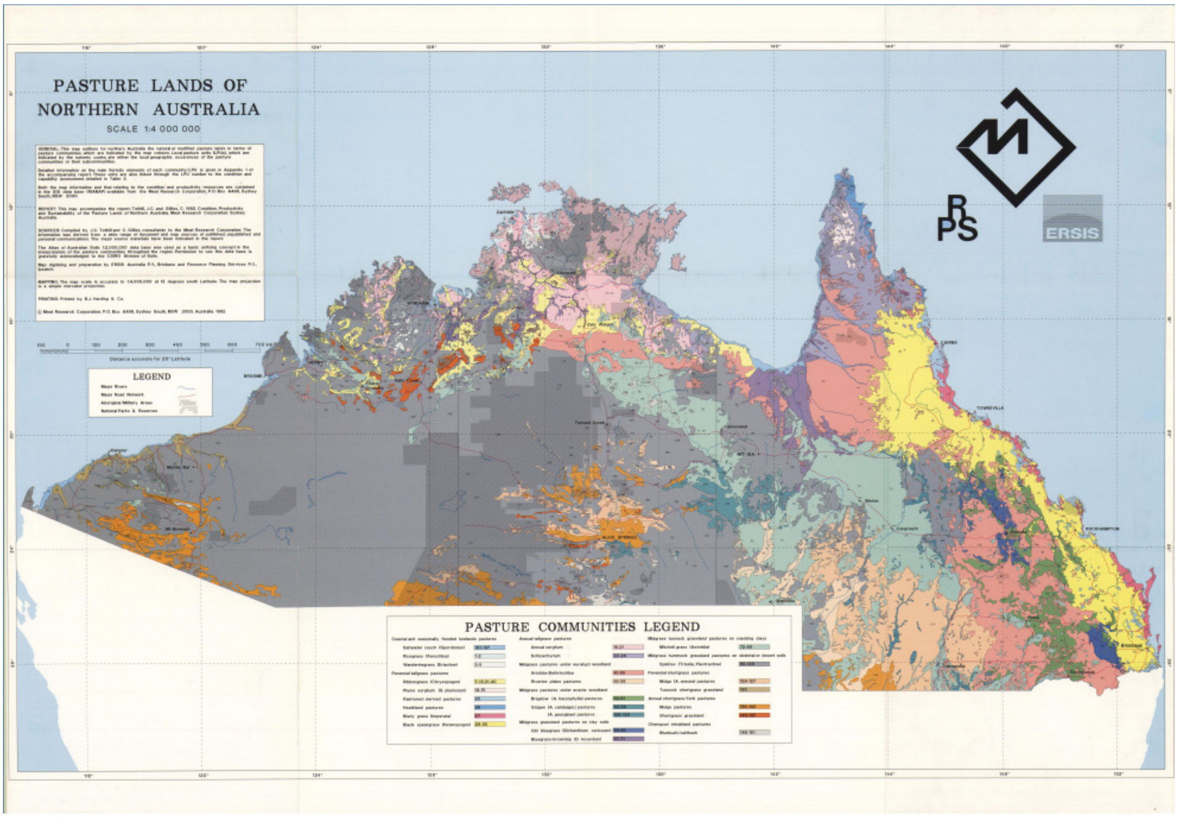
Based on the information collected by Llewellyn and D'Emden (2009) and Llewellyn *et al.* (2012) and using farmer estimates of the historical use of no-till seeding systems back to 1960 clearly shows that there is an increasing trend in adoption of no-tillage practices in Australian grain growing regions (Figure 6.E.8).

New functionality has been added to FullCAM to be able to retain a given management practice or species at the plot level based on reported Agricultural census data. Farming practices which show an increasing adoption rate are based on no-tillage practices and include stubble retention and no-till practices prior to cropping. This FullCAM functionality can also be applied at the species level and is used to simulate regions of pasturelands comprised of native grass species which have remained unchanged over time.

Grazing systems

As with the data preparation for cropping systems, the pasture species identified in Table 6.B.2 were concorded to the then new, Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (Pink 2010) (see Figure 6.E.10) and the recent ABS censuses were used to represent management epochs (Table 6.E.2). The species and management data were, however, collated from a number of sources. Grassland types in southern Australia after 2000 were sourced from Donald (2012) and, prior to 2000, were obtained from the Australian Temperate Pastures Database (Hill *et al.*, 1998). The digitised map (Figure 6.E.9) of the pasture lands of Northern Australia (Tothill and Gillies 1992) provided data for northern Australia for all years and grassland types.

Figure 6.E.9 Pasture Lands of Northern Australia

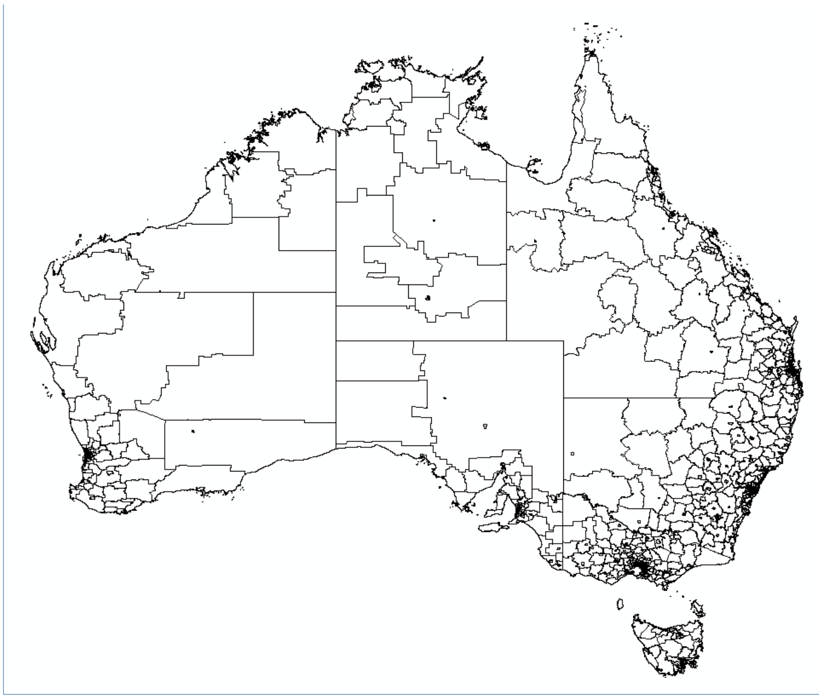


The information collected describes 527 grazing and cropping systems, with associated management practice data also held within the *FullCAM* model relational database. Table 6.E.3 provides an example of the data collected. Allocation to a land use and management system is designated according to the relative frequency of land use and management for each soil type in each SA2 region in each year. For each of these systems the key management practices, such as the use of fire, when grazing is applied (months and intensity), ploughing and herbicide treatment, were implemented in the model.

Table 6.E.3 Example land use table

SA2	Start Year	End Year	Agriculture Species	Management practice
31173	2010	2014	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 122, 10y, Grazing – Normal, 1 burn
71050	1990	1994	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 122, 2y, Grazing – Normal, 0 burns
71055	1990	1994	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 244, 2y, Grazing – Normal, 0 burns
31177	2010	2014	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 244, 5y, Grazing – Normal, 1 burn
31503	1985	1989	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 30, 1y, Grazing – Normal, 0 burns
51207	1990	1994	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 305, 2y, Grazing – Heavy, 0 burns
71068	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 305, 2y, Grazing – Normal, 0 burns
71065	2005	2009	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 305, 2y, Grazing – Very Heavy, 0 burns
71068	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 335, 10y, Grazing – Heavy, 8 burns
31406	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 335, 10y, Grazing – Normal, 8 burns
71055	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 335, 10y, Grazing – Very Heavy, 8 burns
11238	2000	2004	Barley	Barley, No till, stubble cool burn
31282	2010	2014	Barley	Barley, No till, stubble hot burn
11271	1990	1994	Barley	Barley, No till, stubble mulched
41149	1995	1999	Barley	Barley, No till, stubble ploughed
51237	2005	2009	Barley	Barley, No till, stubble removed
21100	2000	2004	Barley	Barley, No till, stubble standing
11198	2005	2009	Barley	Barley, Tilled, stubble cool burn
11175	1995	1999	Barley	Barley, Tilled, stubble hot burn
11098	2005	2009	Barley	Barley, Tilled, stubble mulched
11286	1990	1994	Barley	Barley, Tilled, stubble ploughed
41155	1990	1994	Barley	Barley, Tilled, stubble removed
61003	2010	2014	Barley	Barley, Tilled, stubble standing
31186	2010	2014	Black speargrass	Black speargrass, Estab 122, 10y, Grazing – Normal, 1 burn
31522	1995	1999	Black speargrass	Black speargrass, Estab 244, 2y, Grazing – Normal, 0 burns
31376	2000	2004	Black speargrass	Black speargrass, Estab 244, 5y, Grazing – Normal, 1 burn
31254	1985	1989	Black speargrass	Black speargrass, Estab 30, 1y, Grazing – Normal, 0 burns
71068	1990	1994	Black speargrass	Black speargrass, Estab 305, 2y, Grazing – Heavy, 0 burns
71068	1970	1984	Black speargrass	Black speargrass, Estab 305, 2y, Grazing – Normal, 0 burns
71068	2000	2004	Black speargrass	Black speargrass, Estab 305, 2y, Grazing – Very Heavy, 0 burns
71068	2005	2009	Black speargrass	Black speargrass, Estab 335, 10y, Grazing – Heavy, 8 burns
71068	1970	1984	Black speargrass	Black speargrass, Estab 335, 10y, Grazing – Normal, 8 burns
71068	2000	2004	Black speargrass	Black speargrass, Estab 335, 10y, Grazing – Very Heavy, 8 burns

Figure 6.E.10 Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (Pink 2010)



6.E.4 Crop and pasture yield

Crop/pasture growth model

FullCAM uses crop and pasture yield data in the estimation of biomass accumulation in agricultural systems. Yield data is estimated *by the CSIRO Land and Water* using a crop/pasture growth model to generate estimates based on rainfall availability during the growth period (Unkovich *et al.*. 2009). The model uses a water balance routine to estimate daily evapotranspiration, using fixed crop x region specific splits for bare soil evaporation or crop water use (transpiration) to estimate crop and pasture productivity. Two plant production modules are used, one to accommodate annual crops and pastures (Figure 6.E.11), and the other for perennial pasture systems across the continent (Figure 6.E.12). The two modules cover summer and winter grain and forage crops, sugarcane, sown and native pastures, and grass growth in rangeland ecosystems.

Figure 6.E.11 Conceptual model of annual crop growth module

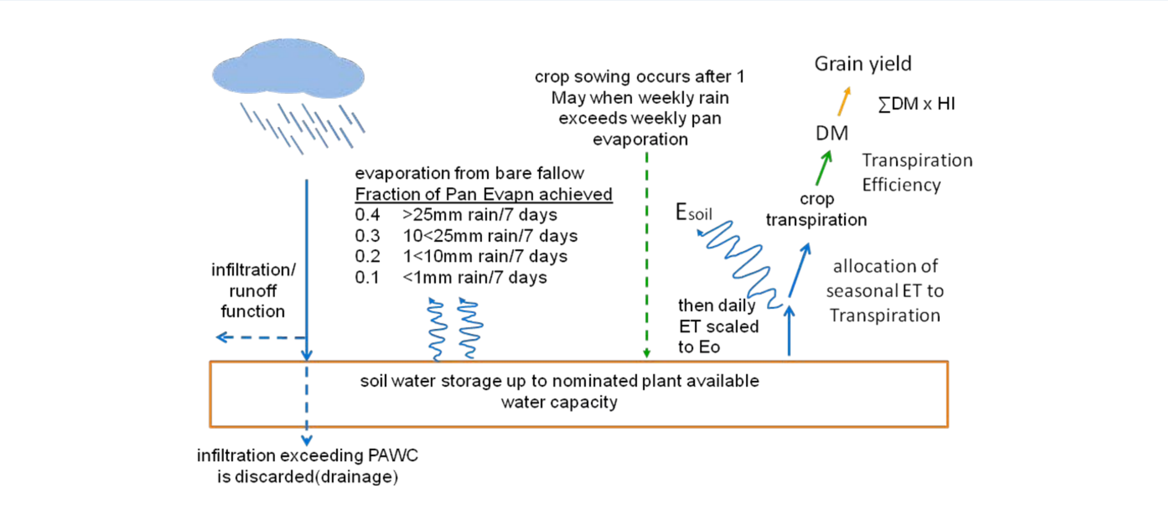
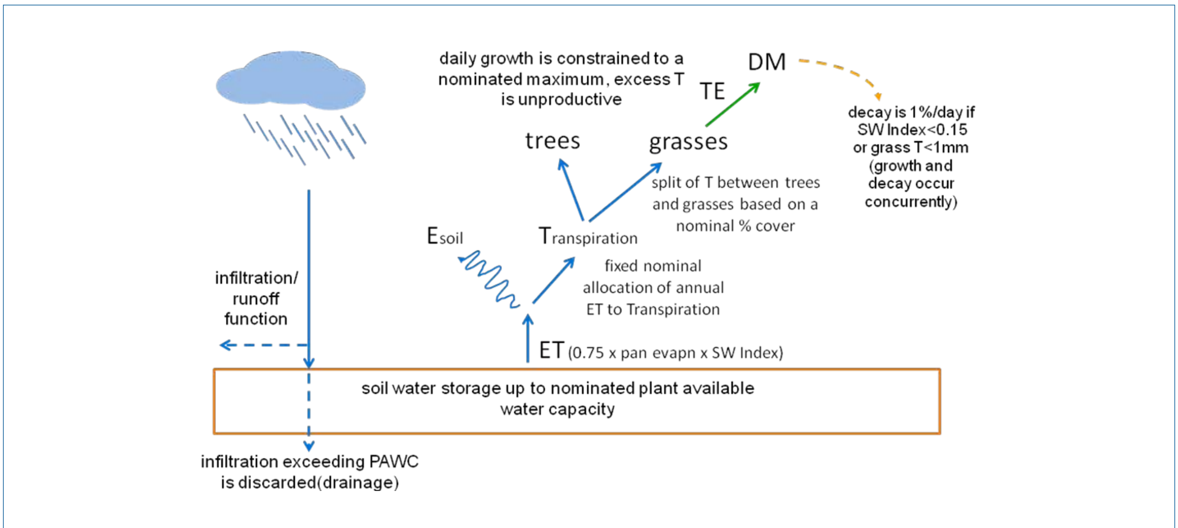


Figure 6.E.12 Conceptual model of perennial grass/pasture module



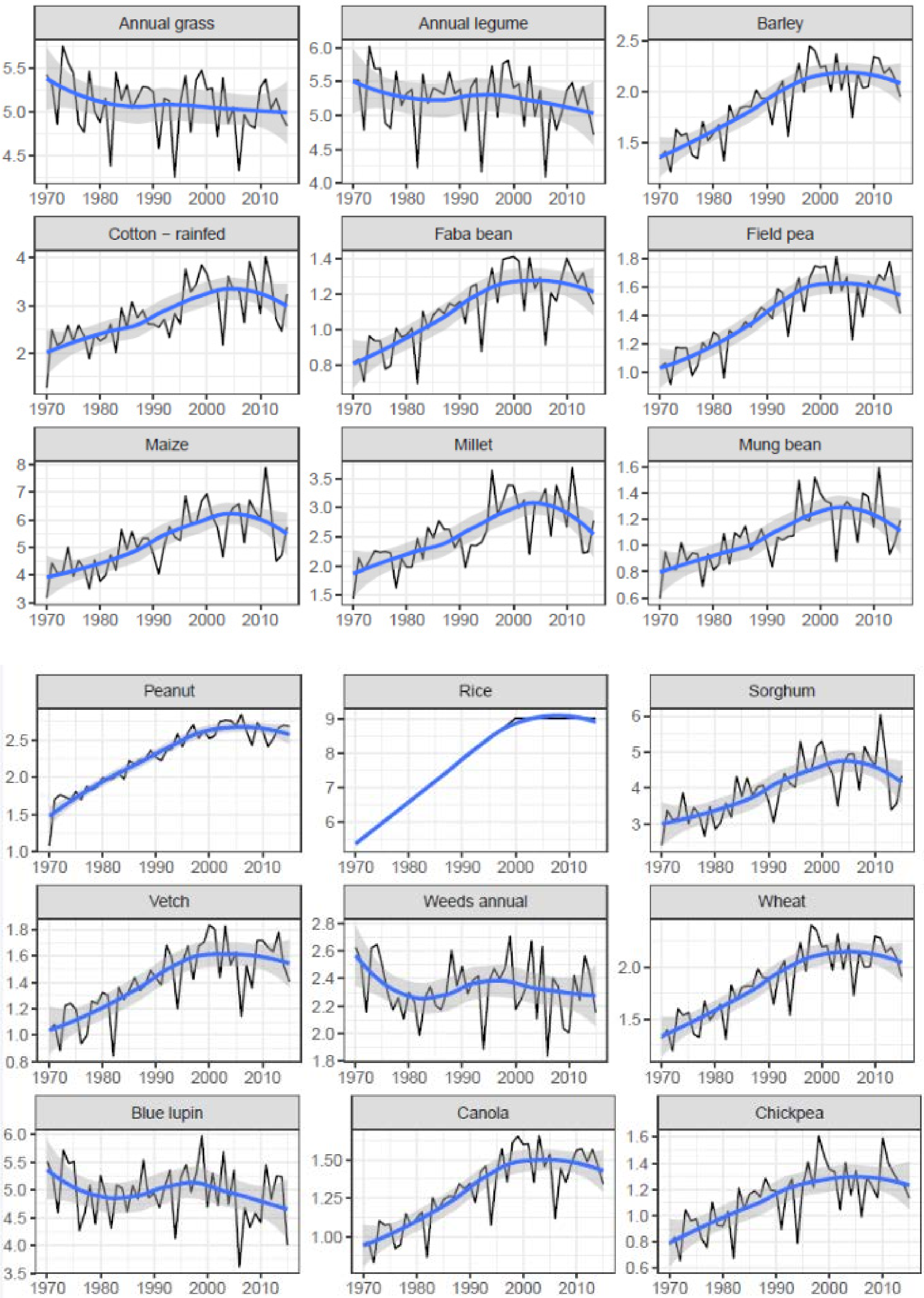
Productivity improvement trends

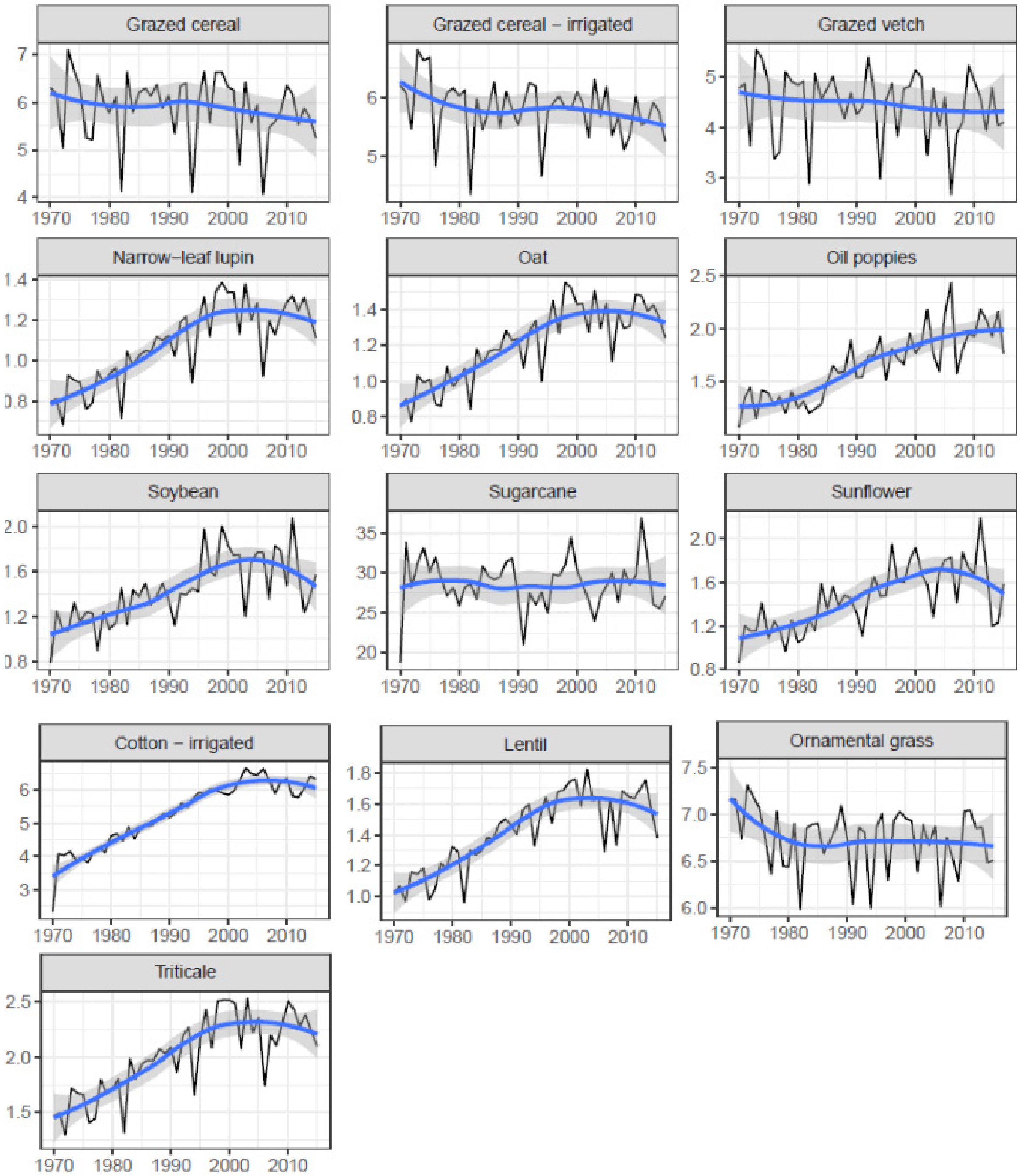
As the model of crop growth is based on recent agricultural management practices it is necessary to scale the modelled dry matter production backwards in time according to long term trends in farm crop productivity. Taking 2000 as the base year, modelled yields have been scaled, both backwards and forwards, from this time at the indicative rate (1.36% pa) for the 1970–2010 time period. While this rate of change also includes yield increases due to improvements in crop harvest index (Unkovich *et al.* 2010) these have not removed from the dry matter productivity increases because HI is currently held constant in *FullCAM*.

Yields validation in *FullCAM*

Figure 6.E.13 depicts the variation of Australia wide annual yield for major crops. The average yield shows high fluctuation due to factors such as climate while the blue line denotes the general trend of the yield for considered crops from 1970 – 2015. Annual yield data plays a major role in flow of carbon masses since this yield data is used to allocate carbon masses to different part of the plant within the *FullCAM* model, with some parts incorporated into soil over the growing period and after the harvest event. Most crops report an increasing trend starting from 1970 while showing a slight decline post 2010.

Figure 6.E.13: Australian average crop yields for crop, tonnes dry matter/ha/year, 1970-2015





Verification of the model

CSIRO has tested the model construct output against a database of crop yield data (Unkovich *et al.* 2014) and, in general (regional) testing, the modules accounted for about 50% of the variance in annual crop grain yield or of shoot dry matter of perennial pastures on any given day. In site specific tests the annual grain crop model was able to explain up to 80% of the variance in crop yield.

Annual species growth model

The annual growth model was conceived and designed to model annual crop growth. Crop growth being for a plant that is planted, grown and then harvested. This model accounts for varying growth periods given crops do not grow for the entire year. The growth modelled is a process within FullCAM of assigning the proportions of species yields generated by the CSIRO to specific time increments.

The annual growth formula is a sigmoidal curve fitted with different parameters specific to individual crops by CSIRO Agriculture and Food and aligns with the work carried out by Unkovich, (2013). The formula gives the step (or daily) fraction, which is a factor applied to yield to produce the daily portion of growth (Figure 6.E.14).

Figure 6.E.14 Exponential equation for calculating fractional daily growth for an annual crop/pasture, where the value on the numerator is equivalent to the total growth for an annual crop/pasture cycle

$$Daily\ \ fraction = \frac{1}{1+e^{\left(\frac{An\_season\_day\ \ \mathrm{sigmoidalGrowthA}*An\_\mathrm{max}\_days}{\mathrm{sigmoidalGrowthB}*An\_sow\_day*An\_\mathrm{max}\_days}\right)}}$$

Perennial species growth model

Running model simulations with perennial species under the annual growth model is unrealistic as it has no ability to simulate a constant, ongoing growth cycle. This has an impact on the fidelity of grassland simulations, producing results that are not shaped well, do not represent perennial growth closely, and produce less soil carbon capture than generally expected from a perennial grassland species.

The CSIRO has provided monthly data for perennial grass species in Australia. Combined with a perennial growth model, this data updates the method for estimating standing dry matter for perennial species within the grassland account.

Perennial species growth is derived from the use of a combination of *growth* and *die-off* and an *initial standing dry matter value* to generate a value for standing dry matter at a point in time. This creates a time series for standing dry matter that is utilised as an input in FullCAM simulations for the different perennial grass species.

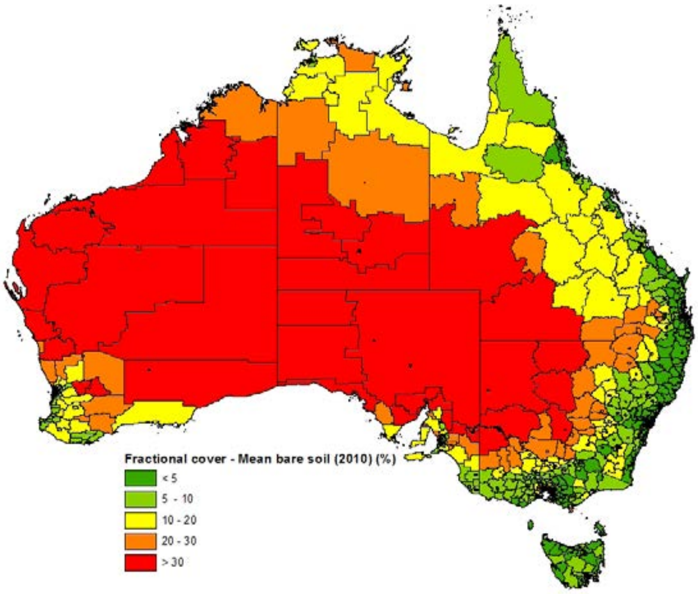
Bare soil correction of pasture lands

In generating the yield data, the CSIRO model assumes that 100% of the land area is covered by biomass. This results in an overestimation of yields.

MODIS satellite derived fractional cover data, namely "*bare soil*" fraction, is used to calculate the vegetation fraction for the grassland remaining grassland simulation in FullCAM. This correction factor is applied to adjust the biomass inputs within the spatial simulation (Geurschman *et al.* 2009).

The static correction/scale factor is used to adjust biomass inputs based on the 2010 MODIS bare soil fractional cover data (Figure 6.E.15).

Figure 6.E.15 Spatial distribution of the mean soil fractional cover data at SA2 level derived from MODIS Bare Soil Fractional cover data for year 2010.



Appendix 6.F Post-1990 Plantations – forest growth model

Forest growth model

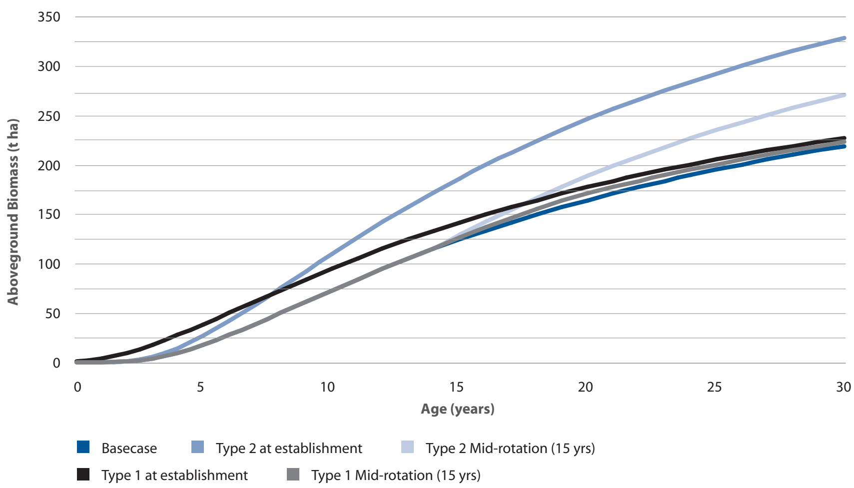
Plantations commonly produce more biomass than native forest systems in Australia, at least in the short to medium term (15-40 years). For example, Baker and Attiwill (1985) showed that *Pinus radiata* achieved 70-100% of the biomass of an 80 year old native forest, grown under similar conditions, in only 20 to 24 years. These growth differences are driven by factors such as nutrient addition, reduction in insect herbivory associated with the use of non-endemic species or through control of pests, site-specific species matching and management, and possibly greater physiological efficiency in utilising site resources by the introduced species.

The initial assumed biomass model (Appendix 6.D) and methods to estimate removals, due to regrowth post clearing, represent forest systems without significant management input and is well suited to the *forest land converted to grassland* and *cropland* sub-categories. However, in plantation systems with significant management inputs, such as fertiliser application or intensive site preparation, and species specific site matching, additional model parameters are needed to accurately estimate forest growth.

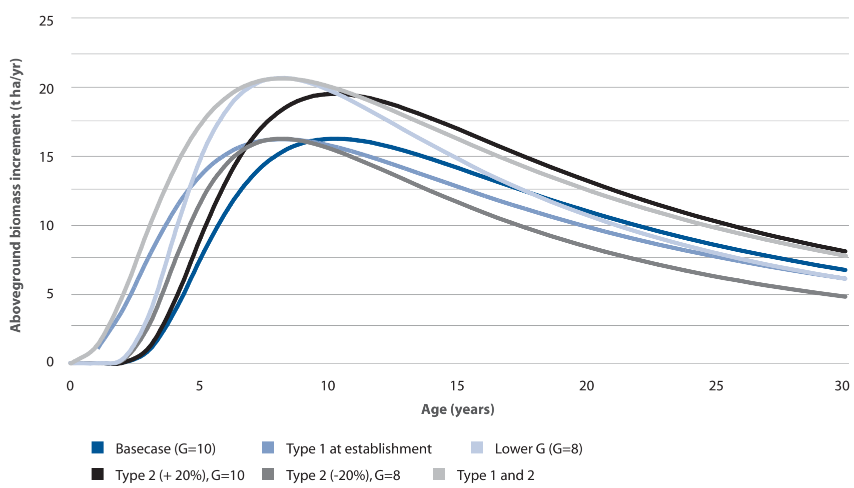
To account for the effects of management practices on growth the native forest regrowth model (the Tree Yield Formula, Appendix 6.B) is supplemented to include functions that represent Type 1 and Type 2 growth responses (Snowdon and Waring, 1984) (Figure 6.F.1). Type 1 management practices advance or retard stand development (effectively age), but do not increase underlying site productivity over the life of the rotation. Weed control at establishment, and nitrogen fertiliser application after thinning, are examples of Type 1 responses (Snowdon, 2002). Type 2 treatments increase (or decrease) a site's carrying capacity in the longer term. Phosphorus application, which in Australia can lead to long-term increase in site productivity (i.e., over several rotations) (Snowdon, 2002) is an example of a Type 2 response.

Figure 6.F.1 Effect of Type 1 and Type 2 management practices on (a) cumulative and (b) annual growth

(a)



(b)



Snowdon (2002) developed methods for including Type 1 and 2 effects in hybrid growth models. These have been implemented in the forest growth component of the *FullCAM* model. In the model, Type 1 forest treatment events are simulated by varying the developmental stage or age of the stand, moving the forest back and forth along the growth curve depending on the degree of treatment (see Equation 3). Type 2 treatments simply change the asymptote (i.e., M; see Equation 6F_4) from the time the treatment is applied. These methods lend themselves well to application in the hybrid empirical-process based structure of *FullCAM*.

A further effect that must be accounted for is the impact of establishing regionally non-endemic plantation species. This effect is expressed through a plantation species multiplier (r; see Equation 6F_1). It is similar to a Type 2 response being applied from the time a species is planted until final harvest. The r multiplier is based on the long term average Forest Productivity Index (P; see Appendix 6.C) for each point, the type of plantation established and is stratified by State and National Plantation Inventory (NPI) region (Figure 6.14). This allows the model to account for variations in growth between regions that cannot be accounted for easily from climatic and broad scale site information (e.g., Sheriff *et al.* 1996; Turner *et al.* 2001), while still accounting for the significant variation that occurs within each region due to site factors.

Calculation of r

The plantation species multiplier (*r*) was determined for each major plantation species on a regional basis. Regional long-term forest productivity index values of plantation areas in each National Plantation Inventory (NPI) region and State were determined by overlaying the long-term forest productivity index (*P*) spatial data, with areas of hardwood and softwood plantation as identified by the plantation type mapping from the remote sensing programme. The average Mean Annual Volume Increment (MAVI) data for each plantation species in each State and NPI region was obtained from Turner and James (1997), Turner and James (2002), Snowdon and James (2008) and Ferguson *et al.* (2002). The values are either based on or represent the data used in Australia's National Forest Inventory (NFI). Minimum and maximum MAVI values that are not available in the NFI data were estimated for each species and NPI region, based on Snowdon and James (2008) and the following assumptions:

- MAVI values of the NFI are the average for the region, not the most common growth rate;
- Minimum MAVI values are effectively set by commercial viability. These are generally not lower than 12 m^3 ha^{-1} yr^{-1}, (although this may vary for certain species within regions, such as Pinus pinaster in dry regions in West Australia); and
- Maximum MAVI values are unlikely to exceed 30 m^3 ha^{-1} yr^{-1} in long rotation systems and 35 m^3 ha^{-1} yr^{-1} in short rotation systems.

Environmental plantings are considered similar to regenerating native forest and assigned an *r* value of 1 (no management/species effect). The distribution of plantations according to plantation typing was mapped to the *P* data to verify that the minimum and maximum values were reasonable given the assumptions applied. For the calculation of *r*, the minimum and maximum *P* values were assumed to be the 5% and 95% of the total distribution of area for each plant type. As species is not identified in the plantation type data, where a plantation type (i.e., hardwood/softwood) consisted of different species with distinct productivity ranges (e.g., *P. pinaster* and *P. radiata* in Western Australia are both softwoods but *P. pinaster* is commonly established in low rainfall areas), the *P* for the dominant species was set values from regions with similar species and conditions, with the other species ranging from the minimum P value to the lowest P value of the dominant species. The MAVI and *P* data used for calibrating *r* are shown in Table 6.F.1.

The *r* value required to adjust the base case native forest growth model to the documented plantation MAVI growth rates and the estimated minimum and maximum MAI's for each State, NPI region and species was calculated based on assumptions of species characteristics and forest management (Equation 6F_1). As the MAVI growth data is not spatially explicit it was assumed that low *P* values represent low MAVI values and high *P* values represent high MAVI values. This is justified through the strong relationship between *P* data and native forest biomass stocks (see Appendix 6.D), and studies using the productivity data in plantation systems that show relationships between *P* and stand height and basal area, but with significant regional variation (Ford, 2004). Expansion factors at final harvest were calculated using the equations from Snowdon *et al.* (2000) and the average rotation length. While the expansion factor data show considerable variability at young ages, there is little variation in older stands, providing a high degree of certainty in these values. Species specific basic wood density values at maturity were obtained from Illic *et al.* (2000) and Polglase *et al.* (2004). Similar to the expansion factors, the range of density values decreases as the stands mature. For species in which management typically includes a thinning prior to final harvest, typically longer rotation sawlog plantations, the basic density value was reduced by 10% to account for the age-related effects and the thinned volume added to the final total harvest biomass. The percentage of maximum potential biomass achieved by final harvest was calculated based on estimates of age of maximum biomass increment, described in the next section.

Table 6.F.1 Range of FPI (P) values on which plantation types occur, the minimum, average and maximum growth rates (Mean Annual Volume Increment, $m^3\ ha^{-1}\ yr^{-1}$) and rotation length

NPI	Plantation type	Species	FPI low	FPI mean	FPI high	Min MAI	Average MAI	Max MAI	Rotation length
Western Australia	Softwood	Pinus radiata	5.0	7.0	11.2	12	20	30	30
Western Australia	Softwood	Pinus pinaster	3.8	5.5	8.0	6	11	16	35
Western Australia	Hardwood	Eucalyptus globulus SR	4.0	6.7	11.9	12	17	30	12
Western Australia	Hardwood	Eucalyptus globulus LR	5.0	7.0	11.9	12	18	27	25
Tasmania	Softwood	Pinus radiata	5.3	10.0	15.3	12	19	30	30
Tasmania	Hardwood	Eucalyptus globulus SR	6.0	11.5	15.5	14	23	30	10
Tasmania	Hardwood	Eucalyptus nitens SR	5.3	10.0	14.5	12	15	27	15
Tasmania	Hardwood	Eucalyptus nitens LR	6.0	11.5	15.5	14	19	27	25
Green Triangle	Softwood	Pinus radiata	4.8	7.4	11.5	12	21	30	35
Green Triangle	Hardwood	Eucalyptus globulus SR	4.8	7.7	11.5	12	17	27	12
Green Triangle	Hardwood	Eucalyptus globulus LR	6.0	8.2	11.5	14	20	25	25
South Australia - Lofty Block	Softwood	Pinus radiata	5.3	6.6	10.6	12	21	27	35
South Australia - Lofty Block	Hardwood	Eucalyptus globulus SR	4.3	6.5	10.4	12	17	27	12
South Australia - Lofty Block	Hardwood	Eucalyptus globulus LR	5.0	7.5	10.4	12	20	25	25
Central Victoria	Softwood	Pinus radiata	5.5	8.0	14.1	12	18	27	35
Central Victoria	Hardwood	Eucalyptus globulus SR	5.3	7.3	13.9	12	18	27	12
Central Victoria	Hardwood	Eucalyptus globulus LR	6.0	8.0	13.9	14	18	25	25
Murray Valley	Softwood	Pinus radiata	5.3	9.4	12.4	12	20	27	30
Murray Valley	Hardwood	Eucalyptus globulus SR	5.3	8.6	13.0	12	16	25	13
Murray Valley	Hardwood	Eucalyptus globulus LR	6.5	9.0	13.0	12	18	25	25
Central Gippsland	Softwood	Pinus radiata	5.9	9.0	16.6	12	20	30	30
Central Gippsland	Hardwood	Eucalyptus globulus SR	5.8	10.4	16.9	12	18	27	12
Central Gippsland	Hardwood	Eucalyptus nitens LR	7.0	13.0	16.9	12	18	27	25
Bombala-East Gippsland	Softwood	Pinus radiata	6.4	11.0	14.9	12	16	27	35
Bombala-East Gippsland	Hardwood	Eucalyptus globulus SR	6.4	9.5	15.1	12	19	27	12
Southern Tablelands	Softwood	Pinus radiata	5.1	7.0	12.4	12	16	27	30
Central Tablelands	Softwood	Pinus radiata	5.3	9.0	11.7	12	16	25	30
Northern Tablelands	Softwood	Pinus radiata	6.2	9.9	16.6	12	16	25	30
Northern Tablelands	Hardwood	Eucalyptus globulus SR	4.7	8.4	16.1	12	16	25	14
Northern Tablelands	Hardwood	Nth Coast Eucs LR	7.4	11.7	16.1	12	14	20	30
North Coast	Softwood	SouthernPines	8.1	12.5	22.3	12	15	25	30
North Coast	Softwood	Hoop pine	8.1	12.5	22.3	9	13	20	40
North Coast	Hardwood	Nth Coast Eucs SR	7.6	10.8	19.6	12	18	27	12
North Coast	Hardwood	Nth Coast Eucs LR	8.0	10.8	19.6	12	18	25	35
South East Queensland	Softwood	SouthernPines	6.3	11.1	21.2	12	13	25	30
South East Queensland	Softwood	Hoop pine	6.3	11.1	21.2	8	13.4	20	40
South East Queensland	Hardwood	Nth Coast Eucs SR	6.0	9.0	21.0	12	18	27	12
South East Queensland	Hardwood	Nth Coast Eucs LR	7.0	11.5	21.0	12	18	25	35
Northern Queensland	Softwood	SouthernPines	6.7	10.4	17.5	12	13	25	30
Northern Queensland	Softwood	Hoop pine	6.7	11.8	25.0	8	13.4	20	50
Northern Queensland	Hardwood	Nth Coast Eucs SR	6.6	10.2	20.9	12	18	27	12
Northern Queensland	Hardwood	Nth Coast Eucs LR	9.0	15.0	20.9	12	18	25	35
Northern Territory	Hardwood	Acacia	6.4	8.4	11.0	20	25	35	8
Northern Territory	Hardwood	NT eucs	6.4	8.5	11.0	8	12	20	30

r = (MAVI x Rotation Length x Basic Density x Expansion Factor) / M .... (6F_ 1)

A $\log_e$-$\log_e$ (ln-ln) model was then fitted to the r and P data by plantation type (hardwood/softwood) (Figure 6.F.2) (Equation 6F_2). Residuals were homogenously distributed. P, NPI region and rotation length (short or long) were found to be significant effects. A separate model based on state was also developed using the same regression to allow predictions for the small area (< 5%) of hardwood and softwood plantations identified outside the NPI regions. There was no significant interaction between NPI and rotation length and no apparent bias in the results.

$\ln(r) = b_0 + b_1 * \mathrm{Ln}(Pav)$ .... (6F_2)

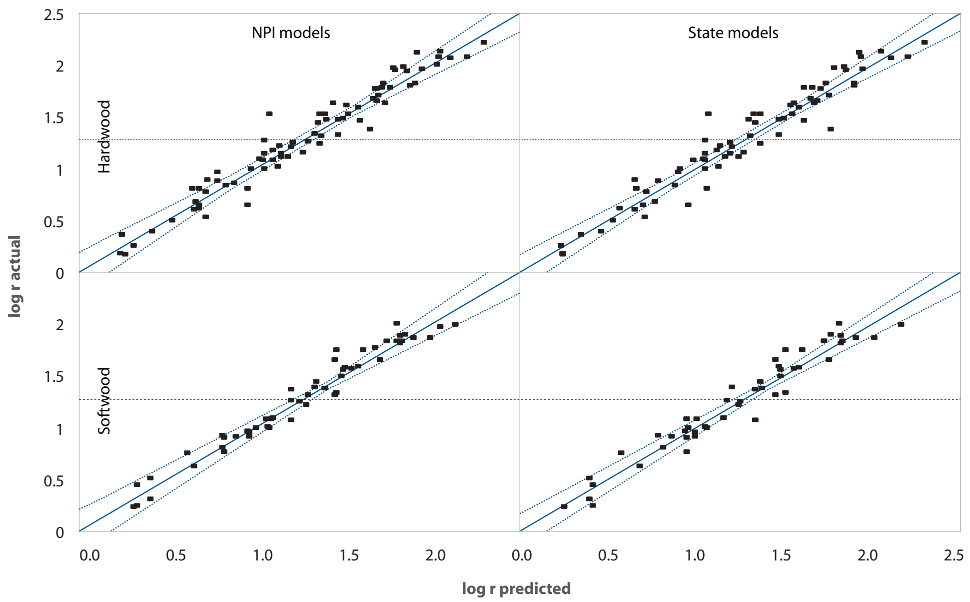
Where r = non-endemic species multiplier

b_0 = value based on NPI region and rotation length (long or short)

b_1 = value based on if the plantation occurs in an NPI region or a state.

P = *long-term average FPI value.*

Figure 6.F.2 Actual vs predicted r values for hardwood and softwood plantations by State and NPI



The analysis showed that plantation forests established on sites with high P values require lower r values than those on sites with lower P values. This was expected, as plantations on low quality sites will often respond better, in percentage response, to good site preparation methods and adequate fertilizer addition (Turner, 1984; Snowdon and James, 2008), leading to a more 'even' range of carbon uptake rates compared with native systems.

The age of maximum biomass increment

The age and magnitude of maximum current annual biomass increment (Max I_B) varies with species, site productivity and management. The age of Max I_B is not typically reported in forest growth studies as it generally occurs before the age of first commercial thinning when direct measurements of stem volume are less commercially important and, hence, less frequent. However, it is generally considered that the age of Max I_B occurs at or around the time of canopy closure (Gower *et al.* 1994; Ryan *et al.* 1997; Law *et al.* 2003). For the purpose of calibrating the model this was assumed to be the case.

In addition to underlying site conditions (soils and climate), fertilisation and improvements in establishment techniques over the past 30 years have reduced the age of canopy closure and promoted early growth in long-rotation plantation systems (Boomsma and Hunter, 1990; Snowdon and James, 2008). Management systems which aim for high biomass outputs with a lower concern for stemwood quality and form (i.e., short rotation pulpwood plantations) will also tend to lower the age of maximum biomass increment through high stocking rates and more intensive initial management.

In *FullCAM* the age of maximum biomass increment can be modified through direct manipulation of G or through applying Type 1 effects prior to G (see Appendix 6.B; Equation 6F_5). Varying G affects both the age and magnitude of Max I_B. Where a Type 1 response is applied prior to G (i.e. between ages 0 and G), the effective age of Max I_B is lowered without affecting the magnitude of growth. The majority of management effects on early age growth, such as weed control and good site establishment methods, are modelled by applying Type 1 effects at planting. This also provides extra flexibility in adjusting stand growth based on specific management regimes. Hence, the unaffected *G* value (i.e., that with little or no management) can be calculated based on the actual age of Max I_B and the sum of Type 1 effects on early age growth due to management (Equation 6F_3):

$$G = G_{man} + T1_{pre\text{-}g} \quad \text{(6F\_ 3)}$$

Where G_{man} = age of maximum biomass increment with management

G = age of maximum biomass increment assuming no management

$T1_{pre\text{-}g}$ = sum of the Type 1 age advance events applied prior to *G*

For native ecosystems an age of maximum current annual growth increment (CAI) of ten years is applied. Many commercial plantations are managed for aggressive early growth that shortens the period to harvest. This is most evident in short rotation (approximately ten year) pulpwood plantations. Silviculture, in particular a dense stocking rate of trees per hectare, is used to supply this early growth. In some instances this can bring the age of maximum current annual increment to being as low as 2-3 years after establishment. Each plantation type/management regime combination is assigned a specific age of maximum current annual increment based on location.

Calibration of G

Values for G were calibrated for each species within each NPI region based on rotation length and the approximate sum of Type 1 effects at planting. Canopy closure (effectively G_{man} in the model) in *P. radiata* plantations established over the last 20 years generally occurs between the ages of seven and 12 years depending on site quality and management (Snowdon and James 2008). On poor quality sites with little management or site improvement it may take even longer. Improved establishment and early age management practices adopted in the last 20 to 30 years, in particular after the late 1970's, have reduced the age of canopy closure by about two to three years (Boomsma and Hunter, 1990; Snowdon and James, 2008) and were modelled as Type 1 effects. Equation (6F_4) was calibrated based on 'unaffected stands' by adding 2 years of Type 1 effect to the current age of canopy closure (Equation 6F_3), resulting in a range of nine to 14 years for *G*. Regionally specific data for *G* and G_{man} was not available so this range was applied for all long rotation systems. However G_{man} DEs vary by region and time depending on management practices. Long-rotation eucalypt plantations are still relatively uncommon and little is known about their future management and prospects. Given the paucity of data it was assumed that long-rotation eucalypt plantations are similar in management to other long rotation systems, although they may reach canopy closure slightly earlier depending on growth conditions, as discussed below. To account for the effect of site productivity on *G* a simple linear relationship between *G* and *M* was included (Equation 6F_4). The results of the calibration are shown in Waterworth *et al.* (2007).

Canopy closure tends to occur much earlier in short rotation plantations due to species characteristics, higher stocking rates, more intensive management and better site/species matching. *Eucalyptus* species tend to reach canopy closure much more quickly than *Pinus* species given suitable conditions, and hence increase in mass much faster during the early stages of development (Myers *et al.* 1996). Therefore G for short rotation plantations was set 2 to 3 years earlier than for long rotation systems.

Final model form used for post-1990 plantations

$$G = s \times M + c \quad \text{(6F\_ 4)}$$

Where G = age of maximum biomass increment of unaffected stand

s = multiplier to account for site productivity

M = unadjusted maximum biomass value

c = region/species dependant intercept

The modified tree yield formula that is used to calculate forest growth for the post-1990 *plantations* sub-category is therefore:

$$I_a = r \times M \times ((y_2 \times e^{-k/d}) - (y_1 \times e^{-k/d-1})) \times (P/P_{av}) \quad \text{(6F- 5)}$$

Where I_a =Aboveground mass increment of the trees, in t DM ha^{-1}

a = Age of trees

r = non-endemic species multiplier

M = maximum aboveground biomass (calculated from P)

y_1 =Type 2 site multiplier at age, a

y_2 = Type 2 site multiplier at age, a-1

$k = 2 * G$

Where, G = Tree age of maximum growth

d = Adjusted age of the trees, in years

= a + sum over each treatment of

0	if a <= W
v * (a – W) / U	if a >= W and a <= W + V
v	if a > W +U

Where, *for each Type 1 treatment,*

v = the age advance due to the treatment, either positive or negative, in years

U = the advancement period, in years

W = the age, a, at which the treatment was applied, in years.

P= the actual FPI over the period d_a to d_{a-1}

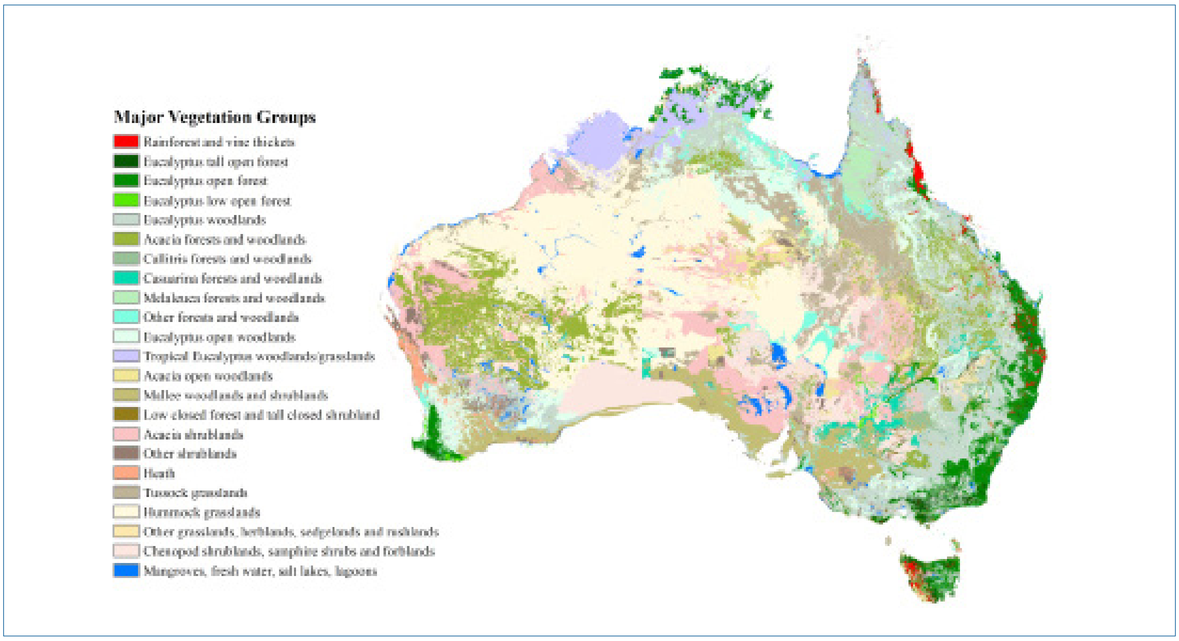
P_{av} =Long term average FPI value

Appendix 6.G Major vegetation groupings classified by the national vegetation information system

The Major Vegetation Groups (MVG) (Figure 6.G.1) are used to specify the biomass allocations of *forest land converted to cropland* or *grassland*. In addition, the MVG are used to spatially disaggregate the land included in the *forest land converted to cropland* or *grassland* classifications in the CRF tables.

The National Vegetation Information System (NVIS, see NLWRA, 2001) provides a composite of the best available vegetation mapping in Australia. For the *forest land converted to cropland* and *forest land converted to grassland* category, various forest characteristics (e.g., forest floor coarse woody debris and litter) are associated with the forest types extracted from the NVIS. The NVIS collates and provides, in a consistent taxonomy and classification, the best available vegetation maps from all available sources. For the purposes of carbon accounting the Level III MVG categories were applied. These vegetation types are described in below.

Figure 6.G.1 Major vegetation groups (MVG)



In addition to the 'current' vegetation mapping which represents a composite of recently collected data, the NVIS also modelled forest distributions to infer a pre-European settlement (i.e., pre 1770) vegetation map. Some of the land clearing identified by Australia's land cover change programme pre-dated the current vegetation mapping (which was generally based on data from 1990 onwards). This meant that areas identified as cleared land in the NVIS could have been forested between 1972 and the date used in the NVIS mapping. In these instances, the vegetation type allocation was drawn from the 1770 modelled (inferred) vegetation map.

Group 1. Rainforest and vine thickets

Rainforest communities in Australia are mostly confined to the wet and cooler areas or climatic refuges in eastern Australia, apart from the semi-evergreen vine thickets of the Brigalow Belt and the monsoonal vine thickets that are found in the tropics in Western Australia and the Northern Territory. Community types include cool temperate rainforest, sub-tropical rainforest, tropical rainforest, vine thickets, and semi-deciduous and deciduous vine thickets. Rainforests were cleared extensively in the late 19th or early 20th centuries for high value timbers, dairying, tobacco/sugar cane or other agricultural production. The best known examples of this are the "Big Scrubs" of Illawarra and northern New South Wales and the Atherton Tableland in north Queensland.

Group 2. Eucalyptus tall open forest

These communities are restricted to all but the wetter areas of eastern Australia from the margins of the wet tropical rainforests of north Queensland to Tasmania, and the south west of Western Australia, often in rugged mountainous areas. At their maximum development in Tasmania and parts of Victoria, they contain the world's tallest flowering plants, with some trees rising to heights in excess of 100 m. These communities are typified by a well-developed often broad-leaved shrubby understorey or sometimes tree ferns and are mostly found adjacent to, or in association with, rainforest communities. Extensive areas of these communities were cleared for agriculture and grazing early in the 20th century, particularly where they occurred in association with rainforests. Major areas remain today in crown reserves as State Forests or National Parks.

Group 3. Eucalyptus open forest

This group is widespread along the sub-coastal plains, foothills and ranges of the Great Dividing Range in eastern Australia and the sub-coastal ranges of the south west of Western Australia. Generally this group has a shrubby understorey which is low to moderate in height, but in drier sites they may have a grassy understorey with scattered shrubs and/or cycads. There has been widespread clearing of these communities for grazing and agriculture in the major agricultural zones of eastern Australia and the south west of Western Australia. The rate of clearing in these communities by the early 20th century saw the development of crown reserves for the protection of forests, either as national parks or as production forests, and the establishment of forestry departments within several jurisdictions.

Group 4. Eucalyptus low open forest

This group contains a series of montane communities of the Great Dividing Range such as Snow Gum, Red Stringybark and Scribbly Gum, and the drier Jarrah communities in the south west of Western Australia. Extensive areas of these communities have been cleared principally for grazing.

Group 5. Eucalyptus woodland

This group is widespread throughout the mountain ranges and plains west of the divide in Eastern Australia and east of the sub-coastal ranges of south west Western Australia. This group includes a series of communities, which have come to typify inland Australia. For example the box (poplar box, white box, yellow box etc.) and ironbark woodlands of eastern Australia are included in this group. The Eucalyptus woodlands have been extensively cleared and modified, particularly in the agricultural zones of eastern Australia and in south west Western Australia. In many regions only small isolated fragments remain today, in many instances found only along creeks and road verges.

Group 6. Acacia forest and woodland

Brigalow (*Acacia harpohylla*) and Mulga (*A. aneura*) dominate this group with mulga covering large parts of the arid interior of the continent. A series of other acacias such as Lancewood (*A. shirelyii*) and Myall (*A. pendula*) are also included. Mulga is one of the most widespread species on the continent, occurring on a series of forest, woodland and shrubland communities. The Mulga and Brigalow communities of eastern Australia have been extensively cleared for grazing and agriculture and in many regions only scattered remnants are found today. Mulga communities in the arid interior have not been subject to clearing to the same degree but many areas have been subject to modification by grazing pressures from cattle/sheep and feral animals, and increased macropod populations supported by the increased availability of water from bores.

Group 7. Callitris forest and woodland

Cypress Pine forests are found mostly in a series of discrete regions, notably in the Brigalow Belt, but also in the arid areas in South Australia and in association with mallee communities near the South Australia – Victoria border. Extensive areas have been cleared for grazing in the Brigalow Belt and in the Mallee bio regions in particular, but major areas are included in State Forests and other crown reserves in Queensland and New South Wales.

Group 8. Casuarina forest and woodland

Containing both Casuarina and Allocasuarina genera, these occur in a series of quite distinct communities, notably foredune (*C. equisetifolia*) communities, swamp (*C. glauca*) communities, riverine (*C. cunninghamiana*) and desert (*C. cristata*) communities. These communities have been extensively cleared in many coastal areas for agriculture, or for industrial uses or urban developments. Areas in the arid zone are subject to modification by grazing of domestic stock and from feral herbivores.

Group 9. Melaleuca forest and woodland

These cover substantial areas in the tropical north, but are also found in temperate climates most often in or adjoining coastal or montane wetlands. These communities have been extensively cleared in many coastal areas for agriculture or housing near major cities. Extensive areas remain in the tropical north, in particular southern Cape York Peninsula.

Group 10. Other forest and woodland

This is a diverse group of communities, some of which such as Banksia woodland are comparatively restricted in their extent, but may be locally abundant. It also includes a series of mixed communities of the arid zone, which are not dominated by any particular species. These communities have been extensively cleared in many coastal areas for agriculture or urban uses. Extensive areas remain in the arid zone but are subject to modification by grazing of domestic stock and from feral herbivores.

Group 11. Eucalyptus open woodland

These cover extensive areas of the arid zone or drier tropical north mostly with a shrubby or grassy ground layer. Little of this group has been cleared. Many areas have been subject to modification by grazing of domestic stock and from feral herbivores.

Group 12. Tropical eucalyptus woodland/grassland

This group contains the so-called tall bunch-grass savannas of north Western Australia and related Eucalyptus woodland and Eucalyptus open woodland communities in the Northern Territory and in far north Queensland, including Cape York Peninsula. They are typified by the presence of a suite of tall annual grasses, notably Sorghum spp, but do not include communities in more arid sites where *Triodia spp* becomes more dominant. The fundamental difference between how Western Australia and the Northern Territory and Queensland describe these vegetation communities, necessitated their separation into a separate MVG.

Group 13. Acacia open woodland

These also cover extensive areas of the arid zone or drier tropical north mostly with a shrubby or grassy ground layer such as Blue Grass (*Dicanthium sericeum*). Eucalyptus species such as the Yapunyah (*E. thozetiana*) may also be present. Little of this group has been cleared but many areas have been subject to modification by grazing of domestic stock and from feral herbivores.

Group 14. Mallee woodland and shrubland

Multi-stemmed eucalyptus trees in association with a broad range of other shrubs or grasses cover extensive areas of the southern arid zone from Victoria to the south west of Western Australia. The mallee communities in Victoria and parts of South Australia have been extensively cleared, with only isolated remnants remaining in some areas, but these communities are still widespread in the arid zone of South Australia and Western Australia. These are subject to modification by grazing of domestic stock and from feral herbivores.

Group 15. Low closed forest and closed shrubland

These dense communities are found mostly in coastal environments, for example Kunzea and Leptospermum scrubs, or sub-coastal plains e.g., Banksia scrubs, and can cover significant areas. They also occur in rugged mountainous areas, such as sub-alpine areas in Tasmania. They have been extensively cleared in many coastal areas for agriculture or urban development.

Group 16. Acacia shrubland

Mulga, Gidgee and mixed species communities of the central Australian deserts dominate this group, but it also includes a series of other desert acacia communities. Little of this group has been cleared outside of the major agricultural zones, but they have been subject to modification by grazing from domestic stock and from feral herbivores.

Group 17. Other shrubland

This is a diverse group containing a series of communities dominated mainly by genera from the Mrytaceae family. Kunzea, Leptospermum and Melaleuca shrublands are important component of this group, but it also includes a suite of mixed arid zone communities and other communities dominated by typical inland genera such as Eremophila and Senna. This group has been extensively cleared in the agricultural regions and in coastal areas adjoining major cities. In the arid zone, little of this group has been cleared but many areas have been subject to modification by grazing of domestic stock and from feral herbivores.

Group 18. Heath

This group includes the stunted (< 1 m tall) vegetation of the coastal sand masses, typified by the family Epacridaceae and also other dense low shrublands in sub-coastal or inland environments, mostly on drainage impeded soils or natural hollows or depressions. The communities have been cleared for sand mining, agriculture and urban development.

Group 19. Tussock grassland

This group contains a broad range of native grasslands from the Blue Grass and Mitchell Grass communities in the far north to the temperate grasslands of Southern New South Wales, Victoria and Tasmania. The group contains many widespread genera including Aristida, Astrebla, Austrodanthonia, Austrostipa, Crysopogon, Dichanthium, Enneapogon, Eragrostis, Eriachne, Heteropogon, Poa, Themeda, Sorghum and Zygochloa and many mixed species communities. Extensive areas of this group have been cleared and replaced by exotic pasture species and most other areas have been subject to modification by grazing, weed invasion and land management practices associated with grazing domestic stock, such as frequent fire and the application of fertilisers.

Group 20. Hummock grassland

The spinifex (*Triodia spp.* and *Plechrachne spp.*) communities of the arid lands are quintessential to the Australian outback. These cover extensive areas of the continent either as the dominant growth form with the occasional emergent shrub or small tree (either acacia or eucalypt). They are also a conspicuous element of other communities such as open woodlands. Little of this group has been cleared but many areas have been subject to modification by grazing of domestic stock and from feral herbivores.

Group 21. Other grassland, herbland, sedgeland and rushland

This diverse group contains a series of communities, some of which are restricted within the landscape, some of which occur as mosaics and others that are otherwise too small or diffuse across the landscape to be easily discerned at a continental scale.

Group 22. Chenopod shrub, samphire shrub and forbland

The chenopods such as Saltbush (*Atriplex spp.*) and Bluebush (*Maireana spp.*), cover extensive areas of the arid interior on saline soils. They are also associated with the ephemeral salt lakes of these arid areas, often in association with samphires such as *Halosarcia* species. Similarly, some forbland communities contain a mix of species including samphires and chenopods. Other forblands containing Asteraceae species are found in Queensland.

Group 23. Mangrove, tidal mudflat, samphire, claypan, salt lakes, bare areas, sand, rock, lagoons and freshwater lakes

Mangroves vary from extensive tall closed forest communities on Cape York Peninsula to low closed forests or shrublands in southern regions. Samphires are found in the coastal mudflats and marine plains, adjoining mangrove areas in many instances, but they also cover extensive marine plains inland from the southern Gulf of Carpentaria and other parts of the tropical north. In the harsh environments of the arid interior extensive areas devoid of vegetation can be found as bare ground, either sand dune, claypan or salt lakes. Similarly, the coastal sand masses can often contain extensive areas of bare sands, mostly as active dunes. In mountainous areas, large areas of bare rock or scree may be a feature of the landscape. This is particularly the case where large rocky outcrops dominate the landscape, such as Uluru and the Olgas in central Australia, Bald Rock in northern New South Wales and many examples of large monadnocks in the south west of Western Australia. There can be widespread clearing or infilling of mangroves and tidal mudflats in coastal areas near urban major centres for industrial uses or urban developments.

Appendix 6.H Tier 2 forest conversion model

Forest land converted to cropland and *grassland* emissions estimates are based on the Tier 3 Approach 3 model and national time-series of Landsat satellite data. Verification of the use of the Tier 3 model to estimate emissions from this sub-category was performed through comparison with a Tier 2, Approach 2 method. The Tier 2 model was developed as an excel spreadsheet model. This model formed the basis for reporting emissions prior to the implementation of the Tier 3, Approach 3 methods and has been subsequently enhanced. The Tier 2 model is used to estimate changes in biomass from the conversion of 'mature' forest, the regrowth of forest on previously cleared land, the growth of crops and grasses on cleared land, and the subsequent re-clearing of a proportion of this regrowth.

The model also calculates changes in the dead organic matter (DOM) and soil pools and emissions (CO_2 and non-CO_2) associated with burning.

The annual area converted or re-cleared (activity data) were the same as those used as input to the Tier 3 model for Forest land converted to Cropland and Grassland.

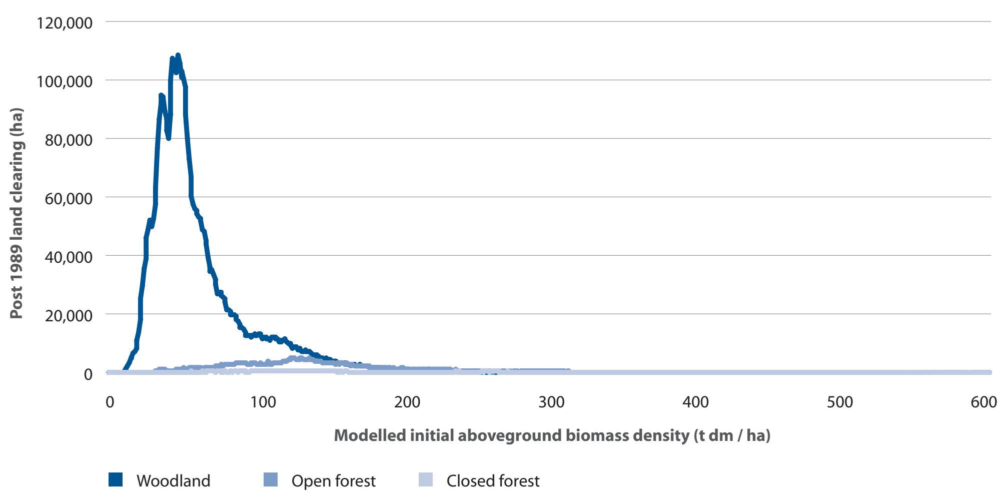
In the Tier 2 model land clearing is stratified into three broad forest classes:

- closed (tropical forest);
- open (predominantly eucalypt forest); and
- woodland forest

This stratification was undertaken by overlaying the areas cleared from the remote sensing analysis on the major vegetation groups of the National Vegetation Information System (NVIS; see Appendix 6.G).

Figure 6.H.1 shows that the majority of land clearing since 1989 has occurred in woodland forests. This information was used in the Tier 2 model to allocate the area cleared in each year to clearing of woodland, open forest and closed forest (Table 6.H.1).

Figure 6.H.1 Initial assumed biomass of land cleared post-1989 which has entered Australia's deforestation accounts



Carbon pools

Biomass – aboveground and below ground trees

To determine the biomass of each forest class that is used in the Tier 2 model, analysis was undertaken of the initial assumed above ground biomass of the lands that are within Australia's deforestation account. To undertake this analysis the simulated cells layer for lands within the deforestation account were intersected with the initial assumed above ground biomass surface. Table 6.H.1shows the results of this analysis. The estimates are expressed as averages within three forest types – closed forest, open forest and woodland. The area converted from forest land to cropland and grassland areas were allocated to the three forest types by matching their locations to the locations of Australia's major vegetation groups.

Table 6.H.1 Tier 2 forest coefficients used to estimate emissions and removals from first time forest clearing

	Closed Forest	Open Forest	Woodland Forest
Proportion of annual clearing (%)	2	10	88
Initial biomass of forests(a)(b) (t dm ha^{-1})	198.7	152.8	67.6
Root : shoot ratio	0.25	0.25	0.40
Debris onsite mass(b) (t dm ha^{-1})	100	75	50
Initial soil carbon (t C ha^{-1})	70	73	60
Proportion of area subject to forest regrowth (%)	25	25	25

(a) Aboveground biomass.
(b) Used for all States and Territories.

Areas of previously cleared land that re-grew to forest are assumed to achieve their original biomass in 25 years. The biomass of forest subject to reclearing is 32% of the mature biomass.

Biomass – above ground and below ground herbaceous species

Sequestration associated with the growth of crop and grass species is included in the model on land which is not subject to forest regrowth. Table 6.H.2 provides the biomass increment parameters applied to estimate this variable. These parameters are multiplied by the total area of clearing recorded each year to estimate the biomass accumulated by crop and grass species on cleared land.

Table 6.H.2 Biomass accumulated by crop and grass species on cleared land

	Crops	Grasses
Proportion of cleared land (%)	15	60
Above ground mass, including debris (tdm ha-1)	4.0	4.2
Root : shoot ratio	0.5	0.5

Dead organic matter

The forest debris onsite prior to forest clearing is presented in Table 6.H.1. Debris associated with crops and grasses is included with living biomass (Table 6.H.2). Forest debris, including initial debris and debris remaining after forest conversion, was assumed to decay over a period of 10 years (IPCC, 2003).

Soil carbon

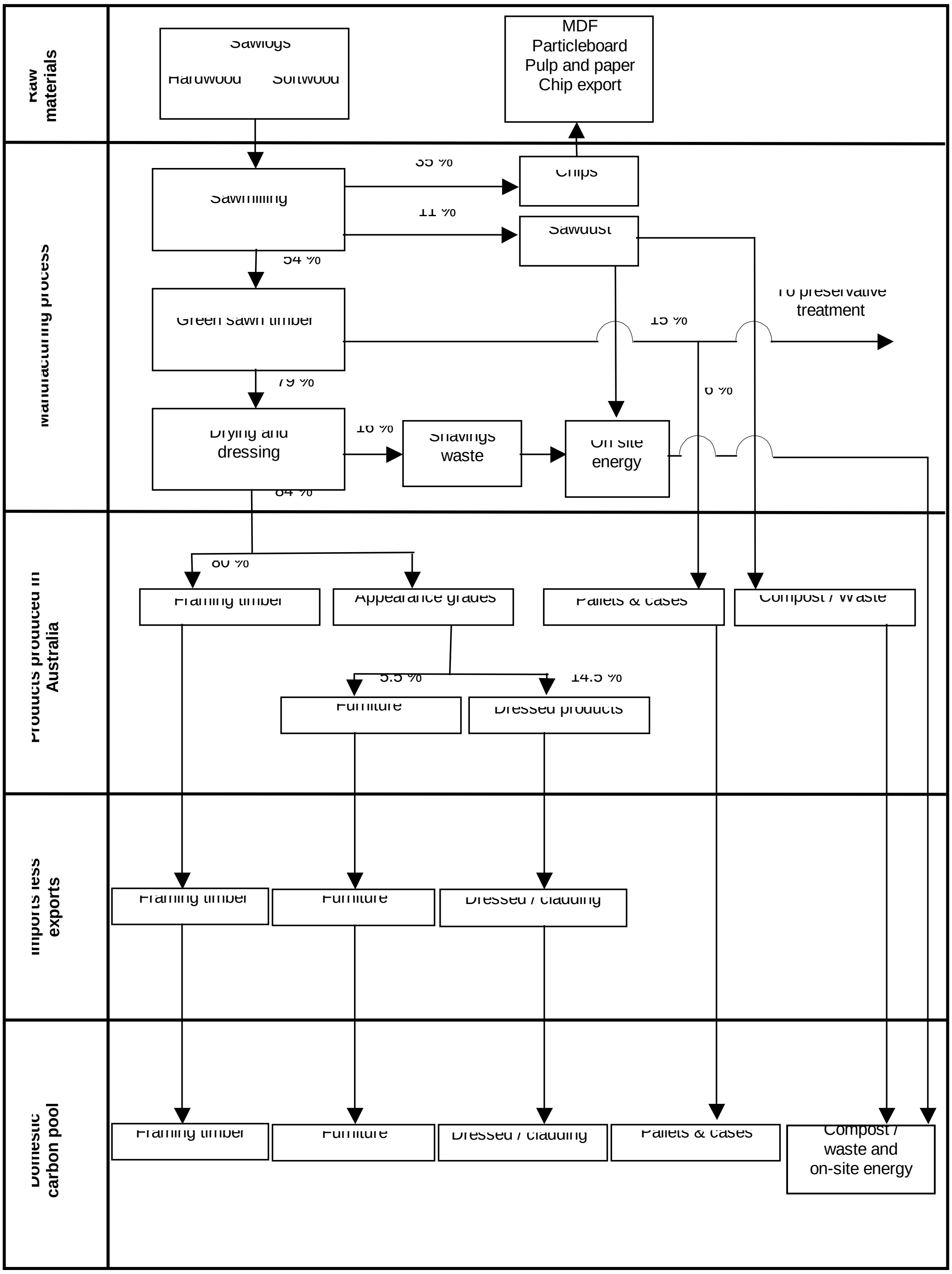
Emissions of soil carbon following conversion are estimated by applying the Roth C model for all first time cleared land (See Appendix 6.B). The Roth C model was parameterised with climate data (rainfall, temperature, open pan evaporation) from a representative site in central Queensland.

Non CO_2 emissions

Non-CO_2 (CH_4 and N_2O) emissions were estimated by multiplying the CO_2 emissions from onsite burning and onsite burning of debris with a ‘non-CO_2 to CO_2’ coefficient. The non-CO_2 to CO_2 coefficient incorporates the ratio of mass of non-CO_2 gas to the mass of carbon it contains, the ratio of non-CO_2 gas emitted to carbon emitted, the ratio of the amount of CO_2 with equivalent greenhouse gas effect to an amount of non-CO_2 gas and the fraction of CO_2 that is carbon by weight.

Appendix 6.I Wood flows by sector

Figure 6.I.1 National Inventory Model – Sawmilling wood flows *



* percentages shown for softwood sawmilling, refer to model for hardwood and cypress pine

Figure 6.I.2 National Inventory Model for Wood Products – Wood flows in preservative treated products

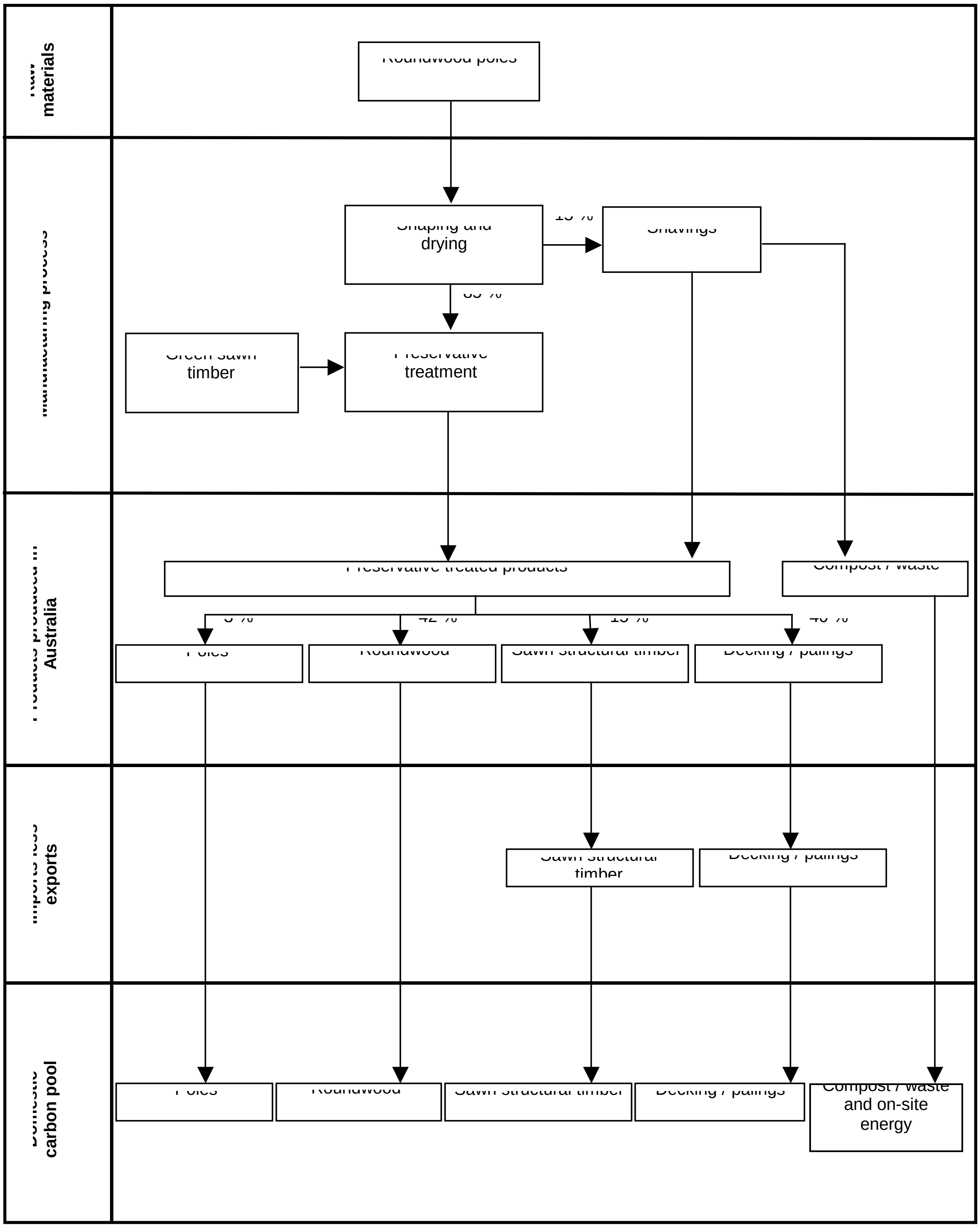


Figure 6.I.3 National Carbon Accounting Model for Wood Products – Wood Flows in plywood production

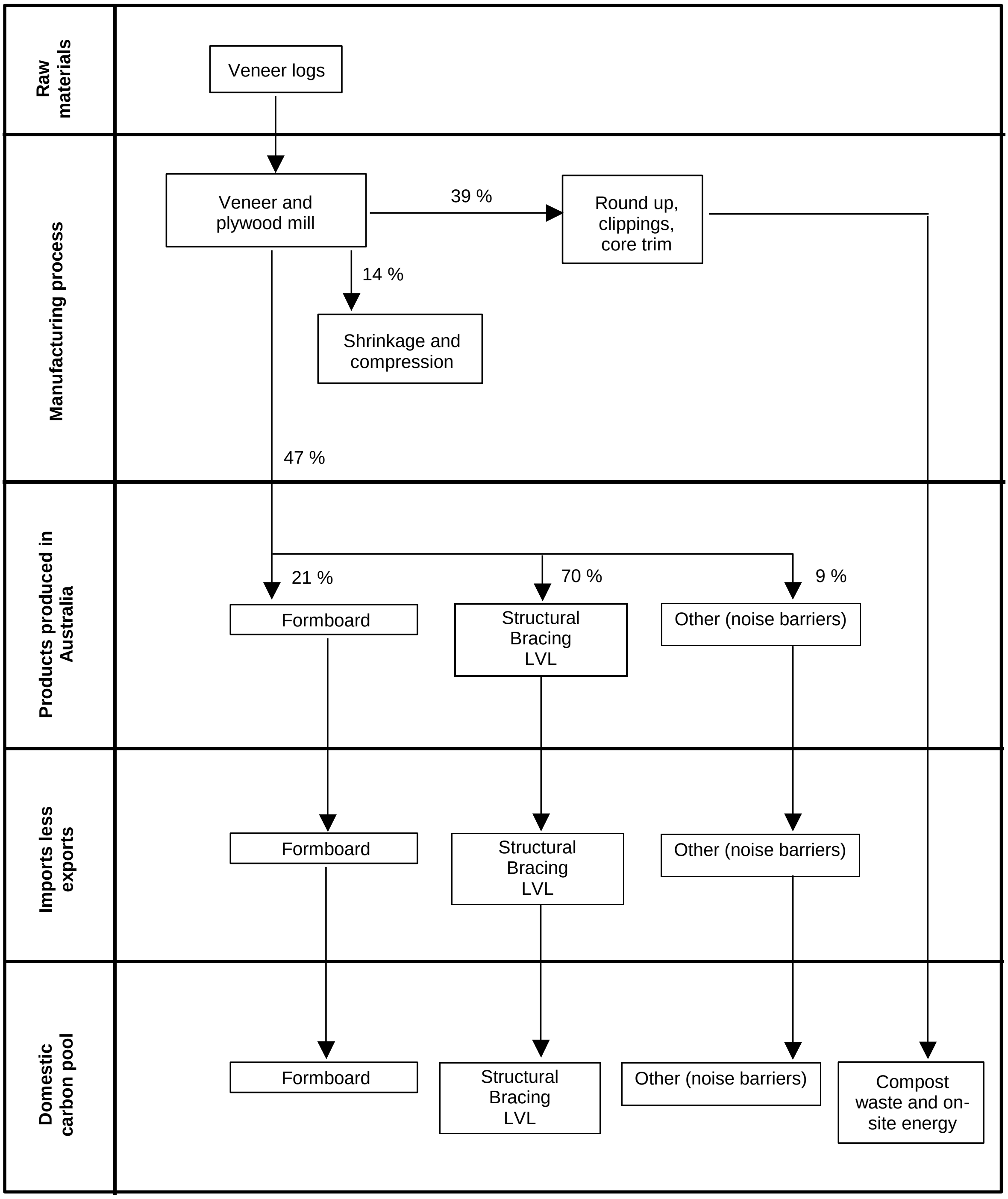


Figure 6.I.4 National Inventory Model for Wood Products – Wood flows in plywood production

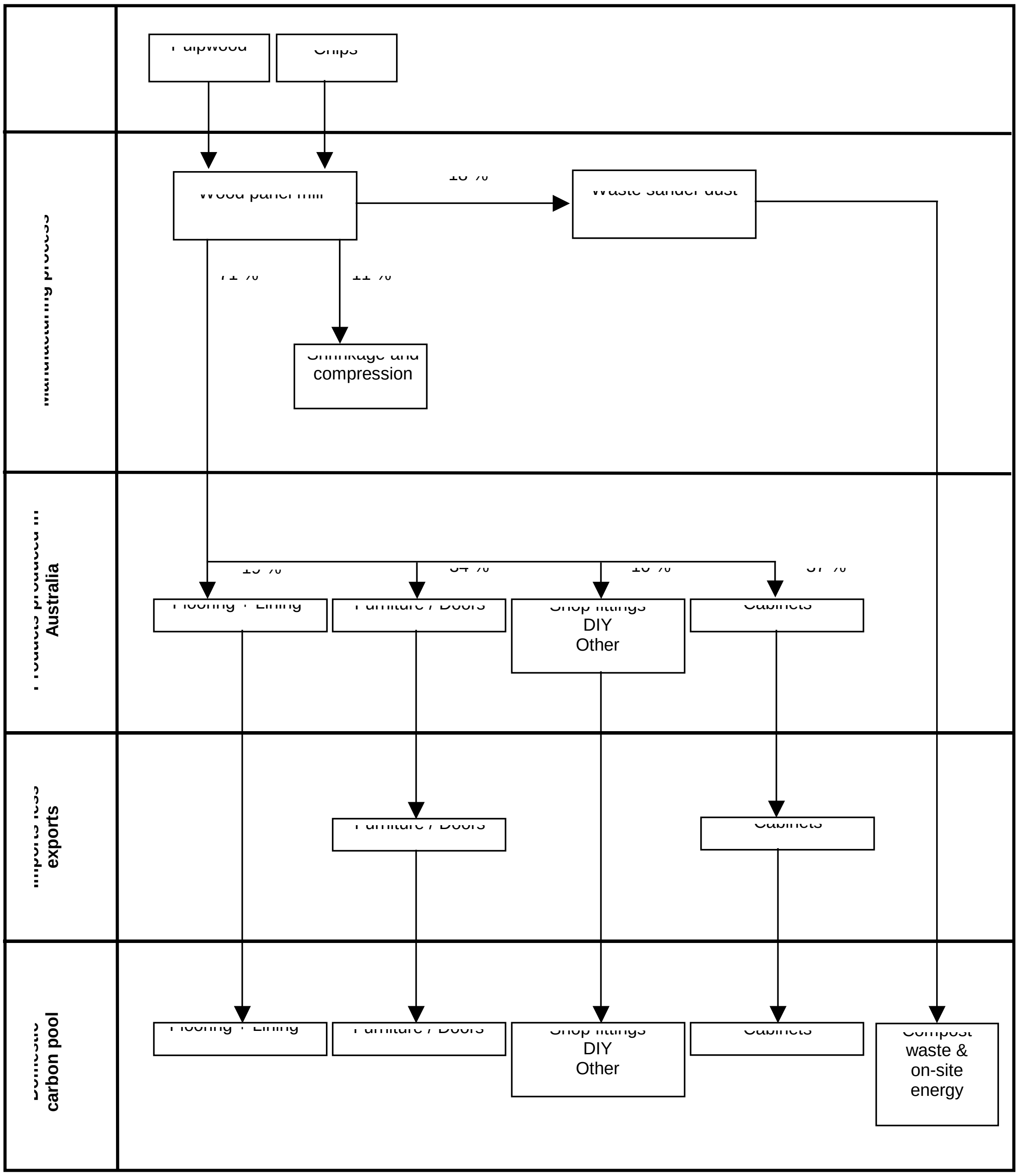
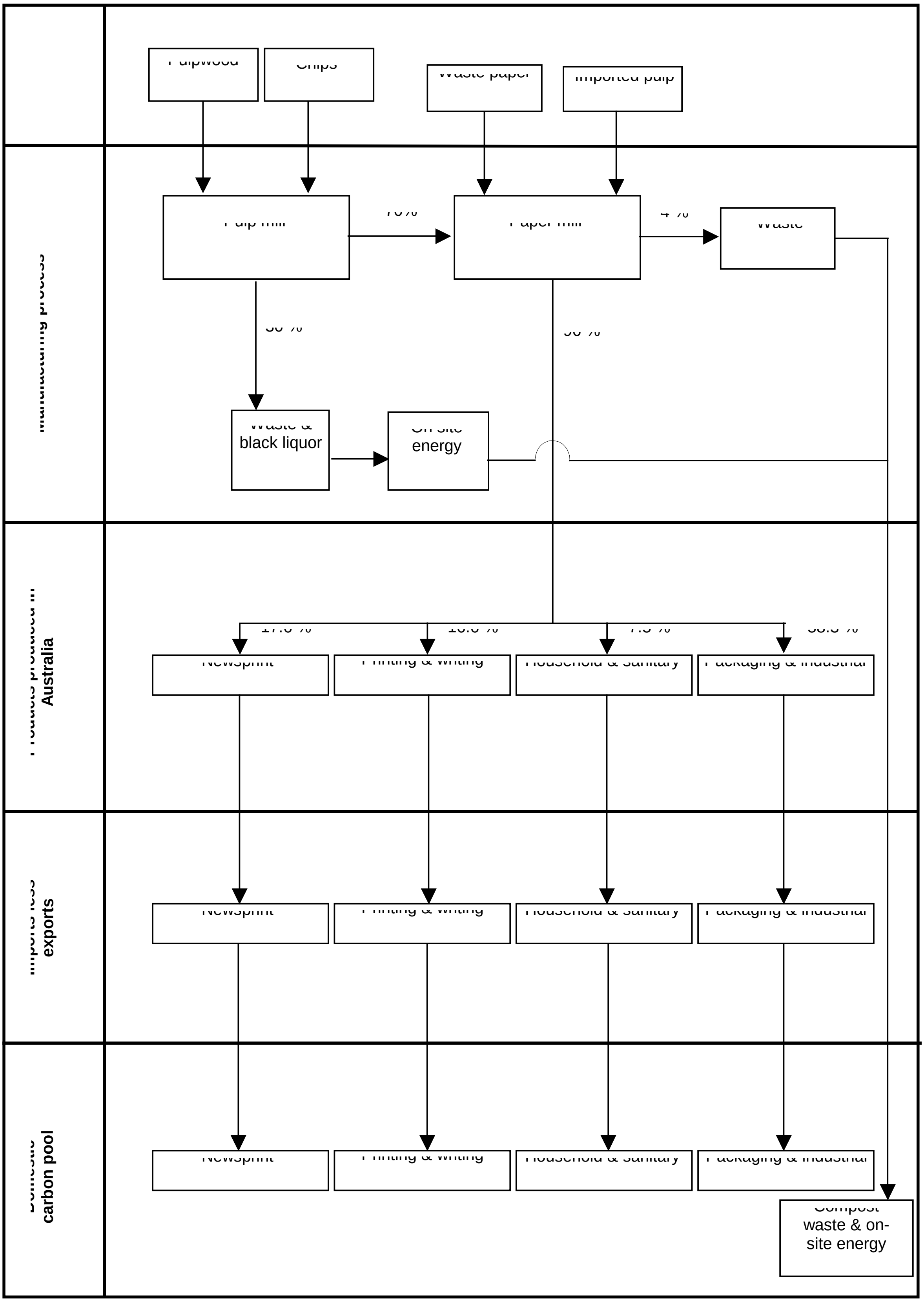
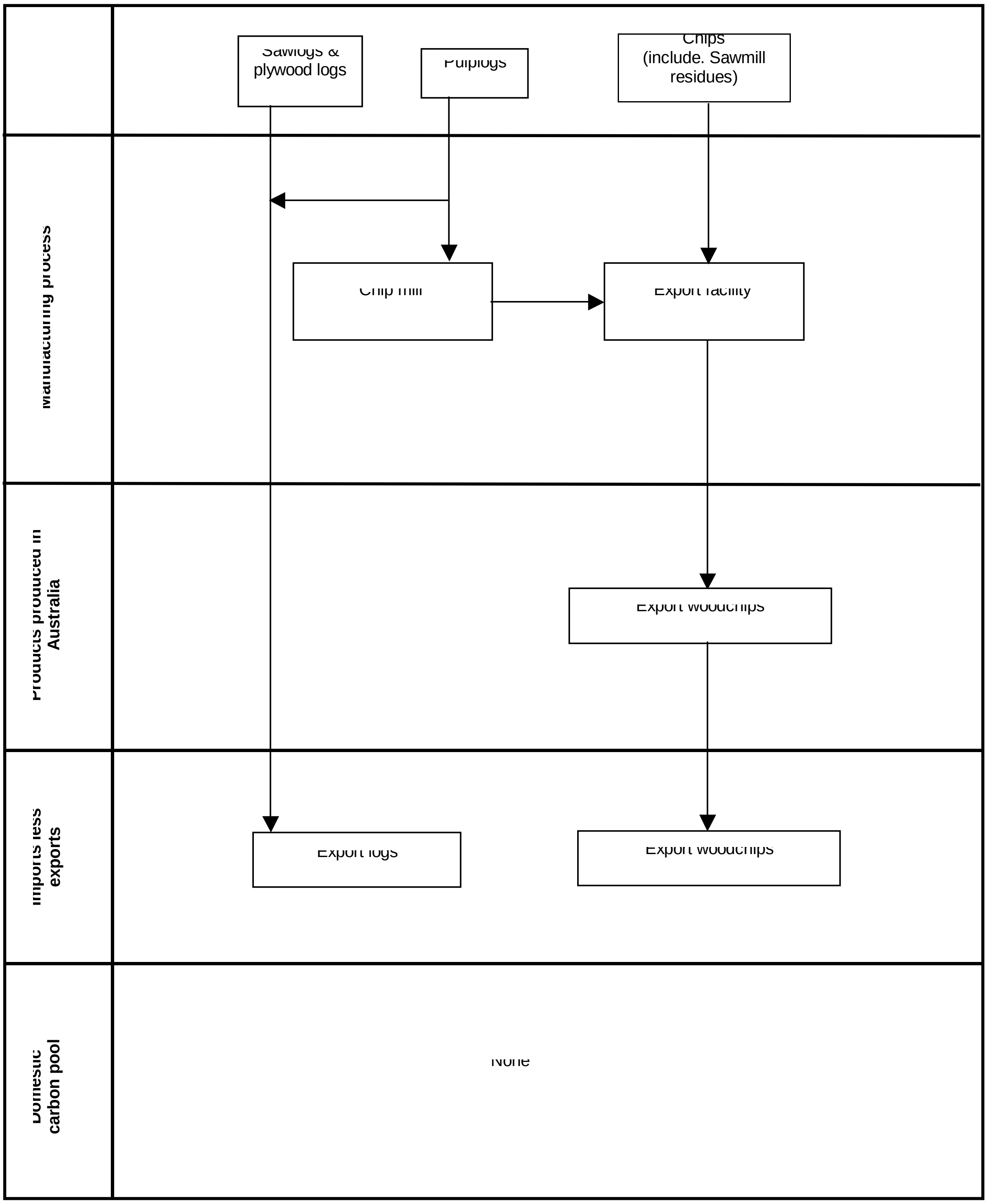


Figure 6.I.5 National Inventory Model for Wood Products – Wood flows in MDF and particleboard manufacture*



* percentages shown for particleboard manufacture – see model for details on MDF

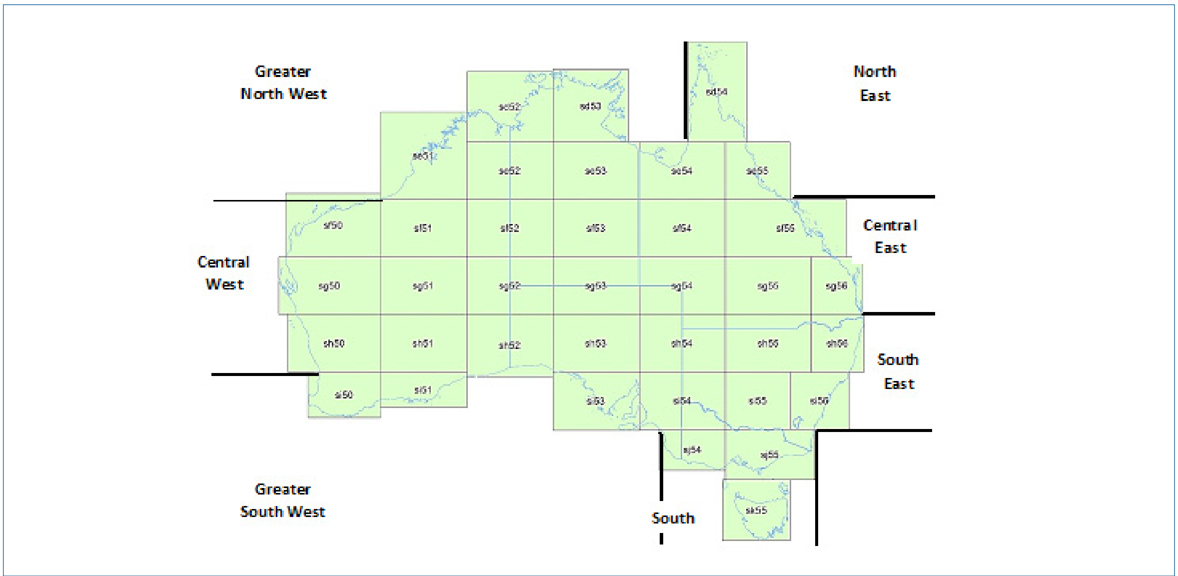
Figure 6.I.6 National Inventory Model for Wood Products – Wood flows in pulp and paper manufacture



Appendix 6J: Wetlands – model parameter values and source documents

The Tier 1 IPCC default values for above ground biomass (AGB), below ground biomass (BGB), dead organic matter (as woody and non-woody litter), and soil organic carbon (SOC), were replaced with values relevant to Australia's varied coastal regions, based on a review of the national and international scientific literature (Table 6.J.1).

Figure 6.J.1 Australian coastal regions related to the development of model parameters for coastal wetlands



Where possible, weighted averages of multiple reported parameter values are calculated for each of seven coastal regions (Table 6.J.1). The seven coastal regions (Figure 6.J.1) are constructs that correspond, approximately, to combinations of mangrove biogeographical regions defined in Cresswell (Cresswell 2012), and also fully incorporate sets of spatial tiles that return areas of vegetation clearance and revegetation used in the analysis of land use and land use change.

Mangrove species common to and across several coastal regions are identified and their relative abundances within each coastal region estimated from surveys undertaken in Australia (Table 6.J.2). Only one species of mangrove (*Avicennia marina*) exists in Victoria and South Australia so that this species had a relative abundance score of 1 in these states.

Finally, tidal marsh is a generic classification in this study. It incorporates all the vegetated, non-forested intertidal habitats that comprise combinations of sparse vegetation (salt marsh mixed with individual mangrove plants), herbs, saline grasses, sedges and rushes. Because tidal marshes form neighbouring and ecotone communities with mangroves any conversion of mangroves to settlement will also result in the clearance of tidal marsh. An estimate of emissions due to this associated clearance of tidal marsh is provided in this inventory. The relative proportions of mangrove, tidal marsh and unvegetated (salt pan, mud flat, tidal flat) within the intertidal wetland used for the modelled estimates are in table 6.J.3 below.

Table 6.J.1 Mangrove (MG) and tidal marsh (TM) parameter values. The values are weighted averages of values obtained from the scientific literature. References are in Table 6.J.4

Habitat and Coastal Sector	Carbon fraction	Wood density (g cm^{-3})	AGB (t ha^{-1})		BGB (t ha^{-1})		Standing stock woody litter (t DM ha^{-1})		Standing stock non-woody litter (t DM ha^{-1})		Min SOC Mg ha^{-1} [1]	Mean SOC Mg ha^{-1}
			Min	Mean/Max	Min	Mean/Max	Min	Mean/Max	Min	Mean/Max	Min	Mean/Max
MG, NE	0.48	0.75	1.33	354.16	0.67	179.94	0.01	9.44	0.01	1.98	31.30	621.00
MG, Central E	0.48	0.68	1.20	90.08	0.80	60.05	0.01	9.44	0.01	1.98	31.30	343.00
MG, SE	0.46	0.68	0.90	92.87	1.10	114.38	0.01	0.76	0.01	0.16	31.30	285.00
MG, South	0.45	0.77	0.87	121.00	1.13	157.00	0.01	0.76	0.01	0.16	31.30	145.00
MG, Greater SW	0.45	0.77	0.30	101.00	1.70	238.00	0.01	0.76	0.01	0.16	31.30	205.00
MG, Central W	0.45	0.77	0.30	101.00	1.70	238.00	0.01	0.68	0.01	2.00	31.30	118.00
MG, Greater NW	0.47	0.76	1.34	406.19	0.66	199.34	0.01	0.68	0.01	2.00	31.30	367.00
TM, NE	0.41	0.00	0.00	6.40	0.00	18.00	0.00	0.00	0.00	0.02	n/a[2]	125.00
TM, Central E	0.41	0.00	0.00	6.40	0.00	18.00	0.00	0.00	0.00	0.02	n/a	125.00
TM, SE	0.41	0.00	0.00	7.00	0.00	5.00	0.00	0.00	0.00	0.02	n/a	191.00
TM, South	0.41	0.00	0.00	7.00	0.00	5.00	0.00	0.00	0.00	0.02	n/a	169.00
TM, Greater SW	0.41	0.00	0.00	6.40	0.00	18.00	0.00	0.00	0.00	0.02	n/a	147.00
TM, Central W	0.41	0.00	0.00	6.40	0.00	18.00	0.00	0.00	0.00	0.02	n/a	413.00
TM, Greater NW	0.41	0.00	0.00	6.40	0.00	18.00	0.00	0.00	0.00	0.02	n/a	413.00

1 Minimum SOC value based on single value for sparse vegetation in intertidal wetland located in Central NSW (Owers *et al.* 2016)

2 Minimum SOC value required for mangrove growth model only.

Table 6.J.2 The relative abundance of common mangrove species used in the modelling. References are listed in Table 6.J.5

Mangrove species	Abundance relative to other mangrove species within each coastal region						
	North East (NE)	Central East (Cent E)	South East (SE)	South (S)	Greater South West (Greater SW)	Central West (Central W)	Greater North West (Greater NW)
Avicennia marina	0.18	0.15	0.65	1	1	1	0.3
Aegiceras corniculatum	0.1	0.4	0.35	0	0	0	0.14
Excoecaria agallocha	0.01	0.01	0	0	0	0	0
Ceriops tagal australis	0.2	0.18	0	0	0	0	0.35
Rhizophora stylosa	0.25	0.14	0	0	0	0	0.1
Bruguiera sp	0.2	0.1	0	0	0	0	0.1
Sonneratia alba	0.01	0.02	0	0	0	0	0
Lumnitzera racemosa	0.05	0	0	0	0	0	0.01

Table 6.J.3 The relative proportion of mangrove, tidal marsh and unvegetated (salt pan, mud flat, tidal flat) within the intertidal wetland. References are listed in Table 6.J.5

Tile	Coastal Region	Mangrove relative area	Tidal marsh relative area	Un-vegetated relative area
sd54	North East Coast	0.4614	0.4178	0.1208
se55	North East Coast	0.6484	0.2968	0.0548
sf55	Central East Coast	0.4194	0.4867	0.0939
sg56	Central East Coast	0.4607	0.1968	0.3425
sh56	South East Coast	0.5346	0.2402	0.2252
si56	South East Coast	0.3655	0.3950	0.2395
sj55	South Coast	0.0570	0.1778	0.7652
sj54	South Coast	0.0013	0.8372	0.1616
sk55	South Coast	0.0000	0.0000	0.0000
si54	Greater South West Coast	0.5279	0.2973	0.1748
si53	Greater South West Coast	0.2100	0.5716	0.2184
sh53	Greater South West Coast	0.0000	0.2000	0.8000
sh52	Greater South West Coast	0.0000	0.2000	0.8000
si51	Greater South West Coast	0.0000	0.2000	0.8000
si50	Greater South West Coast	0.0177	0.4138	0.5685
sh50	Greater South West Coast	0.5541	0.0252	0.4206
sg50	Central West Coast	0.5787	0.2762	0.1451
sf50	Central West Coast	0.1304	0.7036	0.1660

Tile	Coastal Region	Mangrove relative area	Tidal marsh relative area	Un-vegetated relative area
se51	Greater North West Coast	0.1980	0.6152	0.1868
sd52	Greater North West Coast	0.2947	0.6601	0.0452
sd53	Greater North West Coast	0.2860	0.6399	0.0741
se53	Greater North West Coast	0.2860	0.6399	0.0741
se54	Greater North West Coast	0.1347	0.8265	0.0388

Table 6.J.4 Source documents for informing the development of species-specific or locality-specific parameter and emission factor values in Table 6.J.1. Full details are provided in the source documents list following Table 6.J.5

Species / habitat type	Carbon fraction	Wood density	AGB/BGB	Litter production and Litter standing stock	SOC
Avicennia marina	(Adame *et al.* 2015), (Bulmer, Schwendenmann, and Lundquist 2016b), (Bulmer, Schwendenmann, and Lundquist 2016a), (Bhattacharyya, Mitra, and Raha 2015), (Rodrigues *et al.* 2015), (Patil *et al.* 2014), (Perera and Amarasinghe 2014)	(Duke, Mackenzie, and Wood 2013), (Santini *et al.* 2013)	(Alongi *et al.* 2003), (Alongi, Clough, and Robertson 2005), (Mackey 1993), (Burchett *et al.* 2009), (Bulmer, Schwendenmann, and Lundquist 2016a), (Bulmer, Schwendenmann, and Lundquist 2016b), (Lichacz, Hardiman, and Buckney 2009), (Saintilan 1997b), (Saintilan 1997a), (Comley and McGuinness 2005), (Tamooh *et al.* 2008), (Briggs 1977), (Clough and Attiwill 1975), (Hutchings and Saenger 1987)	(Clarke 1994), (Duke, Bunt, and Williams 1981), (Duke 1982), (Mackey and Smail 1995), (May 1999), (Duke 1988), (Metcalfe 1999), (Imgraben and Dittmann 2008), (Woodroffe 1982), (Gladstone-Gallagher, Lundquist, and Pilditch 2014), (Saenger and Snedaker 1993), (Conacher *et al.* 1996), (Goulter and Allaway 1979), (Woodroffe *et al.* 1988), (Murray 1985)	(Carnell *et al.* 2015), (Livesley and Andrusiak 2012), (Saintilan *et al.* 2013), (Lovelock *et al.* 2013), (Page and Dalal 2011), (Matsui 1998), (Howe, Rodríguez, and Saco 2009), (Brown *et al.* 2016), (KELLEWAY *et al.* 2015), (Salmo, Lovelock, and Duke 2013), (Kaly, Eugelink, and Robertson 1997)
Aegiceras sp.	(Hossain *et al.* 2016)	(Duke, Mackenzie, and Wood 2013)	(Lichacz, Hardiman, and Buckney 2009), (Saintilan 1997b), (Saintilan 1997a)		
Ceriops sp.	(Binh and Nam 2014), (Slim *et al.* 1996), (Duke, Burrows, and Mackenzie 2015)	(Clough and Scott 1989), (Duke, Mackenzie, and Wood 2013)	(Duke, Burrows, and Mackenzie 2015), (Robertson and Daniel 1989), (Saintilan 1997a), (Comley and McGuinness 2005)		
Lumnitzera sp.	(Perera and Amarasinghe 2013), (Perera and Amarasinghe 2014)	(Duke, Mackenzie, and Wood 2013)	(Perera and Amarasinghe 2013), (Krishnanantham, Seneviratne, and Jayamanne 2015), (Duke, Mackenzie, and Wood 2013)		
Rhizophora sp.	(Rodrigues *et al.* 2015), (Kauffman *et al.* 2011), (Perera and Amarasinghe 2014), (Slim *et al.* 1996), (Duke, Burrows, and Mackenzie 2015)	(Clough and Scott 1989), (Duke, Mackenzie, and Wood 2013)	(Alongi *et al.* 2003), (Alongi, Clough, and Robertson 2005), (Duke, Burrows, and Mackenzie 2015), (Robertson and Daniel 1989), (Comley and McGuinness 2005), (Tamooh *et al.* 2008)		
Sonneratia sp.	(Kauffman *et al.* 2011), (Bhattacharyya, Mitra, and Raha 2015),	(Duke, Mackenzie, and Wood 2013)	(Ball and Pidsley 1995), (Tamooh *et al.* 2008)		
Bruguiera sp.	(Kauffman *et al.* 2011), (Perera and Amarasinghe 2013), (Duke, Burrows, and Mackenzie 2015)	(Clough and Scott 1989), (Duke, Mackenzie, and Wood 2013)	(Duke, Burrows, and Mackenzie 2015), (Robertson and Daniel 1989), (Comley and McGuinness 2005)		
Excoecaria sp.	(Bhattacharyya, Mitra, and Raha 2015), (Perera and Amarasinghe 2014)	(Duke, Mackenzie, and Wood 2013)	(Saintilan 1997a), (Duke, Mackenzie, and Wood 2013), (Bhattacharyya, Mitra, and Raha 2015)		

Species / habitat type	Carbon fraction	Wood density	AGB/BGB	Litter production and Litter standing stock	SOC
Tidal marsh	(Hemminga *et al.* 1996), (Cartaxana and Catarino 1997)	n/a	(Clarke and Jacoby 1994), (Lichacz, Hardiman, and Buckney 2009), (Macreadie, Hughes, and Kimbro 2013)	(Van Der Valk and Attiwill 1983)	(Carnell *et al.* 2016), (Carnell *et al.* 2015), (Kelleway *et al.* 2016), (Macreadie, Hughes, and Kimbro 2013), (Macreadie *et al.* 2017), (Livesley and Andrusiak 2012), (Saintilan *et al.* 2013), (Lovelock *et al.* 2013), (Page and Dalal 2011), (Howe, Rodríguez, and Saco 2009), (Brown *et al.* 2016), (KELLEWAY *et al.* 2015), (Salmo, Lovelock, and Duke 2013)
Un-vegetated intertidal	n/a	n/a	n/a	n/a	(Maher and Eyre 2010), (Beasy and Ellison 2013)

Table 6.J.5 Sources of biogeographical information that informed the relative abundance of mangrove species within mangrove habitats (Table 6.J.2), and the distribution of mangrove, tidal marsh and unvegetated habitats in each state and territory (Table 6.J.3). Full details are provided in the source documents list below

State/Territory	Source documents
National	(Bridgewater and Cresswell 1999), (Suzuki and Saenger 1996), (Bridgewater and Cresswell 2003), (Cresswell 2012), (Macnae 1966), (NLWRA 1998)
Queensland	(Danaher and Stevens 1995), (Danaher 1995b), (Bruinsma and Duncan 2000), (Bruinsma 2001), (Danaher 1995a), (Bruinsma *et al.* 1999), (Bruinsma and Danaher 2001), (Bruinsma 2000), (Bruinsma and Danaher 2000), (Dowling and Stephens 1998), (Dowling 1986), (Dowling 1978), (Accad *et al.* 2016), (BUNT 1996), (Bunt 1997), (Bunt and Bunt 1999), (Bunt and Williams 1981), (Bunt *et al.* 1991), (Roder *et al.* 2002), (Duke *et al.* 2017), (Duke, Burrows, and Mackenzie 2015), (Mackenzie *et al.* 2012)
New South Wales	(Creese *et al.* 2009), (Astles *et al.* 2010), (West *et al.* 1984), (West, Laird, and Williams 2004), (Outhred and Buckney 2009), (Clarke and Hannon 1967)
Victoria	(Keough *et al.* 2011), (Boon 2012), (Boon 2015), (Boon *et al.* 2015), (French *et al.* 2014), (Ross 2000)
Tasmania	(Kirkpatrick and Glasby 1981), (Prahalad 2014), (Prahalad 2016a), (Prahalad 2016b), (Prahalad 2009), (Prahalad, Kirkpatrick, and Mount 2012), (Prahalad and Jones 2013), (Prahalad and Pearson 2013)
South Australia	(Edyvane 1999), (Foulkes and Heard 2003), (Cann, Scardigno, and Jago 2009), (Rumblelow, Speziali, and Bloomfield 2010), (Scientific Working Group 2011)
Western Australia	(Duke *et al.* 2010), (Cresswell, Bridgewater, and Semeniuk 2011), (Cresswell and Semeniuk 2011), (Pen, Semeniuk, and Semeniuk 2000), (Semeniuk 1985), (Semeniuk 1983), (Semeniuk 1980), (Semeniuk, Semeniuk, and Unno 2000), (Semeniuk, Tauss, and Unno 2000)
Northern Territory	(Duke *et al.* 2010), (O'Grady, McGuinness, and Eamus 1996), (McGuinness 2003), (Coupland, Paling, and McGuinness 2005), (Lee 2003), (Moritz-Zimmermann, Comley, and Lewis 2002), (Duke *et al.* 2017)

Source documents list

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Appendix 6.K Biomass burning

Table 6.K.1 Fine Fuels – fuel accumulation model parameters

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0	L	D	Gc
NT	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.646	4.026	0.800	1.33
NT	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.473	3.960	0.800	1.20
NT	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	1.010	2.704	0.800	1.33
NT	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	1.491	3.991	0.800	1.15
NT	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.484	4.258	0.800	1.25
NT	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.633	2.355	0.800	1.40
NT	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	0.691	2.707	0.800	1.70
NT	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.629	2.475	0.800	1.40
NT	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.650	2.618	0.800	1.00
NT	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.756	2.965	0.800	1.80
QLD	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	2.134	5.219	0.800	1.33
QLD	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.434	3.854	0.800	1.20
QLD	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	1.295	3.468	0.800	1.33
QLD	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	1.582	4.235	0.800	1.15
QLD	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.725	4.949	0.800	1.25
QLD	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.719	2.676	0.800	1.40
QLD	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	0.652	2.552	0.800	1.70
QLD	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.595	2.343	0.800	1.40
QLD	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.609	2.454	0.800	1.00
QLD	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.621	2.433	0.800	1.80
WA	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.597	3.905	0.800	1.33
WA	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.427	3.835	0.800	1.20
WA	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.902	2.414	0.800	1.33
WA	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	1.376	3.684	0.800	1.15
WA	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.393	3.998	0.800	1.25
WA	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.663	2.466	0.800	1.40

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0	L	D	Gc
WA	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	0.696	2.727	0.800	1.70
WA	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.655	2.579	0.800	1.40
WA	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.719	2.896	0.800	1.00
WA	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.752	2.949	0.800	1.80
NSW	Temperate Zone	Temperate Forests	NA	Wildfire	3.744	4.359	0.326	1.00
TAS	Temperate Zone	Temperate Forests	NA	Wildfire	2.453	1.813	0.207	1.00
WA	Temperate Zone	Temperate Forests	NA	Wildfire	3.312	1.692	0.143	1.00
SA	Temperate Zone	Temperate Forests	NA	Wildfire	2.078	1.699	0.229	1.00
VIC	Temperate Zone	Temperate Forests	NA	Wildfire	3.413	3.889	0.319	1.00
Qld	Temperate Zone	Temperate Forests	NA	Wildfire	4.049	8.488	0.587	1.00
NT	Temperate Zone	Temperate Forests	NA	Wildfire	2.016	1.649	0.229	1.00
ACT	Temperate Zone	Temperate Forests	NA	Wildfire	2.232	1.833	0.23	1.00
NSW	Temperate Zone	Temperate Forests	NA	Controlled burning	8.156	5.642	0.422	1.00
TAS	Temperate Zone	Temperate Forests	NA	Controlled burning	5.344	2.339	0.267	1.00
WA	Temperate Zone	Temperate Forests	NA	Controlled burning	7.216	2.200	0.186	1.00
SA	Temperate Zone	Temperate Forests	NA	Controlled burning	4.526	2.204	0.297	1.00
VIC	Temperate Zone	Temperate Forests	NA	Controlled burning	7.436	5.071	0.416	1.00
Qld	Temperate Zone	Temperate Forests	NA	Controlled burning	8.827	11.113	0.768	1.00
NT	Temperate Zone	Temperate Forests	NA	Controlled burning	2.501	1.218	0.297	1.00
ACT	Temperate Zone	Temperate Forests	NA	Controlled burning	4.862	2.391	0.3	1.00

Table 6.K.2 Coarse Fuels – fuel accumulation model parameters

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0 (t dm)	L	D
NT	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	0.3356	0.0704	0.090
NT	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.2862	0.2934	0.090
NT	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.9176	0.2175	0.090
NT	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	0.9176	0.2175	0.090
NT	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.1140	0.2500	0.090
NT	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.5996	0.0871	0.090
NT	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	1.7877	0.2677	0.090
NT	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.9416	0.1446	0.090
NT	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.9293	0.1437	0.090
NT	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	1.4992	0.2434	0.090
QLD	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	0.3356	0.0704	0.090
QLD	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.2862	0.2934	0.090
QLD	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.9176	0.2175	0.090
QLD	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	0.9176	0.2175	0.090
QLD	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.1140	0.2500	0.090
QLD	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.5996	0.0871	0.090
QLD	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	1.7877	0.2677	0.090
QLD	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.9416	0.1446	0.090
QLD	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.9293	0.1437	0.090
QLD	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	1.4992	0.2434	0.090
WA	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	0.3356	0.0704	0.090
WA	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.2862	0.2934	0.090
WA	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.9176	0.2175	0.090
WA	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	0.9176	0.2175	0.090
WA	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.1140	0.2500	0.090
WA	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.5996	0.0871	0.090
WA	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	1.7877	0.2677	0.090
WA	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.9416	0.1446	0.090
WA	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.9293	0.1437	0.090
WA	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	1.4992	0.2434	0.090
NSW	Temperate Zone	Temperate Forests	NA	Wildfire	25.1340	13.65614	0.326

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0 (t dm)	L	D
TAS	Temperate Zone	Temperate Forests	NA	Wildfire	8.9160	3.07602	0.207
WA	Temperate Zone	Temperate Forests	NA	Wildfire	23.6100	5.62705	0.143
SA	Temperate Zone	Temperate Forests	NA	Wildfire	6.8580	2.61747	0.229
VIC	Temperate Zone	Temperate Forests	NA	Wildfire	19.5180	10.37707	0.319
Qld	Temperate Zone	Temperate Forests	NA	Wildfire	18.0600	17.6687	0.587
NT	Temperate Zone	Temperate Forests	NA	Wildfire	4.3200	1.6488	0.229
ACT	Temperate Zone	Temperate Forests	NA	Wildfire	14.2320	5.4556	0.230
NSW	Temperate Zone	Temperate Forests	NA	Controlled burning	33.7215	17.67758	0.422
TAS	Temperate Zone	Temperate Forests	NA	Controlled burning	11.9623	3.96762	0.267
WA	Temperate Zone	Temperate Forests	NA	Controlled burning	31.6687	7.31724	0.186
SA	Temperate Zone	Temperate Forests	NA	Controlled burning	9.2012	3.39471	0.297
VIC	Temperate Zone	Temperate Forests	NA	Controlled burning	26.1867	13.53248	0.416
Qld	Temperate Zone	Temperate Forests	NA	Controlled burning	24.2305	23.1168	0.768
NT	Temperate Zone	Temperate Forests	NA	Controlled burning	3.3005	1.2177	0.297
ACT	Temperate Zone	Temperate Forests	NA	Controlled burning	19.0946	7.116	0.300

Table 6.K.3 Heavy Fuels – fuel accumulation model parameters

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0 (t mF)	L	D
NT	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.6167	0.3423	0.090
NT	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	3.9498	0.8879	0.090
NT	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	1.6386	0.3392	0.090
NT	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	1.6386	0.3392	0.090
NT	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	3.8897	0.5650	0.090
NT	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.2993	0.0375	0.090
NT	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	0.8702	0.1093	0.090
NT	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.7693	0.0946	0.090
NT	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	1.9232	0.2504	0.090
NT	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.9710	0.1941	0.090

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0 (t mF)	L	D
QLD	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.6167	0.3423	0.090
QLD	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	3.9498	0.8879	0.090
QLD	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	1.6386	0.3392	0.090
QLD	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	1.6386	0.3392	0.090
QLD	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	3.8897	0.5650	0.090
QLD	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.2993	0.0375	0.090
QLD	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	0.8702	0.1093	0.090
QLD	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.7693	0.0946	0.090
QLD	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	1.9232	0.2504	0.090
QLD	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.9710	0.1941	0.090
WA	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.6167	0.3423	0.090
WA	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	3.9498	0.8879	0.090
WA	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	1.6386	0.3392	0.090
WA	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	1.6386	0.3392	0.090
WA	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	3.8897	0.5650	0.090
WA	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.2993	0.0375	0.090
WA	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	0.8702	0.1093	0.090
WA	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	0.7693	0.0946	0.090
WA	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	1.9232	0.2504	0.090
WA	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.9710	0.1941	0.090

Table 6.K.4 Shrub and Otherwise Aggregated Fuel loads

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL (t dm)
NT	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.80
NT	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.70
NT	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.49
NT	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	0.50
NT	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.50
NT	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.87
NT	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	1.84
NT	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	1.13
NT	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.66
NT	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.27
QLD	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.80
QLD	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.70
QLD	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.49
QLD	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	0.50
QLD	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.50
QLD	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.87
QLD	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	1.84
QLD	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	1.13
QLD	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.66
QLD	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.27
WA	Wet/dry tropical zone	Shrubland Hummock	High	EDS / LDS	1.80
WA	Wet/dry tropical zone	Woodland Hummock	High	EDS / LDS	1.70
WA	Wet/dry tropical zone	Melaleuca woodland	High	EDS / LDS	0.49
WA	Wet/dry tropical zone	Woodland Mixed	High	EDS / LDS	0.50
WA	Wet/dry tropical zone	Open Forest mixed	High	EDS / LDS	1.50
WA	Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	EDS / LDS	0.87
WA	Wet/dry tropical zone	Woodland with hummock grass	Low	EDS / LDS	1.84
WA	Wet/dry tropical zone	Open woodland with mixed grass	Low	EDS / LDS	1.13
WA	Wet/dry tropical zone	Woodland with mixed grass	Low	EDS / LDS	0.66
WA	Wet/dry tropical zone	Woodland with tussock grass	Low	EDS / LDS	0.27
NSW	Subtropical/semi-arid zone	Savanna Grassland	NA	Other Grassland	3.00
NT	Subtropical/semi-arid zone	Savanna Grassland	NA	Other Grassland	3.00
QLD	Subtropical/semi-arid zone	Savanna Grassland	NA	Other Grassland	3.00

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL (t dm)
SA	Subtropical/semi-arid zone	Savanna Grassland	NA	Other Grassland	3.00
WA	Subtropical/semi-arid zone	Savanna Grassland	NA	Other Grassland	3.00
ACT	Temperate Zone	Temperate Grassland	NA	Other Grassland	11.10
NSW	Temperate Zone	Temperate Grassland	NA	Other Grassland	6.90
SA	Temperate Zone	Temperate Grassland	NA	Other Grassland	3.00
TAS	Temperate Zone	Temperate Grassland	NA	Other Grassland	9.00
VIC	Temperate Zone	Temperate Grassland	NA	Other Grassland	11.70
WA	Temperate Zone	Temperate Grassland	NA	Other Grassland	3.00

Table 6.K.5 Patchiness (P) – fraction of fire scar that is burnt

Fire variant	Rainfall zone	Percent
EDS	High	70.9%
EDS	Low	79.0%
LDS	High	88.9%
LDS	Low	97.0%
Other Grassland	NA	100.0%
Wildfire	NA	80.0%
Controlled burning	NA	65.0%

Table 6.K.6 Burning Efficiency (BEF)

Vegetation class	Fuel Size	Fire variant	Rainfall zone	Percent
Wet/dry tropical zone	Fine	EDS	High	74.4%
Wet/dry tropical zone	Coarse	EDS	High	14.6%
Wet/dry tropical zone	Heavy	EDS	High	17.1%
Wet/dry tropical zone	Shrub	EDS	High	29.0%
Wet/dry tropical zone	Fine	EDS	Low	79.9%
Wet/dry tropical zone	Coarse	EDS	Low	10.9%
Wet/dry tropical zone	Heavy	EDS	Low	6.7%
Wet/dry tropical zone	Shrub	EDS	Low	9.8%
Wet/dry tropical zone	Fine	LDS	High	86.0%
Wet/dry tropical zone	Coarse	LDS	High	35.7%
Wet/dry tropical zone	Heavy	LDS	High	30.9%
Wet/dry tropical zone	Shrub	LDS	High	39.3%
Wet/dry tropical zone	Fine	LDS	Low	83.3%
Wet/dry tropical zone	Coarse	LDS	Low	20.2%
Wet/dry tropical zone	Heavy	LDS	Low	11.9%
Wet/dry tropical zone	Shrub	LDS	Low	11.0%
Subtropical/semi-arid zone	Aggregated	Other Grassland	NA	76.0%
Temperate Zone	Aggregated	Other Grassland	NA	72.0%
Temperate Zone	Fine	Wildfire	NA	90.0%
Temperate Zone	Coarse	Wildfire	NA	50.0%
Temperate Zone	Fine	Controlled burning	NA	60.0%
Temperate Zone	Coarse	Controlled burning	NA	30.0%

Table 6.K.7 Carbon Content in fuel burnt (C)

Vegetation class	Vegetation subclass	Rainfall zone	Fuel Size	Percent
Wet/dry tropical zone	Shrubland Hummock	High	Coarse	46.0%
Wet/dry tropical zone	Woodland Hummock	High	Coarse	46.0%
Wet/dry tropical zone	Melaleuca woodland	High	Coarse	46.0%
Wet/dry tropical zone	Woodland Mixed	High	Coarse	46.0%
Wet/dry tropical zone	Open Forest mixed	High	Coarse	46.0%
Wet/dry tropical zone	Shrubland Hummock	High	Fine	46.0%
Wet/dry tropical zone	Woodland Hummock	High	Fine	46.0%
Wet/dry tropical zone	Melaleuca woodland	High	Fine	46.0%
Wet/dry tropical zone	Woodland Mixed	High	Fine	46.0%
Wet/dry tropical zone	Open Forest mixed	High	Fine	46.0%
Wet/dry tropical zone	Shrubland Hummock	High	Heavy	46.0%
Wet/dry tropical zone	Woodland Hummock	High	Heavy	46.0%
Wet/dry tropical zone	Melaleuca woodland	High	Heavy	46.0%
Wet/dry tropical zone	Woodland Mixed	High	Heavy	46.0%
Wet/dry tropical zone	Open Forest mixed	High	Heavy	46.0%
Wet/dry tropical zone	Shrubland Hummock	High	Shrub	46.0%
Wet/dry tropical zone	Woodland Hummock	High	Shrub	46.0%
Wet/dry tropical zone	Melaleuca woodland	High	Shrub	46.0%
Wet/dry tropical zone	Woodland Mixed	High	Shrub	46.0%
Wet/dry tropical zone	Open Forest mixed	High	Shrub	46.0%
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Coarse	48.2%
Wet/dry tropical zone	Woodland with hummock grass	Low	Coarse	48.2%
Wet/dry tropical zone	Open woodland with mixed grass	Low	Coarse	48.2%
Wet/dry tropical zone	Woodland with mixed grass	Low	Coarse	48.2%
Wet/dry tropical zone	Woodland with tussock grass	Low	Coarse	48.2%
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Fine	39.8%
Wet/dry tropical zone	Woodland with hummock grass	Low	Fine	39.7%
Wet/dry tropical zone	Open woodland with mixed grass	Low	Fine	39.9%
Wet/dry tropical zone	Woodland with mixed grass	Low	Fine	39.7%
Wet/dry tropical zone	Woodland with tussock grass	Low	Fine	41.0%
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Heavy	48.2%
Wet/dry tropical zone	Woodland with hummock grass	Low	Heavy	48.2%
Wet/dry tropical zone	Open woodland with mixed grass	Low	Heavy	48.2%
Wet/dry tropical zone	Woodland with mixed grass	Low	Heavy	48.2%
Wet/dry tropical zone	Woodland with tussock grass	Low	Heavy	48.2%
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Shrub	48.5%
Wet/dry tropical zone	Woodland with hummock grass	Low	Shrub	48.5%
Wet/dry tropical zone	Open woodland with mixed grass	Low	Shrub	48.5%
Wet/dry tropical zone	Woodland with mixed grass	Low	Shrub	48.5%
Wet/dry tropical zone	Woodland with tussock grass	Low	Shrub	48.5%
Subtropical/semi-arid zone	Savanna Grassland	NA	Aggregated	43.9%
Temperate Zone	Temperate Grassland	NA	Aggregated	46.0%
Temperate Zone	Temperate Forests	NA	NA	50.0%

Table 6.K.8 Nitrogen to Carbon ratio in fuel burnt (C)

Vegetation class	Vegetation subclass	Rainfall zone	Fuel Size	Percent
Wet/dry tropical zone	Shrubland Hummock	High	Coarse	0.00810
Wet/dry tropical zone	Woodland Hummock	High	Coarse	0.00810
Wet/dry tropical zone	Melaleuca woodland	High	Coarse	0.00810
Wet/dry tropical zone	Woodland Mixed	High	Coarse	0.00810
Wet/dry tropical zone	Open Forest mixed	High	Coarse	0.00810
Wet/dry tropical zone	Shrubland Hummock	High	Fine	0.00960
Wet/dry tropical zone	Woodland Hummock	High	Fine	0.00960
Wet/dry tropical zone	Melaleuca woodland	High	Fine	0.00960
Wet/dry tropical zone	Woodland Mixed	High	Fine	0.00960
Wet/dry tropical zone	Open Forest mixed	High	Fine	0.00960
Wet/dry tropical zone	Shrubland Hummock	High	Heavy	0.00810
Wet/dry tropical zone	Woodland Hummock	High	Heavy	0.00810
Wet/dry tropical zone	Melaleuca woodland	High	Heavy	0.00810
Wet/dry tropical zone	Woodland Mixed	High	Heavy	0.00810
Wet/dry tropical zone	Open Forest mixed	High	Heavy	0.00810
Wet/dry tropical zone	Shrubland Hummock	High	Shrub	0.00930
Wet/dry tropical zone	Woodland Hummock	High	Shrub	0.00930
Wet/dry tropical zone	Melaleuca woodland	High	Shrub	0.00930
Wet/dry tropical zone	Woodland Mixed	High	Shrub	0.00930
Wet/dry tropical zone	Open Forest mixed	High	Shrub	0.00930
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Coarse	0.00389
Wet/dry tropical zone	Woodland with hummock grass	Low	Coarse	0.00389
Wet/dry tropical zone	Open woodland with mixed grass	Low	Coarse	0.00389
Wet/dry tropical zone	Woodland with mixed grass	Low	Coarse	0.00389
Wet/dry tropical zone	Woodland with tussock grass	Low	Coarse	0.00389
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Fine	0.01070
Wet/dry tropical zone	Woodland with hummock grass	Low	Fine	0.01130
Wet/dry tropical zone	Open woodland with mixed grass	Low	Fine	0.01020
Wet/dry tropical zone	Woodland with mixed grass	Low	Fine	0.01180
Wet/dry tropical zone	Woodland with tussock grass	Low	Fine	0.01050
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Heavy	0.01497
Wet/dry tropical zone	Woodland with hummock grass	Low	Heavy	0.01497
Wet/dry tropical zone	Open woodland with mixed grass	Low	Heavy	0.01497
Wet/dry tropical zone	Woodland with mixed grass	Low	Heavy	0.01497
Wet/dry tropical zone	Woodland with tussock grass	Low	Heavy	0.01497
Wet/dry tropical zone	Shrubland (heath) with hummock grass	Low	Shrub	0.00389
Wet/dry tropical zone	Woodland with hummock grass	Low	Shrub	0.00389
Wet/dry tropical zone	Open woodland with mixed grass	Low	Shrub	0.00389
Wet/dry tropical zone	Woodland with mixed grass	Low	Shrub	0.00389
Wet/dry tropical zone	Woodland with tussock grass	Low	Shrub	0.00389
Subtropical/semi-arid zone	Savanna Grassland	NA	Aggregated	0.00870
Temperate Zone	Temperate Grassland	NA	Aggregated	0.01200
Temperate Zone	Temperate Forests	NA	NA	0.01100

Table 6.K.9 Molecular Mass conversion factors

Conversion	Value
N to N_2O	44/28
C to CH_4	16/12
C to CO_2	44/12
N to NO_X	46/14
C to CO	28/12
C to NMVOC	14/12

Table 6.K.10 CH_4 Emission Factors (Gg CH_4-C/Gg C)

Vegetation class		Rainfall Zone	CH_4 EF (Gg CH_4-C/Gg C)				
			Aggregated	Fine	Coarse	Heavy	Shrub
Tropical Zone[(a)]	Woodland hummock	High	NA	0.0031	0.0031	0.01	0.0031
	Shrubland hummock	High	NA	0.0015	0.0015	0.01	0.0015
	Woodland mixed	High	NA	0.0031	0.0031	0.01	0.0031
	Open forest mixed	High	NA	0.0031	0.0031	0.01	0.0031
	Melaleuca woodland	High	NA	0.0031	0.0031	0.01	0.0031
	Shrubland (heath) with hummock grass	Low	NA	0.0013	0.0013	0.0111	0.0013
	Woodland with mixed grass	Low	NA	0.0017	0.0017	0.0158	0.0017
	Open woodland with mixed grass	Low	NA	0.0012	0.0012	0.0111	0.0012
	Woodland with tussock grass	Low	NA	0.0016	0.0016	0.0158	0.0016
	Woodland with hummock grass	Low	NA	0.0015	0.0015	0.0158	0.0015
Subtropical and semi-arid zone	[(b)]	NA	0.0012	NA	NA	NA	NA
Temperate Forest	[(c)]	NA	NA	0.0025	0.0126	NA	NA
Temperate Grasslands	[(d)]	NA	0.0035	NA	NA	NA	NA

(a) Russell-Smith *et al.* (2015)
(b) Meyer and Cook (2011)
(c) Roxburgh *et al.* (2015)
(d) Hurst *et al.* (1994 a, b)

Table 6.K.11 N_2O Emission Factors (Gg N_2O-N/Gg N)

Vegetation class		Rainfall zone	N_2O EF (N_2O-N/GgN)				
			Aggregated	Fine	Coarse	Heavy	Shrub
Tropical zone [(a)]	Woodland hummock	High	NA	0.0075	0.0075	0.0036	0.0075
	Shrubland hummock	High	NA	0.0066	0.0066	0.0036	0.0066
	Woodland mixed	High	NA	0.0075	0.0075	0.0036	0.0075
	Open forest mixed	High	NA	0.0075	0.0075	0.0036	0.0075
	Melaleuca woodland	High	NA	0.0075	0.0075	0.0036	0.0075
	Shrubland (heath) with hummock grass	Low	NA	0.0059	0.0059	0.0146	0.0059
	Woodland with mixed grass	Low	NA	0.006	0.006	0.0146	0.006
	Open woodland with mixed grass	Low	NA	0.006	0.006	0.0146	0.006
	Woodland with tussock grass	Low	NA	0.012	0.012	0.0146	0.012
	Woodland with hummock grass	Low	NA	0.006	0.006	0.0146	0.006
Subtropical and semi-arid zone	[(b)]	NA	0.0066	NA	NA	NA	NA
Temperate Forest	[(c)]	NA	NA	0.0111	0.0067	NA	NA
Temperate Grasslands	[(d)]	NA	0.0076	NA	NA	NA	NA

(a) Russell-Smith *et al.* 2009; Lynch *et al.* (2015).
(b) Meyer and Cook (2011)
(c) Roxburgh *et al.* (2015)
(d) Hurst *et al.* (1994 a, b)

Table 6.K.12 Emission Factors (CO, NMVOC and NO_x)

Gas	Unit	Tropical and semi – arid Emission Factor	Temperate Emission Factor
CO	Gg CO-C/Gg C	0.078	0.091
NMVOC	Gg NMVOC-C/Gg C	0.0091	0.022
NO_x	Gg NO_x-N/Gg N	0.21	0.15

Hurst *et al.* (1994 a, b)

Appendix 6.L Activity Data - Annual areas of forest conversions and sparse woody transitions

The following tables provide National and State/Territory times series (1990 – 2015) of annual areas of:

- primary forest conversion to other land uses (Table 6.L.1);
- regrowth of forest on previously cleared land , along with areas of clearance of this regrowth forest (Table 6.L.2); and
- gain and loss of sparse woody vegetation across grassland, cropland wetlands and settlements (Table 6.L.3)

Table 6.L.1 Annual areas of primary forest cleared over the period 1990 to 2015 (kha)

	National	NSW	NT	QLD	SA	TAS	VIC	WA	ACT
	Conversion	Conversion	Conversion	Conversion	Conversion	Conversion	Conversion	Conversion	Conversion
1990	591.3	65.4	2.3	422	13.6	11.8	17.1	58.9	0.17
1991	475.4	50.3	1.9	339.7	9.7	13.9	13.3	46.5	0.12
1992	373.4	38.7	2.8	281.2	7	6.4	10.3	26.9	0.1
1993	265.1	25.5	1	200.7	4.4	5.3	7	21.1	0.05
1994	270.3	26.4	1	206.4	3.7	4.6	6.1	22	0.05
1995	215.5	19.4	0.9	163.1	3.1	4.6	5.3	18.9	0.05
1996	220.9	17.8	1.3	172.2	2.8	3.7	5.5	17.6	0.05
1997	219.5	18.1	1.4	169.7	2.9	4.1	5.7	17.6	0.05
1998	223.6	16.8	1	179.2	2.7	3.7	5.5	14.7	0.05
1999	260.8	19	0.9	215.9	3	3.3	5.8	12.9	0.09
2000	267.3	17.1	0.8	226.7	2.6	3	4.5	12.5	0.06
2001	309.7	17.9	0.9	266.9	3.2	3.2	4.1	13.6	0.03
2002	279	16	0.8	230.2	3	3	12.2	13.7	0.07
2003	225.9	15.2	0.9	158.1	2.8	3.8	29	15.9	0.18
2004	233.5	17	0.9	174.1	3.2	4.2	18	16.1	0.14
2005	285.9	19.9	1.4	231.6	3.7	5	6.9	17.2	0.11
2006	240.8	17.1	1.2	186.9	4	4.3	9.5	17.8	0.07
2007	200.7	16.2	1.6	151.8	3.6	4	6.5	16.9	0.03
2008	138.7	11.2	1.5	102.2	2.1	4.2	5.2	12.4	0
2009	103.9	9.7	0.9	69.5	2.2	3.7	7	10.8	0.01
2010	81.3	8.8	0.7	49.7	2.1	3.6	4.9	11.5	0.02
2011	65.6	8.9	0.5	39.7	1.6	2.6	1.8	10.5	0.01
2012	56.3	9.2	0.4	35.4	1.5	1.3	1.2	7.2	0.01
2013	58.8	8.4	0.5	38.4	1.8	1.4	1.5	6.8	0.02
2014	57.9	7.7	0.5	36.2	2.8	1.8	2.1	6.7	0.03
2015	56	7.1	0.7	32.8	2.3	1.6	2	9.5	0.01

Table 6.L.2 Annual areas of forest regrowth and reclearance on previously cleared land, over the period 1990 to 2015 (kha)

	National		NSW		NT		QLD		SA		TAS		VIC		WA		ACT	
	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing	Regrowth	Reclearing
1990	538.5	326.1	100.3	63.4	2.4	2.1	354.6	214.9	10.7	7.3	10.4	4.2	27.2	15.1	32.3	18.9	0.6	0.2
1991	490.6	342.6	101.8	72	2.5	1.9	309	216.2	10.6	7	11.4	7.2	24.2	16.7	30.5	21.3	0.5	0.4
1992	441.4	359.8	102	72.3	3.8	2.8	259.5	235.1	10.3	8.4	6.3	6.4	30.1	18.2	29.2	16.3	0.4	0.4
1993	355.6	300.8	73.1	52.2	2.4	1.5	219.2	206	12.9	5.8	5.4	5	23.7	16.2	18.6	13.9	0.4	0.1
1994	375	320.1	76.3	54.7	2.5	1.6	234.7	222.2	16.6	5.4	5	4	20.6	17.3	18.8	14.8	0.4	0.1
1995	276.5	253.6	56.4	47.3	2.5	1.4	167.5	167.5	13.2	4.8	5	3.9	14.7	14.8	16.8	13.6	0.3	0.2
1996	249.2	272.9	47.1	51.2	2.8	2.1	158.1	183.9	9.3	4.9	3.5	3.5	11.7	13	16.4	14.2	0.2	0.2
1997	247.3	272.3	48.1	52	2.9	2.2	154.2	181.2	9.7	5	3.8	4	12	13.4	16.5	14.2	0.2	0.2
1998	252.8	294.4	49	52.6	2.9	1.7	153	205.3	8	5.6	3.7	3.6	13.6	12.9	22.3	12.5	0.2	0.2
1999	299.2	356.3	61.8	65.9	3.7	1.9	166.8	251.8	7.5	7	6.9	3.9	18.4	13.6	33.6	11.9	0.4	0.3
2000	247.1	336.9	53.5	57	2.6	2	130.1	242.5	7.5	6.8	5.8	3.1	17.8	11.3	29.5	14	0.4	0.3
2001	252.2	373.4	54.4	56.8	2.6	2.4	128.9	274.5	11	8.2	5.9	2.9	21	9.1	28.1	19.1	0.3	0.3
2002	252.8	343.5	57.3	52.1	2.4	2.2	134.4	244.1	10.3	8.3	5.4	3	18.1	13.7	24.6	19.7	0.3	0.4
2003	284.9	348.3	76.2	55.2	4.2	2.3	147.5	225.9	10.7	8.9	6.1	6	17.2	25.9	22.8	23.4	0.2	0.8
2004	309.3	387.9	86.7	65.7	4.3	2.5	154.2	248.7	12.4	11.8	7	6.1	20.5	26.6	24.1	25.9	0.2	0.6
2005	380.4	538.2	101.3	86.9	4.6	5.1	198.5	353.3	14.8	16.6	10	7.3	24.2	34.1	26.7	34.4	0.2	0.5
2006	351	504.7	85.3	96.5	3.5	6.5	189.7	295	13.1	17.3	10.7	7.1	22.2	41.1	26.4	40.5	0.1	0.6
2007	380.6	467.5	86.9	91.8	3.4	5.3	212.7	284	12.2	13.4	7.4	7.1	26.9	29.1	30.7	36.5	0.3	0.4
2008	480.5	362.5	95.6	60.5	3	3.7	297.8	228.3	15.2	8.8	7.2	9.3	31.2	21.9	30.2	29.8	0.4	0.2
2009	566.9	327	109.1	66.5	2.9	3.5	365.8	183.4	21.2	9.8	7.2	7.7	29.9	25.9	30.6	29.8	0.2	0.4
2010	498.2	317.4	99.1	74.7	3.4	3.5	301.1	163.1	23.4	11.2	8.2	8.3	33.4	24.6	29.4	31.6	0.2	0.3
2011	479.5	285.9	77.4	70	3.6	2.2	284.1	155.5	25.7	11.1	9.6	6.5	45.7	14.1	33.2	26.5	0.2	0.2
2012	560.5	309.3	74.4	70.5	2.6	2.6	361.6	186.1	26.9	11.4	9.3	4.3	45.4	12.5	39.9	21.8	0.3	0.1
2013	524.6	388.9	80.4	67.4	1.9	2.8	322.5	255.2	22.7	15	9.8	4.5	35.2	20.5	51.7	23.3	0.4	0.1
2014	576.6	338.2	78.1	49.7	2.5	2.8	382.1	217.7	16.1	16	9.5	4.9	33.2	24.2	54.5	22.7	0.5	0.1
2015	526.2	301.2	75.3	38.3	2.7	3.8	361.1	198.6	13.9	11.3	7.8	5.7	30.3	19.3	34.5	24.1	0.6	0.1

Table 6.L.3 Annual areas of sparse woody vegetation gains and losses over the period 1990 to 2015 (kha)

	National		NSW		NT		QLD		SA		TAS		VIC		WA		ACT	
	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses
1990	881.5	1,377.60	93.4	129.8	191.6	240.8	422.8	623.4	21.3	47.1	2.3	5.2	7.1	15.2	142.7	316	0.2	0.2
1991	1,190.30	2,177.30	93.4	129.8	257	446.2	650.4	1,173.40	21.3	47.1	2.3	5.2	7.1	15.2	158.6	360.2	0.2	0.2
1992	1,091.50	1,333.10	176.3	232.3	177.4	156.9	415.6	502	38.2	69	2.2	10.9	10	26.1	271.3	335.7	0.5	0.3
1993	837.9	792.1	82.1	93.2	177.4	156.9	337.6	340.3	33.6	19.7	1.3	1.8	6.8	5.5	198.6	174.6	0.4	0.1
1994	837.9	792.1	82.1	93.2	177.4	156.9	337.6	340.3	33.6	19.7	1.3	1.8	6.8	5.5	198.6	174.6	0.4	0.1
1995	964.6	722.3	82.1	93.2	215.4	129.3	429.3	293.9	33.6	19.7	1.3	1.8	6.8	5.5	195.7	178.8	0.4	0.1
1996	945.9	757.4	62.7	102.1	215.4	129.3	426.6	317	32	22.5	1.1	1.9	4.4	8.4	203.3	176.2	0.4	0.1
1997	945.9	757.4	62.7	102.1	215.4	129.3	426.6	317	32	22.5	1.1	1.9	4.4	8.4	203.3	176.2	0.4	0.1
1998	1,054.80	974.3	62.7	102.1	237.6	248.8	496.4	411.5	32	22.5	1.1	1.9	4.4	8.4	220.3	179	0.4	0.1
1999	1,173.20	972.1	128.4	80.1	237.6	248.8	526	423.4	40.8	33	1.3	1.5	9.2	6.8	229.5	178.2	0.5	0.2
2000	1,121.20	1,208.30	128.4	80.1	288.6	292.9	427.5	568.9	40.8	33	1.3	1.5	9.2	6.8	225	224.8	0.5	0.2
2001	1,134.30	1,296.00	128.3	87.8	288.6	292.9	443.5	602.8	45.9	36.7	2.4	1.4	13.1	5.3	211.9	268.9	0.5	0.2
2002	1,064.90	1,093.80	128.3	87.8	196.1	297.6	470.4	407.4	45.9	36.7	2.4	1.4	13.1	5.3	208.1	257.4	0.5	0.2
2003	1,023.40	1,129.30	114.9	114.8	196.1	297.6	465.7	433.4	35.1	32.2	1.5	2.5	14.2	6.8	195.7	241.5	0.3	0.4
2004	1,285.90	1,679.20	114.9	114.8	302.7	526.7	535.9	667.9	35.1	32.2	1.5	2.5	14.2	6.8	281.4	327.9	0.3	0.4
2005	1,930.00	1,780.20	263.6	183	372.8	394.1	792.3	828.4	41	79.6	2.2	4.3	20.4	21.1	437	269.2	0.7	0.6
2006	1,749.50	1,730.10	211.3	197.1	461.4	376.2	585.9	766.6	43.4	68.2	2.1	3.1	16.7	24	427.9	294.5	0.8	0.4
2007	1,867.40	1,679.10	190.7	228.6	482.5	328.7	646.5	705.4	59.2	59.1	3.7	2.3	17.2	17.9	467.5	336.1	0.2	1.1
2008	2,557.70	1,252.50	280.7	181.2	531	222.5	1,098.70	506.5	65.3	76.2	3.2	3.1	20.4	17	558.3	245.5	0.3	0.6
2009	3,011.10	1,160.40	315.3	154.7	716.6	232.4	1,129.70	486.4	74.4	48.4	5	2.6	20.2	19.1	749.7	215.7	0.3	1
2010	2,716.90	1,492.60	268.2	251	630.5	333.5	1,006.20	550.9	87.4	41.5	11.2	2.2	34.6	15.8	678.4	297.2	0.4	0.6
2011	2,722.70	1,939.10	301	279.6	470.6	507.8	1,106.30	692.1	103	52.9	5.6	7.2	26.8	18.5	708.4	379.9	1.1	1.2
2012	2,500.40	2,853.20	328.8	195.2	345.1	729.6	879	1,409.20	126.2	61.3	5.6	5.1	76.7	6.8	737.6	445.8	1.3	0.2
2013	2,583.70	2,397.30	391.4	193	433.6	569.4	830.4	1,005.30	120.1	91.8	9.6	4.4	53.4	18.3	742.1	514.8	3.2	0.3
2014	2,477.00	2,561.90	512.3	221.5	368.9	925.3	725.7	810.7	119.7	105.4	9	6	59.8	25.6	679.4	467.2	2.2	0.3
2015	2,474.40	1,934.50	368.7	208.6	279.4	568.7	1,097.20	627.1	105.1	111.7	6.3	5.7	53.8	26.3	562.1	386	1.8	0.5

7 Waste

7.1 Overview

Total estimated waste emissions for 2015 were 11.4 Mt CO_2-e, or 2.2% of total net national emissions (excluding *LULUCF*) (Table 7.1). The majority of these emissions were from solid waste disposal, contributing 8.4 Mt CO_2-e or 74.1% of waste emissions. *Wastewater treatment and discharge* contributed a further 2.8 Mt CO_2-e (24.6%) of waste emissions while waste incineration and biological treatment of solid waste contributed 0.03 Mt CO_2-e (0.3%) and 0.1 Mt CO_2-e (1.0%) respectively. *Waste* emissions are predominantly methane-generated from anaerobic decomposition of organic matter. Small amounts of carbon dioxide are generated through the incineration of solvents and clinical waste and nitrous oxide through the decomposition of human wastes.

Table 7.1 Waste CO_2-e emissions, 2015

Greenhouse gas source and sink categories	CO_2-e emissions (Gg)				
	CO_2	CH_4	N_2O	Total	Preliminary 2016 (CO_2-e)
5 WASTE	30	10,846	491	11,368	11,564
A. Solid waste disposal	NA	8,424	NA	8,424	8,612
B. Biological treatment of solid waste	NA	105	11	116	118
C. Incineration and open burning of waste	30	NA	NE	30	31
D. Wastewater treatment and discharge	NA	2,317	481	2,797	2,804

7.1.1 Trends

Waste emissions were 45.6% (10.2 Mt CO_2-e) lower in 2015 than they were in 1990 and 2.4% (0.3 Mt CO_2-e) lower than in 2014.

Preliminary estimates of Waste sector emissions for 2016 are 11.6 Mt CO_2-e. This estimate is prepared using NGER facility data for 2015/16 and State disposal data for 2014/15. These estimates will therefore be subject to revision in the official inventory submission in 2018.

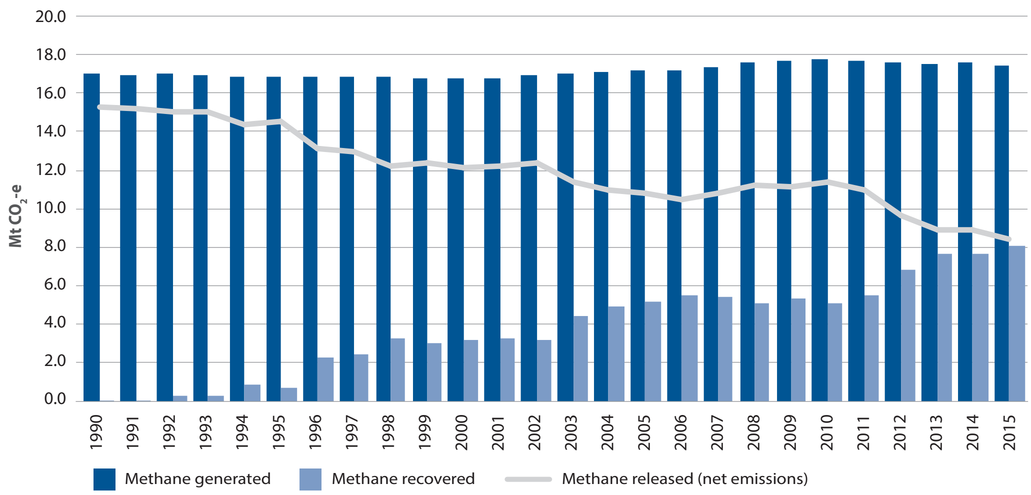
Emissions from municipal *solid waste disposal* decreased by 42.2% (8.3 Mt CO_2-e) over the period 1990 to 2015 (Figure 7.1) and were decreased by 5.3% (0.6 Mt CO_2-e). This decline since 1990 is mainly due to increases in methane recovery over the time-series. As waste degradation is a slow process, estimates of methane generation reflect waste disposal levels and composition over several decades. In recent years, as rates of recycling have increased, paper disposal in particular has declined as a share of total waste disposed. Total waste disposal has also declined in recent years as alternative waste treatment options are becoming more viable, driven by state and territory waste management policy.

Rates of methane recovery from solid waste have improved substantially since 1990, increasing from a negligible amount to 8.1 Mt CO_2-e of methane in 2015.

Emissions from the *Biological treatment of solid waste* have increased by 1.4% (0.002 Mt CO_2-e) since 2014. Emissions of CO_2 from the incineration of solvents and clinical waste decreased by 65.0% (0.1 Mt) between 1990 and 2015.

Wastewater treatment and discharge emissions decreased by 35.3% (1.5 Mt CO_2-e) over the period 1990 to 2015, with a decrease of 4.9% (0.1 Mt CO_2-e) since 2014. Changes in estimates for *wastewater treatment and discharge* emissions are largely driven by changes in industry production, population loads on centralised treatment systems and the amount of methane recovered for combustion or flaring.

Figure 7.1 Emissions from solid waste disposal, 1990–2015



7.2 Overview of source category description and methodology – waste

Table 7.2 Summary of methods and emission factors used to estimate emissions from waste

Greenhouse Gas Source And Sink Categories	CO_2		CH_4		N_2O	
	Method applied	Emission factor	Method applied	Emission factor	Method applied	Emission factor
5. Waste	T2	CS	T2	CS,D	CS	D
A. Solid waste disposal	NA	NA	T2/3	D	NA	NA
B. Biological treatment of solid waste	NA	NA	T1	CS	T1	CS
C. Incineration and open burning of waste	T2	CS	T2	CS	T2	CS
D. Wastewater treatment and discharge	NA	NA	T2/3	CS,D	CS	D

T1= Tier 1, T2 = Tier 2, CS = country specific, M = model, D = default, NE = not estimated, NA = not applicable

7.3 Source Category 5.A Solid Waste Disposal

7.3.1 Source category description

The anaerobic decomposition of organic matter in a landfill is a complex process that requires several groups of microorganisms to act in a synergistic manner under favourable conditions. Emissions emanate from waste deposited over a long period (in excess of 50 years in the Australian inventory). The final products of anaerobic decomposition are CH_4 and CO_2. Emissions of CO_2 generated from solid waste disposal are considered to be from biomass sources and therefore are not included in the waste sector of the inventory. CO_2 produced from the flaring of methane from waste is also considered as having been derived from biomass sources.

Solid waste treatment in Australia

Common with the practice in many other developed economies, solid waste is processed in Australia via four main mechanisms:

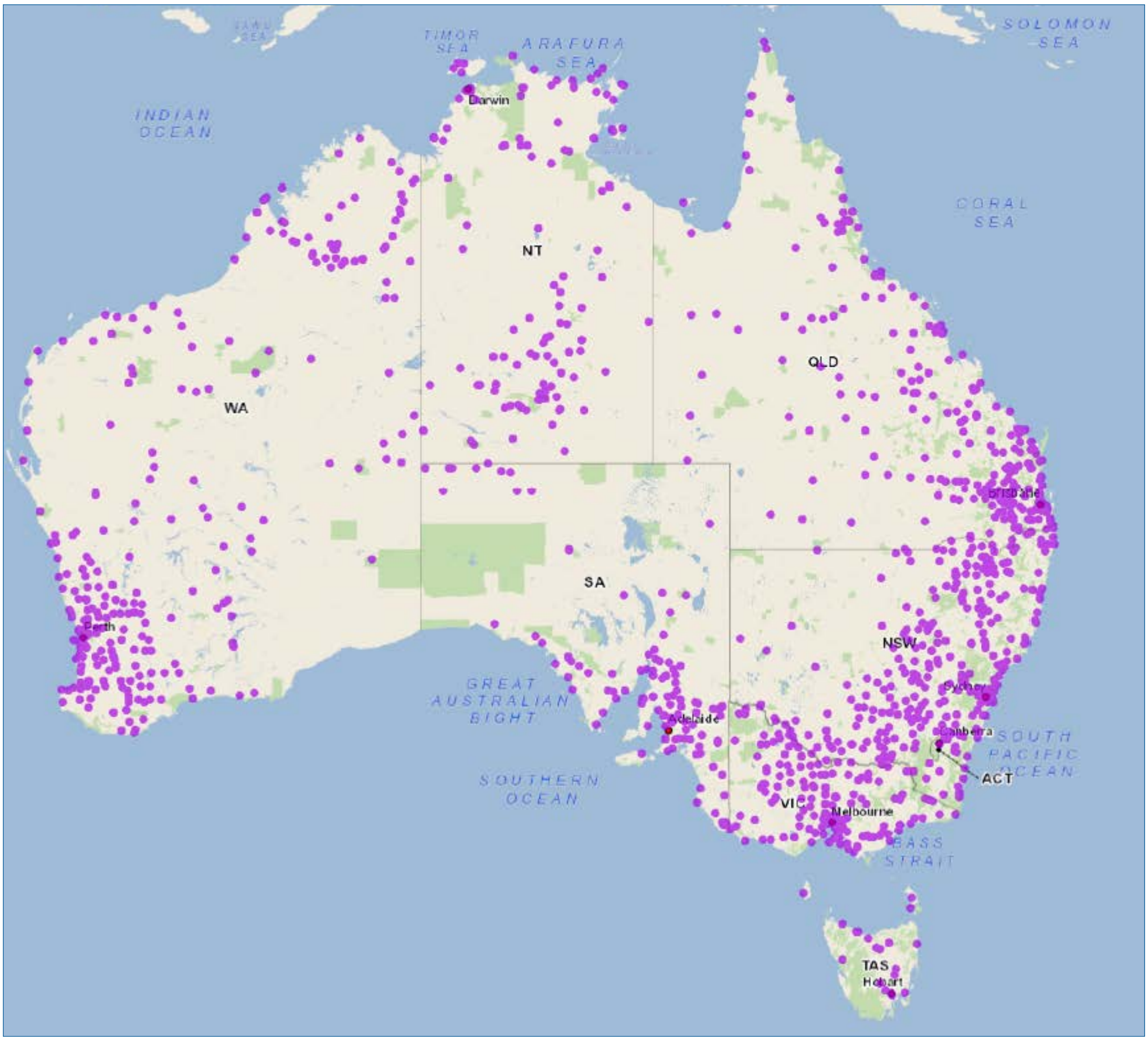
- landfill;
- biological treatment/composting;
- incineration; and
- recycling/reuse.

There are approximately 665 operating landfills in Australia DEWHA (2009). It is reported in Waste Generation and Resource Recovery in Australia (DSEWPaC and Blue Environment Pty Ltd, 2013) that these landfills receive around 21 Mt of waste. This amount equates to approximately 44% of the estimated total waste generated (48 Mt). The balance of waste, 56% of waste material generated, is recycled or reprocessed (including biological treatment/composting) while a negligible amount is treated thermally (incinerated). Figure 7.2 shows the physical locations of the major landfills in Australia. The map shows that landfills are clustered around the large population centres around Australia's coastline.

A landfill industry survey conducted by the Waste Management Association of Australia (WMAA) in 2007 found that a relatively small number of sites are responsible for the bulk of the waste received in Australia. Of the landfills surveyed, 39 process more than 200 kt of waste per year, 24 process between 100 kt and 200 kt per year, 32 process between 50 kt and 100 kt per year, 38 process between 25 kt and 50 kt per year, 61 process between 10 kt and 25 kt per year and the remainder (around 55% of the total number of landfills) process less than 10 kt each per year.

Overall, these statistics show the concentrated nature of the landfill industry in Australia. The top 8% of landfills (i.e. the top 39) manage over 55% of total waste received while almost 90% of solid waste sent to landfill in Australia is received in 133 large landfills with capacity to process 25 kt or more of waste each year. In terms of waste management practices in place at Australian landfills, 11% of landfills have a landfill gas collection system in place. However, in the larger scale landfills, this practice is more common meaning that around 40% of the methane generated is collected for either flaring or energy generation.

Figure 7.2 Australian landfill locations



Source: Geoscience Australia

Common management practices amongst larger landfills include the use of leachate collection systems (38% of landfills). Landfill designs include 38% of landfills with clay cell liners in place, 9% use HDPE cell liners while 7% use GCL liners. In terms of capping practices, 59% of landfills use clay capping, whilst 12% of landfills use either HDPE, GCL or evapotranspiration caps.

7.3.2 Activity data

The Australian methodology for calculating greenhouse gas emissions from solid waste is consistent with the IPCC tier 2 First Order Decay (FOD) Model (IPCC 2006). The methodology deployed utilises a dynamic model driven by landfill data provided by the relevant State/Territory Government agencies responsible for waste management together with facility-level data obtained under the NGER system. Although the structure of the methodology is constant across States, climate-specific parameters introduce variations in estimated emissions depending on location. The model tracks the stock of carbon estimated to be present in the landfill at any given time. Emissions are generated by the decay of that carbon stock, and reflect waste disposal activity over many decades. The methodology is fully integrated with the results of the Harvested Wood Products (HWP) model reported in Chapter 6.

7.3.3 Australian waste generation and disposal to landfill

Quantities of waste disposed to landfill are collected by State Government agencies (and in most cases also published). A mix of steady growth and some declines in waste tonnages disposed to landfill has been observed in Australia's States and Territories since 1990 reflecting, in part, differences in population growth and the impact of State government policies on waste management (Figure 7.5). In addition to total disposal in each State/Territory, disposal at individual landfills is obtained under the NGER system for landfills meeting the reporting thresholds. Approximately 75% of total disposal is covered by NGER facility data (see Figure 7.3). The residual disposal not covered by the NGER system is calculated as the total disposal reported for each state and territory minus the sum of NGER disposal in each State and Territory. Figure 7.4 shows the relationship between State and Territory reported disposal and disposal reported under NGERS.

Figure 7.3 NGERS waste disposal coverage 1990–2015

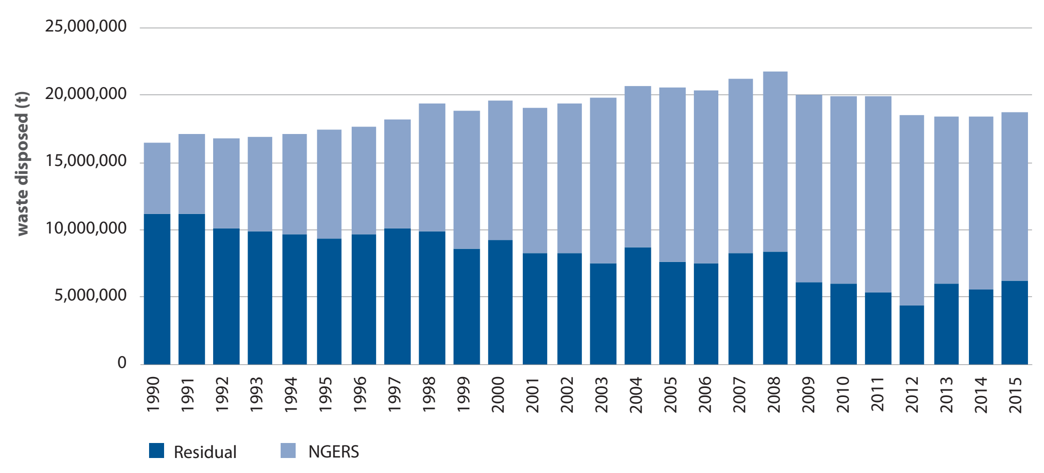
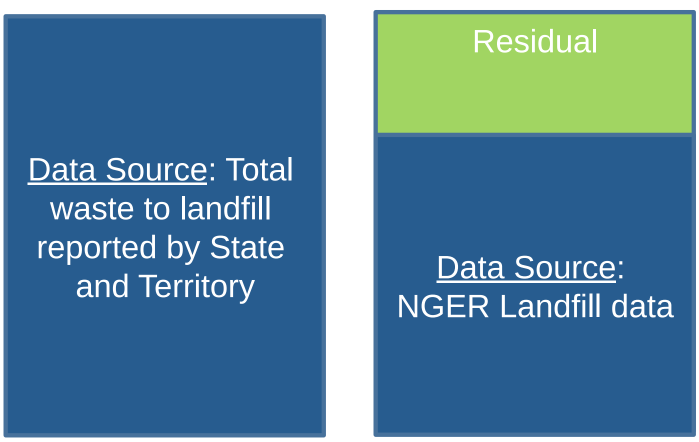
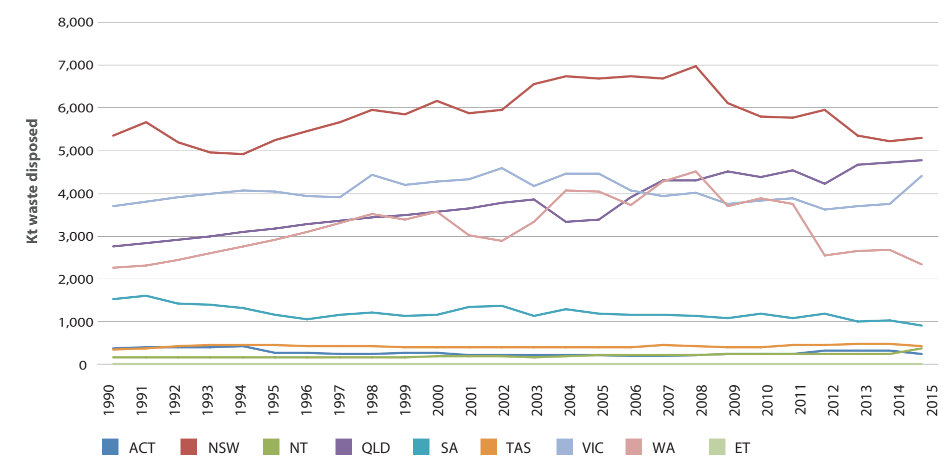


Figure 7.4 Relationship between State and Territory reported disposal and NGERS reported disposal.



It is important to note that activity data reported in this NIR and the accompanying CRF tables are for waste disposal to landfill as opposed to waste generated. State and Territory landfill levy schemes are applied specifically to waste disposed and the NGER system reporting requirements have also been designed to be consistent with this principle.

Figure 7.5 Solid waste to landfill by state 1990–2015



Source: DoEE and NGER 2015

7.3.3.1 Waste streams

Total waste to landfill data is disaggregated into three major waste streams, defined according to relevant State and Territory Government legislation and broadly consistent with the following:

- municipal solid waste – waste generated by households and local government in their maintenance of civic infrastructure such as public parks and gardens;
- commercial and industrial waste – waste generated by business and industry, for example shopping centres and office blocks or manufacturing plants; and,
- construction and demolition waste – waste resulting from the demolition, erection, construction, alteration or refurbishment of buildings and infrastructure. Construction and demolition waste may also include hazardous materials such as contaminated soil or asbestos.

State/Territory and NGER data have been used to determine the stream percentages. Where disaggregated historical data cease, the stream shares have been held constant back to 1940 (Table 7.3).

Table 7.3 Waste streams: municipal, commercial and industrial, construction and demolition: percentages by State: 2015

	NSW	VIC	QLD	NT	SA	WA	TAS	ACT
Municipal Solid Waste	27%	41%	29%	41%	25%	29%	31%	31%
Commercial and Industrial	51%	36%	30%	15%	33%	30%	61%	62%
Construction and Demolition	22%	23%	42%	43%	42%	41%	9%	7%

Source: DoEE and NGER 2015
Note: External Territories waste stream breakdown is assumed to be the same as QLD.

Some States include clean fill (uncontaminated inert solid material) in their waste to landfill estimates provided and this has an influence on the waste stream proportions, however, as this type of waste is largely inert, there is little effect on the final emissions estimate.

7.3.3.2 Individual waste types

Each waste stream is further disaggregated into a mix of individual waste type categories that contain significant fractions of biodegradable carbon. The categories considered are as follows:

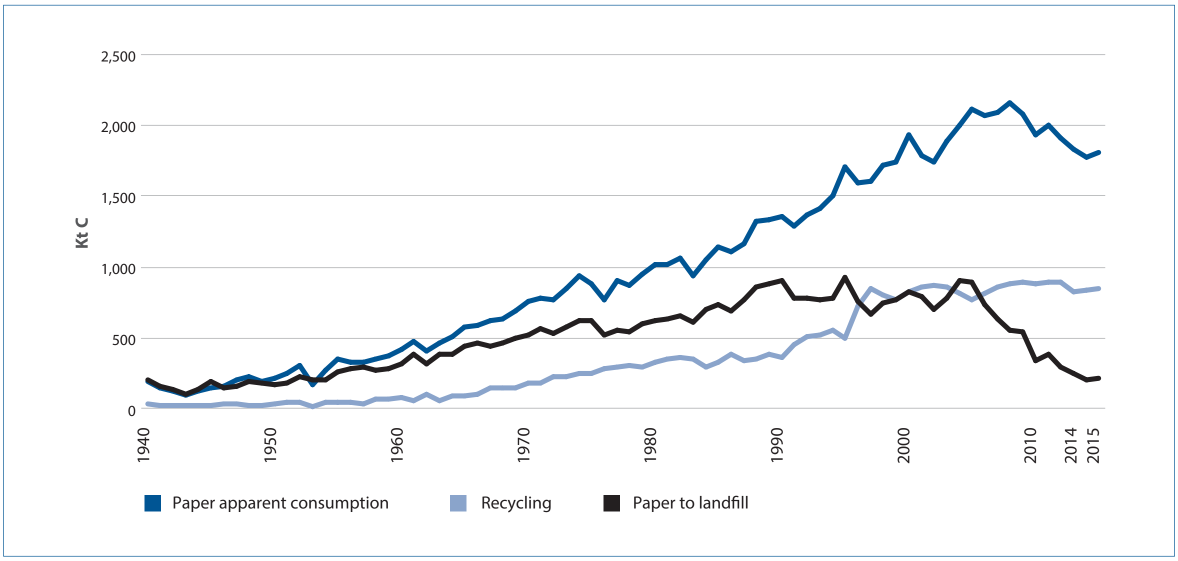
- Food;
- Paper;
- Garden and green;
- Wood;
- Wastes from the production of harvested wood products;
- Textiles;
- Sludge (including biosolids);
- Nappies;
- Rubber and leather; and,
- Inert (concrete, metal, plastics, glass, soil etc).

Harvested wood products – Paper, wood and wood waste generation and disposal

The solid waste disposal estimates and composition are integrated with the wood, wood waste and paper disposal estimates output from the harvested wood products model. These quantities of disposal are used to adjust the waste mix percentages for NGER facilities reporting default waste composition and the non-NGER residual proportion of the waste load going to landfill. This adjustment is undertaken to ensure that the total wood, wood waste and paper disposed to all Australian landfills is consistent with the output of the harvested wood products model.

The amount of paper disposed to landfill reflects those factors that affect the amount of paper in stock reaching the end of its useful life and therefore available for disposal and the changes that have occurred in disposal behaviour – particularly the shift in disposal from landfill to recycling that has occurred since the late 1980s (Figure 7.6). Data on paper and wood reaching the end of their useful life is relatively robust given the long data series available for paper and wood product production, trade and consumption and the assumptions about lifetimes of products reported in Appendix 7.I. This function is a constrained form of the function specified in Section 12.2.2 in IPCC 2006.

Figure 7.6 Paper consumption, recycling and disposal to landfill – Australia: 1940–2015



Source: Refer to Table 7.6

Over time the amount of paper waste generated for disposal will be consistent with the amount of paper consumption given the short life time assumed for this product. Overall paper consumption is estimated to have risen from 380 kt in 1940 to reach 3,625 kt in 2015 (ABARES 2015) reflecting both increasing population and increasing per capita consumption levels. In terms of carbon, these consumption estimates translate into an estimated 190 kt C in 1940 and 1,812 kt C in 2015 (Table 7.4). Per capita consumption of paper has increased from an estimated 26 kg C per person in the 1940s to 77 kg C per person in 2015. Reflecting the growth in paper consumption, waste paper generation is estimated to have increased from 245 kt C in 1940 to 1,808 kt C in 2015.

The proportion of paper waste generated that reaches landfill depends critically on the amount of paper diverted to other disposal paths. In Australia, an increasing trend to paper recycling has led to a decrease in the proportion of paper disposed to landfill. The amount of waste paper disposed to domestic recycling as a share of product reaching the end of its useful life has increased from an estimated 26% in 1990 to 47% in 2015, with a sharp jump recorded in the late 90's reflecting in part the effectiveness of a number of State Government waste management initiatives. The share of paper disposed to landfill has declined commensurately. There is also an increasing quantity of waste paper that is exported which is included in the recycling proportion cited above.

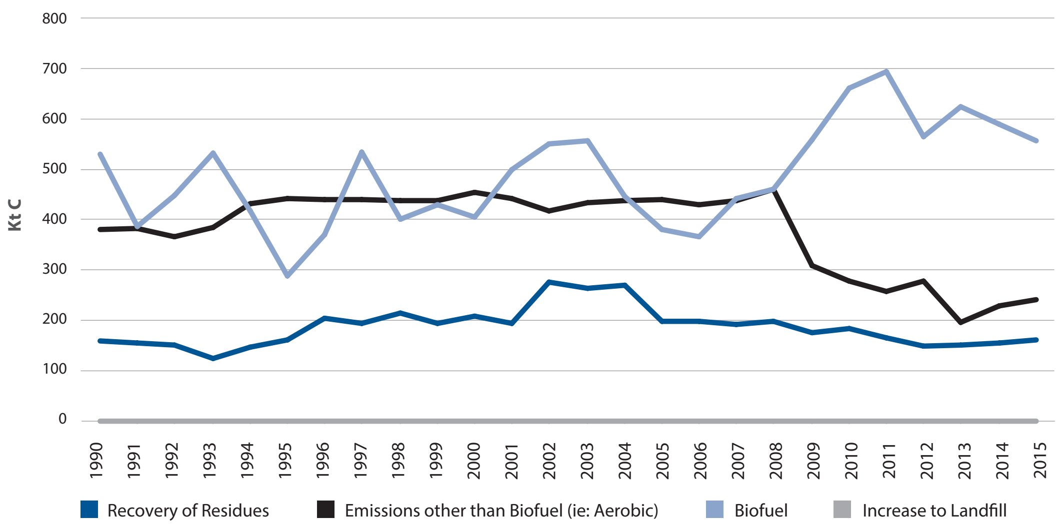
The generation of wastes from the production of harvested wood products, mainly sawmill residues and commercial offcuts, is also a significant source of waste generation and reflects two conflicting trends. The overall production of harvested wood products, particularly sawnwood from hardwoods, increased significantly between 1940 and 1960. Production has increased significantly again since the early 1990s, particularly sawnwood from softwood species and paper production, which has offset declines in the production of sawnwood from hardwood species. The ratio of waste generated to harvested wood product produced has fallen over time, however, reflecting both efficiencies in production and the changes in the mix of products produced and offsetting the effect of the overall increase in production to a large extent. In 1940, the ratio of waste generated to wood and paper product produced was 67%. By 2015, this ratio had fallen to 12%.

The amount of wastes, generated from the production of harvested wood products, that are disposed to landfill depends critically on how much of the wastes are estimated to have been diverted to other disposal paths or uses including the quantities combusted for energy [20], the quantities of fibre used in the production of other products

(paper) and the quantities disposed to aerobic treatment processes. Of these three possible alternative disposal options, there has been rapid growth in the disposal of wastes to aerobic treatment processes in recent years with a concomitant reduction in wood wastes going to landfill (Figure 7.7). For this submission, a change in the assumption determining the amount of sawmill residue sent to landfill has been made to reflect information confirming that residues are almost entirely combusted or treated onsite (Ximenez pers comm.).

20 Non-CO_2 emissions associated with the combustion of HWP wastes are accounted for in the energy sector. CO_2 emissions are reported as a memo item.

Figure 7.7 Estimated wood product wastes production, recycling, aerobic treatment processes and disposal to landfill – Australia: 1990–2015



Source: Refer to Table 7.6

Table 7.4 Paper consumption, waste generation and disposal: Australia

	Apparent paper consumption	Per capita paper consumption	Closing stock of paper product	Total paper available for disposal/ waste generation	Paper recycling	Paper disposal to landfill	Recycling share of total disposal	Disposal to landfill as share of total disposal
	kt C	kg C/head	kt C	kt C	kt C	kt C		
1940	190	26	200	245	27	204	0.14	0.83
1990	1,358	80	751	1,345	401	904	0.30	0.67
2000	1,935	102	1,045	1,854	971	827	0.52	0.45
2005	2,114	104	1,156	2,054	1,098	894	0.53	0.44
2008	2,168	102	1,193	2,136	1,524	548	0.71	0.26
2009	2,081	96	1,168	2,105	1,482	560	0.70	0.27
2010	1,934	88	1,099	2,004	1,611	332	0.80	0.17
2011	2,006	90	1,106	1,999	1,553	386	0.78	0.19
2012	1,908	84	1,074	1,939	1,592	289	0.82	0.15
2013	1,836	79	1,033	1,878	1,573	249	0.84	0.13
2014	1,779	76	998	1,813	1,556	202	0.86	0.11
2015	1,812	77	1,003	1,808	845	211	0.47	0.12

Source: DE estimates: derived from ABARES 2015, Department of National Development 1969, Jaakko Pöyry Consulting 2000, Recycled Organics Unit 2009. See Table 7.6.

Table 7.5 Wood product production, waste generation and disposal: Australia

	HWP production	HWP waste generation	Ratio of HWP waste generation to HWP production	Shares of HWP waste generation combusted (for energy)	Share of HWP waste disposed to landfill	Share of HWP waste disposed to aerobic treatment	Share of HWP waste used in other products
	kt C	kt C					
1940	1,782	931	0.52	0.30	0.00	0.70	0.00
1990	3,961	1,070	0.27	0.36	0.00	0.50	0.15
2000	5,531	1,067	0.19	0.43	0.00	0.38	0.19
2005	6,064	1,018	0.17	0.43	0.00	0.37	0.19
2008	6,355	1,119	0.18	0.43	0.00	0.41	0.18
2009	5,864	1,043	0.18	0.30	0.00	0.54	0.17
2010	5,810	1,123	0.19	0.25	0.00	0.59	0.16
2011	5,931	1,115	0.19	0.23	0.00	0.62	0.15
2012	5,478	991	0.18	0.28	0.00	0.57	0.15
2013	5,202	969	0.19	0.20	0.00	0.64	0.15
2014	5,690	972	0.17	0.24	0.00	0.61	0.16
2015	6,090	958	0.16	0.25	0.00	0.58	0.17

Source: DE: derived from ABARES 2015, Department of National Development 1969, Jaakko Pöyry 2000. See Table 7.6.

Table 7.6 Principal data sources and key assumptions made with respect to disposal of paper; waste from HWP production and wood

	Paper	Waste from HWP production	Wood
Waste generation inputs			
(1) Production and apparent consumption	ABARES 2015; Jaakko Pöyry 2000, Department of National Development 1969.	Not applicable.	ABARES 2015; Jaakko Pöyry 2000, Department of National Development 1969.
(2) End of useful product life	End of useful life function specified in Jaakko Pöyry 2000 (See Appendix 7.I).	Not applicable.	End of useful life function specified in Jaakko Pöyry 2000 (See Appendix 7.I).
(3) Waste generation	Derived from (1) and (2).	Jaakko Pöyry 2000 (See Appendix 7.I).	Derived from (1) and (2).
Method of disposal			
Landfill	Balance of paper waste generation (3) and paper disposed through recycling, combustion and aerobic decay.	Balance of HWP production waste generation (3) and wastes disposed through recycling, combustion and aerobic decay. All waste assumed treated onsite rather than sent to landfill	Determined exogenously based on GHD (2008) and Hyder Consulting (2008).
Recycling	Source: ABARES 2015, Jaakko Pöyry 2000.	Source: Jaakko Pöyry 2000, Australian Plantations Products and Paper Industry Council (2006).	Balance of waste generation from wood reaching end-of-useful life and wood disposed to landfill, combustion and aerobic decay.
Combusted for energy / waste incineration	0% assumed combusted for energy or incineration.	Derived as the balance of wood and wood waste combusted by manufacturing industry (Source: DIS 2015 and ABARES 2015) and assumptions on combustion of wood. No data is available on waste incineration.	Combusted for energy: 5% of product disposal (see Appendix 7.I). Source: Jaakko Pöyry 2000. Zero percent of product disposal assumed to be incinerated (i.e. not for energy).
Aerobic treatment processes	3% of product assumed to decay due to aerobic processes based on expert judgement. Source: Jaakko Pöyry 2000.	Source: Recycled Organics Unit (2009). Prior to 1995, 3% of product assumed to decay due to aerobic processes. Source: Jaakko Pöyry 2000.	Decay assumed to be 0% based on expert judgement. Source: Jaakko Pöyry 2000.

The key data sources and assumptions made in relation to the estimation of the data presented in Table 7.4 and Table 7.5 are reported in Table 7.6. The amount of paper disposed to landfill is estimated as the balance of the amount of paper waste generated from paper in stock reaching the end of its useful life and the amount of paper disposed to recycling, combustion and aerobic treatment processes. This estimator ensures completeness and consistency with the estimates of the stock of harvested wood products presented in Appendix 7.I and is considered to produce robust estimates because of the high quality of the available data on apparent paper consumption (ABARES 2015 and the Department of National Development 1969) and paper recycling (ABARES 2015). It also allows for the share of paper in total waste disposed to landfill to vary in response to observed rapid changes in disposal behaviour, in particular, the rapid increase in recycling of paper in Australia.

Similarly, data on the wastes from HWP production are considered robust because of the availability of high quality data on HWP production (ABARES 2015 and the Department of National Development 1969) and on the combustion of wood and wood waste (DIS 2015). Data on the amount of wastes disposed to aerobic treatment processes is available from the Recycled Organics Unit of the University of New South Wales. The other important assumption set out in Table 7.6 concerns the percentage of wastes lost through incineration. No data is currently available on the amount of waste incinerated as opposed to combusted for energy. Obtaining more accurate data on this variable is difficult. Consequently, the assumption made has been the subject of sensitivity testing, which demonstrates that waste disposed to landfill is inversely related to the assumption on incineration, indicating that there is limited risk of the estimates of waste disposed to landfill used in the inventory being underestimates.

Table 7.7 Additions and deductions from harvested wood products: 2015

	kt C
Additions to the HWP carbon stock	
Apparent consumption of HWP	3,509
Generation of HWP wastes	958
Total additions	4,467
Deductions from the HWP carbon stock	
Disposal to landfill	211
Disposal through combustion for energy/ waste incineration	242
Disposal through aerobic decay	1,308
Recycling/use in other products	1,005
Total deductions	2,766
Net increment in HWP stock	1,701

Combustion of HWP for energy reduces the amount of the HWP stock and is effectively recorded as a reduction in stock (or, equivalently, a source of emissions). In 2015, the reduction in carbon stock from combustion for energy of HWP and wastes generated from HWP production is estimated at 242 ktC. This source of emissions is effectively recorded within the HWP category. Non-CO_2 emissions from the combustion of these products are recorded in Fuel Combustion 1.A. Similarly, the disposal of HWP to landfill reduces the stock of product and is also effectively recorded as a reduction in stock (or source of emissions) against the HWP category. In 2015, the reduction in carbon stock from disposal to landfill is estimated at 211 ktC. Half of this carbon will also eventually be converted to methane in the landfills (effectively, the carbon is counted twice).

Long-term storage of harvested wood products in landfill

Estimates of CO_2 emissions from landfill are estimated using the assumption that landfill gas is 50 per cent CO_2 and are reported under the Harvested Wood Products sub-category Harvested Wood Products in Solid Waste Disposal Sites. The principles of the conservation of mass and carbon are respected and no double counting of carbon occurs. Refer to section 6.13 for further details.

Back casting of total waste disposed to landfill

The data available from State Government agencies on total waste disposed to landfill does not extend to the period prior to 1990. Nor are there any possibilities for filling in the gaps with future surveys. In these circumstances, IPCC 2006 notes that a range of splicing and extrapolation techniques are available. The technique chosen to determine the historical time series was a surrogate-data technique where the drivers used to determine total waste to landfill were the amount of waste generated from paper consumption and the estimated amount of waste generated from the production of harvested wood products. These data were chosen because published datasets of production and consumption of these variables, which are closely related to disposal, were available back to 1936. The surrogate technique applied was to assume that the total waste to landfill is perfectly correlated with the sum of paper and wood wastes available for disposal to landfill for years prior to 1990. This assumption ensures that the more general underlying influences affecting waste generation impact these estimates since: a) rising per capita incomes and rising population are reflected in rising demand for paper consumption and consequent waste generation and b) changes in production functions over time (improvements in efficiency) are reflected in the amount of waste generated in HWP.

For disposal data reported under the NGER system, information is available on the entire operational life of the landfills extending to the pre-1990 period. Where these disposal data are available, they have been used. However, it must be noted that this represents only a small proportion of currently operating landfills.

Waste mixes disposed to landfill

Waste composition is determined in two ways. For landfills covered by the NGER system, their reported waste composition is used directly. Where these data are not available, country-specific waste mix percentages are used. These waste mix percentages are obtained as outlined below.

The base waste mix percentages are derived as a simple average of waste mixes presented in studies conducted by GHD (2008) and Hyder Consulting (2008), except for data on paper and wastes from the production of harvested wood products disposed to landfill which are based on data and assumptions set out in Table 7.8 Actual waste mix percentages change over time as the amount of wood waste and paper entering landfills vary – percentages for 2014 are reported in Table 7.8.

Table 7.8 Individual waste type mix: percentage share of individual waste streams disposed to landfill 2015

	Municipal Solid Waste	Commercial & Industrial	Construction & Demolition
Food	37.8%	22.7%	0.0%
Paper [(a)]	2.7%	4.4%	0.6%
Garden and Green	18.9%	4.9%	2.1%
Wood [(a)]	1.0%	7.6%	4.9%
Waste from HWP production [(a)]	0.0%	0.0%	0.0%
Textiles	1.8%	4.9%	0.0%
Sludge	0.0%	1.8%	0.0%
Nappies	4.4%	0.0%	0.0%
Rubber and Leather	1.2%	4.3%	0.0%
Inert (concrete, metal, plastics and glass, soil etc)	32.2%	49.5%	92.4%

Source: Derived from GHD 2008 and Hyder Consulting 2008; (a) DE estimates based on data and assumptions in Table 7.5 and GHD 2008.

Table 7.9 Total waste and individual waste types disposed to landfill (kt): Australia

Year	Total waste to landfill (a,b)	Food (b)	Paper (b)	Garden (b)	Wood and wood waste (b)	Textiles, Sludge, Nappies, Rubber and Leather (b)	Other (b)
	kt	kt	Kt	kt	kt	kt	kt
1940	10,444	1,978	933	1,878	1,925	421	4,726
1990	16,366	3,260	2,242	1,365	716	839	7,944
2005	19,491	3,583	2,054	1,531	927	1,018	10,378
2008	20,472	3,693	2,219	1,582	925	1,082	10,971
2009	21,692	4,199	1,361	1,758	1,026	1,236	12,112
2010	19,897	3,915	1,390	1,624	916	1,178	10,874
2011	19,813	4,063	827	1,715	909	1,203	11,096
2012	18,445	3,951	719	1,607	851	1,213	10,103
2013	18,398	4,035	621	1,616	842	1,236	10,047
2014	18,458	3,942	505	1,640	842	1,222	10,306
2015	18,730	4,019	527	1,589	842	1,246	10,507

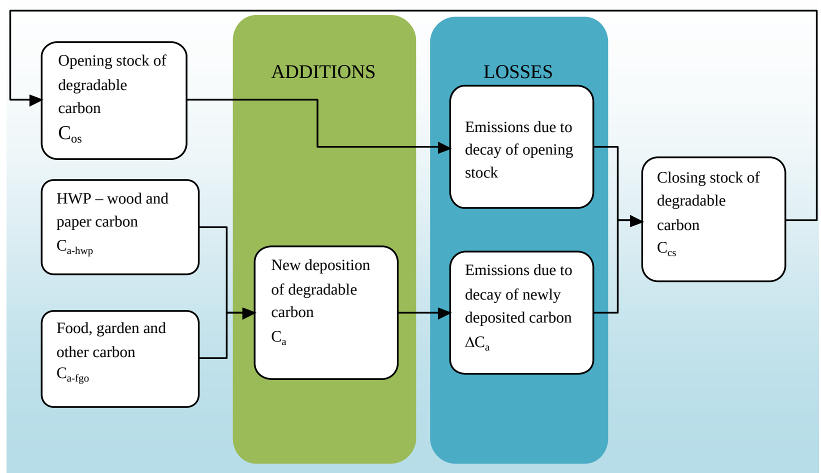
(a) State Government Agencies; (b) Department of Environment estimates.

7.3.4 Methodology

The Australian methodology for the estimation of emissions from solid waste disposal utilises the IPCC tier 2 FOD model presented in the Guidelines for National Greenhouse Gas Inventories (IPCC 2006).

The key parameters determining the amount of methane emissions are the fraction of degradable organic carbon in each individual waste type (DOC); the rate of decay assumed for each individual waste type (decay function 'k'); the fraction of degradable organic carbon that dissimilates through the life of the waste type (DOC_f); the methane correction factor (MCF) and the amount of methane captured for combustion. The model is explained in detail in IPCC 2006. The model takes account of the stock of carbon in a landfill by keeping track of additions of carbon through waste disposal and losses due to anaerobic decay. The concept of the carbon stock model approach is illustrated in Figure 7.8.

Figure 7.8 Carbon stock model flow chart



Carbon enters the landfill system via new deposition of waste C_a. Deposition is based on wood and paper carbon transferred from the HWP carbon pool $C_{a\text{-}hwp}$ and carbon in food, garden and other waste derived from data provided by State and Territory waste authorities $C_{a\text{-}fgo}$. A portion of the newly deposited carbon decays in the first year ΔC_a and the remainder contributes to the closing stock of carbon C_{cs}. Additionally, the opening stock of carbon decays over the year ΔC_{os} with the remainder going to the year's closing stock. The closing stock then becomes the next year's opening stock C_{os}. The total change in carbon stock is estimated simultaneously with estimated emissions of methane.

$C_{cs} = C_{os} - \Delta C_{os}$ (emissions lost from opening stock) $+ C_a - \Delta C_a$ (emissions lost from new deposition)

In Australia recent field work estimating methane generated at particular landfills (Bateman 2009, Dever *et al.* 2009 and Golder Associates 2009) has demonstrated that there is potentially a wide variation in methane generation rates across Australian landfills. In Australia, this is interpreted as principally reflecting:

- differences in waste composition at landfills, reflecting both the differing values of degradable organic carbon (DOC) of individual waste types and differing degradable organic carbon that is dissimitable (DOC_f) values of individual waste types; and
- differences in the decay rate 'k' reflecting differences in waste composition, management regimes or local climatic conditions.

7.3.4.1 Degradable organic carbon

Values for the degradable organic carbon (DOC) content for each waste mix category used in the model are listed in Table 7.10. The source for these parameters is IPCC (2006).

Table 7.10 Key model parameters: DOC values by individual waste type

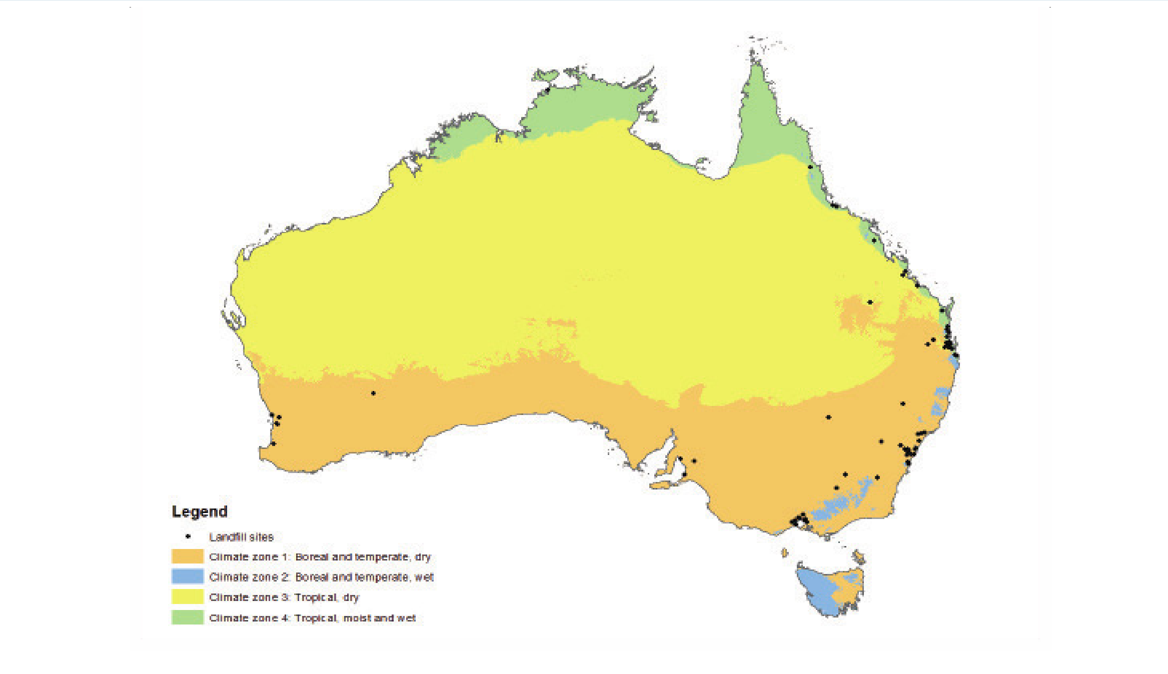
Waste Type (wet)	DOC
Food	0.15
Paper	0.40
Garden and Green	0.20
Wood and waste from HWP production	0.43
Textiles	0.24
Sludge	0.05
Nappies	0.24
Rubber and Leather	0.39
Other	-

Source: IPCC 2006.

7.3.4.2 Decay function values 'k'

The half-lives and associated 'k' values for each waste mix category applied in the FOD model are consistent with those provided in IPCC 2006.

Figure 7.9 Australian climate zones and major landfill locations.



Decay rate constants are applied to disposed waste in two ways. For landfills covered by the NGER system, the geographical location of the landfill is used to determine which of the 4 IPCC climatic zones is applicable. The distribution of the climate zones across Australia is illustrated in Figure 7.9. The map above has been produced on the basis of average monthly grids of rainfall, pan-evaporation and average temperature from Bureau of Meteorology records between 1970 and 2010.

For the proportion of disposed waste which is not covered by the NGER system, decay rate constants are assigned according to the prevailing climatic conditions at the landfill sites of the principal cities in each State and Territory. In each State, average annual temperature and annual rainfall data for the principal landfill sites were taken from data published by the Australian Bureau of Meteorology. The assumptions of climatic conditions for each State/Territory and 'k' values for each waste mix category are outlined in Table 7.11.

Table 7.11 Key model parameters: 'k' values by individual waste type and State

State / Territory	Climate description	Waste mix category	k value
NSW	Wet Temperate	Food	0.185
		Paper and Textiles	0.06
		Garden and Green	0.10
		Wood	0.03
		Textiles	0.06
		Sludge	0.185
		Nappies	0.04
		Rubber and leather	0.06
VIC, WA, SA, TAS, ACT	Dry Temperate	Food	0.06
		Paper and Textiles	0.04
		Garden and Green	0.05
		Wood	0.02
		Textiles	0.04
		Sludge	0.06
		Nappies	0.04
		Rubber and leather	0.04
QLD, NT	Moist and Wet Tropical	Food	0.4
		Paper and Textiles	0.07
		Garden and Green	0.17
		Wood	0.035
		Textiles	0.07
		Sludge	0.4
		Nappies	0.07
		Rubber and leather	0.07

Source: IPCC 2006.

7.3.4.3 Fraction of degradable organic carbon dissimilated (DOC_f)

DOC_f is an estimate of the fraction of carbon in waste that is ultimately degraded anaerobically and released from solid waste disposal site (SWDS) and reflects the fact the some carbon in waste does not degrade or degrades very slowly under anaerobic conditions (IPCC 2006,Vol 5 p3.13).

Values of DOC_f for individual waste types that are appropriate for Australia have been selected based on well documented research on DOC_f values contained in Barlaz 1998, 2005 and 2008 and Wang *et al.* 2011. These estimates provide an upper limit of an appropriate DOC_f value. The approach adopted, while conservative, is based on the recommendations of Guendehou (2010) after consultations with a range of experts in the industry GHD (2010), Hyder Consulting (2010) and Blue Environment (2010).

The results of the Barlaz work are presented in Table 7.12 which shows reported values for the initial carbon content and carbon remaining after decomposition and the derived DOC_f value.

Table 7.12 DOC_f values for individual waste types derived from laboratory experiments

Waste type	Initial total organic carbon (kg/dry kg)	Organic carbon remaining after decomposition (kg/dry kg)	DOC_f (A-B)/A
	A	B	
Newsprint	0.49	0.42	0.15
Office paper	0.4	0.05	0.88
Old corrugated containers	0.47	0.26	0.45
Coated paper	0.34	0.27	0.21
Branches	0.49	0.38	0.23
Grass	0.45	0.24	0.47
Leaves	0.42	0.3	0.28
Food	0.51	0.08	0.84

Source: Derived by Hyder Consulting 2009 in consultation with Morton Barlaz.

For paper, the Barlaz work translates into a range of DOC_f values, for four classes of paper types meaning that it is important to understand the types of paper waste entering the landfill waste system in order to assign the appropriate weights for each of the Barlaz results. Newsprint contains high levels of lignin, which inhibits decomposition in anaerobic conditions, while office paper contains almost no lignin and therefore experiences high levels of decomposition even under anaerobic conditions. In addition, the Barlaz paper classes are not exhaustive of all paper types. Allowance must be made for non-identified paper classes. In these cases, consideration must be given to the possible chemical composition of the paper and theoretical approaches to the estimation of methane potential.

Consequently, it was necessary to make use of available waste audit data to compile a weighted average DOC_f value for the “paper and cardboard” waste mix category. Based on paper waste composition data presented in GHD 2008 and Lamborn 2009, the proportions of paper types corresponding to the Barlaz DOC_f categories have been derived for Australian landfills (Table 7.13).

Given that the classes of paper analysed by Barlaz were not comprehensive, a DOC_f value is also required to be assumed for ‘other’ paper. One factor important to the analysis of decomposition under anaerobic conditions relates to the amount of cellulose and hemicellulose in the product (see for example, Lamborn 2009). In the case of the paper types analysed with DOC_f values, the reported cellulose and hemicellulose proportions in the product range from 51.7 for coated paper up to 91.3 for office paper (Barlaz 1998). For the classification of ‘other’ paper, the value of cellulose and hemicellulose reported by Lamborn 2009 is 72.0 – which is very much in the middle of the range reported for the waste paper types for which DOC_f values are available. Consequently, the assumption made is that the DOC_f for the ‘other’ paper is the weighted average of the paper types for which DOC_f values are available.

Table 7.13 Derivation of a weighted average DOC_f value for paper

Paper type	Composition (% of total paper in analysis) [(a)]	Cellulose and hemicellulose (%) [(b)]	DOC_f [(c)]
Newspaper	4%	54.6	15%
Office paper	11%	91.3	88%
Cardboard	58%	67.2	45%
Coated Paper	1%	51.7	21%
Other paper	25%	72.0	49%
Weighted average of above			**49%**

(a) Lamborn 2009, (b) Barlaz 1998, (c) Hyder consulting 2009, except for 'other paper'.

Micales and Skog (1996) published a range of methane potentials for a comprehensive list of paper types (based on data in Doorn and Barlaz 1995) which show that methane potentials range between 0.054 g CH_4/g refuse for newspaper and 0.131 g CH_4/g refuse for office paper. These results also suggest that the range of DOC_f values shown in Table 7.12 above derived from Barlaz data encompass the broad range of paper types that may be present in Australian landfills and the degradabilities observed in the experimental data.

For wood products, Australia has selected a value of 0.10 to apply to all wood deposited in landfills in Australia based on the mid-point of observations of DOC_f values for various wood species examined in Wang *et al.* 2011 which included results for softwood, hardwood, plywood and MDF as well as some Australian wood species. Results from these laboratory-based experiments suggest that, particularly for the Australian wood species examined, very little anaerobic degradation occurs. Follow up studies by Australian researchers (Ximenes *et al.* 2013) for a range of engineered wood products (particleboard, MDF and high pressure laminate) observed carbon loss factors no higher than 1.6% while previous field studies (Gardner *et al.* 2008b and Gardner *et al.* 2004) also indicate that low DOC_f values are likely for timber products.

For food waste the DOC_f value of 0.84 reported in Table 7.14, based on the work of Barlaz 1998 has been used.

For garden and park waste a DOC_f value of 0.47 based on the work of Barlaz 1998 has been used. This value assumes the upper estimate calculated by Barlaz for "leaves" and "grass". On this assumption, it represents a conservative upper limit on the likely true DOC_f value for this category.

For the remaining waste categories in the inventory the IPCC default value of 0.5 has been retained. This includes values for textiles, sludge, nappies, and rubber and leather which require additional research to be undertaken before waste type specific values are adopted.

The complete list of DOC_f values for each inventory waste mix type is presented in Table 7.14. As indicated in the QA/QC section, the weighted average DOC_f value for Australian landfills is estimated to be 58.2 for 2014.

Table 7.14 Key model parameters: DOC_f values by individual waste types

Waste type	DOC_f value
Food	0.84
Paper and paper board	0.49
Garden and park	0.47
Wood	0.10
Wood waste	0.10
Textiles	0.50
Sludge	0.50
Nappies	0.50
Rubber and Leather	0.50
Inert waste (including concrete, metal, plastic and glass)	0.00

7.3.4.4 Methane correction factor (MCF)

An important parameter for the emissions calculation is the methane correction factor (MCF) which is intended to represent the extent of anaerobic conditions in landfills. It is assumed that all *solid waste disposal on land* in Australia is disposed to well managed landfills, hence a methane correction factor of 1.0 has been applied to all years. Data from a Waste Management Association of Australia (WMAA 2007) survey on waste management practices undertaken in 2007 was reviewed for this inventory and considered to provide strong evidence that the landfills in Australia adopt management practices that are consistent with the IPCC characterisation of well-managed landfills. 71% of landfills, receiving an estimated 95% of waste, operate with some form of permanent cover. The balance of landfills are assumed to operate within the meaning of well-managed landfills, as defined by the IPCC.

7.3.4.5 Delay time

The IPCC default delay time of six months (M =13) has been used to reflect the fact that methane generation does not begin immediately upon deposition of the waste. Under this assumption, and given that all waste is assumed to be delivered at the mid-point of the year, anaerobic decay is set to start, on average, on the first day of the year following deposition.

7.3.4.6 Fraction of decomposition that results in methane (F)

The IPCC default value of 0.5 is assumed for this inventory, reflecting the assumption that the decomposition of organic carbon under anaerobic conditions is equally split between the generation of methane and the generation of carbon dioxide.

7.3.4.7 Oxidation factor (OF)

The IPCC default value of 0.1 is assumed for this inventory, reflecting the proportion of methane generated by the decomposition of organic carbon under anaerobic conditions that is oxidised before the gas reaches the surface of the landfill.

7.3.4.8 Methane capture

Net emissions are derived after accounting for methane recovery undertaken at the landfill site. The quantity of methane recovered for flaring and power is based upon reported methane capture under the NGER system for 2009 onwards and industry survey for the years 1990–2008.

Methane capture reported by landfill gas capture companies is measured according to the gaseous fuels measurement provisions set out in the *NGER (Measurement) Determination*. Under these provisions, a range of options are available to reporters including indirect measurement on the basis of invoices or electricity dispatched or direct measurement at the point of consumption using gas measuring equipment operated in accordance with set standards. Under these reporting provisions, landfill gas companies must also specify whether the collected gas is combusted for power generation, flared or sent offsite for other uses.

Methane recovered (R(t)) is subtracted from the amount generated before applying the oxidation factor, because only landfill gas that is not captured is subject to oxidation in the upper layer of the landfill.

Emissions from the combustion of landfill gas for power generation are reported in the energy sector (1.A.1.a – public electricity and head production)

7.3.5 Emission estimates

7.3.5.1 Methane

Additions to and losses from the pool of organic carbon in landfills including both degradable and non-degradable organic carbon from all waste types are presented in Table 7.15. Half of the carbon losses are assumed to result in the generation of methane (assuming that F, the share of carbon decay resulting in methane, is the IPCC default value of 0.5). The other half is assumed to be carbon dioxide and is effectively estimated when this carbon is deducted from the pool of carbon in the harvested wood product pool.

Table 7.15 Methane generation and emissions, Australia: 1990 to 2015

Year	Carbon additions to landfill (kt C)	Carbon loss (through emissions) (kt C)	Methane generated (Gg CH_4) [a]	Methane capture (Gg CH_4)	Net methane (Gg CH_4)
1990	2,205	1,018	680	2	610
2000	2,348	1,002	669	129	486
2005	2,457	1,028	687	207	431
2008	2,307	1,052	703	205	448
2009	2,176	1,061	709	215	445
2010	2,012	1,064	711	204	456
2011	2,024	1,060	708	221	439
2012	1,902	1,052	702	272	387
2013	1,821	1,049	701	305	356
2014	1,756	1,050	701	304	357
2015	1,830	1,042	697	323	337

Note: (a) methane generated prior to oxidation.
Source: Department of Environment estimates.

7.3.5.2 Non-methane volatile organic compounds (NMVOC)

Small quantities of NMVOC are contained in landfill gas emitted from landfills in Australia. Some of these NMVOC are generated by the decomposition process and others are residuals from the particular types of waste dumped in the landfill.

The CSIRO Division of Coal and Energy Technology in Sydney (Duffy *et al.* 1995) investigated NMVOC emissions from four landfills in the Sydney region. They found significant concentrations, up to 10 parts per million by volume (ppmv), for approximately 60 different compounds. Researchers in the UK (Baldwin and Scott 1991) have found between 2,200 and 4,500 milligrams per cubic metre (mg/m^3) of NMVOC present in landfill gas.

In Australian landfills, liquid waste is rarely disposed of with solid waste whereas co-disposal is common practice in the UK. On this basis the lower range of 2,000 mg/m^3 found by the UK researchers is used for NMVOC emissions from Australian landfills unless other site-specific information is available.

It is assumed that NMVOC emissions from landfills comprise 0.2% of total landfill gas emissions; the average methane fraction of landfill gas as generated before release to the atmosphere is 0.5. This quantity is a weighted mean for all previous years of waste data used to calculate any inventory year's data and the proportion of methane emitted after oxidation is 0.9.

7.4 Source Category 5.B Biological Treatment of Solid Waste

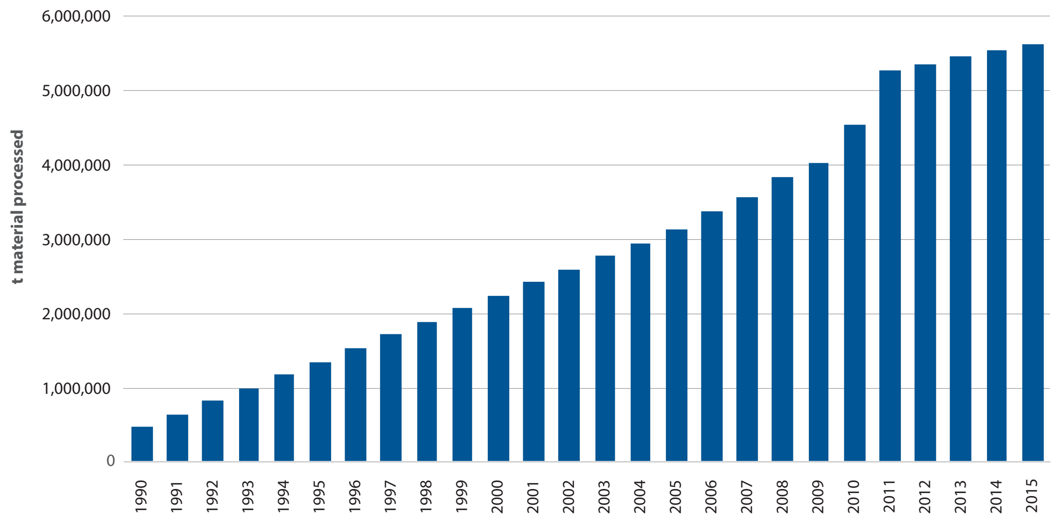
Emissions from the biological treatment of solid waste were 114 Gg CO_2-e in 2015.

Biological treatment of solid waste through processes such as windrow composting and enclosed anaerobic digestion is considered an emerging treatment pathway in Australia and one where a small amount of activity data has become available under the NGER system (2009 onwards) and through an annual industry survey. For this inventory, there is no anaerobic digestion being undertaken in Australia, however, it is expected that the use of these kinds of waste treatment processes will be taken up and reported on in coming years. This is based on more recent NGER facility level data now available.

Methodology

Australia has applied the tier 1 method from the *2006 IPCC Guidelines* to derive estimates of emissions based upon the total amount of material processed through composting and anaerobic digestion. Activity data are obtained from an annual industry survey undertaken by the Recycled Organics Unit at the University of New South Wales. Survey data cover the years 2004 to 2010 with extrapolation used to derive activity data for the years 1990 to 2003 (ROU various years). The time-series of quantities of waste material processed via composting is shown in Figure 7.10.

Figure 7.10 Quantities of material processed via composting 1990–2015



Choice of emission factors

Australia has adopted country-specific emission factors for CH_4 and N_2O emissions from composting based on research conducted by Amlinger (2008) covering the composting of bio-waste, loppings and home composting material. The emission factors are shown in Table 7.16.

Table 7.16 Composting emission factors (t CO_2-e/t material processed) used in the Australian inventory

	CH_4 emission factor (t CO_2-e/t material processed)	N_2O emission factor (t CO_2-e/t material processed)
Composting	0.019	0.002

The country-specific emission factors have been drawn from the document *Update of emission factors for N_2O and CH_4 for composting, anaerobic digestion and waste incineration* (DHV 2010) which itself cites Amlinger 2008 as the source of its recommended emission factors. DHV 2010 presents a synthesis of all available research data covering emissions from the biological treatment of solid.

These emission factors are considered suitable for use in Australia's inventory due to the following:

1. Emission factors fall within the IPCC default ranges.

While the CH_4 and N_2O emission factors chosen are towards the lower end of the default range, it has been concluded by Alminger (2008) that values in excess of 0.065 t CO_2-e / t material processed probably indicate some kind of system mis-management such as insufficient aeration or mechanical turning. The mid-range IPCC default factors according to this conclusion would suggest a level of system mismanagement not thought to occur in Australia.

2. Waste types considered by Amlinger (2008) are representative of waste types commonly processed via biological treatment in Australia (namely bio-waste and greenwaste).

GHD 2010 cites typical materials treated by the various biological processes in Australia:

- Source separated garden organics;
- Source separated garden organic organics with biosolids;
- Source separated garden organics with food waste;
- Source separated garden organics with food waste and biosolids;
- Source separated food waste; and
- Mixed residual waste containing food waste and paper.

3. The technologies examined (windrow composting processes) are reflective of those commonly used in Australia. The Recycled Organics Unit identifies aerobic windrow composting as the dominant form of biological treatment of solid waste currently employed in Australia.

7.5 Source Category 5.C Incineration and Open Burning of Solid Waste

Emissions are estimated from the incineration of solvents and municipal and clinical waste. Incineration estimates include a quantity of solvent generated through various metal product coating and finishing processes. In this instance, incineration is used as a method to minimize emissions of solvents and VOCs to the atmosphere and leads to emissions of CO_2. Data on the incineration of solvents prior to 2004 is based on company data after which emissions from this source have been based on data estimated by the DE.

Carbon dioxide emissions from incineration of solvents are estimated by converting the volume of solvent incinerated (Litres) to the weight of solvent (using specific volume factor of 1229 L/t), deriving the energy content of the mass of solvent (using the energy content of 44 GJ/t), and using a carbon dioxide emission factor per petajoule of solvent (69.6 Gg/PJ).

Between 1990 and 1996, there were three incinerators receiving municipal solid waste. These were located in New South Wales and Queensland. All three incinerators ceased operations in the mid-1990's.

In addition to the incineration of municipal solid waste, a quantity of clinical waste is incinerated in four major facilities located in Queensland, New South Wales, South Australia and Western Australia. Data on the quantities of municipal solid waste incinerated are based upon published processing capacities of the three incineration plants prior to decommissioning. Data on the quantities of clinical waste incinerated have been obtained from a per-capita waste generation rate derived from data reported under the NGER system, by O'Brien (2006b) and an estimate of State population reported by the Australian Bureau of Statistics.

The quantity of CO_2 emitted as a result of the incineration of municipal and clinical waste is based upon the quantity of waste incinerated, the carbon content of the waste and the proportion of that carbon which is of fossil origin and the efficiency of the combustion process (oxidation factor). The country-specific fossil carbon content of municipal waste of 7% is based upon empirical data presented in NGGIC (1995) for incineration activities occurring in 1990. Of this 7% of fossil carbon in municipal waste, it is estimated that 80% of this carbon is combustible (NGGIC 1995). Emissions of N_2O from the incineration of municipal solid waste are also estimated based on a country-specific emission factor of 0.00015 Gg of N_2O/Gg of waste taken from NGGIC (1995). The carbon content factors used in the emissions estimation are shown in Table 7.17. Emissions of methane from the incineration of municipal solid waste have been calculated based on the energy content of "Non-Biomass municipal materials if recycled and combusted to produce heat or electricity" of 12.2 GJ/t MSW used for

NGERS and a CH_4 emission factor of 30 kg CH_4/TJ MSW taken from the 2006 IPCC Guidelines.

The 2006 IPCC guidelines do not provide default CH_4 and N_2O emission factors for the incineration of clinical waste and solvents. Furthermore, when the highest 2006 IPCC default EFs for CH_4 and N_2O listed for municipal solid and general industrial waste incineration are applied to the AD for clinical waste and solvents incineration, emissions estimates contribute around 0.0001% (0.7 Gg CO_2-e) of total emissions from all sectors. Accordingly, emissions of CH_4 and N_2O from this source are not estimated in the inventory on the grounds that emissions fall below the significance threshold.

Table 7.17 Parameters used in estimation of waste incineration emissions

	Municipal Solid Waste [(a)]	Clinical Waste [(b)]
Proportion of waste that contains fossil carbon	0.07	
Proportion of waste that is carbon		0.6
Proportion of fossil carbon containing products that is carbon	0.80	
Fossil carbon content as a proportion of total carbon		0.4
Oxidation factor	1	0.95
Energy content of Non-Biomass municipal materials if recycled and combusted to produce heat or electricity (GJ/t)	12.2	

Source: (a) NGGIC 1995 / NGERS, (b) IPCC 2000.

7.6 Source Category 5.D Wastewater Treatment and Discharge

7.6.1 Source category description

The anaerobic decomposition of organic matter in wastewater results in emissions of methane while chemical processes of nitrification and denitrification in wastewater treatment plants and discharge waters give rise to emissions of nitrous oxide.

Large quantities of CH_4 are not usually found in wastewater due to the fact that even small amounts of oxygen are toxic to the anaerobic bacteria that produce the CH_4. In wastewater treatment plants, however, there are a number of processes that foster the growth of these organisms by providing anaerobic conditions.

As methane is generated by the decomposition of organic matter, the principal factor which determines the methane generation potential of wastewater is the amount of organic material in the wastewater stream. This is typically expressed in terms of Chemical Oxygen Demand (COD). COD is a measure of the oxygen consumed during total chemical oxidation (both biodegradable and non-biodegradable) of all material in the wastewater (IPCC 2006).

Nitrous oxide, N_2O, is also generated from municipal wastewater treatment plants. Nitrogen, which is present in the form of urea in urine and also as ammonia in domestic wastewater, can be converted to another compound—nitrate (NO_3). Nitrate is less harmful to receiving waters since it does not take oxygen from the water. The conversion of nitrogen to nitrate is usually done by secondary and tertiary wastewater treatment plants using special bacteria in a process called nitrification. Following the nitrification step some facilities will also use a second biological process, known as denitrification. Denitrification further converts the nitrogen in the nitrates to nitrogen gas, which is then released into the atmosphere. Nitrification and denitrification processes also take place naturally in rivers and estuaries. N_2O is a by-product of both nitrification and denitrification.

Municipal wastewater treatment plants in Australia treat a major portion of the domestic sewage and commercial wastewater, and a significant part of industrial wastewater. Approximately 5% of the Australian population is not connected to the domestic sewer and instead utilise on-site treatment of wastewater such as septic tank systems (WSAA 2005). Some industrial wastewater is treated on-site and discharged either to an aquatic environment or to the domestic sewer system which then feeds into a municipal wastewater treatment plant. A schematic diagram of the pathways for the treatment of wastewater in Australia is shown in Figure 7.11.

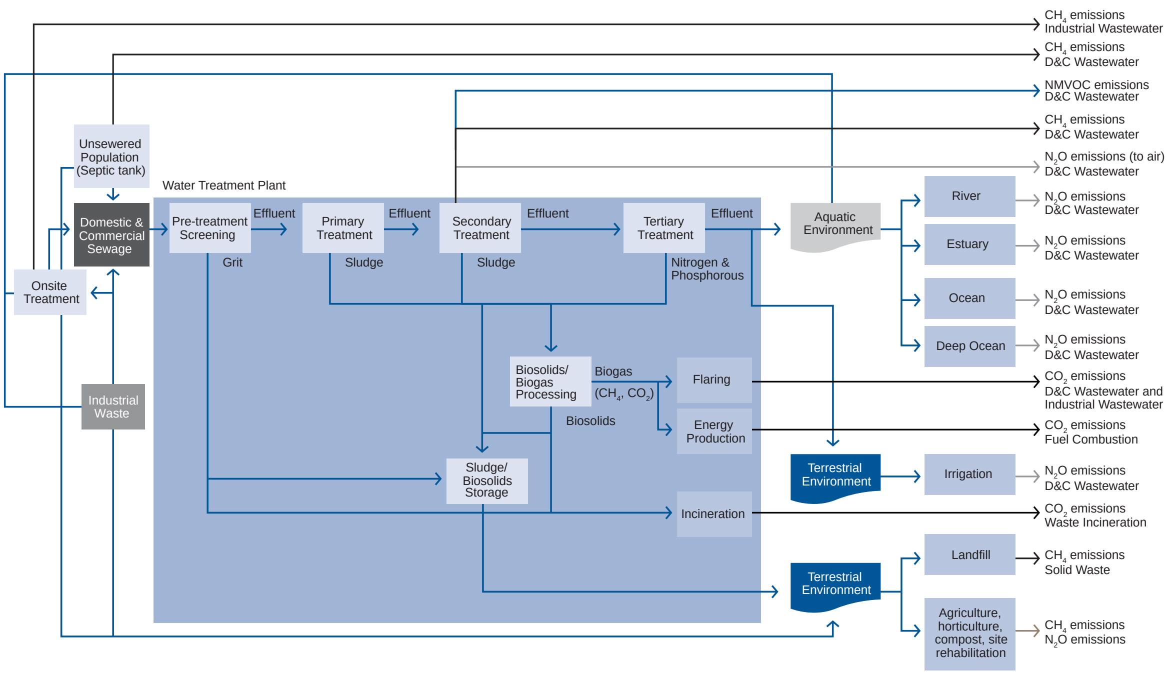
Consistent with IPCC *good practice*, methane emissions from effluent discharge to receiving waters is not reported in the inventory. Similarly, N_2O emissions from any form of industrial wastewater discharge and from discharge of municipal wastewater to ocean and deep ocean waters or used in irrigation are considered negligible and are not reported in the inventory.

Sludge removed from wastewater treatment plants is either disposed to landfill or can be further treated to produce biosolids and then used in a land application such as agriculture, horticulture, composting or site rehabilitation. Emissions of methane from disposal of sludge in a landfill are included in the solid waste sector. Emissions of nitrous oxide from land application are included in the agriculture sector under 3.D Agricultural soils.

Methane generated at wastewater treatment facilities may be captured and combusted for energy purposes or flared. The amount of CH_4 captured or flared is subtracted from the total CH_4 generated. Quantities of sludge biogas combusted for the production of energy and the associated non-CO_2 emissions are reported in the *stationary energy* sector.

Carbon dioxide emissions are not reported in the *wastewater treatment and discharge* sector except where they are derived from non-biomass sources of carbon.

Figure 7.11 Pathways for Wastewater



Wastewater treatment in Australia

A survey of the Australian wastewater industry was conducted by Department of Climate Change in 2009 (DCC 2009) to gather information on the operational characteristics of the wastewater sector including the location of discharge points, treatment levels, effluent volumes and type of aquatic environment to which the effluent flowed. The utilities which participated in the survey were selected on the basis of two criteria: that they serviced more than 50,000 customers and that these customers were living in coastal areas. The 11 utilities in Australia which met these criteria were asked to take part in the survey and 10 of these provided a response. In total, the respondents represented wastewater utilities which operate more than 100 facilities and treat wastewater for over 60% of the Australian population, all of which were living in coastal cities or communities.

More than three quarters of Australia's total population live in coastal areas. According to data from the Australian Bureau of Statistics (ABS 2009e), in 2009 the total Australian population was approximately 22 million people and around 16 million of these were living in capital cities and major centres on the coast of Australia. The residual population not covered by the DCC survey was approximately eight million people and it is estimated that at least three million of these people were also living on the coast of Australia.

The survey found that wastewater treatment facilities in Australia predominantly process wastewater to a secondary or tertiary treatment level before discharging the wastewater into an aquatic environment. However, some large facilities process the wastewater to a primary level only. As the treatment level increases from primary to secondary to tertiary, the number of unit operations used to treat the wastewater and the amount of organic matter and nitrogen removed before discharge to an aquatic environment increases.

Proportions of Australia's population connected to each treatment level are presented in Table 7.18 together with data for the residual population not covered by the survey which has been extrapolated from the survey data where possible. Nitrogen entering and leaving each treatment level is also shown in Table 7.18. The data clearly show that more complex treatment systems remove a greater proportion of nitrogen and thus generate more N_2O.

Table 7.18 Wastewater treatment plants by level of treatment

Wastewater Treatment Level	Population serviced		Annual quantity of nitrogen entering the system (tonnes of N)		Annual quantity of nitrogen in effluent discharged (tonnes of N) [c]	
Primary	2,761,280	13%	15,931	14%	16,169 [d]	66%
Secondary	6,960,027	32%	27,333	25%	6,170	25%
Tertiary	3,231,570	15%	15,849	14%	2,001	8%
Residual – Coastal Area	3,131,923 [a]	14%	18,040 [b]	16%	N/A	N/A
Residual – Inland Area	5,880,487 [a]	27%	33,872 [b]	31%	N/A	N/A
Total	**21,965,287**		**111,024**		**24,341**	

(a) Estimated using data from Australian Bureau of Statistics 2008a.
(b) Estimated using the IPCC default method and protein intake of 0.036 tonnes per year and IPCC default, 0.16 tonnes of nitrogen per tonne of protein.
(c) Total nitrogen discharged does not include the nitrogen discharged for the residual.
(d) Nitrogen discharged from primary treatment is greater than nitrogen received due to the lower removal rate for primary systems and the transfer of wastewater between plants.

The survey also examined the discharge practices of Australian wastewater facilities. The effluent discharged by wastewater treatment plants enters one of four classes of aquatic environment which are defined as follows:

- River means all waters other than estuarine, ocean or deep ocean waters;
- Estuarine waters means all waters (other than ocean or deep ocean waters):
  - (a) that are ordinarily subject to tidal influence, and
  - (b) that have a mean tidal range greater than 800 mm (being the average difference between the mean high-water mark and the mean low-water mark, expressed in millimetres, over the course of a year);
- Ocean means all waters except for those waters enclosed by a straight line drawn between the low-water marks of consecutive headlands and deep ocean waters; and
- Deep ocean means all waters, except for river and estuarine waters, that are more than 50 metres below the ocean surface.

Survey results shown in Table 7.19 indicate that the majority of effluent is discharged to either ocean or deep ocean outfalls. Only a small proportion of effluent from coastal treatment plants is discharged to a river environment (9%). However, when the non-coastal population is taken into consideration, this proportion becomes 29%, with the additional assumption that all wastewater generated from the non-coastal population is also discharged to river. The residual population also includes the population that is unsewered; estimated at approximately 5% of the Australian population. As the type of discharge environment is critical to emissions of N_2O from discharge, this information is also included in Table 7.19 and shows a large proportion of nitrogen discharged goes to deep ocean outfalls, typically more than two kilometres from the coastline at a depth of 50 metres or more.

Table 7.19 Effluent discharged from wastewater treatment plants by type of aquatic environment for 2008 and 2009

Type of aquatic environment	Population serviced		Annual volume of effluent discharged (kilolitres)		Annual quantity of nitrogen entering the plant (t)		Annual quantity of nitrogen in effluent discharged (t)	
River	2,564,463	12%	117,734,320	9%	11,545	10%	1,334	5%
Estuary	2,920,629	13%	187,480,682	14%	16,862	15%	1,775	6%
Ocean	4,405,912	20%	385,746,932	29%	23,055	20%	6,376	22%
Deep Ocean	3,015,430	14%	360,797,519	27%	17,601	15%	16,562	57%
Residual – Coastal Area	3,178,366 [a]	14%	N/A	N/A	18,307 [b]	16%	N/A	N/A
Residual – Inland Area	5,880,487 [a]	27%	269,972,736	20%	28,384 [b]	25%	3,162 [c]	11%
Total	**21,965,287**		**1,321,732,189** [d]		**115,756**		**29,210** [d]	

(a) Estimated using data from Australian Bureau of Statistics 2008a.
(b) Estimated using the IPCC default method and protein intake of 0.036 tonnes per year and IPCC default, 0.16 tonnes of nitrogen per tonne of protein
(c) Data value estimated from extrapolation of survey data for river discharge
(d) Total effluent and nitrogen discharged does not include the nitrogen discharged for the residual coastal population.

Sludge treatment and disposal practices were also examined in the survey. Results show that approximately 87% of the nitrogen in sludge transferred out of treatment plants was reported as being used in a land application and 13% was reported as being sent to landfills. The sludge generated by the residual population not covered by the survey has been estimated by extrapolating the data from the survey using a per-capita sludge generation value. Emissions from sludge sent to landfills are included in the solid waste sector while emissions from biosolids (treated sludge) used in a land application are included in wastewater treatment.

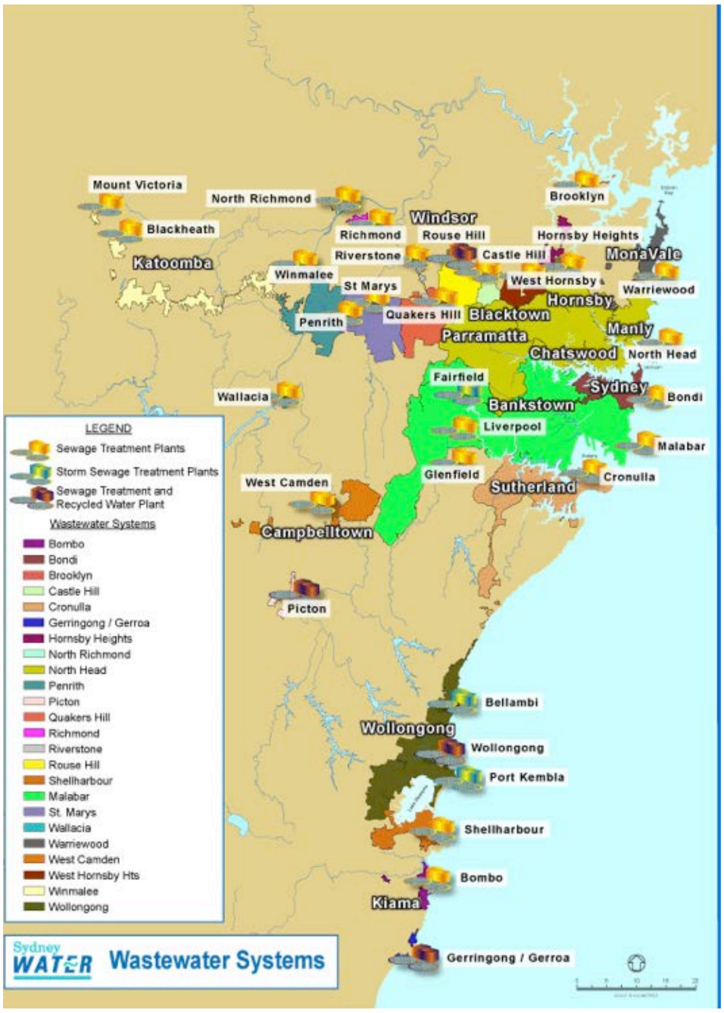
Table 7.20 Survey data for sludge reuse and disposal in 2008 and 2009

	Nitrogen (t)	% Contribution
Sludge to Landfill	1,435	13%
Sludge Reused in Land Application	5,494	49%
Residual Population – Sludge	4,336 (a)	38%
Total	**11,264**	

(a) Data value estimated from extrapolation of survey data for sludge

Sectoral snapshot: Sydney Water's effluent discharge Sydney Water Corporation is Australia's largest wastewater utility, with around 30 facilities servicing approximately 20% of Australia's population mainly living in the cities of Sydney and Wollongong. In addition to providing annual reports on each facility to the New South Wales state government, Sydney Water also publish information about their operations on their website at www.sydneywater.com.au. A map of Sydney Water's operations is shown in Figure 7.10 and information made available on their website has been summarised in Table 7.21 below. The data in Table 7.21 shows that 17 of Sydney Water's facilities discharge into a river, however, most of the effluent discharged by volume, approximately 87%, enters ocean and deep ocean waters.

Figure 7.12 Sydney Water Wastewater Systems



Source: Sydney water

Table 7.21 Sydney Water Corporation Wastewater Treatment Plants 2008

	Discharge Type	Discharge Point	Level of Treatment	Total volume of treated wastewater discharged to the waterway (million litres)	Estimated population Serviced	Total discharge load to waterway (kg)	
						BOD	Total nitrogen
Inland sewage treatment plants							
St Marys	River	South Creek (a tributary of South Creek)	Tertiary treatment	14,829	139,700	57,925	63,824
Quakers Hill	River	South Creek (Breakfast Creek, a tributary of Eastern Creek)	Tertiary treatment	13,816	144,400	36,693	64,606
Riverstone	River	South Creek (Eastern Creek, a tributary of South Creek)	Tertiary treatment	743	8400	1,532	5,796
Brooklyn	River	Hawkesbury River at Kangaroo Point	Tertiary treatment	14	500	36	127
West Hornsby	River	Waitara Creek, a tributary of Berowra Creek	Tertiary treatment	5,210	53,500	9,876	21,645
West Camden	River	Matahill Creek, a tributary of the Nepean River	Tertiary treatment	3,913	49,700	13,156	49,545
North Richmond	River	Redbank Creek, a tributary of the Hawkesbury River	Tertiary treatment	341	3,760	886	2,005
Richmond	River	Discharging mainly to irrigation schemes for a local university campus and golf course. Excess flows are discharged to an inland waterway (Rickabys Creek).	Tertiary treatment	391	7,800	675	1,671
Winmalee	River	Unnamed tributary of the Nepean River	Tertiary treatment	6,792	56,300	22,005	66,220
Hornsby Heights	River	Calna Creek, a tributary of Berowra Creek	Tertiary treatment	2,496	28,300	6,058	7,826
Rouse Hill	River	Second Ponds Creek, a tributary of Cattai Creek (partial discharge only)	Tertiary treatment plant and recycled water plant	4,355	63,100	6,168	31,662
Castle Hill	River	Cattai Creek	Tertiary treatment	3,134	24,900	13,157	46,805
Penrith	River	Boundary Creek, a tributary of the Nepean River	Tertiary treatment	9,541	96,800	18,776	39,799
Wallacia	River	Warragamba River	Tertiary treatment	242	2,670	721	1,351
Blackheath	River	Hat Hill Creek, a tributary of the Grose River	Tertiary treatment	424		1,676	10,983
Mount Victoria	River	Fairy Dell Creek, a tributary of the Cox's River	Tertiary treatment	72		843	885
Gerringong Gerroa	Recycled or to wetland	Treated wastewater is mainly discharged to an irrigation scheme for a local dairy farm.	Tertiary treatment		11,000	326	201

	Discharge Type	Discharge Point	Level of Treatment	Total volume of treated wastewater discharged to the waterway (million litres)	Estimated population Serviced	Total discharge load to waterway (kg)	
						BOD	Total nitrogen
Coastal sewage treatment plants							
Wollongong (incl. Bellambi and Port Kembla STPs)	Ocean	Reuse at Bluescope steelworks with remainder discharging to the ocean via an extended outfall one kilometre from the shoreline	Tertiary treatment	21,238	199,000	142,551	377,149
Shellharbour	Ocean	Ocean via a nearshore outfall (at Barrack Point).	Secondary treatment	6,681	60,000	29,557	121,904
Bombo	Ocean	Ocean via a shoreline outfall at the headland north of Bombo Beach	Secondary treatment	1,372	13,300	7,212	11,683
North Head	Deep Ocean	Ocean Outfall – The outfall discharges 3.7 km from the shoreline at 65 m maximum water depth	Primary treatment	138,623	1,240,000	34,096,767	6,816,185
Malabar (incl. Liverpool, Glenfield and Fairfield STPs)	Deep Ocean	Ocean Outfall – outfall discharges 3.6 km from the shoreline at 82 m maximum water depth	Primary treatment	185,415	1,690,000	38,204,663	7,669,426
Bondi	Deep Ocean	Ocean outfall 2.2 km from the shoreline at 63 m maximum water depth	Primary treatment	45,256	480,000	9,441,442	2,218,050
Cronulla	Ocean	Ocean via a shoreline outfall at Potter Point	Tertiary treatment	26,930	200,000	84,719	551,882
Warriewood	Ocean	Ocean via a shoreline outfall at Turimetta Head	Secondary treatment	6,878	59,000	71,445	216,595
TOTAL (for all plants)				**498,782**	**4,647,335**	**82,268,865**	**18,397,999**

7.6.2 Domestic wastewater (5.D.1) methodology

7.6.2.1 Methane emissions from wastewater treatment at municipal wastewater treatment plants (MWTPs)

Methane emissions from the treatment of wastewater at municipal wastewater treatment plants are estimated according to the default method set out in The IPCC *Good Practice Guidance* which relates emissions to the total quantity of organic waste treated at the MWTP. The emission factors applied to this quantity of organic waste are derived from a consideration of the type of treatment process used at the MWTP and the degree to which the organic waste is treated anaerobically.

Activity data: organic waste in wastewater

Quantities of organic waste in wastewater treated at individual MWTPs have been obtained under the NGER system (2009 onwards). Around 60% of facilities reporting under the NGER system (numbering 75 in total and servicing around 60% of Australia's population) measured the quantity of COD entering their facility directly. The weighted average per-capita COD entering these facilities is.0.677 tonnes of COD per person per year.

For the remainder of the category's facilities, a country-specific value of 0.0585 tonnes of COD per person per year (NGGIC 1995) was used for the amount of organic waste in wastewater received at their sites.

Utilities reporting under the NGER system are also required to report the quantities of COD leaving their facility in effluent and treated in the form of sludge. Sludge refers to the solids generated in the wastewater treatment process. All wastewater treatment plants produce sludge requiring disposal. Sludge generated in Australia is often treated in sludge lagoons, sludge drying beds or anaerobic digesters. Treatment of this sludge can produce methane if it is allowed to decompose anaerobically. The amount of methane generated is variable depending on the type of treatment applied to the sludge. Biosolids are the product of sludge treatment suitable for use in land applications. Emissions from application of biosolids to land are included in the agriculture sector. Sludge and biosolids may also be sent to landfill. Emissions arising from the decomposition of sludge disposed to landfill are included in the solid waste sector.

As with the COD entering the facilities, NGER facility-specific data on COD sludge leaving the facility has been used where this variable has been measured directly. Where this data was unavailable, a country-specific fraction of COD removed and treated as sludge of 0.54 has been applied (NGGIC 1995).

Methodology

Emissions generated from the treatment of COD in wastewater are estimated according to the following equation:

$$CH_{4(t)} = (COD_{in} - COD_{sl} - COD_{out}) * EF_t$$

Where $CH_{4(t)}$ is the estimated CH_4 emissions from the treatment of sewage at wastewater plants

COD_{in} is the amount of COD input entering into wastewater treatment plants

COD_{sl} is the amount of COD treated separately as sludge

COD_{out} is the amount of COD effluent discharged from wastewater treatment plants into aquatic environments

EF_t is the emission factor for wastewater treated by wastewater plants.

Emissions generated from the treatment of sludge are estimated according to the following equation:

$$CH_{4(t)} = (COD_{sl} - COD_{trl} - COD_{tro}) * EF_{sl}$$

Where $CH_{4(t)}$ is the estimated CH_4 emissions from the treatment of sewage at wastewater plants

COD_{sl} is the amount of COD treated separately as sludge

COD_{trl} is the amount of COD as sludge removed and sent to landfill

COD_{tro} is the amount of COD as sludge removed and to a site other than landfill

EF_{sl} is the emission factor for sludge treated by wastewater plants.

Under the NGER system reporting provisions, wastewater facilities must characterise the type of treatment process used in terms of the fraction of COD (as both sludge and wastewater) treated anaerobically. This parameter is defined as the methane conversion factor (MCF). The 2006 IPCC default MCF values and the definition of the corresponding treatment processes associated with these defaults in Australia are shown in Table 7.22. Facilities reporting under the NGER system select the most appropriate MCF value for their operational circumstances.

Table 7.22 MCF values listed by wastewater treatment process

Classes of wastewater treatment in 2006 IPCC Guidelines	MCF Values	Applicable Wastewater Treatment Processes
Managed Aerobic Treatment	0.0	• Preliminary treatment (i.e. screens and grit removal) • Primary sedimentation tanks (PST) • Activated sludge processes, inc. anaerobic fermentation zones and anoxic zones for biological nutrient removal (BNR) • Secondary sedimentation tanks or clarifiers • Intermittently decanted extended aeration (IDEA), intermittently decanted aerated lagoons (IDAL) and sequencing batch reactors (SBR) • Oxidation ditches and carrousels • Membrane bioreactors (MBR) • Mechanically aerated lagoons • Trickling filters • Dissolved air flotation • Aerobic digesters • Tertiary filtration • Disinfection processes (e.g. chlorination inc. contact tanks, ultraviolet, ozonation) • Mechanical dewatering (e.g. centrifuges, belt filter presses)
Unmanaged Aerobic Treatment	0.3	• Gravity thickeners • Imhoff tanks
Anaerobic Digester / Reactor	0.8	• Anaerobic digesters • High-rate anaerobic reactors (e.g. UASB)
Anaerobic Shallow Lagoon (< 2 m deep)	0.2	• Facultative lagoons • Maturation / polishing lagoons • Sludge drying pans
Anaerobic Deep Lagoon (> 2 m deep)	0.8	• Sludge lagoons • Covered anaerobic lagoons

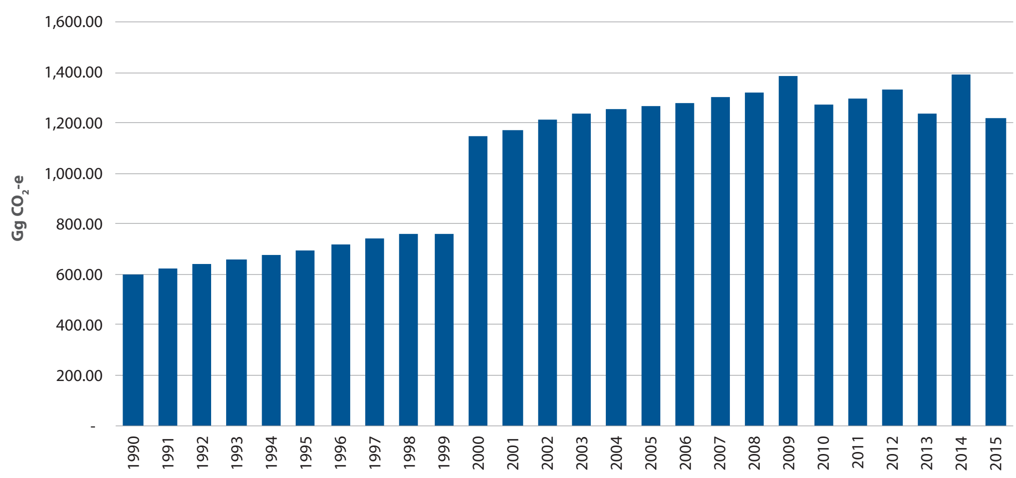
Source: WSAA 2011

Emission factors for each facility for wastewater and sludge are derived using equation 6.2 in the IPCC *Good Practice Guidance*. The IPCC default maximum methane producing capacity (B_o) of 0.25 kg CH_4/kg COD is used for all facilities.

Methane capture

Methane recovered for combustion for energy or flared is deducted from the estimated methane generated and is based on directly measured quantities of methane captured for combustion and flaring reported under the NGER system (2009 onwards)for the years 2009 onwards. For 1990–2008, recovery is based upon a consideration of historical changes in methane capture capacity at individual wastewater treatment plants. A capture time-series for each wastewater utility has been established based on capture rates for 1990 reported in NGGIC 1995 and on subsequent reported commissioning of cogeneration plants, odour control system upgrades, and general plant capacity upgrades. Figure 7.13 shows the time-series for methane capture from domestic and commercial wastewater treatment. The significant increase in capture from the year 2000 corresponds to an improvement in capture capacity due to the commissioning of cogeneration facilities at a number of key wastewater treatment facilities serving particularly large populations. The small decline in capture in 2010 reflects a combination of changes to treatment processes (i.e. a shift to aerobic treatment) and reported declines in flaring and combustion of sludge biogas for energy production. The decline in capture in 2015 is due declines in capture levels reported under the NGER System.

Figure 7.13 Methane capture from domestic and commercial wastewater treatment 1990–2015



No data is available on the precise split of methane recovery between wastewater and sludge treatment. For the purposes of reporting in table 5.B.s1 of the CRF table, methane recovery is allocated between wastewater and sludge such that emissions generated from the treatment of sludge are captured and the balance of reported capture is then allocated to wastewater treatment.

Choice of emission factor

There is a proportion of the wastewater treatment sector where no facility-specific data is available under NGER. The choice of parameters applicable to the residual portion of the sector was made in accordance with the decision tree described in Section 1.4.1.

As treatment processes employed at individual facilities are highly technology specific, it was not considered reasonable to extrapolate the factors obtained from NGER data to the facilities in the residual portion of the sector. Consequently, the per-capita COD and region-specific MCF values from NGGIC 1995 were used for 2009 for the residual of the category where no facility-specific data under NGER was available.

Time-series consistency

The use of NGER data has required careful consideration of time-series consistency issues. Facility-level activity data and emission factors are available from 2009 onwards. In order to preserve time-series consistency, facility-level activity data obtained under NGER has been back-cast as a fixed proportion of total population serviced in each state. Constant facility level MCF values and the proportion of methane generated that was captured in 2009 have been used with the back-cast activity data. This approach to maintaining time series consistency was based on the consideration that the larger-scale facilities covered by NGER utilise well established infrastructure and treatment processes that have not undergone significant changes since 1990.

The residual portion of the sector, for which no NGER facility-specific data is available, has been handled as described above for the entire time-series.

7.6.2.2 Methane emissions from on-site domestic and commercial wastewater treatment

The IPCC *good practice* default method for estimating methane emissions is used to estimate emissions from on-site domestic and commercial wastewater treatment. The total unsewered population on a State by State basis is calculated according to the Australian Bureau of Statistics (ABS 2009e) and WSAA data (WSAA 2005). It is assumed that each person in unsewered areas in Australia produces 0.0585 tonnes of COD per person per year (NGGIC 1995). The amount of COD that settles out as solids and undergoes anaerobic decomposition (MCF) is assumed to be 15%, which is the IPCC default fraction for total urban wastewater (IPCC Vol. 3 1997). The IPCC good practice default emission factor of 0.25 kg CH_4/kg COD is used.

Sludge is also generated by on-site domestic and commercial wastewater treatment. Septic tank systems must be emptied occasionally of the sludge that accumulates inside the system. This sludge is typically transferred to a municipal wastewater treatment facility for further treatment.

7.6.2.3 Nitrous oxide emissions from domestic and commercial wastewater treatment

The methodology used to estimate N_2O emissions from domestic and commercial wastewater treatment utilises a detailed IPCC good practice methodology and comprises estimates for emissions from sewage treatment at a wastewater plant; emissions from discharge of effluent into aquatic environments; and emissions from disposal of treated sludge to land.

$$\text{Total } N_2O\text{-}N = N_2O_{(t)}\text{-}N + N_2O_{(d)}\text{-}N + N_2O_{(l)}\text{-}N$$

Where N_2O-N is the estimated N_2O emissions from domestic and commercial wastewater treatment

$N_2O_{(t)}$-N is the estimated N_2O emissions from sewage treatment at a wastewater plant

$N_2O_{(d)}$-N is the estimated N_2O emissions from discharge of effluent

$N_2O_{(l)}$-N is the estimated N_2O emissions from application of treated sludge to land

N_2O emissions from sewage treatment at wastewater treatment plants

The emissions of N_2O from sewage treatment at wastewater treatment plants are estimated using the following equation:

$$N_2O_{(t)}\text{-}N = (N_{in} - N_{out} - N_{trl} - N_{tro}) * EF_6$$

Where $N_2O_{(t)}$-N is the estimated emissions from the treatment of sewage at wastewater plants

N_{in} is the amount of nitrogen input entering into wastewater treatment plants

N_{out} is the amount of nitrogen effluent discharged from wastewater treatment plants into aquatic environments

N_{trl} is the amount of nitrogen removed from wastewater treatment plants as sludge and disposed to landfill

N_{tro} is the amount of nitrogen removed from wastewater treatment plants as sludge and disposed at a site other than landfill (reused in land applications) and

EF_6 is the emission factor for sewage treated by wastewater plants

The total nitrogen input entering wastewater treatment plants for Australia in 2009 is obtained from facility specific measurements under NGER and, in addition, DCC 2009 yielded nitrogen treatment and discharge data for a group of utilities not captured under NGER. In total, facility level data obtained under NGER and DCC 2009 covered 108 facilities.

Estimates of the remainder of the nitrogen entering the national system is based on the residual population not covered by the facilities reporting under NGER or DCC 2009 and the average nitrogen input received by the wastewater plants per person serviced by the plants derived from the NGER system (2009 onwards)and DCC 2009 facility data. Together with the IPCC good practice assumption for the fraction of nitrogen in protein, 0.16 kg N/kg protein, the facility level data translates into a per capita protein consumption level of 103.6 kg per person per year in 2015.

Estimates of nitrogen leaving the system as effluent or as sludge disposed to landfill or to a land application, N_{out}, N_{trl} and N_{tro} have also been obtained by facility under the NGER system and DCC (2009).

The emission factor for the estimation of N_2O emissions from wastewater treatment, EF_6, is the IPCC good practice default, 0.01 kg N_2O-N/kg N.

N_2O emissions from discharge of effluent

The effluent discharged into an aquatic environment may enter directly into a river, estuary, ocean surface waters or deep ocean environment depending on the location of the wastewater outfall of each treatment plant. As extensive facility-level information has been collected from verifiable sources on the quantities of nitrogen discharged by location of outfall, Australia is able to use a more detailed country-specific method rather than the IPCC tier 1 method while using IPCC (1997) default factors available for each aquatic receiving environment.

The emissions of N_2O from the discharge of effluent are estimated using the following equation:

$$N_2O_{(d)}\text{-}N = N_{outr} * (EF_{5\text{-}r} + EF_{5\text{-}e}) + N_{oute} * (EF_{5\text{-}e})$$

Where

$N_2O_{(d)}$-N is the emissions from discharge of effluent

N_{outr} is the amount of nitrogen discharged into rivers which then flows into an estuary

N_{oute} is the amount of nitrogen discharged into estuaries

$EF_{5\text{-}r}$ is the emission factor for rivers

$EF_{5\text{-}e}$ is the emission factor for estuaries

The amount of nitrogen discharged by aquatic environment for 2014 is obtained by facility under the NGER system and DCC 2009.

The IPCC good practice default initial emission factors are 0.0075 kg N_2O-N/kg N for wastewater discharged into rivers ($EF_{5\text{-}r}$) and 0.0025 kg N_2O-N/kg N for wastewater discharged into estuaries ($EF_{5\text{-}e}$) (IPCC good practice 4.73). For wastewater discharged into rivers, the final emission factor is cumulative, ($EF_{5\text{-}r}$ + $EF_{5\text{-}e}$), as it is assumed that the wastewater passes from the river system, through the estuaries and then into the sea. For wastewater discharged directly into an estuary, only ($EF_{5\text{-}e}$) is applied.

While the IPCC *Guidelines* state that nitrous oxide emissions resulting from sewage nitrogen are estimated from 'nitrogen discharge to aquatic environment' (IPCC 2006 page 6.25) it only an N_2O emission factor based on discharge to rivers and estuaries. Consequently, it is considered that there is no IPCC default method available for the estimation of emissions from effluent discharged directly to ocean waters. Nor is there any empirical literature available on emissions from disposal to ocean waters in Australia – such a study would be prohibitively expensive at this time. The results of the limited number of studies conducted that relate to ocean bodies outside of Australia are not considered appropriate to Australian marine conditions. They are, nonetheless, reviewed in the QA-QC section of this Chapter.

Ocean waters are defined to include only those bodies of water that are beyond the straight line drawn between the low-water marks of consecutive headlands so that waters within headlands, such as bays and basins, are included as part of the estuarine waters. Consequently, the delineation of ocean waters is considered conservative.

Table 7.23 IPCC emission factors for disposal of effluent by type of aquatic environment

Type of Aquatic Environment	Emission factor for initial disposal
River (EF5-r).	0.0075 kg N_2O-N/kg N
Estuary (EF5-e).	0.0025 kg N_2O-N/kg N

Source: IPCC (1997) page 4.110.

N_2O emissions from the application of treated sludge to land

The emissions of N_2O from the application of treated sludge to land is estimated using the following equation:

$$N_2O_{(l)}\text{-}N = N_{tro} * EF_7$$

Where $N_2O_{(l)}$-N is the emissions from treated sludge applied to the land

N_{tro} is the amount of nitrogen removed as treated sludge and applied to the land

EF_7 is the emission factor for treated sludge applied to land

The amount of nitrogen applied to land is obtained by facility under the NGER system (2009 onwards)and DCCEE (2009b). The emission factor for the application of treated sewage to land is 0.009 kg N_2O-N/kg N applied and is consistent with the N_2O emission factors for manure applied to crops and pastures (Bouwman *et al.* 2002). Emissions from the application of sludge to agricultural land are reported under agricultural soils (4.D) consistent with good practice guidance.

Non-methane volatile organic compounds (NMVOC)

There has been little research into the release of NMVOC from wastewater treatment plants. BOD values obtained and used for calculations of methane emissions are used for the calculation of NMVOC from domestic and commercial wastewater and for industrial wastewater. A default value of 0.3 kg NMVOC/ tonne BOD for municipal wastewater treatment plants is used.

7.6.3 Industrial wastewater (5.D.2) methodology

Technologies for dealing with industrial wastewater in Australia are varied. Some industrial wastewater is treated entirely on-site, while a large amount is treated entirely off-site at municipal wastewater treatment plants. Increasingly industrial wastewater is partially treated on-site before being recycled or discharged to the sewer and treated at municipal wastewater treatment plants. This is due to trade waste discharge licence compliance requirements for a certain quality of wastewater to be achieved prior to sewer discharge.

Most of the industrially produced COD in wastewater comes from the manufacturing industry. According to the IPCC, sectors like food and beverage manufacturing produce significant amounts of COD, some of which is anaerobically treated. Some concentrated industrial wastewater is removed from factories in tankers operated by specialised waste disposal services. This wastewater is usually transported to a special treatment facility.

The methodology to determine the amount of CH_4 generated from industrial wastewater is based on IPCC 2000 and focuses on the 9 industrial sectors which are considered to generate the most significant quantities of wastewater in Australia:

- Dairy production;
- Pulp and paper production;
- Meat and poultry processing;
- Organic chemicals production;
- Sugar production;
- Beer production;
- Wine production;
- Fruit processing; and
- Vegetable processing.

Organic waste in wastewater

Quantities of organic waste in wastewater treated at industrial facilities have been obtained under the NGER system for 2009 onwards. Where available, the quantity of COD treated at each facility has been taken from direct measurements reported under the NGER system. Where facility-specific data under the NGER system are unavailable, estimates are based on country-specific wastewater and COD generation rates shown in Table 7.24.

NGER data are used where industry coverage is considered sufficient to provide a representative picture of wastewater treatment practices in a given industry. In the 2016 inventory submission, NGER data covering the pulp and paper, beer and sugar, dairy, meat and poultry, wine, fruit and vegetables and organic chemicals industries are used.

Table 7.24 Country-specific COD generation rates for industrial wastewater, 2015

Commodity	Wastewater generation rate (m^3 wastewater/ t commodity produced)	COD generation rate (kg COD/m^3 wastewater generated)
Dairy	1.3	4.6
Pulp and Paper	26.7	0.4
Meat and Poultry	9.9	8.0
Organic Chemicals	68.5	2.9
Sugar	0.4	3.4
Beer [(c)]	C	C
Wine	23.0	1.7
Fruit	20.0	0.2
Vegetables	20.0	0.2

Source: NGER 2015 (b) facility-level parameters obtained for beer production under the NGER system are confidential.

Choice of methane correction factor

Emission factors for each facility for wastewater and sludge are derived using equation 6.2 in the IPCC *Good Practice Guidance*. The IPCC default maximum methane producing capacity (B_o) of 0.25 kg CH_4/kg COD is used for all facilities.

Under the NGER system reporting provisions, industrial wastewater facilities must characterise the type of treatment process used in terms of the fraction of COD (as both sludge and wastewater) treated anaerobically. This parameter is defined as the methane conversion factor (MCF). As with COD, data on facility-specific MCF values at industrial wastewater facilities are available for the airy, paper, meat and poultry, sugar, beer, wine, fruit and vegetable processing industries. Country-specific values outlined in Table 7.25 have been used by NGER reporters who have not taken site-specific measurements based on data in O'Brien (2006a) or NGGIC (1995).

Table 7.25 Methane conversion factors for industrial wastewater emissions, 2015

Commodity	MCF wastewater	MCF Sludge
Dairy	0.5	0.3
Pulp and Paper	0.8	0.8
Meat and Poultry	0.4	0.2
Organic Chemicals	0.1	0.2
Sugar	0.3	0.04
Beer [(b)]	C	C
Wine	0.2	0.2
Fruit	1.0	0.2
Vegetables	1.0	0.2

Note: These values represent weighted averages where facility-level MCF values are reported.
Source: NGER 2015 unless otherwise stated.(a) facility-level parameters.

7.6.3.1 Methane emissions from disposal of sludge generated by industrial wastewater treatment

A proportion of the COD generated in the industrial wastewater is ultimately treated as sludge. Quantities of COD treated as sludge have been obtained for the dairy, paper, meat and poultry, sugar, beer, wine, fruit and vegetable processing industries from the NGER system. For the organic chemicals, a constant fraction of COD of 0.15 is assumed to be treated separately as sludge (NGGIC 1995).

Methane capture

Estimates of the quantities of methane captured have been obtained from the NGER system for dairy, paper, meat and poultry, sugar, beer, wine, fruit and vegetable processing facilities for 2009 onwards and derived from facility-level data in O'Brien (2006a) and NGGIC (1995) for the years 1990–2008. For organic chemicals for which NGER data has not been used, the sources are O'Brien (2006a) and NGGIC (1995).

As with domestic and commercial wastewater treatment, no data is available on the precise split of methane recovery between wastewater and sludge treatment. For the purposes of reporting in Table 5.B.s1 of the CRF table, methane recovery is allocated between wastewater and sludge on the basis of emissions generated from sludge treatment as a proportion of total capture with the balance being allocated to wastewater.

Table 7.26 Methane recovered as a percentage of industrial wastewater treatment 2015

Commodity	Fraction of methane recovered/flared (%)
Dairy	16%
Pulp and Paper	61%
Meat and Poultry	19%
Organic Chemicals	2%
Sugar	0%
Beer	58%
Wine	42%
Fruit	0.3%
Vegetables	4%

Source: NGER 2015.

Time-series consistency

Time-series consistency has been maintained through the interpolation of MCF values and proportions of methane captured for pulp and paper , sugar, dairy, meat and poultry, wine and fruit and vegetables for 1990–2008. For the beer industry, facility-specific MCF values and quantities of methane captured were available for the years 2003 to 2005. For the years 1990–2002 in the beer time series, the 2003 values for MCF and proportion of methane generated that was captured have been used. For the years 2006 – 2008, the 2009 NGER MCF and proportion of methane captured have been applied. This introduces a step change in the methane capture estimates for beer in 2006 where the amount of methane captured doubles, reflecting a doubling in treatment plant capacity in the beer industry during 2006.

For the organic chemicals where NGER data have not been used, time-series consistency is ensured through the use of a consistent methodology and associated parameters.

7.6.3.2 Nitrous oxide emissions from industrial wastewater

Nitrogen generated and discharged to the sewer system is ultimately treated at centralised municipal wastewater treatment plants. As N_2O emissions estimates at these plants are estimated based on the measurement of nitrogen entering the plant, this value is also inclusive of any nitrogen originating from industrial sources. Therefore emissions of N_2O from *industrial wastewater* are included in the estimate of N_2O emissions from *domestic wastewater*.

7.7 Uncertainties and time series consistency

7.7.1 Waste sector

The uncertainty analysis in Annex 7 provides estimates of uncertainty according to IPCC source category and gas. Time-series consistency is ensured by use of consistent models, model parameters and datasets for the calculations of emissions estimates. Where changes to emission factors or methodologies occur, a full time-series recalculation is undertaken.

7.7.2 Wastewater treatment and discharge

Facility level data on nitrogen entering the domestic and commercial wastewater system is used for the years 2008 onwards, as reported in DCC 2009 and under the NGER system (2009 onwards). Time-series consistency has been maintained for the estimates of Australia's protein per capita intake through the following assumptions. The protein per capita consumption value for the years 1990 to 1993 of 99.4 g/day (36.28 kg/year) is sourced from the Australian Institute of Health and Welfare (AIHW) (de Looper and Bhatia 1998). The values for 1994 to 1998 are based upon data presented in AIHW 2002. Linear interpolation was used to derive values for 1999 to 2007, which is the period for which no data are available. The following table shows the time series for values used for protein per capita consumption.

Table 7.27 Estimates of implied protein per capita: Australia: 1990–2015

Year	Protein per capita g/capita/day
1990	99.4
2000	100.0
2005	97.6
2008	96.1
2009	98.3
2010	87.3
2011	85.2
2012	90.6
2013	89.8
2014	94.4
2015	103.6

Source: de Looper and Bhatia 1998 (1990-1993), AIHW 2002 (1994 – 1998), DCC 2009 (2008), NGER 2009 onwards.
Note: interpolation used for years 1999 to 2007 inclusive.

7.8 Source specific QA/QC

7.8.1 Solid waste disposal

Emissions from solid waste disposal reflect a large amount of activity data and assumptions in relation to parameters in the IPCC first order decay model. Consequently, an intensive and systematic quality control system is required to ensure that emission estimates meet the required quality characteristics of accuracy, completeness, comparability, time series consistency and transparency.

The quality control system has established measures to test the key data inputs and emissions estimates against each of these criteria.

The solid waste sector category is covered by the general QC measures undertaken for inventory identified in Section 1.6. In particular, emissions are estimated subject to the application of carbon balance constraints that ensures completeness; that carbon is tracked from harvest to disposal and that consistency between the harvested wood product and landfill pools is maintained. Estimates of carbon stored in wood products and in landfills are provided in Annex 6.

Quality assurance in relation to key parameters and the overall method for the sector was provided through review by an international external expert not involved in the inventory process (Guendehou 2009). Independent external review provides assurance that the approach adopted by Australia is consistent with the approaches adopted by other parties.

Additionally, as part of a systematic quality control process the emission estimates obtained for the Australian inventory are compared with those reported by other parties. Methane generation at landfills in Australia was assessed against the reported estimates of methane generated at landfills across all Annex I parties. It was concluded that the implied emission factor for Australian landfills was not significantly different to the mean implied emission factor for all Annex I parties.

Key parameters such as waste type fractions have been the subject of consultations with industry and industry experts. In particular, external experts have been utilised or review of available waste audit data, MCF, DOC_f and oxidation rates.

Analysis of available waste audit data utilised in this inventory was undertaken independently by two external expert consultancies (Hyder consulting 2008, GHD 2008).

The methane correction factor (MCF), which is intended to represent the extent of anaerobic conditions in landfills, was reviewed for this inventory by GHD 2010. The assessment of GHD confirmed that an MCF factor of 1.0 is appropriate for Australian landfills.

Country specific values for DOC_f for individual waste types were selected after consultation with independent consultants (GHD 2010, Hyder consulting 2010, Blue Environment 2010) and reviewed by an international expert reviewer not involved in the preparation of the inventory (Guendehou 2010). Guendehou concluded that the approach adopted lead to a significant improvement in the emission estimates.

Oxidation rates were reviewed (GHD 2010). Following the review, it was decided to retain the IPCC default assumption of 10% until further research can be undertaken.

When NGER data were used for methane capture for the first time in the inventory in 2010, it was important to ensure time-series consistency was maintained. In order to ensure this was the case, the DCCEE engaged the external consultant who was previously used to collect methane capture information from landfill gas capture companies to undertake a QC analysis of the NGER capture data. Data were assessed for completeness and consistency with previously reported values. Capture estimates were compared with data available from the renewable energy certificate register as well as the NSW Greenhouse Gas Reduction Scheme register. The analysis confirmed that methane capture for energy generation was complete and consistent with previously reported data. For methane flaring, the analysis highlighted a completeness issue with respect to flaring occurring at local council landfills (in general, councils are not required to report under the NGER (2009 onwards) system). Therefore, this portion of flaring activity data had to be estimated for 2009 based on previously reported data.

Through this QC project, the DE was able to ensure continuity of expertise and knowledge used in the compilation of previous inventory submissions.

CRF table checks

The CRF tables are populated automatically using a piece of software developed in Australia called the CRF wizard. The CRF wizard is the interface between our Australian Greenhouse Emissions Information System (AGEIS) and the CRF reporter tool. The wizard undertakes the process of merging AGEIS data into CRF reporter XML output files.

In order to check CRF data are merged correctly by the wizard, there are general checks that are undertaken:

Emissions

- Check overall aggregate emissions exactly match those output by our AGEIS software – if there is a mismatch then go to 2.
- Check sectoral totals match AGEIS output – if there is a mismatch then go to 3
- Check sub-sectoral emissions by gas match AGEIS output by gas
- These steps are taken iteratively until Aggregate CO_2-e exactly match the AGEIS output.

Activity data

Activity data issues are identified using 3 main approaches:

- Check implied emission factor time-series fluctuations. Where implied emission factors change beyond the expected levels, then AD are assessed and corrected manually where necessary.
- Check time-series AD using CRF reporter chart functionality
- Sectoral experts perform manual checks of AD

CRF additional information

CRF additional information is more difficult to check than emissions or AD. Additional information is not generated by AGEIS in many cases. Most additional information is calculated within the calculation spread-sheets that are used as a QC check for AGEIS output.

CRF additional information QC these checks rely on manual crosschecking between the CRF reporter information and the spread-sheets used to derive additional information.

7.8.2 Wastewater treatment and discharge

The quality of the data utilised in this report has been assessed against facility data available through the State Government EPA licensing system. The Australian wastewater industry is heavily regulated by State Governments, which administer relevant state legislation such as the *Environmental Protection Act* 1994 in Queensland and the *Protection of the Environment Operations Act* 1997 in New South Wales. Under this legislation the State Governments issue environment protection licences to each premises treating wastewater. The licences require compliance with strict conditions including limits on odours, noise and organic matter and nutrients (nitrogen and phosphorus) discharged to water catchments. Annual reports must be submitted by wastewater facility operators to their state government to demonstrate their compliance and some of this information is publicly available through public registers, the National Pollutant Inventory and, in some cases, the operator's own website.

The protein per capita intake applied in this inventory was compared with an estimate calculated using the nitrogen entering treatment plants reported by Sydney Water in DCC 2009 and the population for Sydney Water's service area in 2007 according to the Australian Bureau of Statistics (Sydney Water services the cities of Sydney and Wollongong excluding Gosford and Wyong). A comparison of the calculated values for protein per capita is presented in Table 7.28 below.

Table 7.28 Estimates of implied protein per capita for Sydney Water Corporation: 2008, 2009

	Population	Protein per capita g/capita/day 2009
Sydney Water Estimated Population Serviced (DCC 2009)	4,262,840	98.3
ABS Population for Sydney and Wollongong (excluding Gosford and Wyong) in 2007	4,307,057	97.3
Inventory values used for residual population connected to the sewer	6,734,007	98.3

The estimated population serviced as reported by Sydney Water in DCC (2009) is less than the 2007 population reported by the Australian Bureau of Statistics (ABS 2007). Sydney Water's estimate of population serviced excludes four of the smaller facilities and the unsewered population and is derived from forecast dwellings in the NSW Government's Metropolitan Development Program (MDP) for 2007/08. The protein per capita values calculated using the Sydney Water estimated population therefore provide a more appropriate estimate of the protein per capita value than those derived from the ABS population figures. Per capita protein consumption based on Sydney Water population serviced and DCC 2009 has been estimated as 98.3 g/day for 2009.

The protein per capita consumption for the 2014 inventory, derived from NGER facility data, has decreased to 94.4 g/day. Facility data received under the NGER system for the first 5 years of reporting indicates a degree of volatility associated with this factor. Those facilities reporting the underlying data, however, do undertake frequent sampling and analysis and must also adhere to legislated requirements to ensure the data is representative and free from bias. Nitrous oxide emissions are concentrated in rivers and estuaries where the processes for N_2O production can take place in both the water column and the sediments. N_2O emissions also arise from ocean waters in the continental shelf region; however, while these emissions may occur from human activity, they also occur naturally and are very difficult to isolate empirically.

A good understanding of how N_2O emissions occur in the continental shelf region and the influences of human activity on them is still being formed. Nitrous oxide formation is very dependent on regional conditions and chemistry and location of outfalls. Some studies have been undertaken which attempt to measure or characterise the N_2O in the continental shelf regions of Europe (Bange 2006, Barnes and Owens 1998), Canada (Punshon and Moore 2004) and North China (Zhang *et al.* 2008). A literature survey of four such studies determined an average emission rate for continental shelf/oceanic coastal waters of 0.0018 kg N_2O-N/kg N discharged. The regions studied, however, are influenced by very different marine conditions to those in Australian waters and also do not consider the effects of treated wastewater discharges (Foley and Lant, 2007). The regional marine conditions are a major influence on the production of N_2O (Zhang *et al.* 2008). An appropriate method and emission factor for estimating N_2O emissions from wastewater discharged to coastal and continental shelf waters would require further research.

A reconciliation of the quantity of sludge transferred from wastewater treatment to landfills and the sludge entering the landfills has been undertaken. To estimate the sludge transferred from industrial wastewater treatment it is assumed that 40% of the sludge removed from the wastewater is sent to landfill. The conversion of COD to wet sludge is calculated by assuming the volatile solids proportion of dry solids is in the range of 60 – 90% and the dry content matter of wet sludge is 15%. For domestic and commercial wastewater, the tonnes of nitrogen sent to landfill are converted to wet sludge using a nitrogen content range of 40,000 to 80,000 mgN per kg dry solids and a dry content matter of wet sludge of 15%.

Using these assumptions an estimate of the minimum and maximum possible quantities of wet sludge sent to landfill has been calculated for 1990 to 2015. The range of estimates for each year was found to be very large. In 2014, the minimum quantity of wet sludge sent to landfill from wastewater treatment was 621 kt while the maximum quantity was estimated to be 248 kt. These values are significantly higher than the estimate of wet sludge disposed to landfills estimated under the solid waste sector (less than 100 kt). This comparison highlights the challenges in converting quantities of nitrogen and COD to a quantity of wet sludge disposed to landfill. The assumptions and parameters such as nitrogen content of dry solids require further investigation to determine their suitability and exact magnitude.

The wastewater sector source categories are also covered by the general QA/QC of the greenhouse gas inventory in section 1.6.

7.9 Recalculations since the 2014 Inventory

7.9.1 Solid waste disposal

Minor recalculations have been performed for solid waste as a result of the application of revisions to parameters and corrections.

Table 7.29 5.A Solid Waste: recalculation of methane emissions (Gg CO_2-e)

	2016 Submission Gg CO_2-e	2017 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.A Solid Waste Disposal				
1990	15,235	15,242	7	0.04%
2000	12,149	12,154	5	0.04%
2005	10,779	10,783	5	0.04%
2008	11,190	11,195	5	0.04%
2009	11,116	11,121	5	0.05%
2010	11,393	11,397	4	0.03%
2011	10,959	10,963	4	0.04%
2012	9,673	9,678	4	0.05%
2013	8,902	8,907	5	0.05%
2014	8,917	8,922	5	0.06%

7.9.2 Wastewater treatment and discharge

Minor recalculations have been made to industrial wastewater treatment and discharge as a result of revisions to AD.

Table 7.30 5.D Domestic wastewater: recalculation of emissions (Gg CO_2-e)

	2016 Submission Gg CO_2-e	2017 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.D.1 Domestic Wastewater				
1990	1,964	1,964	–	0.00%
2000	1,747	1,747	–	0.00%
2005	1,811	1,811	–	0.00%
2008	1,954	1,954	–	0.00%
2009	1,951	1,951	–	0.00%
2010	2,085	2,085	–	0.00%
2011	1,949	1,949	–	0.00%
2012	1,642	1,642	–	0.00%
2013	1,409	1,409	–	0.00%
2014	1,614	1,614	–	0.00%

Table 7.31 5.D Industrial wastewater: recalculation of emissions (Gg CO_2-e)

	2016 Submission Gg CO_2-e	2017 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.D.2 Industrial Wastewater				
1990	2,356	2,356	–	0.00%
2000	1,446	1,446	–	0.00%
2005	1,405	1,405	–	0.00%
2008	1,417	1,417	–	0.00%
2009	1,413	1,413	–	0.00%
2010	1,317	1,317	–	0.00%
2011	1,259	1,257	-1.11	-0.09%
2012	1,194	1,194	–	0.00%
2013	1,414	1,388	-26.12	-1.85%
2014	1,328	1,328	–	0.00%

7.9.3 Incineration and open burning of waste

Minor recalculations have been made to Incineration and open burning of waste as a result of revisions to AD.

Table 7.32 5.C Incineration: recalculation of emissions (Gg CO_2-e)

	2016 Submission Gg CO_2-e	2017 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.B Biological Treatment of Solid Waste				
1990	87	87	0.10	0.12%
2000	28	28	0.00	0.00%
2005	28	28	–	0.00%
2008	29	29	–	0.00%
2009	30	30	–	0.00%
2010	30	30	–	0.00%
2011	30	30	0.20	0.66%
2012	30	30	0.20	0.67%
2013	30	30	0.47	1.59%
2014	30	31	0.94	3.13%

7.9.4 Biological treatment of solid waste

Minor recalculations have been made to Biological treatment of solid waste as a result of revisions to AD.

Table 7.33 5.B Biological Treatment of Solid Waste: recalculation of emissions (Gg CO_2-e)

	2016 Submission Gg CO_2-e	2017 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.B Biological Treatment of Solid Waste				
1990	10	10	–	0.00%
2000	46	46	–	0.00%
2005	65	65	–	0.00%
2008	79	79	–	0.00%
2009	83	83	–	0.00%
2010	94	94	–	0.00%
2011	109	109	–	0.00%
2012	111	111	0.01	0.01%
2013	113	113	-0.17	-0.15%
2014	115	115	-0.10	-0.09%

7.10 Source specific planned improvements

7.10.1 Solid waste disposal

The DE initiated a move to the use of tier 3 methods for the estimation of emissions from solid waste disposal in the 2013 submission. The availability of facility-level data collected under the NGER system has enabled a facility-specific and spatially explicit approach to be adopted for the largest landfills which has supplemented the previous State-based approach which continues to be used for the non-NGER proportion of the landfill sector.

Facility-level data used in this submission are limited to waste disposal quantities and composition and methane capture for all landfill facilities triggering NGER system reporting thresholds. Decay rate constants have been assigned to each landfill based on their individual geospatial coordinates and BOM climate data.

Under the NGER system, operators of landfills are encouraged to undertake audits of waste data received and to collect data on methane generation rates to enable the operator to determine a facility-specific 'k' value so that 'k' will reflect both localised climate and management conditions. However, to date, no landfills have undertaken these measurements. The DE will continue to review the availability of data and where available these will be used to ensure that the decay functions applied at individual landfills reflect both local climatic conditions and facility management practices. The latter is particularly important as practices can vary considerably – for example, two in every five landfills practice leachate control which would significantly increase the value of 'k' at a landfill facility.

Initial testing of the methods at landfills has demonstrated the value of ensuring that local climate and management practices are explicitly taken into account. The methods to be used to determine 'k' are provided in the *National Greenhouse and Energy Reporting (Measurement) Determination 2008*.

For the residual disposal not covered by the NGER system reporting, The DE will explore the possibility of estimating emissions at a more spatially disaggregated level to enable climatic variation to be accounted for in the residual estimates. The implementation of this planned improvement will depend of the availability of disposal data at a more disaggregated level than is currently available.

As part of the in-country review of Australia's 2008 national inventory, the Expert Review Team encouraged The DE to develop country-specific DOC values. This will be explored over coming years to determine the best empirical approach to support the development of such values.

During the 2015 review, the ERT encouraged Australia to assess the possibility of using a monthly time-step rather than annual in the FOD model. While Australia is fully compliant with the requirements of the 2006 IPCC Guidelines, this potential improvement will be kept under consideration, subject to the availability of necessary resources to enable the analysis to be undertaken.

7.10.2 Wastewater treatment and discharge

The DE will keep industrial wastewater model parameters and methods under review based on facility level data reported under the NGER system.

7.10.3 Incineration and open burning of waste

The DE will review NGER system reports with a view to the potential inclusion of additional facility data for future inventory submissions.

7.10.4 Biological treatment of solid waste

Methods and emission factors will be kept under review.

8 Other (CRF Sector 6)

Australia does not report any emissions under CRF sector 6, ‘Other’.

9 Indirect CO_2 and nitrous oxide emissions

For the purpose of paragraph 29 of decision 24/CP.19, Australia has elected not to report indirect CO_2 and nitrous oxide emissions. Information on indirect CO_2 and nitrous oxide emissions in the *Energy* and *Agriculture* sectors can be found in Chapters 3 and 5 respectively.

10 Recalculations and improvements

Emissions processes are pervasive and complex and, consequently, emissions estimation techniques and data sources for the Australian inventory continue to be refined, updated and improved.

More generally, the development effort behind recalculations is undertaken in line with the *Inventory Improvement Plan* for the Australian inventory. This plan is aimed at reducing existing emission estimate uncertainties as much as possible, with development focused on key source categories, sources with high uncertainties and where implementation of new methods is feasible (for example, as a result of new data becoming available). The Australian improvement plan also responds to international expert reviews and changes in international practice. Some of the elements of the improvement program are set out in section 10.4.

10.1 Explanations and justifications for recalculations

Key reasons for recalculations in this inventory are given in the sectoral chapters and are summarised in Table 10.1. Principal reasons include revisions of activity data, the inclusion of additional sources of data or from refinements in the estimation methodology including in response to recommendations of previous UNFCCC expert reviews. To ensure the accuracy of the estimates, and to maintain consistency of the series through time, recalculations of past emission estimates are undertaken for all previous years.

In response to the ERT recommendation that "the Party transparently report, in chapter 10 of its NIR, the reasons and associated quantitative impacts of the largest recalculations", Table 10.1 has been enhanced to include a cross reference to where the quantitative impact of the largest recalculations[21] can be found in this Report.

Table 10.1 Recalculations in the 2015 inventory (compared with the 2014 inventory): key reasons and quantitative impact

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
1.A	Energy Industries	1.A.1	A key reason for recalculations arises from revisions by Department of Industry,Innovation and Science (DIIS) to the Australian Energy Statistics (AES). The revisions to the AES are due to the incorporation of improved activity data available under the NGER. 1.A.1.a Electricity and heat production There were some minor corrections to non CO_2 emission factors. 1.A.1.c Manufacturing of solid fuels and other energy industries Coke Ovens; Revisions were made by DIIS to the AES to the coal by-product produced from coke oven operations. This contributed to an upward revision of 1 to 3 per cent of the recalculations seen in the Manufacturing of solid fuels and other energy industries between the period 2003 to 2014. Natural Gas Distribution; Recalculations were made in response to revisions by DIS in natural gas consumed in 2013 and 2014.I	Section 3.3.5 of NIR Volume 1.

21 Large recalculations are determined consistent with the Review Handbook guidance to desk reviewers. The Review Handbook states desk reviewers should "Analyse any recalculations that have changed the emission/removal estimate for a category by 2 per cent and/or national total emissions by 0.5 per cent" (see figure 6-1 from the Review Handbook).

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
1.A	Manufacturing Industries and Construction	1.A.2	Recalculations were made in response to revisions by DIIS in the fuel consumption reported in the AES that better aligns with NGER and results in improvements in time series consistency. The revisions have improved time series consistency from 2003 onwards; however, a step change exists after 2002 in the time series for a small number of fuel types within source categories. Minor revisions were applied to non-CO2 emission factors aimed to improve accuracy and consistency across the sectors. 1.A.2.b Non ferrous metals Recalculations were made in response to revisions by DIIS in the fuel consumption reported in the AES that better aligns with NGER and results in improvements in time series consistency. Minor recalculation was introduced to the petroleum products nec fuel in the non ferrous metals sector as a result of double counting with the natural gas fuel. This resulted in a 2 to 3 per cent change for the period 2009 to 2014. 1.A.2.a, c, d, e, f, and g Recalculations were made in response to revisions by DIIS in the fuel consumption reported in the AES that better aligns with NGER and results in improvements in time series consistency. In 1.A.2.c, the main driver for 2013 recalculation was AES revision to the natural gas and petroleum refining fuel. In 1.A.2.d, the main driver for the recalculations in the period 2011 to 2014 were attributed to AES revision to dry wood fuel. In 1.A.2.e, the main driver for AES revisions were made between the period 2009 to 2014 to the dry wood and petroleum product nec fuels. In 1.A.2.f, the main driver for 2013 recalculation was AES revision to petroleum products nec fuel. There has also been inclusions of petroleum product nec fuels for the period between 2009 to 2014 as DIIS utilised NGER data to improve time series consistency.	See Section 3.4.5 of NIR Volume 1.

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
1.A	Transport	1.A.3.	Ongoing review of the Australian Energy Statistics The DIIS maintains an ongoing review of the AES, focusing on improving the coverage and accuracy of data by undertaking a detailed and broad review of data collection methods utilised to inform the Australian Energy Statistics. For the 2015 release of the AES, the DIIS applied a number of key changes, which have resulted in recalculations. These primarily are; • Reallocation of fuel consumption of key transport fuels to states, with minor change to national numbers resulting in changes in the rounding/precision of the source data. Recalculations of transport fuels have been made at the national level, primarily effecting Railways and Navigation. The DIIS was also responsible for the submission of Australia's energy supply and consumption reports to the International Energy Agency, and has applied revisions to the 2015 annual report to the IEA. Ongoing review of the Australian Petroleum Statistics Australia's authoritative source of data on the supply of transport fuels to the economy is the Australian Petroleum Statistics, and is a key source of data for the Australian Energy Statistics. This is informed on a voluntary basis by major fuel suppliers and is intended to be the authoritative source of data on transport fuel supply. However, as it is reliant on voluntary reporting by industry there is a certain amount of unreported fuel that is not captured – this is corrected for with data from other sources such as industry surveys and taxation information. Other recalculations These are minor corrections in the application of emission factors in the model and allocation of fuels to transport modes. A recalculation to 2008 for Other Transportation was made due to the inclusion of missing activity data. An insignificant recalculation has also been made to International Bunkers in Memo Items with the additions of a new aircraft type to the international fleet based in Australia.	

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
1.A	Other Sectors	1.A.4	Recalculations were made in response to revisions by DIIS in the fuel consumption reported in the AES that better aligns with NGER and results in improvements in time series consistency. 1.A.4.a In 1.A.4.a, the main driver was the revision in the consumption of ADO and natural gas fuels in the Commercial/institutional sector. 1.A.4b, 1.A.4.c Minor recalculation were made to increase accuracy and consistency applied to all non-CO_2 emission factors in 1.A.4.b and 1.A.4.c sectors which prompted minor changes to non-CO_2 emissions.	Recalculations to 1.A.4 other are detailed at the sub-category level in Table 3.27.
	Other	1.A.5	Military Transport has had minor recalculations for the period 2009-2013 with the inclusion of updated data from the Department of Defence.	
1.B	Fugitive Emissions – Coal mining	1.B.1	No recalculations	
	Fugitive Emissions – Oil and Natural Gas	1.B.2	The recalculations since the 2016 UNFCCC Submission were undertaken to address ERT recommendations E.7 and E.8 (2016). New methods have been introduced for the estimation of fugitive methane and carbon dioxide emissions from the gas supply chain reflecting empirical studies of Australian gas fields conducted by the CSIRO and international developments. The changes have caused reductions in estimates of emissions from fracking in coal seam gas fields and increases in emissions from other parts of the supply chain including from produced water at coal seam gas wellheads, gathering and boosting stations, gas processing plants, storage sites and from Liquid Natural Gas terminals. The details of these recalculations can be found in NIR 2015 Volume 1: 3.9.5 *Recalculations since the 2014 inventory*.	Section 3.3.5 of NIR Volume 1
2	Industrial Processes	2.A	Note that the data presented in Table 4.11 includes soda ash production, which is allocated to 2.B.7 soda ash production in accordance with the 2006 IPCC Guidelines. There are insignificant recalculations of around 0.003% due to the application of improved precision in emission factors and molecular weights.	

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
2	Industrial Processes	2.B	There are insignificant recalculations of around 0.003% due to the application of improved precision in emission factors and molecular weights.	
		2.C	There are insignificant recalculations of around 0.003% due to the application of improved precision in emission factors and molecular weights. Recalculations were also a result of revisions to emissions factors to align with revised emissions factors applied in Stationary Energy. There were no other recalculations of activity data or updates to methods.	
		2.D	There are no recalculations of activity data or updates to methods.	
3	Agriculture	3.A	Implementation of corrections and rounding policy.	Section 5.3.8
		3.B	Implementation of corrections and rounding policy. Updates to FracWet values for Northern Territory, Queensland and Western Australia.	Section 5.4.11
		3.C	There were no recalculations affecting this subsector in the 2017 submission.	
	Agriculture	3.D	Implementation of corrections and rounding policy.	Section 5.6.13
		3E	There were no recalculations affecting this subsector in the 2017 submission.	
		3F	There were no recalculations affecting this subsector in the 2017 submission.	
		3G	There were no recalculations affecting this subsector in the 2017 submission.	
		3H	There were no recalculations affecting this subsector in the 2017 submission.	
4	LULUCF	4.A.1	A. Recalculation of harvest attributable to deforestation events B. Rounding policy update C. Alignment with sectoral estimation periods D. Data improvements (climate long term average) E. Updated area of other native forests (3 class CPN)	Section 6.4.5

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
4	LULUCF	4.A.2	A. FullCAM simulation improvements B. First inclusion of Wetlands converted to Forest lands C. Updated and expanded spatial inputs D. Impacts consequent of revisions to Forest Conversions E. Rounding policy update F. Alignment with sectoral estimation periods	Section 6.5.5
		4.B.1	Significant revisions to modelling, data and parameters	Section 6.6.5
		4.B.2	A. Enhanced geospatial monitoring B. Empirical revisions to FullCAM maximum biomass 'M' parameter C. FullCAM tree parameter updates D. Alignment with sectoral estimation periods E. Rounding policy update	Section 6.7.5
		4.C.1	A. Significant revision to pasture management modelling, data and parameters B. Implementation of rounding policy C. Changes to live biomass activity data D. Changes due to new activity data for dead organic matter	Section 6.8.5
		4.C.2	A. Enhanced geospatial monitoring B. Empirical revisions to FullCAM maximum biomass 'M' parameter C. FullCAM tree parameter updates D. Alignment with sectoral estimation periods E. Rounding policy update	Section 6.9.5
		4.D.1	A. Enhanced Geospatial monitoring B. New estimates for aquaculture production	Section 6.10.5
		4.D.2	A. Refinement of preliminary estimates	Section 6.11.5
		4.E.1	Enhanced geospatial monitoring	Section 6.12.5
		4.E.2	A. Refinement of preliminary estimates B. Rounding policy update C. Separate modelling of mangrove converted to settlements D. New estimates of wetlands converted to settlements	Section 6.13.5
		4.G	A. Improvements to estimates of harvested wood products in solid waste disposal sites (HWP in SWDS. B. Minor improvements and corrections to activity data and parameters	Section 6.15.5

Sector		Category	Reason for Recalculation	Further explanation and quantitative impact
6	Waste	5.A	Minor recalculations have been performed for solid waste as a result of the application of revisions to parameters and corrections.	Section 7.9.1
		5. B	Minor recalculations have been made to Biological treatment of solid waste as a result of revisions to AD.	Section 7.9.4
		5. C	Minor recalculations have been made to Incineration and open burning of waste as a result of revisions to AD.	Section 7.9.3
		5. D	Minor recalculations has have been made to industrial wastewater treatment and discharge as a result of revisions to AD.	Section 7.9.2

10.2 Implications for emission levels

The impact of the recalculations on emission levels for the sectors excluding *LULUCF* was an increase in the estimate of total emissions; these increases were 1.2 Mt or 0.3 per cent in 1990 and 3.4 Mt or 0.6 per cent in 2014 compared with last year's submission in the common reporting format table submitted on 24 October 2016 (see Table 10.3). The recalculations including the *LULUCF* sector resulted in an increase in the estimate of total emissions of 31.8 Mt or 5.8 per cent in 1990 and an increase of 2.9 Mt or 0.6 per cent in 2014 compared with last year's submission in the common reporting format table submitted on 24 October 2016 (see Table 10.3).

Table 10.2 gives the estimated recalculations for this submission for each category for 1990 and the past eight years.

Table 10.2 Estimated recalculations for this submission (compared with last year's submission in the common reporting format table submitted on 24 October 2016): 1990, 2007–2014

Sector	1990 Mt	2007 Mt	2008 Mt	2009 Mt	2010 Mt	2011 Mt	2012 Mt	2013 Mt	2014 Mt
1.A Fuel Combustion	0.0	0.4	0.6	0.2	0.4	0.5	0.6	1.3	0.4
1.A.1, 2, 4, 5 Stationary Energy	0.0	0.4	0.4	-0.1	0.5	0.8	0.7	1.2	0.2
1.A.3 Transport	0.0	0.0	0.2	0.3	-0.1	-0.3	-0.1	0.2	0.2
1.B Fugitives	1.1	1.7	1.8	2.3	2.9	3.5	3.0	2.8	2.6
2 Industrial Processes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 Agriculture	0.1	0.6	0.1	-0.1	-0.1	0.5	0.3	0.3	0.4
6 Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total recalculation (excluding LULUCF)	1.2	2.7	2.5	2.5	3.2	4.5	3.9	4.4	3.4
5 Land use, land use change and forestry	30.5	19.5	2.5	-4.5	3.1	11.0	-9.2	-10.7	-0.5
Total recalculation (including LULUCF)	31.8	22.2	5.0	-2.0	6.3	15.5	-5.3	-6.3	2.9

10.3 Implications for emission trends, including time series consistency

The full time series of estimated recalculations is set out in Table 10.3. The net effect of the recalculations on aggregate emission trends for the sectors excluding *LULUCF* is an increase of emission estimates between 0.2 and 0.8 per cent. The net effect of the recalculations on aggregate emission trends for the sectors including LULUCF is between a decrease of 1.2 per cent and an increase of 7.2 per cent of emission estimates.

Table 10.3 Estimated recalculations for this submission (compared with last year's submission in the common reporting format table submitted on 24 October 2016); 1990–2014

	Including LULUCF				Excluding LULUCF			
	Previous estimate	Current Estimate	Difference		Previous estimate	Current Estimate	Difference	
	Mt CO_2-e	Mt CO_2-e	Mt	%	Mt CO_2-e	Mt CO_2-e	Mt	%
1990	547.60	579.3	31.8	5.8	418.6	419.8	1.2	0.3
1991	520.3	557.6	37.2	7.2	418.7	420.9	2.3	0.5
1992	487.5	516.5	28.9	5.9	423.1	425.8	2.7	0.6
1993	483.4	500.8	17.4	3.6	423.8	426.1	2.4	0.6
1994	501.3	496.1	-5.2	-1.0	424.1	426.1	2.0	0.5
1995	480.4	490.5	10.1	2.1	433.5	435.4	1.9	0.4
1996	498.0	500.5	2.6	0.5	439.8	442.5	2.6	0.6
1997	519.2	515.5	-3.7	-0.7	451.7	454.5	2.8	0.6
1998	517.0	520.5	3.5	0.7	466.4	468.3	1.9	0.4
1999	531.5	541.0	9.5	1.8	472.2	474.0	1.8	0.4
2000	550.0	551.3	1.3	0.2	483.4	484.8	1.4	0.3
2001	544.8	570.0	25.3	4.6	491.4	492.4	0.9	0.2
2002	568.1	567.9	-0.1	0.0	494.7	496.1	1.3	0.3
2003	551.7	561.4	9.7	1.8	495.2	497.5	2.3	0.5
2004	566.3	573.8	7.6	1.3	511.7	514.7	2.9	0.6
2005	595.2	597.4	2.2	0.4	518.9	521.3	2.4	0.5
2006	612.1	610.2	-2.0	-0.3	522.5	525.2	2.7	0.5
2007	583.9	606.1	22.2	3.8	529.8	532.5	2.7	0.5
2008	584.8	589.8	5.0	0.9	533.7	536.2	2.5	0.5
2009	586.3	584.3	-2.0	-0.3	537.9	540.4	2.5	0.5
2010	555.7	562.0	6.3	1.1	533.9	537.2	3.2	0.6
2011	541.2	556.6	15.5	2.9	534.1	538.5	4.5	0.8
2012	540.4	535.1	-5.3	-1.0	537.4	541.3	3.9	0.7
2013	529.9	523.7	-6.3	-1.2	526.9	531.3	4.4	0.8
2014	523.9	526.8	2.9	0.6	522.4	525.8	3.4	0.6

10.4 Planned improvements – national inventory systems

Priorities for the inventory development process have been set out in the *National Inventory Systems Inventory Improvement Plan* and have been informed by analysis of key sources and key trends. The overall aim of inventory improvement is to improve the accuracy and reduce uncertainties associated with the national inventory estimates.

The Department has implemented systematic review processes into the national inventory system to drive continuous improvements in inventory quality. *The Quality Assurance-Quality Control Plan* is an integral part of this process. In terms of emission estimation methodologies, these annual processes are principally implemented by the following.

Review of selection of methods

Decisions are made each year as to whether IPCC tier 1, 2 or 3 methods should be applied for a category, implementing QC Measure 3.A.1 (i) as set out in the *National Inventory Systems Quality Assurance-Quality Control Plan*. Method selection is reviewed in light of enhanced national data collection at facility or project level data available from private sources; public empirical literature; and in relation to updates in international guidelines and international practice.

Review of model parameters and emission factors – model validation and calibration

This review implements QC Measures 3.A.1 (ii)-(iv) set out in the *National Inventory Systems Quality Assurance-Quality Control Plan*. The measures provide for review of model parameters in light of new data collected from private measurements or from public empirical research and provide either evidence to validate existing parameters or a basis for improving the parameters or method specification based on newly available information.

External factors

The key external catalysts for inventory improvement include:

Changing international practice

The Department actively monitors the implementation of inventory guidelines by other Parties to the UNFCCC / Kyoto Protocol to ensure comparability of national inventories. More specifically, the Department also monitors the implementation of other major domestic reporting systems. The European Union, for example, has established facility-level methods for the estimation of emissions for its emission trading system while the United States Environment Protection Agency has established similar methods for its mandatory reporting system. These major systems may set new benchmarks of international practice that the Department monitors and evaluates for their potential implications for Australia.

Enhancements to Australian National Greenhouse Accounts Framework

Australia's national inventory system incorporates an integrated national greenhouse accounts framework. This builds common approaches and estimation methods from national to State to company, facility and project levels across the national greenhouse accounts. Investment will also be undertaken in a set of regional greenhouse accounts, including in support of the national income accounts framework, and a carbon stock account, including for Australia's forest lands which will provide complementary information for the national inventory.

Responses to Quality Control Outcomes and Quality Assurance reviews

Responses to quality assurance reviews are an integral part of the inventory improvement process – in particular, the UNFCCC ERT reviews, the performance audit by the Australian National Audit Office (forthcoming) and public consultations on NGER methods. As part of the national inventory development process all issues identified by the UNFCCC ERT review teams are assessed for their implications for the national inventory. A full set of UNFCCC ERT recommendations, and Australia's responses to these recommendations, are included in Annex 6. Areas for inventory improvement are identified each year in the *Evaluation of Outcomes* document.

10.4.1 Investment in national inventory systems

Ultimately, the quality of emission estimates depends on the quality of measurement, data management and quality control systems.

Investment in the National Measurement System

The national inventory system relies on a large number of measurements undertaken by private organisations. For this inventory, data collected for the energy, *industrial process and waste* sectors is largely obtained through the National Greenhouse and Energy Reporting (NGER) System. Estimation methods used for NGER are governed by the *National Greenhouse and Energy Reporting (Measurement) Determination 2008* and are designed to be consistent with the national inventory estimation methods. Improvements in accuracy of measurement will flow into improvements in the quality of the national inventory.

In support of the Emission Reduction Fund, new standards are being developed to support improved measurements across the land sector. The Department has supported the development of sampling and testing protocols for the direct measurement of Soil Organic Carbon at paddock scale. New measurement protocols are also being developed for the measurement of vegetation for rangelands vegetation. The new standards are designed to support confidence in data collected under private measurement systems and should be considered in conjunction with the Emission Reduction Fund's compliance and enforcement regime.

Investment in Research and Development

The national inventory system utilises public funding for research into greenhouse gas measurement in Australia. In recent years there has been a focus on the land based sectors given the land sectors contribute significant key categories, the extent of the sectors, the relatively high cost of private measurement and the relatively high variability of spatial and temporal emission processes.

National Inventory quality control systems

The Department will continue to invest in the quality control framework that provides a systematic approach to the assessment of new information on emissions as it emerges over time.

In relation to NGER, a systematic assessment of all new facility-specific information received will be undertaken to test the quality of existing tier 2 country-specific parameters. New information will be assessed against predetermined criteria for applicability. As a test of the quality of the existing parameters, the new information will either verify values currently used in the inventory or be used to update the parameters.'

New functionalities have been introduced into the AGEIS to achieve efficiencies in the QC process for this submission, which mitigate the risk of transcription errors during QC activity checks, and centralise all QC activities for review and archiving. As a result AGEIS can conduct tier 1 and tier 2 quality controls based on user-defined selections of QC activities. It can also populate the National Inventory Systems: *Evaluation of Outcomes* document to record the results of the monitoring program designed to implement the risk mitigation strategies and quality control measures detailed in the QA/QC Plan. The Department will continue to invest in enhanced quality control and output reporting systems for the *LULUCF* sector.

Australia has a small network of atmospheric monitoring stations that provide data on atmospheric greenhouse gas concentrations which, when combined with air dispersion models, provide a complementary verification system to the estimates presented in this national inventory. In this submission, estimates are presented for PFCs, HFCs and SF_6. Work on other gases, particularly methane and nitrous oxide, is ongoing.

Investment in IT systems

Investment in IT software systems including the Australian Greenhouse Emissions Information System (AGEIS) and *FullCAM* for *LULUCF* is a critical part of the improvement plan. Investment will be focused on the integration of the AGEIS and *FullCAM* systems, increasing the flexibility of the *FullCAM* with regard to the possibility of producing specific parameters and intermediate outputs to support enhanced quality control systems as well as regional accounts; and the development of project level tools to support the Emission Reduction Fund.

10.5 Improvements to activity data

The Department is investing in an ongoing program to review and to update the quality of activity data used in the national inventory.

Outside the sectors covered by NGER and the Emission Reduction Fund (ERF), the Department has been seeking to update the following activity data sources to improve their reliability, completeness, time series consistency or accuracy. Much of the improvements will occur in spatially explicit data for the land sectors, as efforts are made to better provide for the progressive implementation of the *2006 IPCC Guidelines*.

Improved mapping of forest areas and forest management activities

Investment in the use of remote sensing techniques to support estimates of forest management activities is ongoing, utilising available spatial information for calibration. Time-series mapping of the transfer of harvested native forests to conservation reserves and improved accuracy of mapping of harvested native forest areas, public and private and including mapping of areas that are not available for harvesting due to, inter alia, codes of practice. The Department is collaborating with CSIRO and GeoScience Australia to advance the use of more high-resolution imagery such as Sentinel in future submissions.

Integrated estimation of emissions from forest management and biomass burning

The Department is working to integrate the estimation and reporting of forest management and biomass burning in *FullCAM* to improve accuracy and coherence of emissions estimates and to support the development of ERF methods. This will include the integration of spatial mapping of fire events across all forests and grasslands in *FullCAM*.

Mapping of sparse woody vegetation cover for the Grasslands remaining grasslands category

Enhancement of the mapping of time series sparse woody vegetation across Australia through remote sensing has been completed by CSIRO to improve the consistency of this data and, in combination with research into fire dynamics, will be used to improve estimates of emissions from grasslands remaining grasslands and savanna burning.

Implementation of an accounting system for wetlands

This year, for the first time, Australia's inventory includes estimates for the *Wetlands* land classification. Our initial focus is on coastal wetlands, (Sections 6.10, 6.11 and 6.13 of Volume 2). Successful implementation will rely initially on capturing data on a broad range of management activities affecting coastal mangrove, tidal marsh and seagrass habitats, extending in the future to inland wetland habitats. Toward this end, the Department is reviewing relevant environmental impact processes and consulting with state and territory Environmental Protection Authorities and other relevant government and private organisations.

10.6 Updates to method and method selection

10.6.1 Using National Greenhouse and Energy Reporting System and other private sources of data for model validation and calibration

NGER establishes a framework to encourage the private measurement of key emissions data. Sources covered by NGER include *energy (fuel combustion), energy (fugitive emissions), industrial processes and product use* and *waste*.

Data made available under NGER from private measurements of facility-specific emission factors and other parameters is used to systematically review or validate existing tier 2 model parameters in relevant sectors. If a tier 2 model parameter is not validated by new NGER data, then the inventory parameter may be recalibrated or the equation may be re-specified in accordance with the provisions of the Inventory Improvement plan.

Each year, as new data or information is collected under NGER, the method selected to estimate emissions for a source will be reviewed. At this stage there is a presumption that the inventory will transition to tier 3 methods over time as more data based on private measurements of emission parameters becomes available, assuming that data preconditions for a more disaggregated tier 3 structure to be implemented have been met.

10.6.2 Using data from public research for method development and model validation and calibration

New information generated by publicly funded research programs or other sources also provide opportunities to test the validity of existing parameters, to consider changes to model structures, or to develop new methods.

Major areas of inventory where research data are being used for these purposes include the following:

Land sector

Enhanced calibration of modelling of forest eco-system dynamics reflecting biomass data collected and available from TERN and related research.

Enteric fermentation

Research on enteric fermentation emissions from livestock, co-ordinated through the Reducing Emissions from Livestock Research Program, has now produced an important dataset on methane emissions from Australian cattle and sheep. A process to review the sheep data has been initiated to determine if changes are required to the current methods.

Coastal wetlands

The implementation of a wetlands account in Australia's greenhouse gas inventory includes the development and ongoing improvement of methods to estimate emissions from coastal wetlands. Empirical research into carbon processes and related emissions and removals arising from activities affecting coastal wetlands are a vitally important input to successful implementation. The Department has established an informal expert advisory group of academic and government wetland specialists to advise on the development and ongoing enhancement of methods to model wetlands carbon processes and to encourage well-targeted empirical research to inform the further development and enhancement of these models.

Emissions from animal waste

The National Agricultural Manure Management Program (NAMMP) has been funded by the Australian Government to provide data on emissions from manure management systems and animal waste applied to soils. As data from the NAMMP are published the results will be used to check the quality of the EFs selected in the inventory. Where new studies give values that are significantly different from the current EFs these factors are identified for review.

Waste

The DOCf, decay and oxidation values applicable to Australian waste types in Australia under both laboratory conditions and in situ across various regions of Australia continue to be monitored by the Department for possible elaboration and future update given the emerging character of this field of research. For example, for the 2016 submission the Department revised the fraction of wood subject to decay in light of new research.

Oil and gas fugitives

New methods have been introduced for the estimation of fugitive methane and carbon dioxide emissions from the gas supply chain reflecting empirical studies of Australian gas fields conducted by the CSIRO and international developments. The changes have caused reductions in estimates of emissions from fracking in coal seam gas fields and increases in emissions from other parts of the supply chain including from produced water at coal seam gas wellheads, gathering and boosting stations, gas processing plants, storage sites and from Liquid Natural Gas terminals. Further detail is available in NIR Volume 1, section 3.9.

10.6.3 Elaboration of national inventory methods

In general, Australia is planning to implement tier 3 models and approaches wherever appropriate in order to enhance accuracy of emission estimates, particularly of the land sector.

Within the land sectors, development activity will build on existing inventory models contained in *FullCAM* and will need to take into account:

- existing and future guidance under the UNFCCC inventory reporting guidelines;
- emerging empirical data from publicly-funded research programs into the effects on emissions and removals of changes in land management actions;
- the integration of project level data generated, for example, through the Emission Reduction Fund;
- the importance of modelling long term responses to land management actions while abstracting from short term, temporal effects that are ephemeral in nature to ensure policy relevance;
- costs of data management and associated complexities; and
- the need for transparency and other related factors identified in the IPCC Workshop, 'Use of Models and Facility-Level Data in Greenhouse Gas Inventories, Report of the IPCC Expert Meeting on Use of Models and Measurements in GHG Inventories', 9-11 August 2010, Sydney, Australia.[22]

Model development will be progressed across all land sectors. In particular, it is intended that the *FullCAM* will be extended to provide an improved modelling framework for the consideration of new data as it becomes available:

- use of more advanced, high resolution imagery to support forest detection of changes in forest cover;
- methods for forest lands remaining forests will be elaborated over time to provide for a tier 3 spatially explicit method with additional estimation of forest carbon stocks as well as fluxes;
- methods for spatial modelling of sparse woody vegetation across Australia's grasslands;
- fire mapping will be incorporated to support improved estimates of emissions and carbon stocks across both forests and grasslands;
- grassland modelling will be developed to ensure the reconciliation of vegetation and livestock models; and
- modeling of wetlands emissions and removals resulting from management activities and changes in management practices will be developed and enhanced over time.

22 Reporting requirements include basis and type of model, application and adaptation of the model, main equations/processes, key assumptions, domain of application, how the model parameters were estimated, description of key inputs and outputs, details of calibration and model evaluation, uncertainty and sensitivity analysis, QA/QC procedures adopted and references to peer-reviewed literature.

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