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Australian National Greenhouse Accounts

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VOLUME 2

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6. Land Use, Land Use Change and Forestry

6.1 Emission trends

The net emissions from the *Land Use, Land Use Change and Forestry (LULUCF)* sector were -26.3 Mt CO_2-e in 2019, and preliminary estimates indicate net emissions of -25.8 Mt CO_2-e in 2020.

Table 6.1 Land Use, Land Use Change and Forestry net CO_2-e emissions, 2019

	CO_2-e emission (Gg)			
Greenhouse gas source and sink categories	CO_2	CH_4	N_2O	Total
4 Land use, land use change and forestry	-42,693.7	13,176.4	3,230.3	-26,287.0
A. Forest land	-54,650.8	4,880.0	1,160.5	-48,610.3
A.1 Forest land remaining forest land	-25,250.4	4,812.6	903.0	-19,534.8
A.2 Land converted to forest land	-29,400.4	67.4	257.5	-29,075.5
B. Cropland	-3,195.8	16.5	26.1	-3,153.2
B.1 Cropland remaining cropland	-5,885.2	-	-	-5,885.2
B.2 Land converted to cropland	2,689.4	16.5	26.1	2,732.0
C. Grassland	19,041.3	5,115.9	1,915.0	26,072.3
C.1 Grassland remaining grassland	-10,989.5	4,165.7	1,592.7	-5,231.1
C.2 Land converted to grassland	30,030.8	950.3	322.3	31,303.4
D. Wetlands	186.6	3,147.5	119.4	3,453.5
D.1 Wetlands remaining wetlands	183.7	3,147.5	119.4	3,450.6
D.2 Land converted to wetlands	2.8	-	-	2.8
E. Settlements	740.3	16.5	9.3	766.1
E.1 Settlements remaining settlements	-77.0	-	-	-77.0
E.2 Land converted to settlements	817.3	16.5	9.3	843.0
F. Other land	NO,NA	NO,NA	NO,NA	NO,NA
G. Harvested wood products	-4,815.3	-	-	-4,815.3

Notes: 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 historic 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, croplands, settlements and wetlands (tidal marsh) on which forest, including new plantations, is identified to emerge. The *forest land* category is estimated to have constituted a net sink of -48.6 Mt CO_2-e in 2019.

Cropland (4B) comprises emissions and removals from *cropland remaining cropland, forest land converted to cropland* and *wetlands converted to cropland*. The *cropland* category is estimated to have constituted a net sink of -3.2 Mt CO_2-e in 2019.

Grassland (4C) comprises emissions and removals from *grassland remaining grassland, forest land converted to grassland* and *wetlands converted to grassland.* The *grassland* category is estimated to have constituted a net source of 26.1 Mt CO_2-e in 2019.

Wetlands (4D) comprises emissions and removals from *wetlands remaining wetlands* and *forest land converted to wetlands. Wetlands remaining wetlands* estimates include CH_4 emissions from *reservoirs* and *other constructed ponds,* N_2O emissions from aquaculture use in tidal wetlands and net CO_2 emissions from removal of seagrass due to capital dredging in addition to other vegetation-related sources of emissions and removals. The *wetlands* category is estimated to have constituted a net source of 3.5 Mt CO_2-e in 2019.

Settlements (4E) comprises emissions and removals from *settlements remaining settlements, forest land converted to settlements* and *wetlands converted to settlements.* The *settlements* category is estimated to have constituted a net source of 0.8 Mt CO_2-e, in 2019.

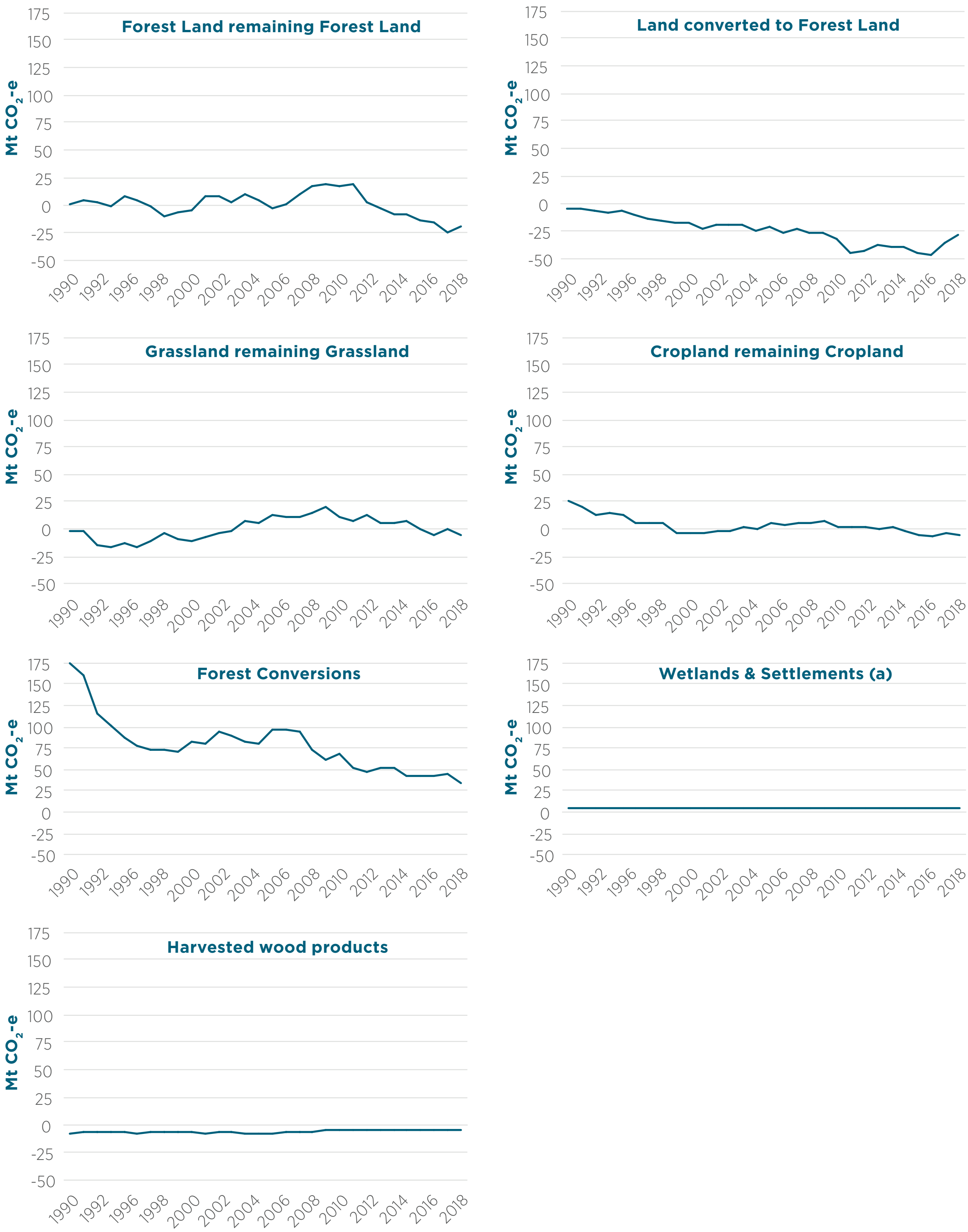
Forest land converted to cropland, *to grassland, to wetlands* and *to settlements* together constituted a net source of 34.0 Mt CO_2-e in 2019. These estimates account for the direct emissions associated with the land conversion operation in the year being reported, along with the ongoing emissions and removals on land converted in previous years, but excluding the removals associated with forest regrowth on previously converted land. These removals are reported as part of *land converted to forest land.*

The net accumulation of carbon in the *harvested wood products* pool equated to a sink of -4.8 Mt CO_2-e in 2019, including net accumulations in solid waste disposal sites.

Net *LULUCF* emissions decreased from 191.8 Mt CO_2-e in 1990 to -26.3 Mt CO_2-e in 2019. The preliminary estimate for 2020 is -25.8 Mt CO_2-e, a change of around 2 per cent compared to 2019 levels.

The underlying trend of declining emissions from *LULUCF* since 1990 has been mainly driven by the decline in emissions from *forest land conversions* and the increase in removals through forest regrowth on previously cleared land (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, 1990–2019



(a) excluding forest conversion

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 had previously been classed as *forest land* are reported under forest conversion to other land use classifications. In 2019, the additional area reported under forest conversion to other land uses was 108 kha.

Temporary losses of woody vegetation on *forest land* are reported under the *forest land remaining forest land* classification. In 2019, the area of temporary loss of vegetation – or area of harvest from native forests – was 45 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. Note that most wildfires in Australia are not stand-replacing and do not result in vegetation losses, however where forest cover loss occurs, these temporary losses are also included in monitoring for land use-change or salvage logging (See Chapter 6.4).

Losses of woody vegetation that are 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 2019, the area of sparse woody vegetation lost was 1,583 kha (Figure 6.5).

Increases in woody vegetation cover classed as *forest land* are reported under *land converted to forest land.* These changes include new plantations and forest regrowth on land previously cleared for other uses, environmental plantings and the regeneration of forest from natural seed sources. In 2019, the additional area reported under *land converted to forest land* was 443 kha.

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

Increases in the area of sparse woody vegetation not classed as *forest land* are reported under *grassland remaining grassland, wetlands remaining wetlands* and *settlements remaining settlements.* In 2019, the area of gains in sparse woody vegetation was 2,035 kha. (Figure 6.5)

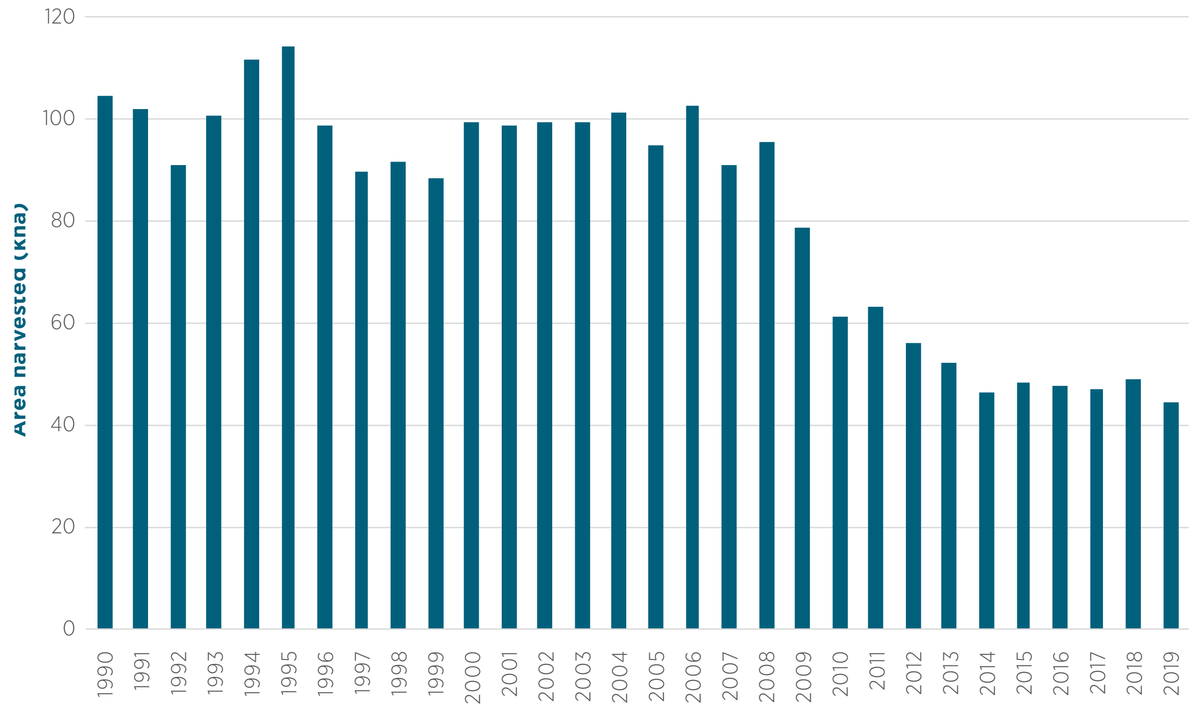
Forest land

Net emissions from *forest land* (4A) were -48.6 Mt CO_2-e in 2019 compared with -4.2 Mt CO_2-e in 1990, a difference of -44.4 Mt CO_2-e. Within the *forest land* category, *forest land remaining forest land* net emissions were -19.5 Mt CO_2-e in 2019 compared with 0.3 Mt CO_2-e in 1990, while the net emissions from *land converted to forest land* were -29.1 Mt CO_2-e in 2019 compared with -4.5 Mt CO_2-e in 1990.

The key drivers of variation in *forest land* outcomes are: annual harvest areas; the areas of new forest from regeneration of natural seed sources and from plantations; 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 has reached historically low levels (Figure 6.2).

Figure 6.2 Area harvested in native forests 1990–2019



The areas of new plantations from 1990 to 2019 are shown in Figure 6.3a and cumulative area of new softwood and hardwood plantings from 1990 to 2019 compared with the ABARES Australian Plantation Statistics (2020) update, is shown in Figure 6.3b.

Figure 6.3a Area of new plantings 1990 to 2019

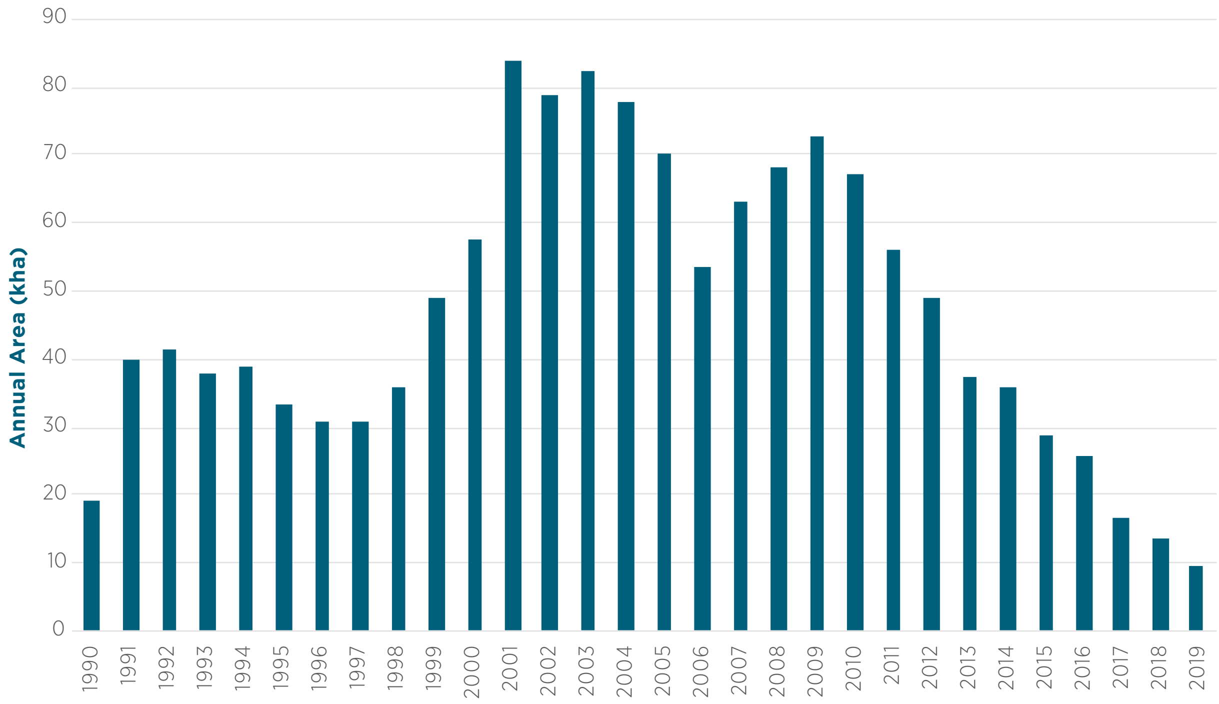
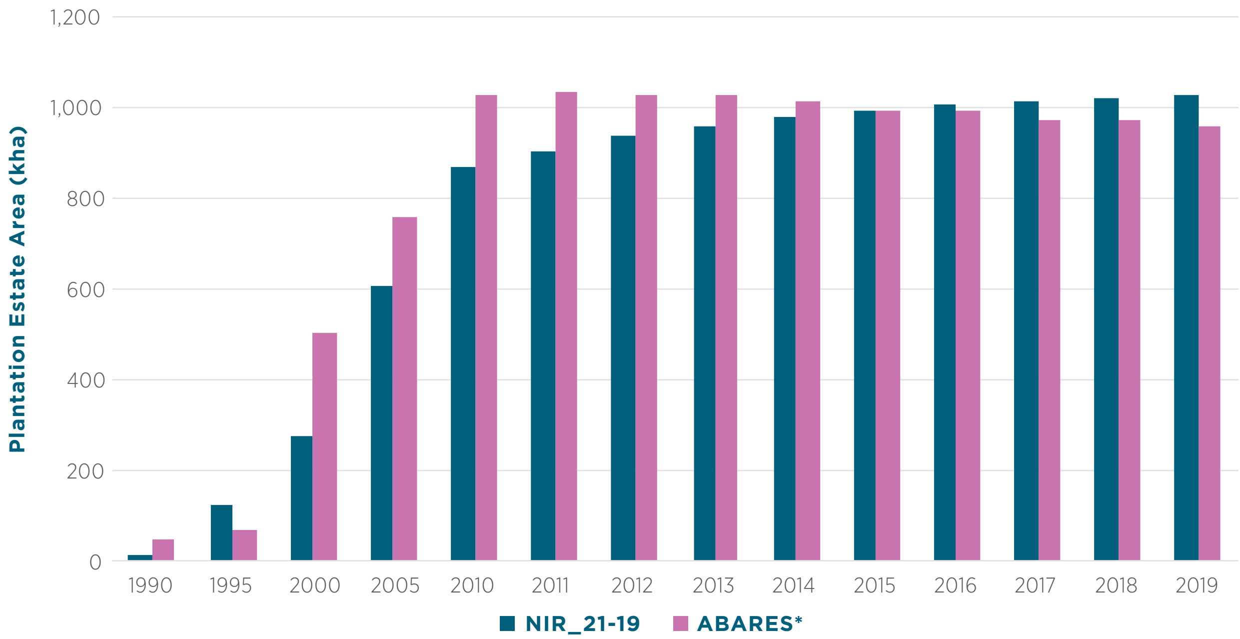


Figure 6.3b Cumulative area of post-89 Softwood and Hardwood plantations 1990–2019



Notes: *Australia Plantation Statistics 2020 update, June 2020

Wildfires are the largest cause of variability in emissions from *forest land remaining forest land.* Wildfires occur annually across Australia's 134 million hectares of forests with the area burnt varying considerably from year to year (Figure 6.4a). 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.

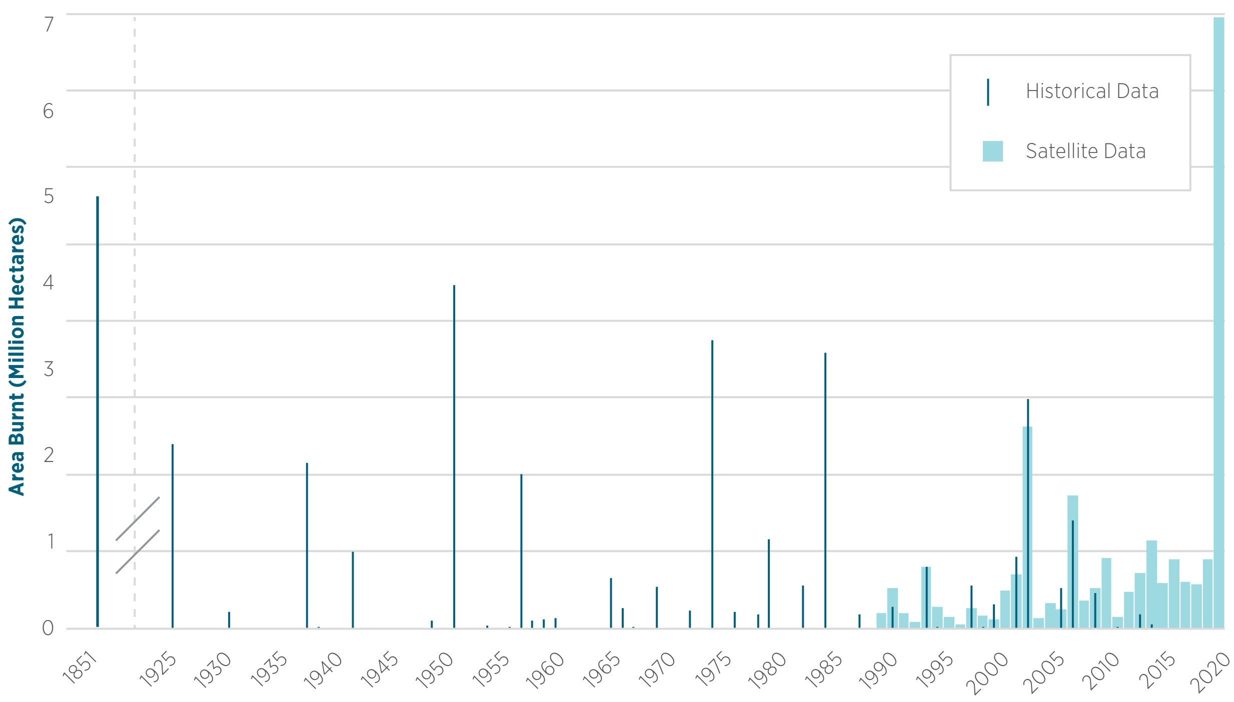
Consistent with the latest IPCC guidance (IPCC, 2019), to ensure transparency, two wildfire estimates are reported: net emissions including inter-annual variability from non-anthropogenic natural disturbances; and the long run trend in net anthropogenic greenhouse gas emissions from the wildfire disturbances and post-fire removals as the forest recovers.

In order to identify emissions from human activity, a statistical approach has been developed to identify non-anthropogenic natural disturbances on *forest land remaining forest land.* For these fires, carbon stock loss and subsequent recovery 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 (Figure 6.4b).

All prescribed fires are 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.

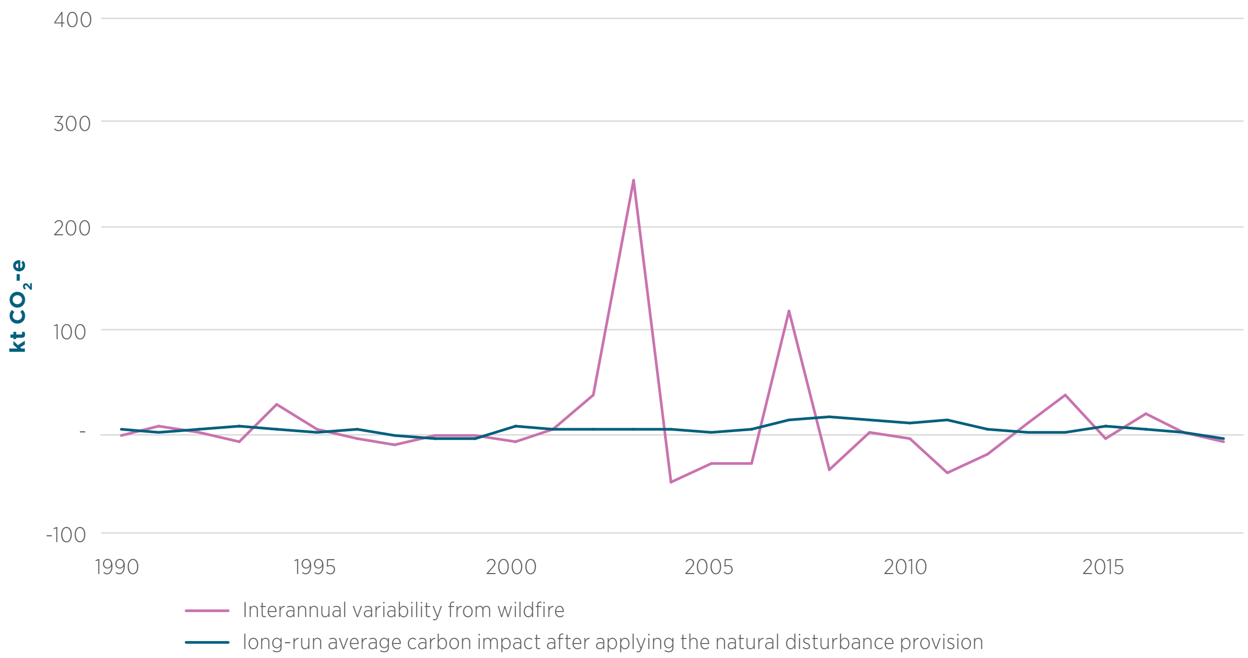
Net emissions due to wildfire in forests in 2019 were -0.4 Mt CO_2-e.

Figure 6.4a Annual area burnt by bushfires in Australian temperate forests



Source: Satellite data: DISER using data supplied by Landgate. Note that 2020 areas also include data supplied by Emergency Management Spatial Information Network Australia (EMSINA).
Historical data: based on a range of sources, including a mixture of historical records, anecdotal evidence, and satellite imagery. Updated (with corrections) from Roxburgh *et al* 2014.

Figure 6.4b Net emissions from wildfire showing: with inter-annual variability; and long-run trend in carbon impact after applying the natural disturbances provision



Cropland

Net emissions from *cropland* (4.B) were an estimated -3.2 Mt CO_2-e in 2019 compared with 44.0 Mt CO_2-e in 1990, a difference of -47.1 Mt CO_2-e. Within the *cropland* category, *cropland remaining cropland* net emissions were -5.9 Mt CO_2-e in 2019 compared with 24.8 Mt CO_2-e in 1990. The uptake of reduced, minimum and no-till management techniques through the 1980s and 90s is reflected in decreasing emissions during this period as a new soil C state of equilibrium is reached. Further management changes in recent years and their impact on the soil C steady state can be detected in shifts later in the emissions trend.

The net emissions from *land converted to cropland* were 2.7 Mt CO_2-e in 2019 compared with 19.2 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 26.1 Mt CO_2-e in 2019 compared with 149.5 Mt CO_2-e in 1990, a difference of -123.3 Mt CO_2-e. Within the *grassland* category, *remaining grassland* net emissions were -5.2 Mt CO_2-e in 2019 compared with -1.5 Mt CO_2-e in 1990.

Grassland remaining grassland

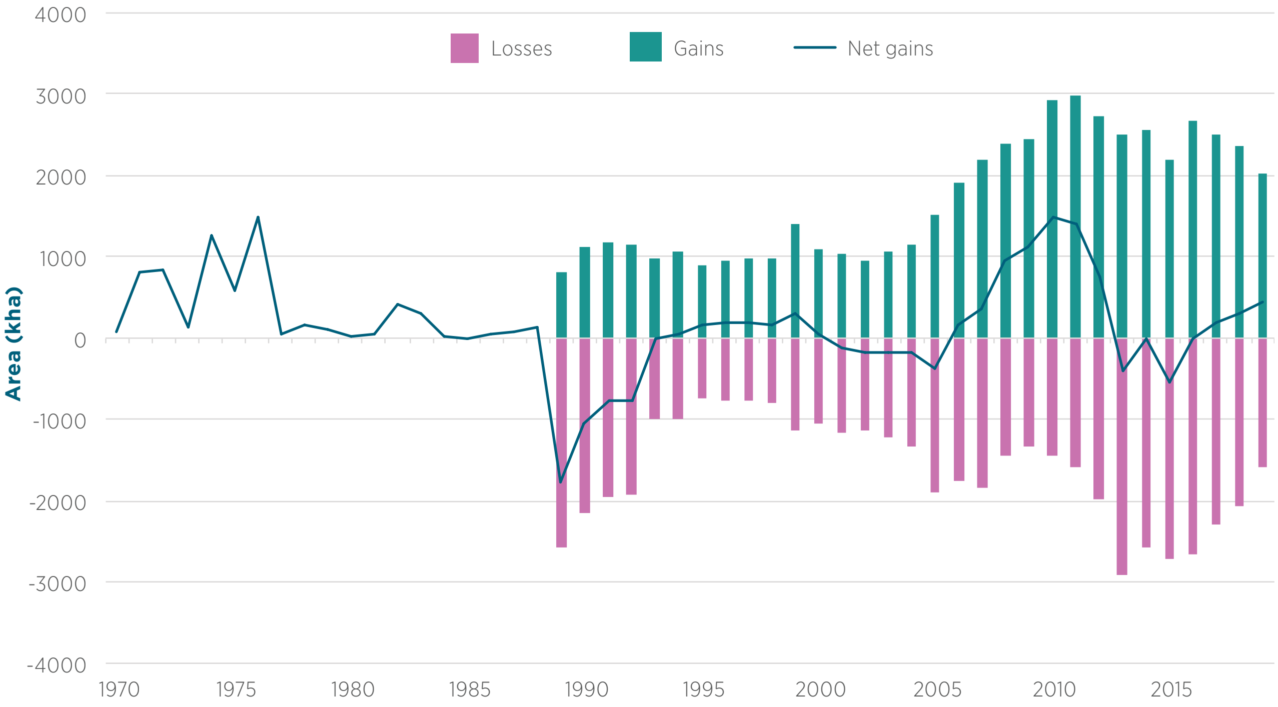
Changes in carbon stocks in *grassland remaining grassland* are largely driven by changes in land management practices and climate. These factors determine the amount of live biomass and dead organic matter (DOM) as well as the amount of residues, root and manure inputs to soil carbon. The results are reported in three components to reflect the three elements of the emission estimation:

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

In the reported estimates for herbaceous grasslands, management and climatic changes can be detected as the emissions trend moves to new equilibrium levels through time. In the arid and semi-arid rangelands of central Australia, soil carbon stocks under natural grass species are assumed to have reached a steady state.

Woody shrubs are a key component of grassland ecosystems in semi-arid and arid regions of central Australia Emissions 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 6.5.

Figure 6.5 Area of sparse woody vegetation gains and losses, kha, 1970–2019



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 (e.g. 55 per cent of all lost sparse vegetation in the Northern Territory coincides with a fire event) and mechanical clearing activity by land managers.

Fire is an important management action used on Australia's grasslands. Net emissions associated with management fires are reported in section 6.8.

Land converted to grassland

The net emissions from *land converted to grassland* were 31.3 Mt CO_2-e in 2019 compared with 150.9 Mt CO_2-e in 1990. This subcategory includes *forest land converted to 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 other land uses

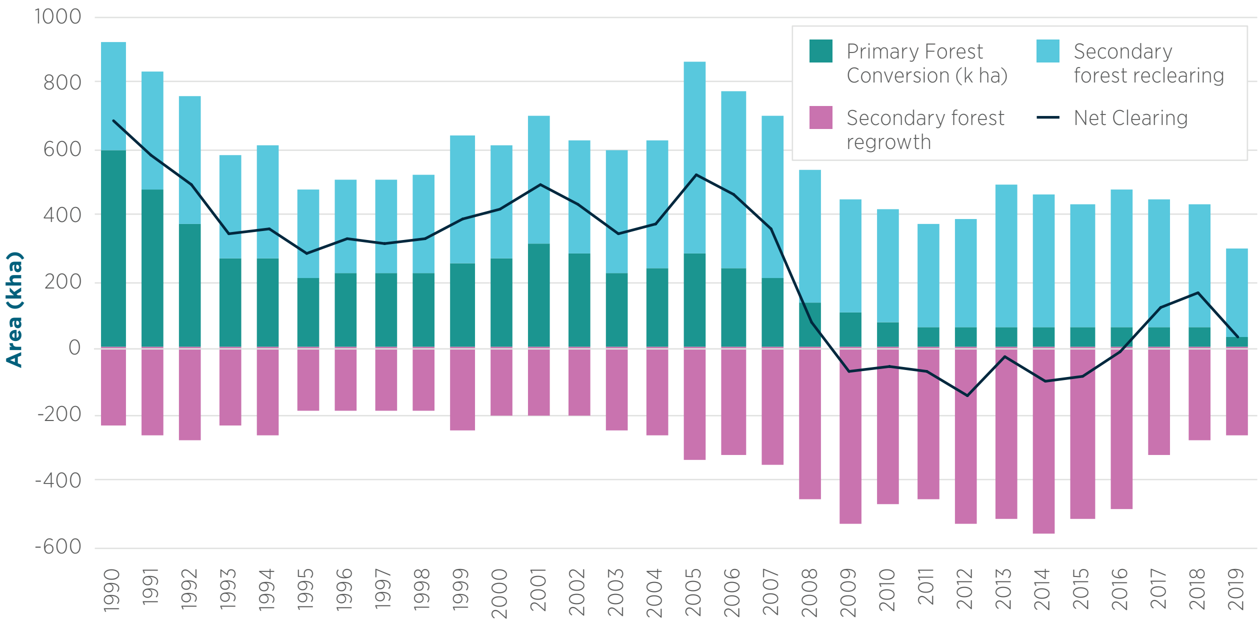
In 2019, total emissions from *forest land converted to cropland, forest land converted to grassland* and *forest converted to settlements* were around 80 per cent (135.7 Mt CO_2-e) lower than in 1990. The total emissions associated with the transition from forest to non-forest land use include the immediate 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 and other ongoing emissions and removals associated with the new land use. CO_2 removals associated with forest regrowth emerging on previously cleared land are accounted for separately as part of *land converted to forest land.* See also the sub-section "Forest Conversions" below.

The management of native vegetation and the majority of forest conversion processes in Australia are 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. Land clearing is also regulated at a national level through the *Environmental Protection and Biodiversity Conservation Act 1999* if the clearing in question is likely to have a significant impact on threatened or endangered species.

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.

Figure 6.6 illustrates the trend in forest land conversion to other land uses in Australia between 1990 and 2019 and shows 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 6.6 also shows, for each year, the area on which forest has been observed to re-emerge on previously cleared land.

Figure 6.6 Area of primary and secondary forest conversion and regrowth, Australia, 1990–2019



Note: Losses of woody vegetation that falls below the threshold for a forest are shown in Figure 6.5.

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 2008 onwards (Figure 6.6). In addition, the sharpness of the decline may also reflect land managers bringing forward decisions to clear land to the period 2004 to 2007 – the period between the announcement of new policies and when they came into force.

The shift in the balance between first-time conversion and re-clearing evident in Figure 6.6 also contributes to the trend in emissions from *forest land converted to other land uses.* Where land is re-cleared the biomass stock at clearing will be significantly less than the initial biomass of first time conversion.

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) are estimated to be 3.5 Mt CO_2-e in 2019. Within wetlands, *wetlands remaining wetlands* net emissions were 3.5 Mt CO_2-e in 2019 compared with 4.3 Mt CO_2-e in 1990 (See section 6.10.2). The estimate includes CH_4 emissions from *reservoirs* and *other constructed ponds*, net changes in sparse woody vegetation, loss of seagrass beds due to capital dredging and N_2O emissions from aquaculture operations. CH_4 emissions from *reservoirs* and *other constructed ponds* exert 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 0.003 Mt CO_2-e in 2019 compared with 0.70 Mt CO_2-e in 1990. This sub-category comprises *forest land converted to flooded lands* (e.g. new and expanded reservoirs) (Table 6.60 in section 6.11.2).

Settlements

Net emissions from *settlements* (4.E), are estimated to be 0.8 Mt CO_2-e in 2019. Within the *settlements* category, *settlements remaining settlements* net emissions were -0.08 Mt CO_2-e in 2019 compared with -0.03 Mt CO_2-e in 1990 (See section 6.12.2). The estimate comprises net changes in sparse woody vegetation (Table 6.62).

The net emissions from *land converted to settlements* were 0.8 Mt CO_2-e in 2019 compared with 5.0 Mt CO_2-e in 1990 (table 6.65). 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.

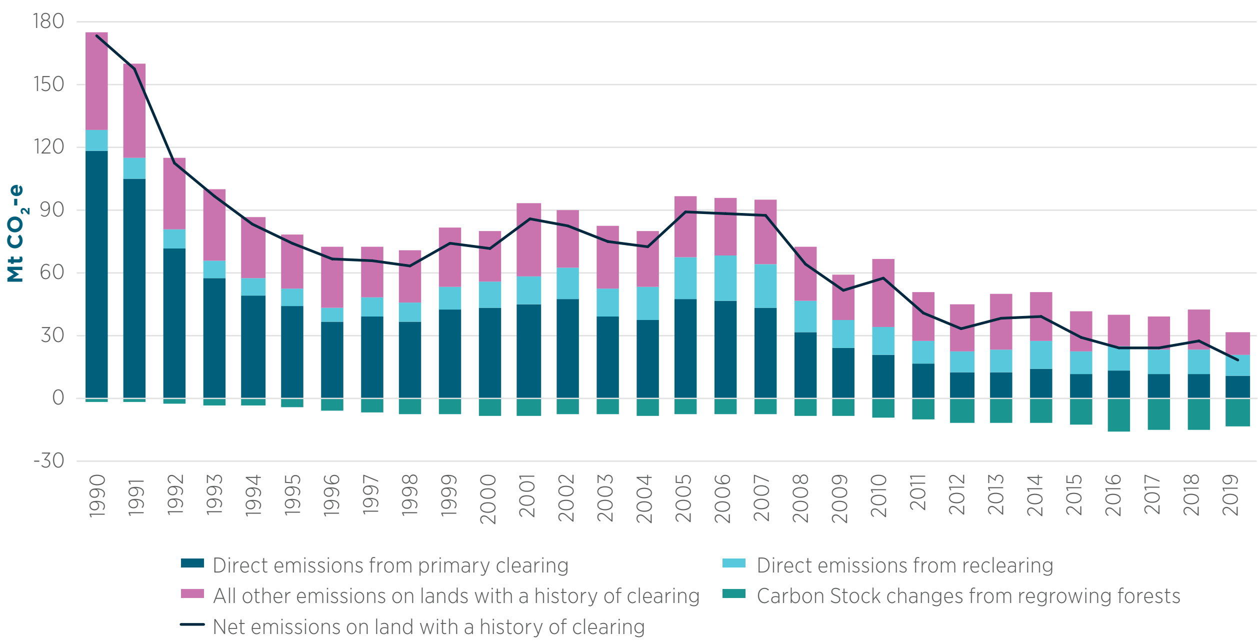
Forest Conversions

National net forest conversions to cropland, grassland, wetlands (flooded land) and settlements emissions (Figure 6.7) are disaggregated as follows:

- Direct emissions from the forest clearing activity, including:
  - the emissions from the primary conversion of land that was forested in 1972; and
  - the emissions associated with secondary clearing (reclearing) of forest which has regrown on cleared land.
- Indirect emissions from the converted land under the changed land use – subcomponents include the gradual loss of soil carbon and other emissions and removals associated with the new land use.
- Removals of CO_2 from the atmosphere on previously converted land on which forest has re-emerged.

While all four components are shown in Figure 6.7, the removals associated with re-growing forests are reported under the *land converted to forest* category rather than the forest conversions categories.

Figure 6.7 Disaggregated emissions and removals associated with forest conversions



Carbon-stock accounting

In addition to reporting on carbon stock changes, another perspective on the data underpinning land sector calculations are the departments carbon-stock accounts compiled under the System of Environmental-Economic Accounting (UN, 2014a).

These carbon stocks can be spatially mapped using the Full Carbon Accounting Model (FullCAM) architecture underpinning the estimates. Figure 6.8 shows carbon density (t/ha) on the whole of the Australian landscape, and Figure 6.9 shows the changes in forest-related carbon stocks with a focus on South-Western Australia. These maps show the higher density of carbon in Australia's native forests and highlight the mixed stories of land clearing and regeneration over the recent decades.

Figure 6.8 Carbon stocks on the Australian continent, 2016, t/ha

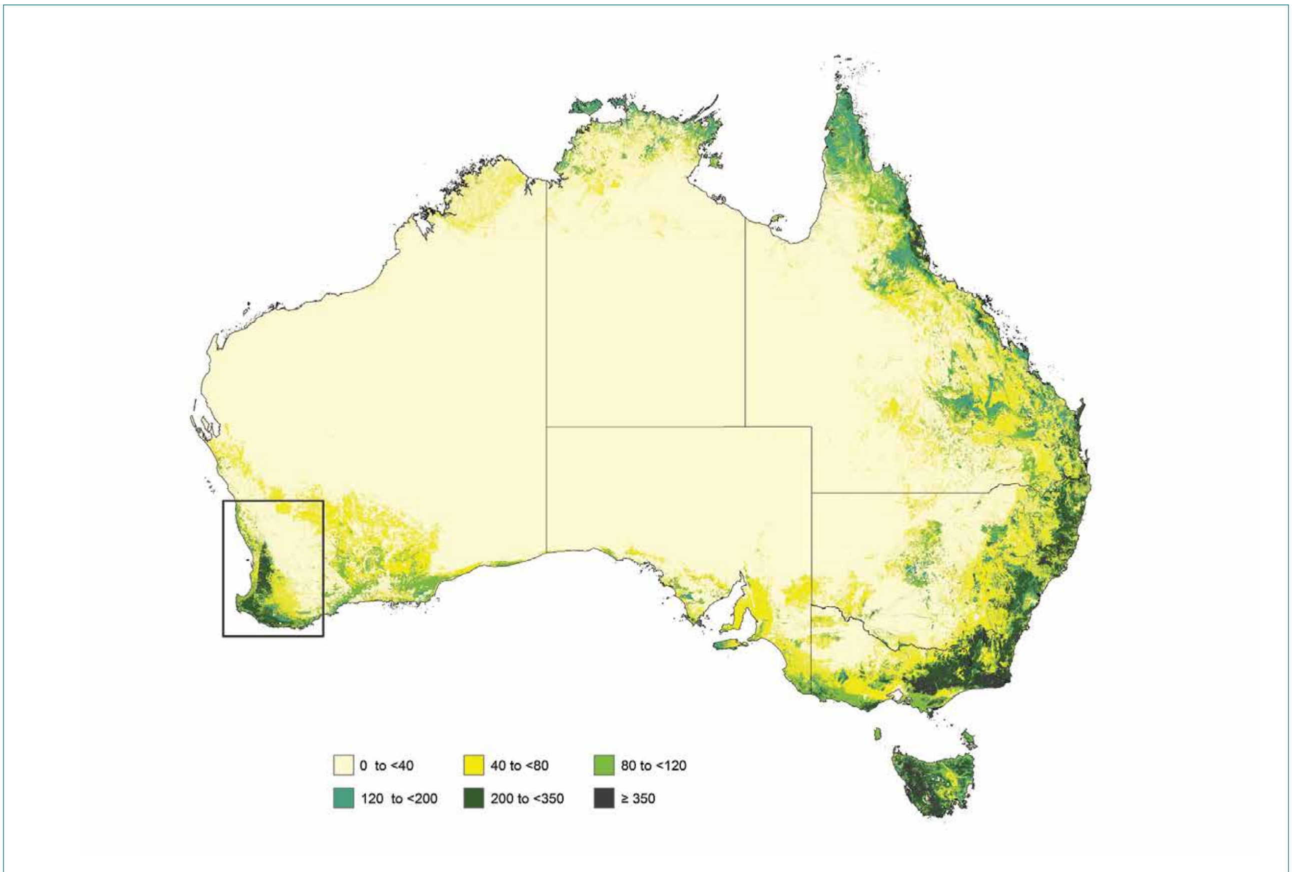
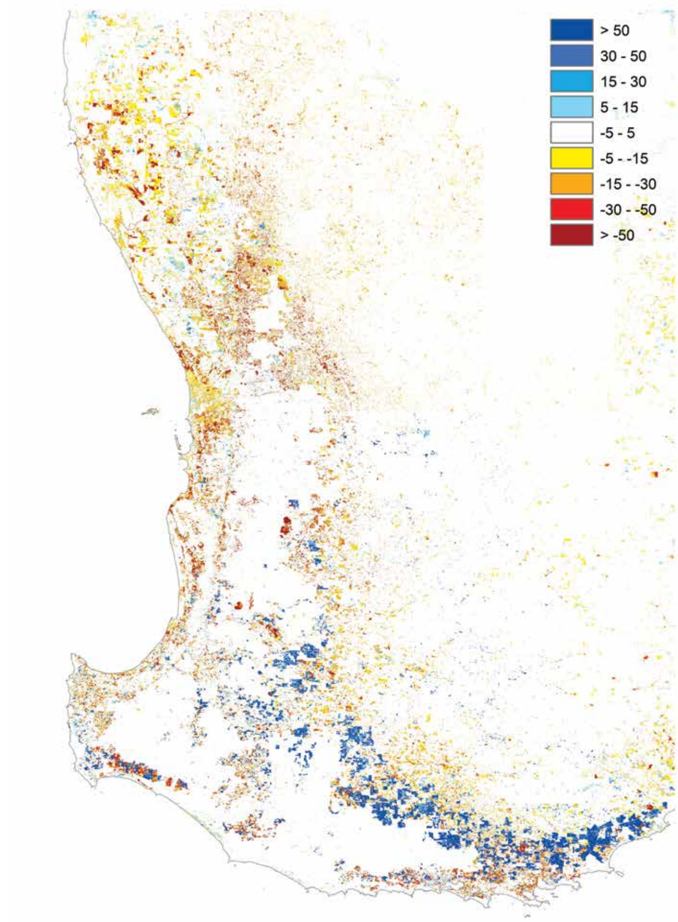


Figure 6.9 Carbon stock changes in South-Western Australia due to forest gains and losses, 1990–2016, t/ha



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 6.10a and Figure 6.10b).

Figure 6.10a Long-term average annual rainfall

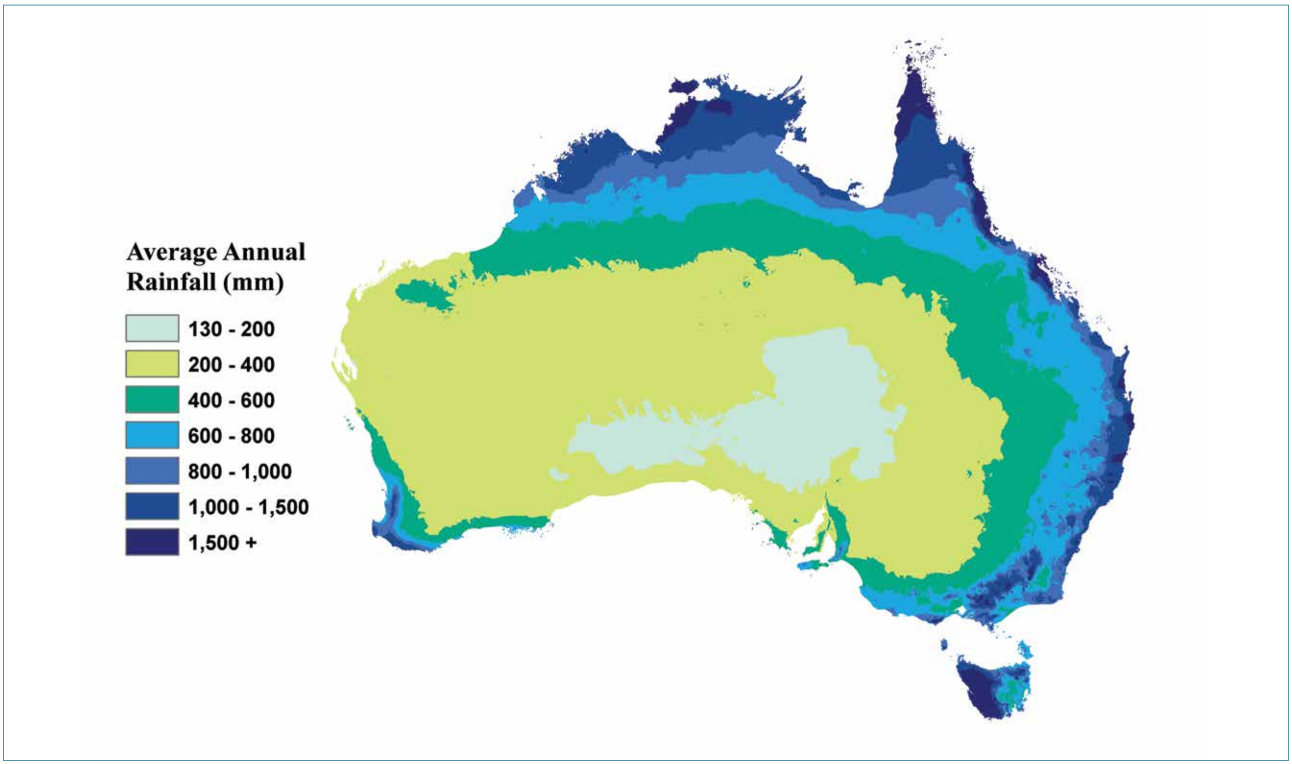
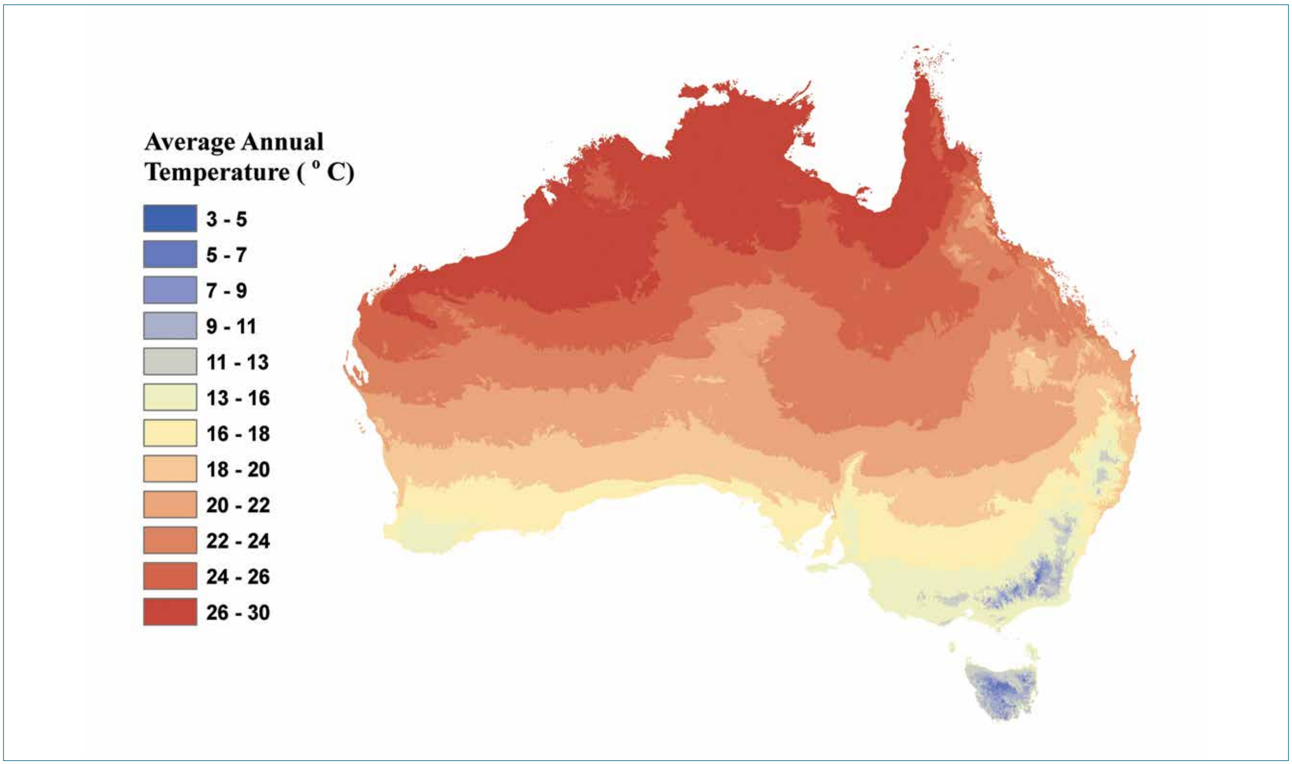


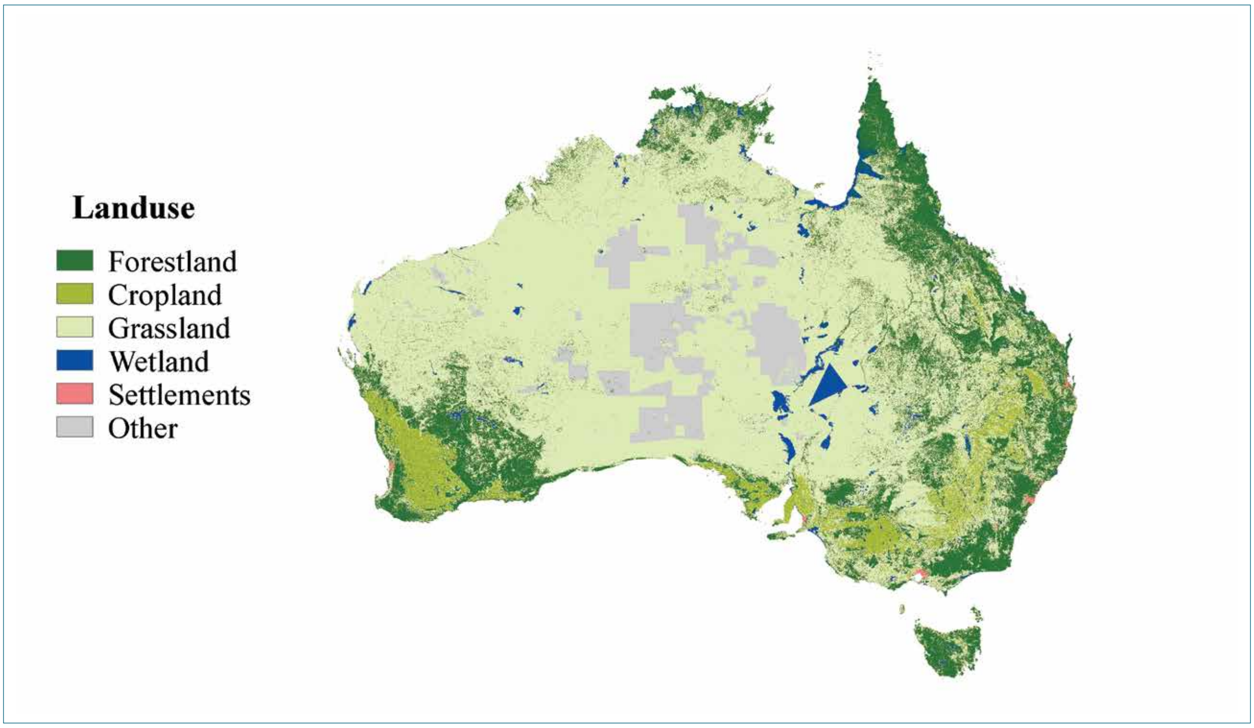
Figure 6.10b Long-term average annual temperature



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 the remaining 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 6.11. 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).

Figure 6.11 Map of land use in Australia



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 2013 IPCC 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, 1999; 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 are reported as subdivisions under *wetlands remaining wetlands.* Emissions and removals associated with anthropogenic changes in tidal marsh extent were reported for the first time in the 2015 Inventory and anthropogenic emissions associated with seagrass removal were included for the first time in the 2016 Inventory.

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.

The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories expanded the scope of available guidance for Wetlands, which now includes, in part, methane emissions from *reservoirs* and *other constructed waterbodies* within *flooded land remaining flooded land.* Australia reports methane emissions that arise from *reservoirs,* and from a subset of *other constructed waterbodies, freshwater ponds.* The national methodology, drawing from the 2019 Refinement guidance is described in Chapter 6.10 Wetlands Remaining Wetlands (Source Category 4.D.1).

6.2.2 Methodology

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.

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).

FullCAM has been designed to comply with IPCC Guidelines and to meet the Australian Government's international treaty estimation and reporting commitments.

FullCAM is designed to fully integrate the estimation of carbon stock changes and related emissions across the Australian landscape.

Model parameterization has been informed by the latest empirical science, and is continuously updated.

A comprehensive modelling approach to the estimation of carbon stock changes was originally chosen for the Australian land sector because of the absence of extensive forest inventory or measurement systems, reflecting the circumstance that timber industry activity has been confined in recent times to approximately 10 per cent of Australia's forest.

Spatial datasets for key disturbance events such as land clearing, forest planting and natural regeneration are derived by the Department of Industry, Science, Energy and Resources from LandSat satellite imagery held by the GeoScience Australia datacube (Digital Earth Australia) and processed by CSIRO Data61 and are informed by land use and vegetation datasets provided by the Department of Agriculture, Water and the Environment.

Spatial data for fire areas are derived from AVHRR satellite imagery. (Figures 6.12–6.13)

Figure 6.12 Spatial mapping of fire activity in Australia, 2019–20

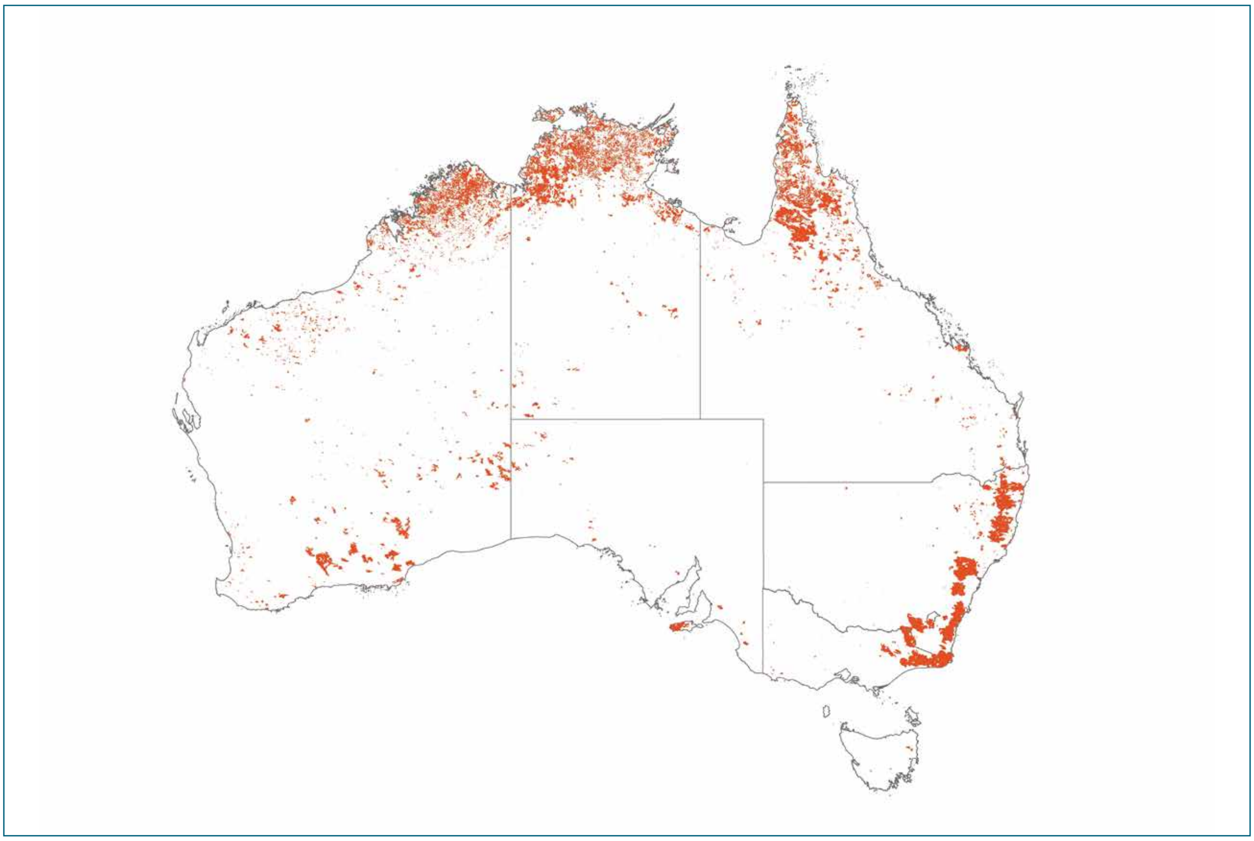
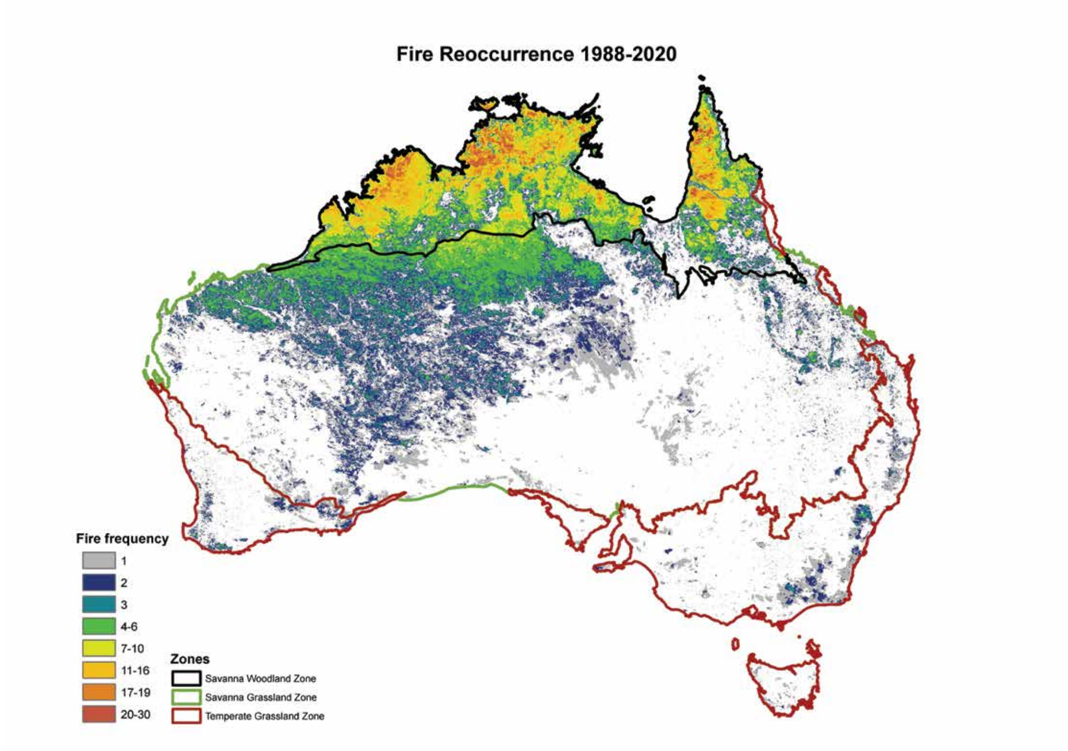


Figure 6.13 Spatial mapping of forest and grassland wildfire, 1988–2020



The system supports Tier 3, Approach 3 spatial enumeration of emissions and removals calculations for the following sub-categories:

- *Forest land remaining forest land*
- *Forest land converted to cropland, wetlands (Flooded Land), grassland, and settlements*
- *Grassland, cropland and settlements converted to forest land; and*
- *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 and sparse woody vegetation 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, *wetlands converted to forest land, forest land* (mangrove) *converted to settlements, wetlands* (tidal marsh) *converted to settlements, wetlands remaining wetlands* and *settlements remaining settlements* are reported using Tier 2 and Tier 3 methods.

Table 6.2 Summary of methodologies and emission factors – LULUCF sector

Greenhouse Gas Source and Sink	CO_2		CH_4		N_2O		NOx, 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, T3	CS, M						
Other native forests	T2, T3	CS, M						
Pre-1990 Plantations	T3	M						
Fuelwood consumed	T2	CS						
2. Land converted to Forest land								
Cropland converted to forest land	T3	M						
Grassland converted to forest land	T3	M						
Settlements converted to forest land	T3	M						
Wetlands converted to forest land	T2	CS						
B. Cropland								
1. Cropland remaining Cropland	T3, T2	CS, 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/M	T1/2	D		
2. Land converted to Wetlands	T3	M						
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						

Greenhouse Gas Source and Sink	CO_2		CH_4		N_2O		NOx, CO and NMVOC	
	Method applied	EF	Method applied	EF	Method applied	EF	Method applied	EF
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
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, T3	IE, CS	T2, T3	CS	T2, T3	CS	T2, T3	CS
H. Other (d)	NA	NA	NA	NA	IE	IE	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.

(d) Emissions from aquaculture, and from artificial waterbodies, in CRF Table 4.H are reported in the NIR under *wetlands remaining wetlands.*

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.

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).

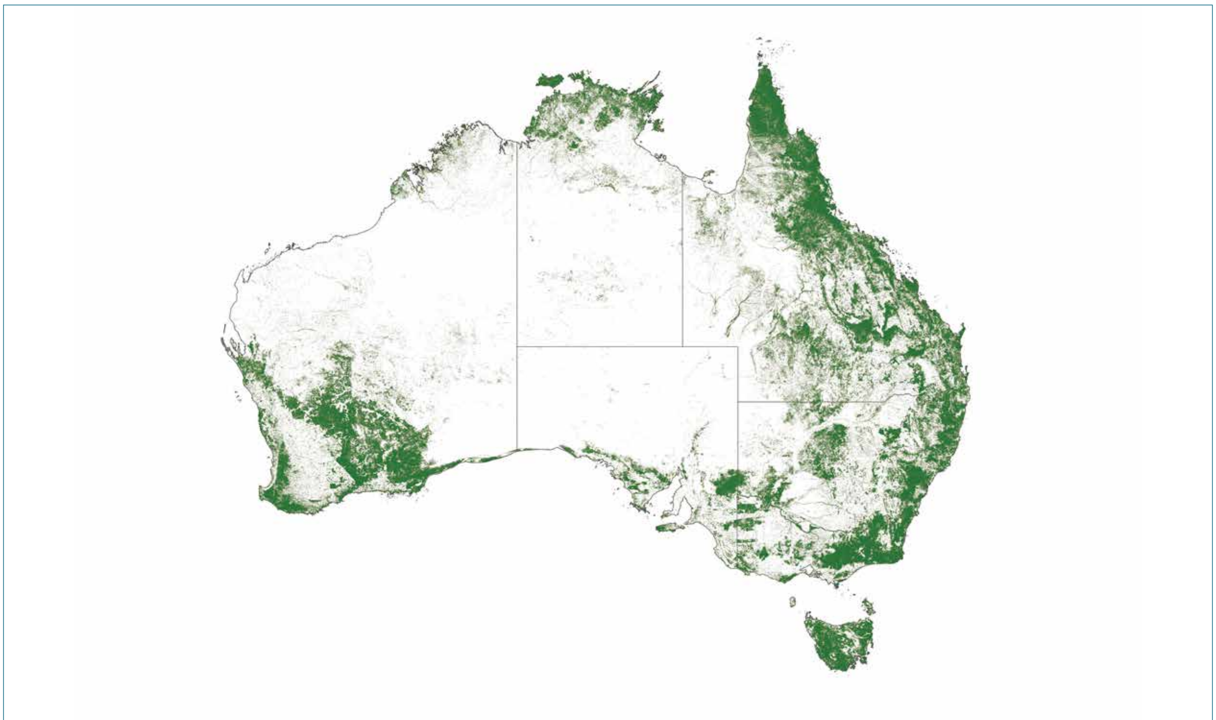
6.3.1 Land classifications

Forest land includes all lands with a vegetation height of at least 2 metres and crown canopy cover of 20 per cent or more (Figure 6.14) 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 and environmental plantings 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.

Australia has adopted a minimum forest area of 0.2 ha.

Figure 6.14 Forest extent in Australia

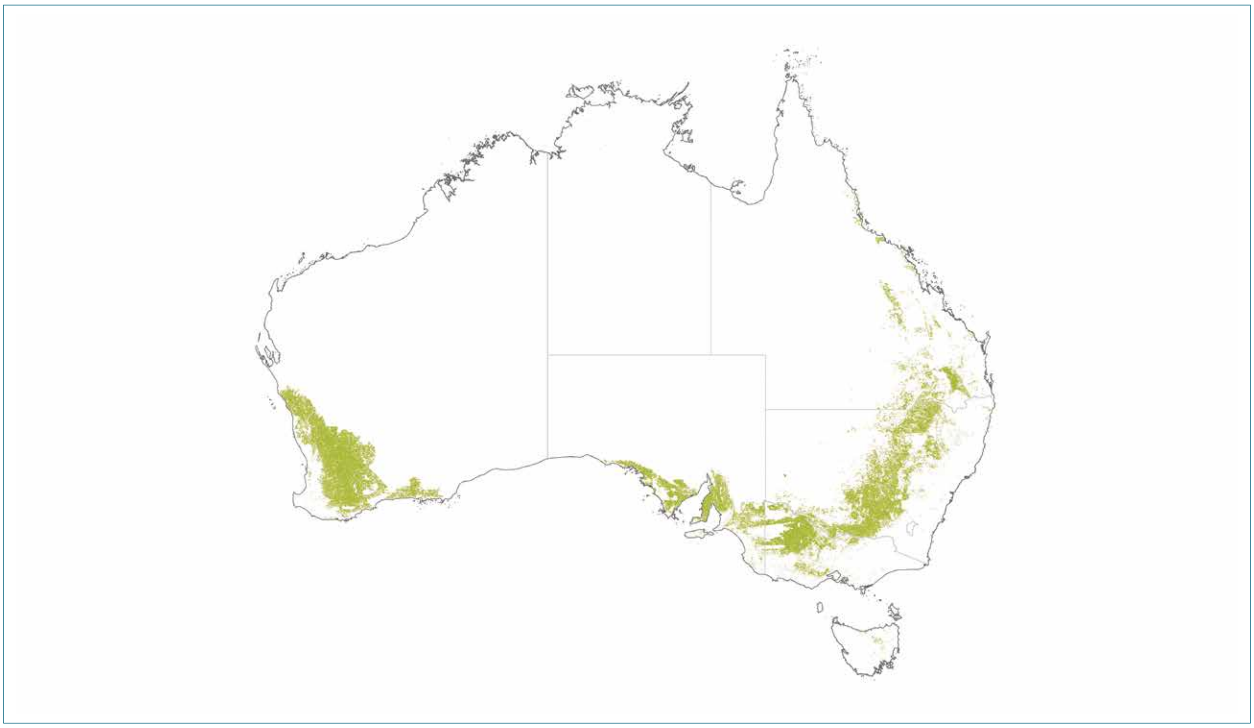


Cropland includes all land that is used for continuous cropping and those lands managed as crop-pasture (grassland) rotations (Figure 6.15) (ABARES, 2017).

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 6.15 Cropland remaining cropland distribution in Australia



The *grassland* category represents a diverse range of climate, management and vegetation cover (Figure 6.16) (ABARES, 2014). The *grassland* category also includes sub-forest forms of woody vegetation (shrubs).

Figure 6.16 Grassland remaining grassland distribution in Australia

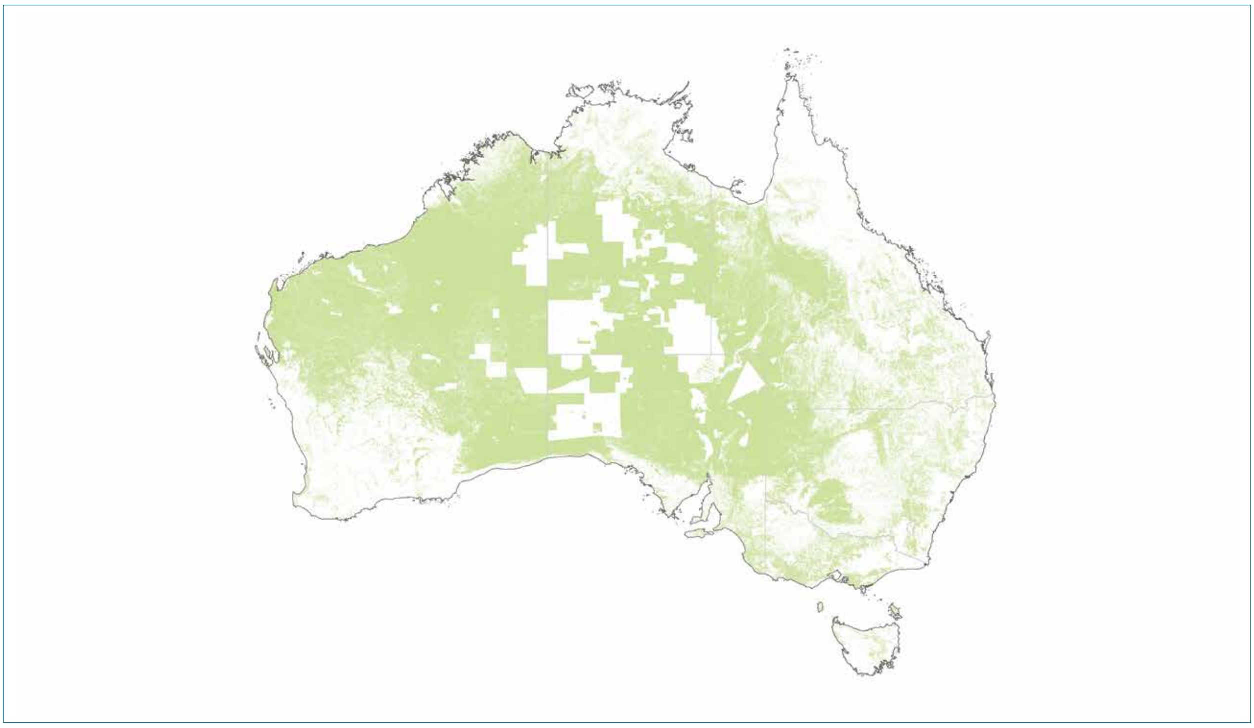


Figure 6.17 Examples of forest types and clearing activity

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) ABARES (2013), (bottom left) ABC 2015, (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 2017 ABARES catchments scale land use data (ABARES, 2017), 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 Agriculture, Water and the Environment. 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 (2014).

The allocation of a particular forest conversion area to either *wetland (flooded land), settlement, cropland* or *grassland* is determined using the same criteria as outlined above for the location in which the conversion occurred. Where the regrowth of forest is observed on these lands, the land is re-assigned to the inverse category for conversion to forest.

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*.

6.3.2 Land monitoring systems

Australia uses Approaches 1 and 3 as described in the *2006IPCC 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 (see Appendix 6.A for details).

The remote sensing programme is implemented by the Department of Industry, Science, Energy and Resources. 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 nearly 50 years from 1972 to 2020 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 *forest land remaining forest land,* data on areas of forest management are drawn from Australia's National Forest and Wood Products Statistics (ABARES 2020a), 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 grassland, wetlands and other land categories. Cropland has been updated to the September 2017 revision of these areas (ABARES, 2017). Settlements has also been updated using this revision and supplemented by spatial data from other unpublished sources. The other land categories are expected to be progressively updated over time. This information supports an Approach 1 representation of land, where only total areas are known for the areas under these land categories, not the prior land-use. In accordance with the 2006 IPCC Guidelines where the prior land-use is not known, emissions and removals associated with conversions to these land uses are estimated using the methods for land remaining in a land category. 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.

Loss of forest cover

Human-induced land-use changes from forest land to other land uses are visually attributed by trained operators, as described in Appendix 6.A.2.

In cases where there is a temporary loss of 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.

Losses in forest cover due to changes that occur within land tenures where it is expected that the land will revert to forest (e.g. harvested forest) 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, most of the 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. As an interim estimate for reporting purposes, a small proportion of the area being monitored within plantations is assumed to have undergone a land use change. This proportion is based on historical observations.

In Australia, land remains in the "conversion" sub-category for 50 years. This period is longer than the IPCC default, and reflects the long term impacts of conversion on carbon dynamics in Australian systems.

Once classified as a forest conversion event, the land continues to be monitored for subsequent forest cover changes associated with regrowth and re-clearing. Where subsequent forest-cover changes occur within a period shorter than 50 years, the land is reported in each reporting year based on the end-use category of the land in that year (either land *converted to forest land* following regrowth, or to the relevant *"forest land converted to... "* subcategory following re-clearing).

Gain in forest cover

In cases where new forest cover is detected on land previously under another land use (cropland, grassland, wetland or settlement), the land enters the *land converted to forest land* subcategory. Land monitored for this cover gain includes:

- Establishment of new commercial plantations
- Environmental plantings
- Forest emerging through natural regeneration (from seed or rootstock) on previously not forested, protected lands (i.e. land that has vegetation which is protected or requires a permit to clear under the relevant state's or territory's vegetation management laws, including conservation areas)
- Forest re-emerging on land that has previously been converted from forest to a non-forest land use.

Movement between sub-categories – greater than 50 years

After 50 years without further forest cover changes, the lands will be moved into the *"land remaining… "* sub-categories. Archives of satellite data currently support only 48 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 Industry, Science, Energy and Resources. 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.

Areas under each land-use as defined by the IPCC 2006 Guidelines are reported in Table 6.3 and Table 6.4 below.

Modelling of emissions and removals on land takes account of all forest cover changes, regardless of whether this forest cover loss or gain is considered to be a change in land-use.

Table 6.3 Area under land use, land use change and forestry classifications, 1989–2019 (kha)

Year	Forest remaining Forest	Land converted to Forest	Cropland remaining Cropland	Land converted to Cropland	Grassland remaining Grassland	Land converted to Grassland	Wetlands remaining Wetlands	Land converted to Wetlands	Settlements remaining Settlements	Land converted to Settlements	Other land
1989	132,084	2,549	37,692	1,852	513,167	6,339	13,163	23	1,134	133	60,692
1990	131,303	3,087	37,680	1,936	512,648	7,014	13,159	26	1,132	152	60,692
1991	130,410	3,740	37,680	1,993	512,289	7,542	13,156	28	1,132	168	60,692
1992	129,575	4,281	37,681	2,023	512,067	8,010	13,152	30	1,132	186	60,692
1993	129,056	4,706	37,682	2,039	511,847	8,298	13,149	31	1,132	198	60,692
1994	128,491	5,084	37,682	2,059	511,653	8,647	13,145	32	1,132	211	60,692
1995	128,075	5,470	37,683	2,075	511,460	8,846	13,142	33	1,132	220	60,692
1996	127,652	5,763	37,683	2,100	511,264	9,136	13,139	33	1,132	233	60,692
1997	127,224	6,062	37,684	2,126	511,076	9,416	13,136	34	1,132	246	60,692
1998	126,813	6,339	37,685	2,148	510,867	9,728	13,132	35	1,132	258	60,692
1999	126,252	6,617	37,685	2,169	510,700	10,144	13,129	35	1,132	273	60,692
2000	125,727	6,928	37,686	2,181	510,545	10,493	13,126	36	1,132	282	60,692
2001	125,106	7,169	37,687	2,200	510,410	10,982	13,122	36	1,132	291	60,692
2002	124,558	7,421	37,687	2,215	510,278	11,390	13,119	37	1,132	298	60,692
2003	124,089	7,652	37,688	2,230	510,120	11,762	13,116	37	1,132	312	60,692
2004	123,628	7,924	37,689	2,244	509,917	12,127	13,113	37	1,132	326	60,692
2005	123,019	8,139	37,689	2,263	509,703	12,694	13,109	37	1,132	350	60,692
2006	122,478	8,414	37,690	2,276	509,510	13,123	13,106	38	1,132	369	60,692
2007	121,993	8,665	37,690	2,288	509,355	13,491	13,103	38	1,132	382	60,692
2008	121,656	8,960	37,691	2,294	509,203	13,668	13,099	39	1,132	394	60,692
2009	121,396	9,387	37,692	2,297	509,025	13,669	13,096	39	1,132	403	60,692
2010	121,211	9,906	37,692	2,297	508,792	13,566	13,093	40	1,132	407	60,692
2011	121,022	10,414	37,693	2,297	508,547	13,492	13,090	43	1,132	408	60,692
2012	120,858	10,904	37,694	2,298	508,272	13,443	13,086	43	1,132	406	60,692
2013	120,687	11,420	37,694	2,300	507,951	13,420	13,083	43	1,132	407	60,692
2014	120,500	11,985	37,695	2,301	507,617	13,378	13,080	43	1,132	407	60,692
2015	120,394	12,618	37,695	2,298	507,207	13,269	13,077	43	1,132	404	60,692
2016	120,187	13,240	37,696	2,298	506,818	13,245	13,073	43	1,132	404	60,692
2017	119,978	13,817	37,697	2,292	506,479	13,227	13,070	43	1,132	402	60,692
2018	119,793	14,187	37,697	2,291	506,169	13,355	13,067	43	1,132	402	60,692
2019	119,533	14,562	37,698	2,290	506,016	13,403	13,063	43	1,132	397	60,692

Table 6.4 All land use totals, 1989–2019 (kha)

Year ending June	Forest land	Cropland	Grassland	Wetland	Settlements	Other land
1989	134,633	39,543	519,506	13,186	1,268	60,692
1990	134,389	39,616	519,662	13,185	1,284	60,692
1991	134,150	39,673	519,830	13,184	1,300	60,692
1992	133,855	39,704	520,078	13,182	1,318	60,692
1993	133,762	39,721	520,145	13,180	1,330	60,692
1994	133,575	39,741	520,300	13,177	1,343	60,692
1995	133,545	39,758	520,306	13,175	1,352	60,692
1996	133,415	39,784	520,400	13,172	1,365	60,692
1997	133,286	39,810	520,493	13,170	1,378	60,692
1998	133,151	39,832	520,595	13,167	1,390	60,692
1999	132,869	39,854	520,844	13,164	1,405	60,692
2000	132,655	39,867	521,038	13,162	1,414	60,692
2001	132,275	39,887	521,393	13,159	1,423	60,692
2002	131,979	39,902	521,668	13,156	1,430	60,692
2003	131,740	39,918	521,882	13,153	1,443	60,692
2004	131,552	39,933	522,044	13,150	1,458	60,692
2005	131,158	39,952	522,397	13,147	1,482	60,692
2006	130,893	39,966	522,633	13,144	1,501	60,692
2007	130,657	39,978	522,846	13,141	1,514	60,692
2008	130,616	39,985	522,871	13,138	1,526	60,692
2009	130,783	39,989	522,694	13,135	1,535	60,692
2010	131,117	39,989	522,358	13,133	1,539	60,692
2011	131,436	39,990	522,038	13,132	1,540	60,692
2012	131,763	39,991	521,715	13,129	1,538	60,692
2013	132,108	39,994	521,370	13,126	1,539	60,692
2014	132,484	39,996	520,995	13,123	1,539	60,692
2015	133,012	39,993	520,477	13,119	1,536	60,692
2016	133,427	39,994	520,063	13,116	1,536	60,692
2017	133,794	39,989	519,707	13,113	1,534	60,692
2018	133,981	39,988	519,524	13,110	1,534	60,692
2019	134,095	39,988	519,419	13,106	1,529	60,692

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.

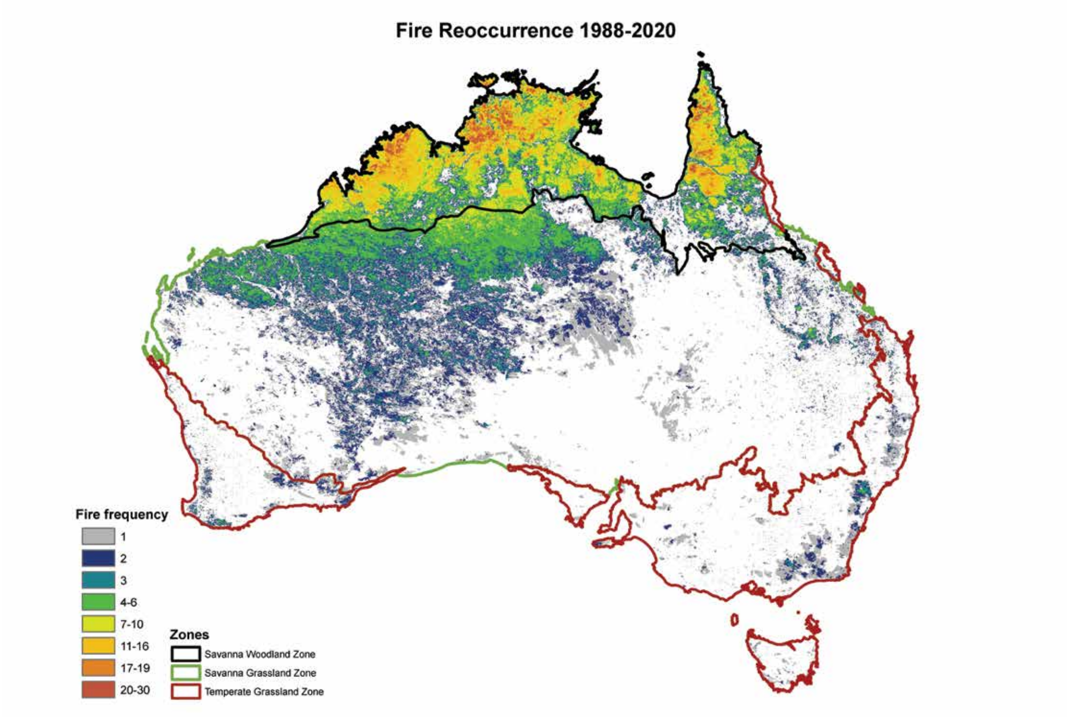
Other native forests include those forests that are comprised of endemic species, which are not *harvested native forests* or plantations. The *other native forests* sub-division includes protected areas (such as wilderness areas and national parks) not previously subject to harvesting and areas of extensive 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
- management fires 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 6.18, with implications for the estimation of carbon stocks.

Figure 6.18 AVHRR* burned area frequency and extent (1988–2020)



*Advanced Very High resolution Radiometry

Fire is a very frequent occurrence in the northern and central Australian wet/dry tropical, subtropical and semi-arid forest ecosystems. Many fires are from anthropogenic sources due to ongoing Indigenous fire management and the pastoral use of fire as a land management tool.

The seasonality of burning in this region has profound impacts on the fire behaviour and emissions associated with a fire event. Fires in the late dry season (LDS) are typically larger, more intense and consume more fuel than fires that occur during the early dry season (EDS). A primary aim of anthropogenic burning is to encourage more fires in the EDS to mitigate the impacts of the larger, more intense fires in the LDS. These strategic fires in the EDS can decrease net greenhouse gas emissions from these landscapes.

Australia's temperate forests are also highly adapted to fire although do not exhibit the same fire frequency as those in the north of the continent. Rather the majority of these forests are characterised by fire intervals on the decadal scale.

Prescribed burning in temperate forests involves conducting managed fires that aim to mitigate the risk and severity of wildfires by reducing fuel loads. Prescribed burning is typically low intensity and performed during the cooler and wetter months, 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 understorey 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, in addition to reporting inter-annual variability from natural disturbances, the trend in net emissions from anthropogenic fires (which include prescribed fires and wildfires) is reported. In order to estimate the trend in anthropogenic fires, 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

Emissions and removals from *harvested native forests* have been estimated using a spatially explicit Tier 3 FullCAM model for *harvested native forests* for the states of Victoria and New South Wales, described in section 6.4.1.2. The non-spatially explicit Estate modelling capability of FullCAM is used in other states, as described in Section 6.4.1.1.

6.4.1.1 Harvested native forests – Estate Method

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 modelled 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 6.7).

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	Eucalypt low closed
	Tall Closed Shrublands	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	Eucalypt 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) (Estate method, Australia-wide).

Forest Type	Establishment 1–10yrs	Juvenile 11–30yrs	Immature 31–100yrs	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

	Fraction of biomass allocated to:					
Forest Type	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, 2019a) using a historical relationship between roundwood removals and harvest area data collated by state agencies (Table 6.18).

The broad silvicultural systems applicable to each state are reported in Table 6.10. 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 cool 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 cool temperate rainforests spatially and in successional sequence (Hickey, 1994).

Table 6.10 Broad silvicultural systems used in the Estate model for harvested native forests

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 6.11. 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 6.12.

Table 6.11 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 6.12 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 (FCjk) 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:

$$E_{ijk} = FC_{jk} \times EF_{ijk} \times C_i \qquad (4.A.1\_1))$$

and for total annual emissions for NO and N O are:

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

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)

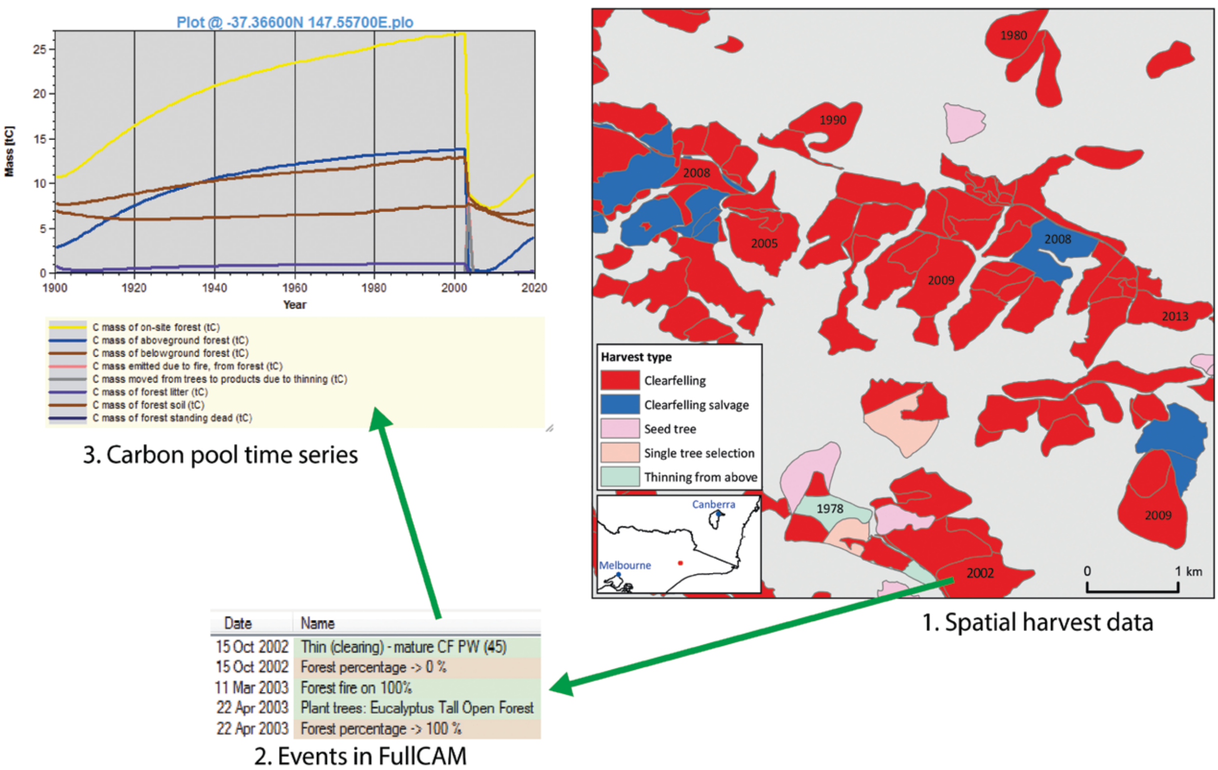
C_j = factor to convert from elemental mass of gas species *i* to molecular mass (Appendix 6.K.9).

6.4.1.2 Harvested native forests – Spatial Method

The spatially explicit Tier 3 FullCAM model for *harvested native forests*, has been applied to the states of Victoria and New South Wales.

The FullCAM spatial method for *harvested native forests* simulates carbon stock changes due to tree growth, timber harvesting and associated management, and fire. The general operation of FullCAM spatial simulations is described in Appendix 6.B. In the spatial method for *harvested native forests*, the type, location and date of timber harvesting activities are drawn from historical harvest data provided by state forestry agencies. This is illustrated in Figure 6.19, in which harvest areas drawn from the spatial harvest data trigger events in the FullCAM simulation, and resulting changes to the forest carbon pools. The yellow line represents the on-site carbon mass at one site increasing with tree growth, decreasing with timber harvesting in 2002, and again increasing with regrowth.

Figure 6.19 Overview of the spatial method for harvested native forests.



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 and post-harvest fire where this occurs. 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 modelled based on Major Vegetation Groups of the National Vegetation Information System (NVIS, see NLWRA, 2001). The changes in carbon stock are estimated using FullCAM for areas defined as Multiple Use Forest (Appendix 6.E.3), with the model run separately for each 25m x 25m grid cell within these areas. Growth of living biomass in each cell is calculated according to the Tree Yield Formula (TYF), as described in Appendix 6.B.2, using biomass increments which are defined as a function of the:

- age of the tree stand;
- assumed initial biomass, M predicted by model (Appendix 4.D) which also defines the maximum biomass for a mature forest at each location; and
- estimated constant that determines the rate of approach towards M.

Post-harvest growth is modelled according to the type of harvest that took place. Areas subject to clearfell harvest regrow from age zero according to the TYF.

After disturbance events which leave living biomass, such as partial harvesting or fire, a biomass recovery function determines the rate of regrowth in the post-disturbance recovery phase. The biomass recovery function is based on the calculated amount of biomass lost from disturbances, which is then added back as an addition to the annual increment over a number of years, until the 'target biomass' is reached (see *Biomass recovery function* in Appendix 6.B.2).

Partitioning of biomass among tree components

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 rainfall zone (Table 6.13).

Table 6.13 Partitioning of biomass between the tree components under different rainfall zones.

Rainfall zone	Fraction of biomass allocated to:					
	Stems	Branches	Bark	Leaves	Coarse Roots	Fine Roots
≥500mm	0.49	0.11	0.09	0.04	0.24	0.03
<500mm	0.28	0.22	0.08	0.07	0.27	0.08

Carbon fraction of biomass

The carbon fractions of the tree components (Table 6.14) are based on studies of Australian vegetation (Gifford, 2000a and 2000b).

Table 6.14 Carbon Fraction of biomass for each tree component based on Gifford (2000a and 2000b)

Tree component	% Carbon
Stems	50
Branches	47
Bark	49
Leaves	52
Coarse roots	50
Fine roots	48

Forest harvest

Harvest events are applied at the locations and dates specified in the spatial data for harvest history provided by state government agencies (currently Victoria and New South Wales) which also specifies the harvest type used in each case. The harvest history data is described in Appendix 6.E.3. The characteristics of each harvest type used in FullCAM, are the proportion of above ground tree biomass harvested, the proportion of tree stems which are removed from the site as product, and management associated with the harvest type, such as a post-logging regeneration burn. These harvest characteristics were determined based on advice provided by organisations responsible for managing timber production on public land (VicForests and the Forestry Corporation of New South Wales). The characteristics of each harvest type are listed in Table 6.15.

The amount of carbon affected by each harvest event is determined for each 25 x 25 m pixel by characteristics of the harvest type, and the size of each carbon pool at that location resulting from past growth, and regrowth from past disturbance by harvests and fires.

Table 6.15 Harvest types used in the spatial model for harvested native forests, and their parameters.

State	Harvest type	Major Vegetation Group	Percentage harvested	Pulpwood taken	Percentage of stem to product	Post-harvest fire
Vic	Clearfell (including salvage)	Eucalyptus Tall Open Forest; Eucalyptus Open Forest; Eucalyptus Low Open Forest; Low Closed Forest & Closed Shrublands	100%	Yes	95%	Yes
		Other forest types	100%	No	35%	Yes
Vic	Group (or Gap) selection	Eucalyptus Tall Open Forest	100%	No	67%	No
		Eucalyptus Tall Open Forest	50%	Yes	95%	No
		Other forest types	50%	No	45%	No
		Other forest types	50%	Yes	55%	No
Vic	Regrowth retention harvesting	Eucalyptus Tall Open Forest;	100%	Yes	95%	Yes
		All forest types	100%	No	35%	Yes
Vic	Dangerous tree removal / road alignment	Eucalyptus Tall Open Forest; Eucalyptus Open Forest	100%	Yes	95%	No
		All forest types	100%	No	35%	No
Vic	Seed tree	Eucalyptus Tall Open Forest; Eucalyptus Low Open Forest; Low Closed Forest and Closed Shrublands;	85%	Yes	90%	No
		All forest types	85%	No	50%	No
Vic	First Shelterwood	Eucalyptus Tall Open Forest; Eucalyptus Open Forest; Eucalyptus Low Open Forest	85%	Yes	55%	No
		All forest types	85%	No	50%	No
Vic	Second Shelterwood	All forest types	100%	---	65%	No
Vic	Single tree selection	All forest types	20%	---	90%	No
Vic	Thinning from above / below	Eucalyptus Tall Open Forest; Eucalyptus Open Woodland	50%	---	90%	No
		Other forest types	40%	---	90%	No
NSW	Australian group selection	All forest types	25%	---	90%	No
NSW	Plantation clearfell	All forest types	65%	Yes	85%	Yes
NSW	Salvage - roadline & storm	All forest types	100%	---	90%	No
NSW	Salvage – fire & other	All forest types	50%	---	90%	No
NSW	Alternate coupe	All forest types	80%	Yes	90%	Yes
NSW	Miscellaneous	All forest types	10%	No	90%	No
NSW	Non-commercial harvest	All forest types	100%	No	0%	No
NSW	Thinning	All forest types	40%	No	90%	No
NSW	Single tree selection - light	All forest types	20%	No	90%	No
NSW	Single tree selection - mix	All forest types	30%	No	90%	No
NSW	Single tree selection - moderate	All forest types	30%	No	90%	No

State	Harvest type	Major Vegetation Group	Percentage harvested	Pulpwood taken	Percentage of stem to product	Post-harvest fire
NSW	Single tree selection – release	All forest types	30%	No	90%	No
NSW	Single tree selection – heavy	All forest types	40%	No	90%	No
NSW	Single tree selection – regeneration	All forest types	60%	No	90%	No

Pulpwood taken is not specified where it does not affect percentage harvested or percentage stem to product. Once harvested, in the model, the removal of products is assumed to result in a transfer of carbon to the *harvested wood products* modelling (see section 6.15) 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 turnover rates applied for each plant component in the model are shown in Table 6.16. The decomposition rates used are shown in Table 6.17. Along with the initial amount of forest debris, these values were derived from Paul *et al.* (2017).

Table 6.16 Turnover for tree components

Tree component	Turnover % month^{-1}
Branches	0.74
Bark	0.41
Leaves (rainfall ≥500mm)	2.96
Leaves (rainfall <500mm)	1.28
Coarse Roots	0.87
Fine Roots	12.55

Table 6.17 Decomposition rates for debris pools used in the harvested native forests model

Debris component	Breakdown % month^{-1}	
	Decomposable	Resistant
Deadwood	-	1.25
Bark litter	-	1.44
Leaf litter	81.2	2.70
Coarse dead roots	-	2.93
Fine dead roots	81.2	81.2

Breakdown rates are not given for decomposable deadwood, bark litter and coarse dead roots because these pools are treated as entirely resistant.

Estimating changes in soil carbon

Soil carbon is estimated using FullCAM 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. Consistent with the method outlined in the *IPCC 2006 Vol 4, 2.3.3.1,* a mean incremental value for the transitions between SOC near steady states is derived, in this case from the simulated annual data, consistent with the method applied in croplands and grasslands.

Harvested native forests – biomass burning

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

The CO_2 emissions associated with slash burning which follows some harvest types (see table 6.15) in *harvested native forests* similarly modelled in FullCAM as part of the *harvested native forests* model. The mass of carbon burnt annually (FCjk) is taken directly from FullCAM and is used to estimate the CO_2 and non-CO_2 gas emissions associated with slash burning.

6.4.1.3 Harvested Native Forests Activity Data

Table 6.18 Area of harvesting activity by year and modelling method.

Year	Area harvested (ha)		
	Estate method (Qld, Tas, WA)	Spatial method (Vic, NSW)	Total
1990	34,917	69,540	104,457
1995	42,745	71,672	114,418
2000	29,141	70,398	99,539
2005	33,134	61,814	94,948
2006	48,690	53,948	102,638
2007	33,384	57,820	91,203
2008	34,497	60,772	95,269
2009	27,364	51,209	78,573
2010	21,189	40,012	61,201
2011	21,993	40,914	62,907
2012	25,842	30,422	56,263
2013	25,272	26,841	52,112
2014	18,337	27,823	46,159
2015	21,598	26,772	48,370
2016	18,711	28,961	47,672
2017	16,363	30,498	46,861
2018	19,072	29,655	48,727
2019	15,056	29,550	44,606

Source: Estate method derived from ABARES 2020. Spatial method based on Department of Jobs, Precincts and Regions Victoria (2020) and Forestry Corporation of New South Wales (2020).

6.4.1.4 Pre-1990 Plantations

Plantations included within *forest land remaining forest land* are commercial plantations (predominantly softwood) established in Australia up to the end of 1989.

Pre-1990 plantations are simulated using a fully spatial FullCAM simulation. Spatial layers based on information obtained from ABARES are constructed for plantings and harvesting is identified from Landsat satellite imagery.

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

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).

The plantation management database incorporated in the FullCAM 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 6.31.

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 above ground harvest residues were assumed to be standing dead material, which slowly breaks down (Table 6.35a) to produce CO_2 and debris at an assume ratio of 9:1 (Paul and Roxburgh 2019b). 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 6.19.

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) and Paul *et al.* (2017). Table 6.20 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.I.3.

Table 6.19 Tree component annual turnover rates

Tree Component	Softwood Turnover % month^{-1}	Hardwood Turnover % month^{-1}
Branches	0.74	0.74
Bark	0.41	0.41
Leaves	3.07	4.22
Coarse Roots	0.87	0.87
Fine Roots	12.55	12.55

Table 6.20 Debris decomposition rates

Debris Component	Softwood Turnover % month^{-1}	Hardwood Turnover % month^{-1}
Deadwood	1.25	1.25
Bark Litter	1.44	1.44
Foliage litter, decomposable	81.16	81.16
Foliage litter, resistant	1.84	2.70
Coarse Dead Roots	2.93	2.93
Fine Dead Roots	81.16	81.16

Table 6.21 Plantation types, wood densities, carbon content and management regimes

Region(s)	Species	Density	CC% Leaf	CC% Branch	CC% Wood	CC% Bark	CC% Fine Roots	CC% Roots	Coarse 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	Southern Pine (P. elliotti, P. taeda.	440	52	51	52	53	46	49	Average Sites – 27% thinning @ 14 years.
Tableland	Araucaria cunninghamii)								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
Victoria (Central Gippsland)	Eucalyptus plantations	550	52	47	52	49	46	49	All Sites – CF @ 25

Region(s)	Species	Density	CC% Leaf	CC% Branch	CC% Wood	CC% Bark	CC% Fine Roots	CC% Roots	Coarse Regime Description(a)
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	Clearfall @ 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. This also applies to pre-1990 plantations.

Estimating changes in soil carbon

Soil carbon is estimated using FullCAM 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* establishment is sourced from the National Plantation Inventory (NPI) (ABARES, 2016), which provides spatial information on area planted during 1940 to 1989, year of planting and plant type/species. The plantation area is spread over the 15 NPI regions (Figure 6.20) in three broad classes defined as – Short Rotation Hardwood (SRH), Long Rotation Hardwood (LRH) and Softwood (SW). Table 6.22 shows the plantation establishment activity data.

As explained above, the timing of harvesting is based on satellite imagery while the timing of thinning is based on region and species specific management practices.

Figure 6.20 The National Plantation Inventory regions

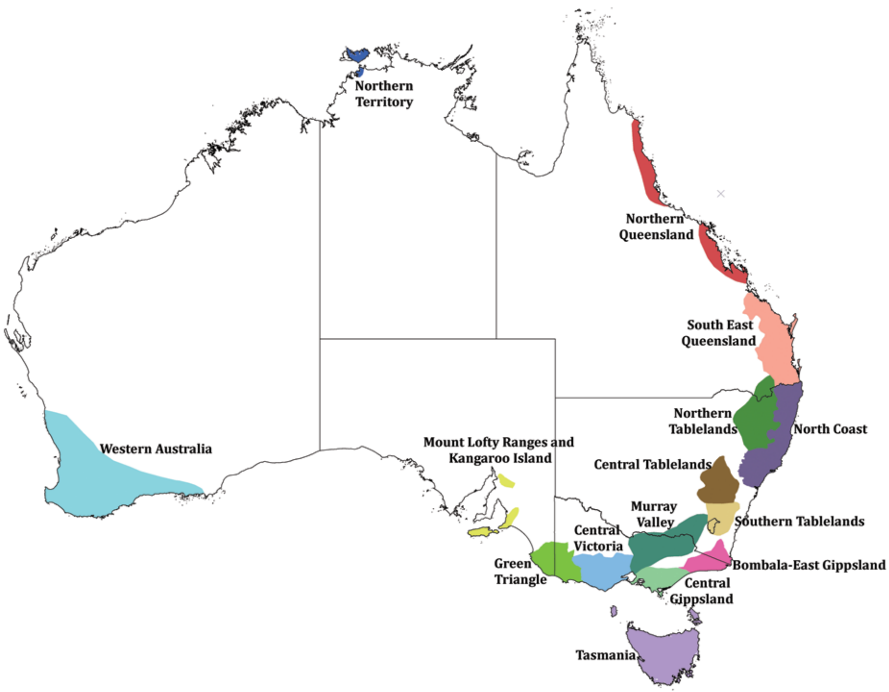


Table 6.22 Cumulative area of land converted to plantation from 1940–1989

Year	Area (ha)	Year	Area (ha)
1940	820	1965	87,893
1941	1,479	1966	100,890
1942	2,451	1967	116,985
1943	2,988	1968	132,384
1944	4,141	1969	152,774
1945	5,961	1970	174,239
1946	7,772	1971	197,289
1947	9,971	1972	221,709
1948	11,908	1973	246,367
1949	14,638	1974	271,962
1950	17,211	1975	297,274
1951	19,842	1976	324,124
1952	22,465	1977	349,916
1953	25,099	1978	376,636
1954	27,826	1979	403,176
1955	30,468	1980	427,662
1956	33,343	1981	454,019
1957	36,221	1982	477,377
1958	39,316	1983	504,496
1959	43,907	1984	532,543
1960	49,457	1985	560,313
1961	55,183	1986	589,618
1962	61,018	1987	620,649
1963	68,345	1988	652,105
1964	77,546	1989	683,082

6.4.1.5 Other native forests

Wildfire emissions and removals in temperate and tropical zone forests are estimated using a Tier 3, Approach 3 spatial simulation using FullCAM.

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

This inventory report introduces Tier 3 modelling of prescribed burning of temperate forests in New South Wales, Victoria, Australian Capital Territory and South Australia. Tier 2 models are used for prescribed burning in the remaining states which contain temperate forests, and fire in the arid and semi-arid central Australian forests and grasslands (see below).

Stratification of forests

Other native forests are stratified into three geographic / climatic zones where fires demonstrate significantly different behaviour. The boundaries of these zones are shown in Figure 6.18.

a) Tropical zone forests – the northern part of the Northern Territory (NT), Western Australia (WA) and Queensland (Qld), are 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 6.23). These classes are derived using a combination of validated vegetation, land use and geological data sets (Lynch *et al.* 2015; Meyer and Cook, 2015).

Table 6.23 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	1.1 = Woodland hummock	1 = High	2 = Late Dry Season (LDS)	2 = Coarse
3 = NT	1.2 = Shrubland hummock	1 = High	3 = Other fire	3 = Heavy
4 = SA	1.3 = Woodland mixed	1 = High	4 = Temperate Wildfire	4 = Shrub
5 = Tas	1.4 = Open forest mixed	1 = High	5 = Temperate Controlled burning	5 = Aggregated
6 = Qld	1.5 = Melaleuca woodland	1 = High		
7 = Vic	1.6 = Shrubland (heath) with hummock grass	2 = Low		
8 = WA	1.7 = Woodland with mixed grass	2 = Low		
	1.8 = Open woodland with mixed grass	2 = Low		
	1.9 = Woodland with tussock grass	2 = Low		
	1.10 = Woodland with hummock grass	2 = Low		
	2 = Subtropical and semi-arid zone	3 = NA		
	3 = Temperate zone	3 = NA		

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

Carbon stock changes

A time-series of monthly satellite data is used to identify the time and location of fires, which are simulated at the 25m x 25m plot size (Figure 6.18). 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.

The AVHRR burnt area product is not used for prescribed burning identification as it is limited in its ability to identify fires where the canopy remains intact. Areas of land where prescribed burns were conducted are identified either through;

1. the supply of digitised, spatially explicit mapping of prescribed burning treatment areas from state or territory fire authorities (spatial data); or
2. tabular reports of the sum of land areas treated with prescribed burning from state or territory fire authorities (tabular data).

For this report, New South Wales, Victoria, Australian Capital Territory and South Australia provide spatial data to allow a Tier 3 modelling approach for prescribed burning. The remaining states, Western Australia, Queensland, Tasmania and the Northern Territory, are modelled using the tabular data in a Tier 2 approach. The department is consulting with state and territory governments in these states to acquire data to expand the Tier 3 spatially explicit model.

When fires are detected, impacts on all pools excluding soil carbon are modelled (including live biomass, standing dead stem, branches bark and coarse woody debris, bark debris and grasses). Further research is required to estimate the impacts of fire on soil carbon.

Carbon stock changes in all pools are modelled using the spatially explicit (Approach 3) capabilities of the Tier 3 FullCAM modelling system. These were parameterised for typical fires, and not assumed to be highly intense stand-replacing fires which are unusual in most Australian eucalypt and dominated forests. Hence, for both woody and grass live biomass components, it was assumed that fire did not burn roots, with live root biomass assumed to continue at equilibrium conditions of growth and turnover regardless of the fire simulation. A full description of the modelling system is provided in Appendix 6.B and 6.D, Waterworth *et al,* 2007; Waterworth and Richards, 2008; and Paul and Roxburgh, 2019a.

Changes in live biomass are estimated using the gain-loss method. The *other native forests* component excludes areas subject to observed harvesting and deforestation, therefore are assumed to represent mature stands in equilibrium conditions, with annual increments in living biomass and soil carbon stocks balanced by annual losses in the absence of disturbances. The main processes leading to emissions and removals in these forests are related to fire management practices. For this reason the loss of biomass due to wood removals (harvesting) is zero.

Biomass losses due to disturbances (as a percentage of pre-fire biomass) are shown in Table 6.K.5.

Live woody biomass is simulated as mature stands at equilibrium conditions. The model inputs of initial above-ground biomass of living woody vegetation were derived from the maximum site carrying capacity (Roxburgh *et al.* 2019).

Simulations include short-term fire-induced impacts on the predicted relative allocation of woody biomass due to: (i) fires resulting in only partial burning of live woody biomass components, with the extent of impact varying between components, and; (ii) rates of post-fire re-sprouting or regeneration differing between components, e.g. relatively fast for foliage and relatively slow for stem wood.

Therefore annual increment in these forests is calculated directly as recovery following the loss of live biomass from disturbances. Based on Ximenes *et al.* (2016), recovery of live woody biomass from wildfires (which are not stand-replacing, and typically only affect 10 percent of initial live biomass) is modelled over 12 years, with the exception of foliage, which takes 3 years. For all other fire types (whose impact on live biomass is smaller), it was assumed that recovery of live woody biomass took 2 years, with the exception of foliage, which took only 0.5 years. Consistent with *grassland remaining grassland* when disturbances cause a biomass reduction of > 40%, perennial grasses recover biomass over a 60 day period. Changes in dead organic matter stocks in *other native forests* are calculated in accordance with the gain-loss method in 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 $_{ijk|m}$ are the dimensions over which DOM is stratified for the purposes of this estimate (see table 6.24)

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

A = area of land remaining in land-use category

DOM_{in} = average annual transfer of biomass into the dead wood / litter pool due to annual processes and disturbances;

DOM_{out} = average annual carbon loss out of dead wood or litter pool

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

DOM stocks are modelled using the spatially explicit (Approach 3) capabilities of the Tier 3 FullCAM modelling system.

Table 6.24 Comparison of carbon pools modelled under the previous T2 model and the current T3 FullCAM implementation

Pool type	Fuel pools calculated using previous T2 method	Fuel pools simulated using FullCAM
Live biomass	Shrub	Live Above-Ground Biomass impacted by fire, but which recovers quickly
Fine DOM	Fine-grass	Decomposable grass litter + Resistant grass litter + above-ground biomass of grass
Fine DOM	Fine-woody	Standing Dead foliage + Decomposable foliage litter + Resistant foliage litter
Coarse DOM	Coarse-light	Standing dead bark + Decomposable bark litter + Resistant bark litter
Coarse DOM	Coarse-heavy	Standing Dead stem + Standing Dead branch + Decomposable deadwood + Resistant deadwood

FullCAM simulates turnover and decay processes for each pool based on site conditions (productivity and vegetation type) and monthly climate data, until a fire event is identified based on the Advanced Very High Resolution Radiometry (AVHRR) satellite data. Fire events were individually parameterized for each State (i), Vegetation Class (j), Rainfall Zone (k), Fire Variant / seasonality (l), and DOM size class (m) (Meyer *et al.* 2015; Roxburgh *et al.* 2015), with the resulting fuel dynamics being replicated by FullCAM as described by Paul and Roxburgh (2019 a).

Where supported by empirical data, the default IPCC DOM classes of litter and dead wood are further disaggregated into fine (grass live biomass, grass litter, foliage on standing dead material, and foliage litter), coarse-light (standing dead bark, and bark litter), coarse-heavy (standing dead stem and branches, and coarse woody debris) and live woody biomass (Table 6.K.4).

In order to initialise the model ahead of the reporting period, fires prior to 1988 are simulated based on available estimates of typical fire return intervals, time of year fires occur, area of the fire scar, and the proportion of EDS to LDS burns in tropical savanna fire zones, where available from previous studies and expert opinion (Meyer *et al*. 2009; Murphy *et al.* 2013). To introduce variation in the simulated fire events, uniform probability distribution functions were applied to vary these assumptions between what was deemed to be their upper and lower bounds.

It was also assumed that grasses were a component of the total live biomass within each fire zone. FullCAM has existing default inputs (e.g. yields, allocation of biomass, die-off, decomposition, etc.) for simulation of different perennial grass species (Table 6.K.3).

Carbon stock changes from prescribed burning on temperate forest are estimated using a non-spatially explicit Tier 2 model which estimates carbon stock changes in DOM pools based on the balance of inputs from litterfall and outputs (losses due to disturbances, or through decay) described in the equation (the burning efficiency and carbon content used in this T2 model are listed in Tables 6.K.15 and 6.K.16):

$$DOM_{i,j=3,k=3,l=5,m=1,2,\,t} = (L_{ijklm}/D_{ijkm} \times (1 - e\text{-}_{Dt}) + FL_{0,ijklm} \times e\text{-}_{Dt}\,) \times 10_{-3} \qquad (4.A.1\_4)$$

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

L_{ijklm} = average annual rate of fresh litter input (Tables 6.K.13 and 6.K.14);

D_{ijkm} = average decay constant (Tables 6.K.13 and 6.K.14);

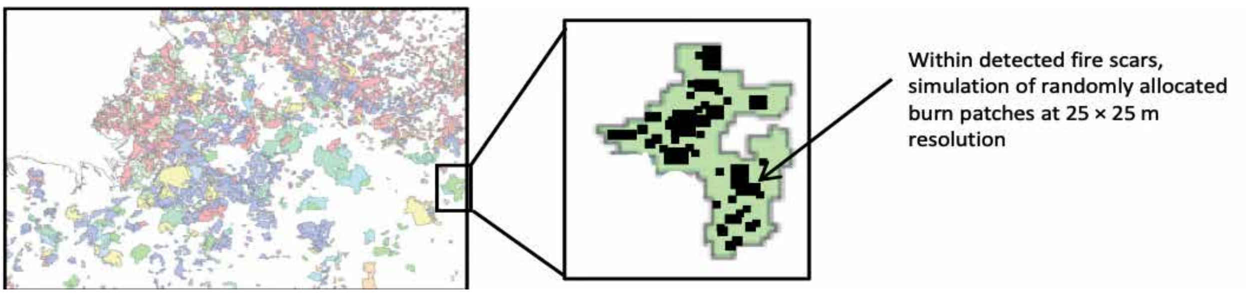
t = years since the last burn (YSLB).

Burning efficiencies and Patchiness

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).

Fires do not uniformly affect the landscape, and will leave unburned patches at a finer scale than the resolution of the satellite data. In FullCAM fire events are only applied to a proportion of cells randomly selected within the fire scar in accordance with the assumed Patchiness values *(P).* Patchiness depends on fire intensity, and varies based on State, Vegetation Type and Fire Variant (e.g. seasonality). Figure 6.21 shows fire patches (various colours indicate different year in which the fire occurred) in north-west Australia. As indicated in the panel to the right, within each fire scar detected, the patchiness assumption is applied such that a burning event is simulated within only a randomly selected proportion of pixels within each fire scar.

Figure 6.21 Diagrammatic example indicating how spatial fire is implemented within FullCAM



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

FullCAM calculates area burned, the DOM stocks at time t, and the losses due to fire based on the burning efficiency, providing an output in terms of carbon flow to atmosphere due to fire for each State (i), Vegetation Class (j), Rainfall Zone (k), Fire Variant (l), and DOM size class (m). Using these calculations, emission factors 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) were then applied to calculated non-CO_2 emissions Table 6.K.9 to Table 6.K.11.

Non-CO2 emissions

For CH_4, CO, and NMVOCs calculate emissions as:

$$E = \Sigma_{ijklm\ YSLB} (A \times DOM_{out\ ijklmYSLB} \times CC_{jkm} \times EF_{g,jkm} \times C_g) \qquad (4A.1\_5)$$

and for NO_X, N_2O:

$$E = \Sigma_{ijklm\ YSLB} (A \times DOM_{out\ ijklmYSLB} \times CC_{jkm} \times NC_{jkm} \times EF_{g,jkm} \times C_g) \qquad (4A.1\_6)$$

Where E = emissions from fires (Gg);

A = Area of land remaining in land-use category

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

CC_{jkm} = carbon content (Table 6.K.5)

NC_{jkm} = nitrogen:carbon ratio (Table 6.K.7)

EF_{gjkm} = emission factor (g N or C emitted as trace species / g DOM N or C emitted) (Tables 6.K9–6.K.11);

C_g = elemental to molecular mass conversion factor (Table 6.K.8); and

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

1. Definition of natural disturbances and types of disturbances identified in the inventory

The fire-adapted ecology of Australian eucalypt-dominated temperate forests leads to infrequent, extreme wildfires. Natural 'background' emissions and removals caused by natural disturbance fires are considered to be caused by non-anthropogenic events and circumstances 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. These fires are considered to be part of the 'natural background' of non-anthropogenic emissions and removals, which under the Managed Land Proxy (MLP) are understood to average out over time and space.[3]

This national definition of natural disturbances applies to wildfires on temperate forests, and does not apply to fires reported as controlled burning (e.g. in temperate forests or in wet-dry tropical forests and woodlands). All fires on *land converted to forest land* are treated as anthropogenic.

The impacts of human activities (e.g. salvage logging, prescribed burning, deforestation) are excluded from the identification of natural disturbances through the application of an Approach 3 representation of lands which is used to track lands subject to natural disturbances and separately identify and exclude land subject to human activities, as explained in section 6.3.

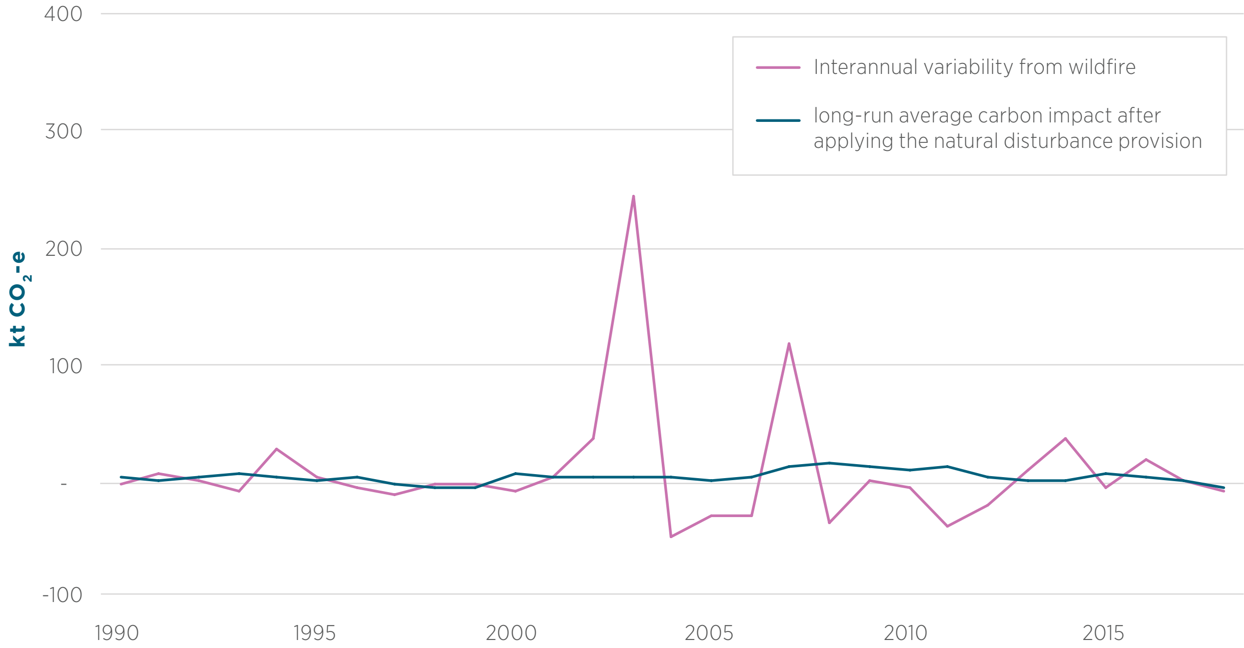
2. Quantification of inter-annual variability due to all wildfire and natural disturbances (total Managed Land Proxy (MLP) flux)

In Australia, all lands are considered managed lands. All carbon stock changes on managed land from anthropogenic and natural 'background' emissions and removals are reported, consistent with the MLP, including from wildfires.

Inter-annual variability in natural 'background' of emissions and removals is modelled as shown in figure 6.22 below, along with the estimated trend in net emission and removals associated with human activities.

3 IPCC 2006 Guidelines, Volume 4, Chapter 1 (p 1.5) states that, *"…while local and short-term variability in emissions and removals due to natural causes can be substantial (e.g. emissions from fire, see footnote 1), the natural 'background' of greenhouse gas emissions and removals by sinks tends to average out over time and space"*

Figure 6.22 Interannual variability from wildfire, including natural 'background' emissions and removals (total MLP flux)



3. Methods used for identification and quantification of emissions and removals due to natural disturbances

The quantification of emissions and subsequent removals from natural disturbances is done by identifying fires which meet the definition of natural disturbances both at the total (landscape-level) emissions and regional levels, and tracking disturbed areas at fine spatial scales within the Tier 3, Approach 3 FullCAM modelling system.

In order to disaggregate emissions and removals due to natural disturbances under the Tier 3 method applied in this inventory, natural disturbances are explicitly identified in the activity data. Both initial carbon losses and subsequent recoveries in carbon stocks are modelled as part of the disturbance event, and carbon stocks are spatially tracked until pre-disturbance levels are reached to ensure completeness and balance in reporting. A modelling approach is then 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 in the national inventory (IPCC 2006 Volume 4 1.5), consistent with the Managed Land Proxy (see footnote 4). The approach ensures that Australia's modelled implementation of the MLP is comparable with estimates generated using other methods, such as Tier 3 stock-difference approaches, that tend to average out interannual variability due to natural causes over space (scaling from plots to region) and time (averaging between periodic re-measurements). Natural disturbances evident in the activity data are identified in two steps, summarised in Table 6.25.

1. 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.

2. 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.

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.

Table 6.25 Calculations for the natural disturbance test in States and Territories, 1990–2019

	Calibration period	Calculation details	Threshold	Number of natural disturbance years 1990–2019
Step 1: National Level Test	2000–2012	Applied to: gross emissions (not including removals). Threshold calculation: mean plus two standard deviations of calibration period.	63,138 kt CO_2-e	5
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			0.01 kha	2
NSW			224.28 kha	2
Qld			169.29 kha	1
SA			42.45 kha	2
Tas			16.87 kha	3
VIC			122.16 kha	4
WA			359.75 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.*

4. Disaggregation of emissions and removals due to natural disturbances and identification of the trend in emissions and removals associated with human activity

After identifying lands subject to natural disturbances, and associated emissions and removals, anthropogenic emissions and removals are estimated using the remaining time series of area burned in anthropogenic fire in each State or Territory. The 2019 Refinement to the 2006 IPCC guidelines note that even after disaggregating natural disturbances, "This remaining aggregate of emission and removals associated with human activities might still include some effects of IAV [inter-annual variability] of natural disturbances and other natural effects on anthropogenic emission and removals" (IPCC 2019 Refinement, Volume 4, Chapter 2.6.1.1). In order to control for this remaining inter-annual variability the long-run trend in carbon stocks is reported, reflecting the balance of the carbon lost in the fire and that re-absorbed by regrowth. This information is reported in Table 6.26 below.

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

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

Table 6.26 Disaggregation of total managed land proxy flux into natural disturbances component and identification of trend in emissions associated with human activity

Land use category		Forest land remaining forest land									
Years		1990	1995	2000	2003	2004	2005	2006	2007	2008	2009
Total MLP flux from wildfires	Total area under the MLP (kha)	131,303	128,075	125,727	124,089	123,628	123,019	122,478	121,993	121,656	121,396
	Annual area of wildfires including natural disturbances, reported in NIR (kha)	199	279	111	2,624	125	321	245	1,729	354	518
	Carbon stock change (kt)	66	-772	1,718	-59,681	12,792	8,417	7,690	-27,814	10,007	1,116
	Non-CO_2 fluxes (tonnes)	1,049	1,925	452	26,992	1,029	1,959	1,425	16,326	2,385	5,379
	CO_2-e (kt)	807	4,757	-5,849	245,822	-45,874	-28,902	-26,772	118,311	-34,309	1,287
Natural disturbances component	Annual area of natural disturbances (in reporting year) (kha)	-	-	-	2,587	-	-	-	1,309	-	-
	Cumulative area subject to natural disturbances (kha)	-	-	-	-	2,583	2,577	2,566	2,440	3,727	3,699
	Carbon stock change (kt)	-	-	-	-63,183	11,679	9,556	7,639	-24,188	11,091	9,195
	Non-CO_2 fluxes (tonnes)	-	-	-	26,719	-	-	-	13,238	-	-
	CO_2-e (kt)	-	-	-	258,389	-42,824	-35,038	-28,008	101,926	-40,666	-33,716
Inter-annual variability in non-natural disturbance wildfires	Remaining area of managed land (kha)[1]	131,303	128,075	125,727	124,089	123,628	123,019	122,478	121,993	121,656	121,396
	Annual area of wildfires reported in NIR (kha)	199	279	111	37	125	321	245	420	354	518
	Carbon stock change (kt)	66	-772	1,718	3,502	1,112	-1,139	51	-3,626	-1,083	-8,079
	Non-CO_2 fluxes(tonnes)	1,049	1,925	452	273	1,029	1,959	1,425	3,088	2,385	5,379
	CO_2-e (kt)	807	4,757	-5,849	-12,567	-3,050	6,136	1,236	16,385	6,357	35,002
Refined MLP flux	Remaining area of managed land (kha)[1]	131,303	128,075	125,727	124,089	123,628	123,019	122,478	121,993	121,656	121,396
	Annual area of wildfires reported in NIR (kha)	199	279	111	2,624	125	321	245	1,729	354	518
	Carbon stock change (kt)	-733	-307	-1,456	-1,313	-1,100	-20	-937	-2,775	-3,558	-2,728
	Non-CO_2 fluxes (tonnes)	1,391	1,528	1,832	1,956	1,929	1,555	1,977	2,847	3,425	3,379
	CO_2-e (kt)	4,077	2,653	7,171	6,770	5,962	1,628	5,413	13,023	16,472	13,381

Land use category		Forest land remaining forest land									
Years		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total MLP flux from wildfires	Total area under the MLP (kha)	121,211	121,022	120,858	120,687	120,500	120,394	120,187	119,978	119,793	119,533
	Annual area of wildfires including natural disturbances, reported in NIR (kha)	919	153	474	712	1,139	594	904	603	564	896
	Carbon stock change (kt)	2,349	10,443	6,015	-1,873	-8,136	2,203	-4,112	971	2,776	-4,989
	Non-CO_2 fluxes (tonnes)	4,850	1,193	2,392	5,085	7,998	4,035	6,458	4,606	3,860	6,718
	CO_2-e (kt)	-3,762	-37,097	-19,664	11,952	37,830	-4,043	21,536	1,045	-6,318	25,009
Natural disturbances component	Annual area of natural disturbances (in reporting year) (kha)	-	-	-	-	854	-	799	-	-	762
	Cumulative area subject to natural disturbances (kha)	3,669	3,632	3,599	3,512	3,415	4,203	4,072	4,802	4,719	4,548
	Carbon stock change (kt)	7,402	6,239	5,070	4,036	-11,526	5,045	-8,545	5,595	4,568	-10,808
	Non-CO_2 fluxes (tonnes)	-	-	-	-	6,272	-	5,546	-	-	6,033
	CO_2-e (kt)	-27,142	-22,877	-18,590	-14,799	48,534	-18,500	36,876	-20,516	-16,750	45,661
Inter-annual variability in non-natural disturbance wildfires	Remaining area of managed land (kha)[1]	121,211	121,022	120,858	120,687	120,500	120,394	120,187	119,978	119,793	119,533
	Annual area of wildfires reported in NIR (kha)	919	153	474	712	284	594	105	603	564	135
	Carbon stock change (kt)	-5,054	4,203	945	-5,909	3,390	-2,842	4,432	-4,624	-1,792	5,819
	Non-CO_2 fluxes(tonnes)	4,850	1,193	2,392	5,085	1,726	4,035	912	4,606	3,860	685
	CO_2-e (kt)	23,380	-14,219	-1,074	26,751	-10,704	14,457	-15,340	21,561	10,432	-20,651
Refined MLP flux	Remaining area of managed land (kha)[1]	121,211	121,022	120,858	120,687	120,500	120,394	120,187	119,978	119,793	119,533
	Annual area of wildfires reported in NIR (kha)	919	153	474	712	1,139	594	904	603	564	896
	Carbon stock change (kt)	-1,813	-2,779	-485	-42	3	-1,110	-287	199	1,777	1,900
	Non-CO_2 fluxes (tonnes)	3,240	3,780	3,049	2,886	2,830	3,273	3,028	2,820	2,013	1,830
	CO_2-e (kt)	9,889	13,968	4,827	3,042	2,818	7,345	4,081	2,092	-4,503	-5,138

1 The remaining area of managed land is the same as the total area of forest land, because area and net emissions from natural disturbances are still included in reporting, as the long-run trend in carbon stock change reflecting the balance of the carbon lost in the fire and that re-absorbed by regrowth.

5. Identification of lands subject to natural disturbances and monitoring for forest recovery (expectation of balance between emissions and subsequent removals)

The Tier 3, Approach 3, modelling system using FullCAM has been designed to comply with the following safeguard mechanisms:

- the use of geo-located 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.

FullCAM uses two remote sensing data sources. The Advanced Very High Resolution Radiometer (AVHRR) is used identify and map natural disturbance impacts due to wildfire on forest lands, whereas Landsat data is used to map forest cover changes and identify permanent land-use changes across all forest lands.

FullCAM spatially tracks areas and carbon stocks at the 25m x 25m pixel-level on lands identified as experiencing natural disturbances in a particular year, until another anthropogenic activity occurs (e.g. non-natural disturbance fire, salvage logging or land-use change).

Further information to demonstrate the disaggregation and monitoring of recovery of carbon stocks lost during disturbances is included in section 6.4.4.3 (Source specific QAQC – Other native forests).

6. 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-anthropogenic disturbance.

7. Demonstrating practicable efforts to prevent, manage and control wildfires in Australia (how the requirements of natural definition of disturbances have been met)

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 firefighting 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
- Firefighting 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)[4] 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 (BoM) 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.

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 BoM.

BoM 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, BoM 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.

4 https://knowledge.aidr.org.au/media/4935/nationalbushfiremanagementpolicy_2014.pdf

BoM 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 BoM 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 (NSW)

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, including Lord Howe Island.

This plan describes the arrangements for the control and coordination by the New South Wales Rural Fire Service (NSW RFS) Commissioner for the response to Class 2 & 3 bush and grass fires, including those managed under the provisions of section 44 of the Rural Fires Act 1997, and the provisions for emergency warnings at all classes of fires.

These arrangements ensure that the two combat agencies, NSW RFS and Fire & Rescue NSW, are able to manage small scale bush and grass fires, utilising assistance from the National Park & Wildlife Service and Forestry Corporation NSW where appropriate.

The current NSW State Bush Fire plan is available at www.emergency.nsw.gov.au

Victoria (VIC)

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.

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

Victoria's State Bushfire Plan is available at www.emv.vic.gov.au

Queensland (QLD)

In Queensland, fire management policies and plans are developed at the regional level rather than at the state level.

The Queensland Government provides an overview of the approach to disaster management in the *Queensland Prevention, Preparedness, Response,* and *Recovery Disaster Management Guideline* for local, district, and state disaster management stakeholders with regard to their functions, obligations and legislative requirements under the *Disaster Management Act 2003.*

The aim of the Guideline is to provide flexible, good practice suggestions and advice to those responsible for implementing disaster management practices. It is augmented with other manuals, reference guides, forms, templates, maps, diagrams, handbooks and links to related publications, designed to support stakeholders to fulfil their disaster management responsibilities to the Queensland community.

The Guideline and additional items can be accessed from the Queensland Government Disaster Management website at www.disaster.qld.gov.au

Western Australia (WA)

Western Australia has developed a series of State Hazard Plans (Westplans) through its State Emergency Management Committee. These include a hazard plan for fire which is intended to be read in conjunction with the State Emergency Management Plan.

The State Hazard Plan for Fire provides an overview of arrangements for the management of fire in WA and contains information on fire prevention, preparedness, response and initial recovery. These plans are available at www.semc.wa.gov.au

South Australia (SA)

In South Australia, the State Emergency Management Committee (SEMC) is responsible for the State Emergency Management Plan (SEMP), which sets out the state's comprehensive emergency management arrangements. The South Australian Fire and Emergency Service Commission is the lead agency for disaster resilience in SA and is a member of the SEMC.

The SEMP describes SAs emergency management arrangements to support resilience, preserve and save lives, and reduce risk to the environment, property and infrastructure. It takes an 'all-hazards' approach to emergency management including bush fires as a large range of hazards can cause similar problems and similar arrangements are required to manage them.

The South Australian State Emergency Management Plan is available at www.dpc.sa.gov.au

Tasmania (TAS)

Tasmania's State Fire Management Council (SFMC) is established under Section 14 of the Fire Service Act 1979 (Tasmania). It is an independent body that has the responsibility of providing advice to the Minister and the State Fire Commission about the management of vegetation fire across Tasmania, particularly in the areas of prevention and mitigation of fires. It also formulates and promulgates policy in relation to vegetation fire management within Tasmania in relation to bushfire fuels and mitigation. The primary function of the SFMC is to develop a State Vegetation Fire Management Policy that is used as the basis for all fire management planning.

Fire protection plans have been prepared for each of the ten fire management areas in Tasmania to identify and prioritise bushfire risks in the landscape and strategically identify work that can be done to mitigate that risk.

The objective of the plans is to effectively manage bushfire related risk within those areas in order to protect people, assets and other things valuable to the community. The plans identify that strategic fuel management needs to occur across public and private property boundaries in order to be effective and that management of bushfire related risk is not the sole responsibility of any one land manager or agency but a shared responsibility of the whole community.

Fire protection plans for the various regions of Tasmania are maintained on the SFMC website at www.sfmc.tas.gov.au

Northern Territory (NT)

In the Northern Territory, fire management in urban areas is the responsibility of the NT Fire and Rescue Service, and in rural areas is the responsibility of Bushfires NT.

Bushfires NT is the lead government agency for rural bushfire management in the NT and exists to help protect life, property and the environment from bushfire by providing support for mitigation, management and suppression activities, and coordinating landowner and volunteer participation in response to significant fires.

The Territory Emergency Plan has been prepared by the Northern Territory Emergency Service in accordance with the Emergency Management Act in order to describe NT's approach to emergency and recovery operations, the governance and coordination arrangements, and roles and responsibilities of agencies. It is supported by regional, local and hazard-specific sub plans and functional group supporting plans.

The Territory Emergency Plan and further information is available at www.pfes.nt.gov.au

Australian Capital Territory (ACT)

The ACT Government Emergency Services Agency's Strategic Bushfire Management Plan is the overarching document that directs all levels of bushfire planning in the ACT. Its purpose is to provide a strategic framework to protect the ACT community from bushfires and reduce resulting harm to the physical, social, cultural, and economic environment of the ACT.

The plan sets objectives and actions for agency and community preparation and response for bushfires, bushfire hazard assessment and risk analysis, bushfire prevention including hazard reduction, and adaptive management to apply best practice to bushfire management and prevention practices in the ACT in a changing environment.

The latest version of the plan draws on continuing research into fire management, bushfire behavior, the effects of climate change and seasonal weather, the important role of the community, lessons learned nationally and internationally, and feedback from the community. It is available at www.esa.act.gov.au

8. 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.

6.4.1.6 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 Australian Energy Statistics. 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 modelled decay or fires affecting the DOM pool, these instant losses through fuelwood consumption are offset against an Olson fuel accumulation curve (T95 per cent = 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 6.27.

Table 6.27 Emissions and removals from forest land remaining forest land (1990–2019) (Gg CO_2-e)

Year	Harvested native forests	Plantations	Other native forests				Total
			Fuelwood consumed	Wildfires	Prescribed burning of temperate forests	Non-temperate forest fires	
1990	1,094	-8,353	446	4,077	1,077	1,961	302
1995	5,398	-9,324	501	2,653	3,076	1,541	3,845
2000	5,781	-5,925	244	7,171	-2,389	3,912	8,794
2005	-3,419	-4,212	-419	1,628	560	2,361	-3,501
2006	-4,433	-2,826	-491	5,413	630	3,009	1,302
2007	-2,263	-3,200	-555	13,023	433	3,018	10,455
2008	-1,837	-2,078	-612	16,472	1,005	4,270	17,220
2009	2,032	-930	-662	13,381	1,203	4,312	19,336
2010	3,903	-1,181	-711	9,889	695	4,180	16,776
2011	85	237	-757	13,968	303	4,732	18,567
2012	-4,712	-386	-577	4,827	-558	4,010	2,605
2013	-7,435	-159	-439	3,042	-1,133	3,629	-2,495
2014	-14,875	-441	-415	2,818	-312	4,375	-8,850
2015	-20,881	1,568	-465	7,345	509	3,706	-8,218
2016	-21,218	902	-403	4,081	817	1,997	-13,825
2017	-24,084	3,155	-342	2,092	1,700	2,004	-15,476
2018	-27,223	4,225	-304	-4,503	1,267	1,342	-25,197
2019	-26,746	5,572	-278	-372	772	1,516	-19,535

6.4.3 Uncertainties and time series consistency

Uncertainties for the *forest land remaining forest land* sub-category are estimated to be ±33.5 per cent 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

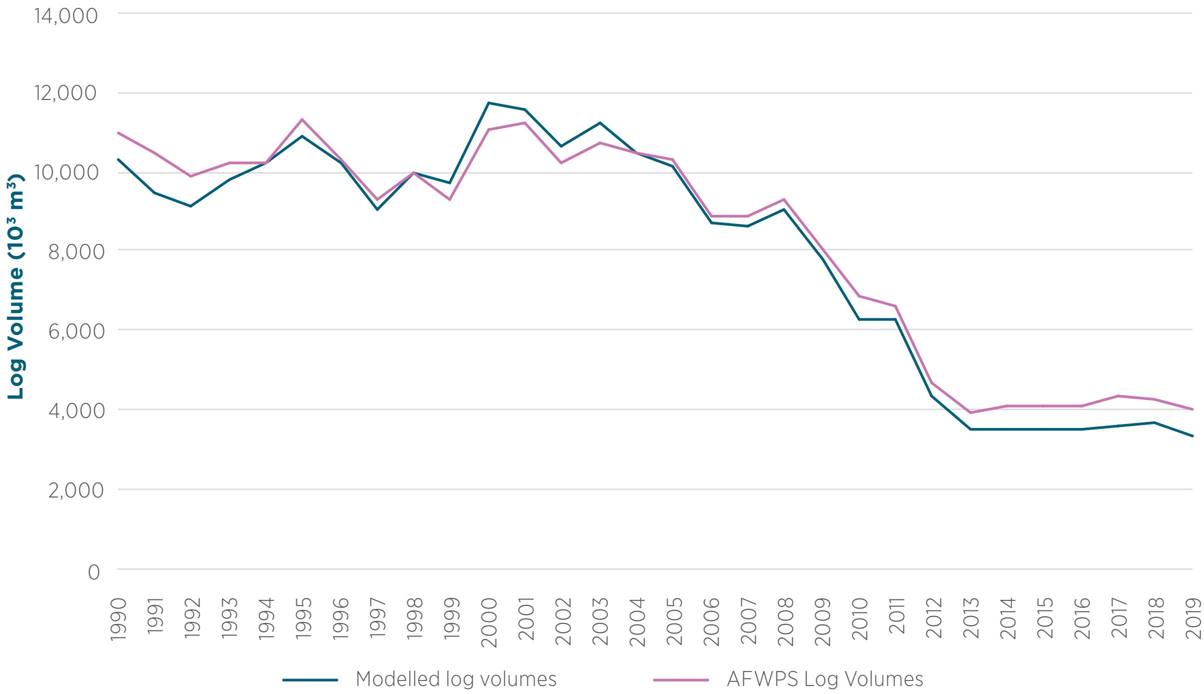
For the Estate method for *harvested native forests*, data on harvesting is derived from roundwood log volumes for each state (ABARES, 2020a) using a historical relationship between roundwood removals and harvest area data collated by state agencies. Roundwood log volumes are published in the biannual Australian Forest and Wood Products Statistics report (ABARES, 2020a), 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).

For the Spatial method for *harvested native forests*, data on harvesting is provided directly by state forest management agencies. These data on the location, type and date of harvesting, along with parameters for tree growth, debris and soil processes are used to generate the estimate of net emissions and also of the carbon mass removed from the harvested areas as product. Conversion of this carbon mass to wood volume provides a model output which can be compared directly to the roundwood log volumes (ABARES, 2020a, Figure 6.23).

The overall *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, 2020a) (Figure 6.23). 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 750 kg/m^3. The modelled log volumes closely track the published statistics over time.

Figure 6.23 Estimated removals in Harvested Native Forests, FullCAM outputs compared to national harvesting statistics (ABARES, 2019a)



6.4.4.2 Pre-90 Plantations

The calibration and validation of FullCAM, 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

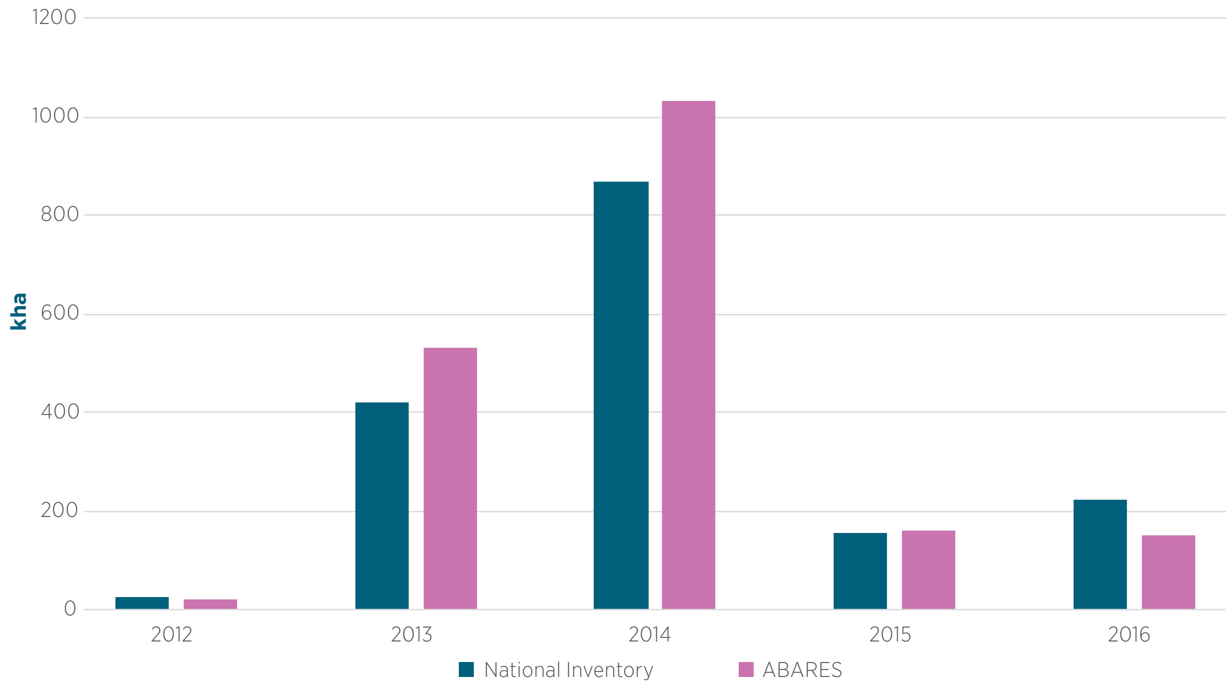
The activity data for wildfire was assessed by the Royal Melbourne Institute of Technology (RMIT) (Lowell, 2014), and compared with a range of alternative datasets, and was found to be the most suitable and highest quality time series data available. The datasets considered by the RMIT included:

1. Monthly AVHRR burnt area products (1990 to 2014), obtained from the Western Australian Land Information Authority (Landgate);
2. Monthly MODIS burnt area 500m products (2000 to 2013), obtained from the global database maintained by the University of Maryland, USA;
3. Limited coverage of wildfire data from the Landsat series of satellites; and
4. Reference bushfire history data supplied by state agencies.

The overall quality of the post-2000 AVHRR burnt area products had a low commission error (5.4 per cent) which indicates that 94.6 per cent of the wildfire detected in the Landgate AVHRR burnt area product were correctly classified. The omission error was around 11 per cent after accounting for the undetected low-intensity prescribed burns (22 per cent) and smaller fires below the minimum mapping unit (9 per cent) which the 1km resolution AVHRR optical sensors were not expected to detect.

The data reported in the NIR also aligns with reporting to FAO forest resources assessment in the ABARES State of the Forests Report 2018 covering data up to 2016 (Figure 6.24).

Figure 6.24 Comparison of annual forest area experiencing wildfire, Australia, 2012–2016 (kha)



The reporting of net emissions from *other native forests,* and the identification and disaggregation 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. This methodology and outcomes have been subjected to independent review (Federici, 2016a).

Demonstrating balance of emission and subsequent removals associated with natural 'background' fires

Over time, average net emissions of CO_2 from non-anthropogenic emissions and subsequent removals will approach zero. Therefore the disaggregation of natural disturbance emissions will neither over- nor under-estimate net emissions in the long term. This can be further demonstrated when simulating a fire event at the plot level – over the long-term the average net carbon dioxide emissions from natural disturbances is zero.

Natural disturbance emissions and removals are not in exact balance over the 1990–2019 period due to a number of recent disturbances from 2007 to 2019, recovery from which is ongoing. Given the recovery rates for a typical disturbance event, it is projected to take an extended period 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.

Net emissions and removals from wildfires prior to 1990 are included in reporting. However no natural disturbances have been identified which affect net emissions and removals during the reporting period.

Table 6.28 Balancing of natural disturbance CO_2 emissions and removals

Year	Natural disturbance CO_2 emissions	Natural disturbance CO_2 removals
	Mt CO_2	
1990	0.00	0.00
1991	0.00	0.00
1992	0.00	0.00
1993	0.00	0.00
1994	0.00	0.00
1995	0.00	0.00
1996	0.00	0.00
1997	0.00	0.00
1998	0.00	0.00
1999	0.00	0.00
2000	0.00	0.00
2001	0.00	0.00
2002	0.00	0.00
2003	231.67	0.00
2004	0.00	-42.82
2005	0.00	-35.04
2006	0.00	-28.01
2007	111.09	-22.40
2008	0.00	-40.67
2009	0.00	-33.72
2010	0.00	-27.14
2011	0.00	-22.88
2012	0.00	-18.59
2013	0.00	-14.80
2014	52.90	-10.64
2015	0.00	-18.50
2016	46.35	-15.02
2017	0.00	-20.52
2018	0.00	-16.75
2019	52.95	-13.32
Total (1990–2019)	494.96	-380.82
1990–2019 net average	2.57	
1990–2019 net standard deviation	51.3	

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 disaggregation 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.

6.4.5 Recalculations since the 2018 Inventory

The recalculations reported in the current submission are shown in Table 6.29 and include:

A. Other native forests – fire simulations

Improvements have been made to spatial fire simulations in South-Eastern Australia. Spatially explicit information on prescribed burning in Victoria, South Australia, the Australian Capital Territory and New South Wales have been utilised for estimation of emissions using Tier 3 FullCAM methodology.

Recovery functions for fire-affected areas have also been revised from a linear to a non-linear method. More information on the updates to fire simulation methodology is included above in chapter 6.4.1.5 and in Appendix 6.B.3 and 6.K.

B. Pre-90 Plantations

There are small differences in net emissions/removals between last year's simulation and this year's simulation mainly due to updates to modelling inputs such as soil cover factor, climate data and fixes to turnover/decomposition database tables (Figure 6.25a).

A comparison of carbon stock change in the on-site tree and debris pools (Figure 6.25b) indicates that during 1975–2019, the annual net carbon mass gains were similar in both the new and the old simulations indicating that the annual harvesting during this period generally remained at the same level.

Figure 6.25a Comparison of Pre-90 Plantation emissions from the previous (2020–18) and the new (2021–19) spatial simulations

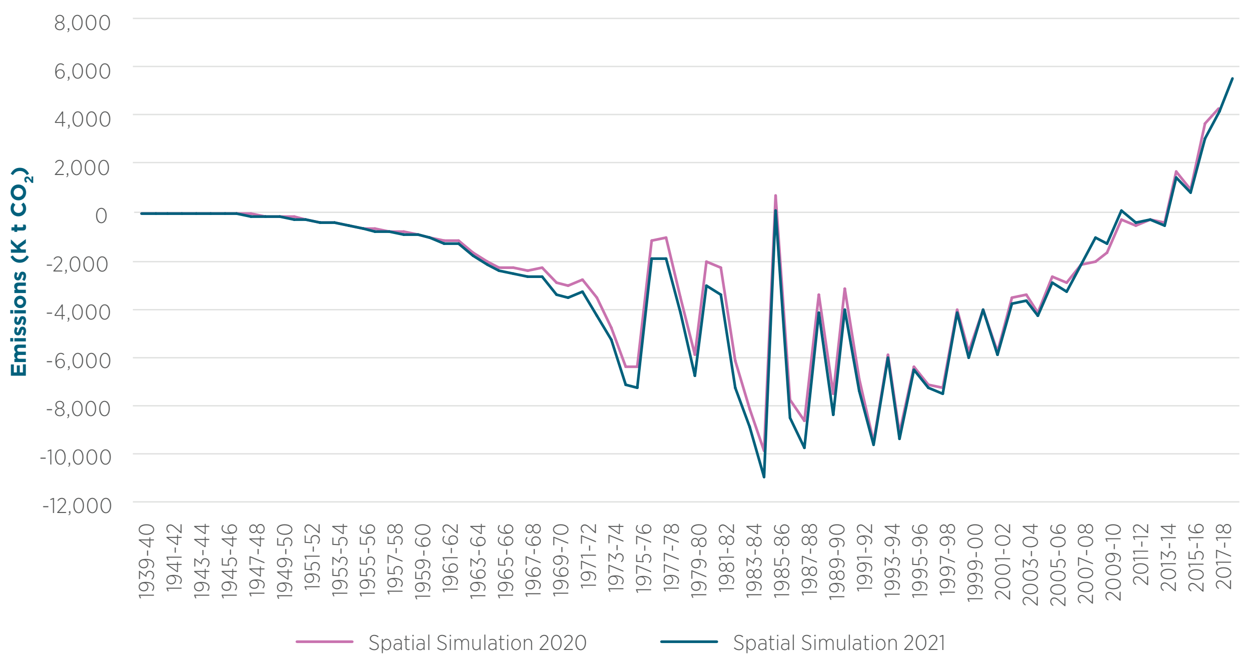
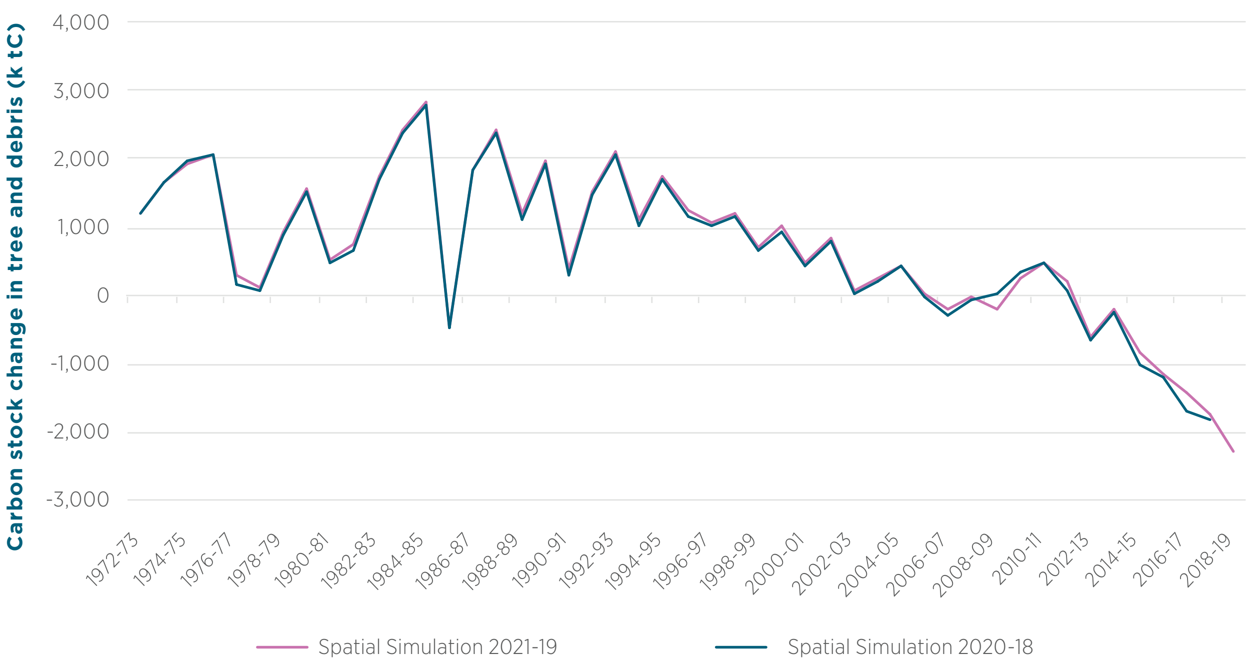


Figure 6.25b Carbon stock change in the tree and debris pools from the previous (2020–18) and new (2021–19), Pre-1990 plantation spatial simulations



C. Harvested native forests – new methodology

New spatial methodology has been introduced to estimate emissions from native forestry on public lands in the states of Victoria and New South Wales. The changes in reported emissions in these states are due to using specific, reported timber harvesting events and locations. The changes also reflect the effects of the weather record on tree growth, and particularly on the soil carbon pool which responds strongly to inter-annual variability in rainfall.

The revised methodology is described in chapter 6.4.1.2, and the newly included spatial data on timber harvesting used by this method, in Appendix 6.E.4.

Table 6.29 Forest land remaining forest land: recalculation of total CO_2-e emissions (Gg), 1990–2018

Year	2020 submission	2021 submission	Change		Reasons for recalculation		
	(Gg CO_2)	(Gg CO_2)	(Gg CO_2)	%	A. Fire Simulations	B. Pre-90 plantations	C. Harvested Native Forests new methodology
1990	-1,754	302	2,056	117%	-2,935	-891	5,883
1995	960	3,845	2,885	300%	-3,537	-279	6,702
2000	3,392	8,794	5,402	159%	-1,256	-179	6,837
2005	-2,586	-3,501	-915	-35%	-220	-121	-574
2006	-949	1,302	2,251	237%	-683	-220	3,155
2007	7,452	10,455	3,004	40%	-1,735	-406	5,144
2008	15,756	17,220	1,464	9%	-2,805	9	4,260
2009	9,354	19,336	9,982	107%	-3,308	1,039	12,250
2010	693	16,776	16,083	2320%	-3,656	473	19,266
2011	6,091	18,567	12,476	205%	-4,902	394	16,984
2012	-13,362	2,605	15,967	119%	-3,774	59	19,681
2013	-19,646	-2,495	17,152	87%	-3,407	-6	20,565
2014	-19,084	-8,850	10,234	54%	-3,266	-62	13,563
2015	-13,408	-8,218	5,189	39%	-3,018	-175	8,382
2016	-20,313	-13,825	6,488	32%	-1,608	-188	8,284
2017	-17,892	-15,476	2,416	14%	-1,919	-615	4,950
2018	-21,989	-25,197	-3,208	-15%	-5,146	-220	2,157

6.4.6 Source specific planned improvements

Harvested native forests

The Australian government plans to complete the transition to a comprehensive Tier 3, Approach 3 fully spatial model for the *harvested native forests* sub-category. This approach has been implemented for two states, Victoria and New South Wales in the current report. This enables the ongoing incorporation of the most recent empirical research into aboveground biomass, allometrics, turnover and decay factors into the *harvested native forests* sub-category. The inclusion in this method for the remaining states in which native forest harvesting occurs, remains a priority.

Other native forests

The department is looking to complete a national spatial dataset on the prescribed burning activity in high-biomass temperate forests (below-canopy fires are not reliably detected using current remote-sensing data) in order to fully utilize FullCAM Tier 3 modelling for this activity. The department will also be commencing a pilot to utilise mapping of fire intensity for the prescribed burning activity to enhance the Tier 3 modelling for this activity.

The department also plans to finalise an update to calibrations for tropical zone fires using additional field studies, particularly focusing on live-biomass and standing-dead pool dynamics post-fire.

Pre-1990 plantations

Significant updates to FullCAM model parameters are underway for plantations, based on a dataset of over 15,000 field measurements of biomass, as described in section 6.5.1 (Grassland converted to forest land).

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, cropland converted to forest land, settlements 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 commercial plantations and environmental plantings, forest that has regrown on land that was previously converted from a forest to grassland, and regeneration from natural seed sources on land protected as forest by State or Territory vegetation management policies.

Cropland converted to forest land and *settlements converted to forest land* contains forest that has regrown on land that was previously converted from forest land to the land use identified.

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*, including regrowth forest on land previously converted from forest to grassland and initially reported under section 6.9, and areas of forest regenerated from natural seed sources, are drawn from remotely sensed data as per the methods described in Appendix 6.A. The time-series of Landsat satellite data 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 x 25 m pixel identified as being a *plantation* is modelled through time from the time of establishment. Each 25 m x 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. Precise pixel areas are adjusted for the curvature of the earth to ensure the most accurate representation of areas and emissions for each location.

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).

The greenhouse gas removals associated with the regrowing forest detected by the remote sensing system on previously converted land is modelled via the generic forest regrowth model in FullCAM (Appendix 6.B and 6.D).

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 6.30).

Table 6.30 Example of the different partitioning of biomass to each of the tree components under different types of plantation species.

Forest Type	Fraction of biomass allocated to:					
	Stems	Branches	Bark	Leaves	Coarse Roots	Fine Roots
E. globulus	0.41	0.19	0.07	0.11	0.19	0.03
P. radiata	0.47	0.14	0.06	0.09	0.21	0.03
P. pinaster	0.38	0.11	0.05	0.07	0.33	0.07
Env plantings	0.29	0.20	0.09	0.13	0.25	0.05
Mallees	0.24	0.16	0.04	0.11	0.36	0.08

Carbon content

The carbon fractions of above and below ground biomass components for Australian vegetation are reported in Table 6.31 and taken from Gifford, 2000a and 2000b.

Table 6.31 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 6.32. 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 6.33) (Waterworth and Richards, 2008).

Table 6.32 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
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 6.33 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 above ground harvest residues were assumed to be standing dead material, which slowly breaks down (Table 6.35a) to produce CO_2 and debris at an assume ratio of 9:1 (Paul and Roxburgh 2019b).

The turnover rate of leaves and fine roots (Table 6.34) 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 6.34 Tree component turnover rates

Tree Component	Turnover % mth^{-1}
Branches	0.74
Bark	0.41
Leaves; Softwood	3.07
Leaves; Hardwood	4.22
Leaves; Other Environmental Plantings	1.41
Coarse Roots	0.87
Fine Roots	12.55

The rates of decomposition (Tables 6.35a and b) are based on datasets reviewed by Paul *et al.* (2017) and Paul and Roxburgh (2019b).

Table 6.35a Decomposition rates of standing dead pools.

Standing Dead Component	Breakdown Rate % mth^{-1}
Stems, branches and coarse roots	0.83
Bark	1.25
Leaves and fine roots	1.67

Table 6.35b Debris decomposition rates

Debris Component	Breakdown Rate % mth^{-1}
Deadwood	1.25
Bark litter	1.44
Leaf litter, decomposable*	81.16
Leaf litter, resistant* – Softwoods	1.84
Leaf litter, resistant* – Hardwoods	2.70
Coarse dead roots	2.93
Fine dead roots	81.16

* The fraction of leaf litter that was resistant was 77 per cent and 85 per cent 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 *grassland converted to forest land* classification is drawn from the remote sensing program (see Appendix 6.A) (Table 6.36).

Table 6.36 Cumulative area of grassland converted to forest land 1990–2019

Year	Area (ha)
1990	3,034,755
1995	5,369,483
2000	6,817,541
2005	8,031,033
2010	9,788,522
2011	10,287,582
2012	10,768,041
2013	11,276,756
2014	11,833,490
2015	12,452,737
2016	13,067,662
2017	13,631,105
2018	13,995,735
2019	14,361,413

6.5.1.2 Cropland converted to forest land and settlements converted to forest land

Cropland converted to forest land and *settlements converted to forest land* contain forest that has regrown on land that was previously converted from forest land to the land use in question. These conversions do not always mean that the land has ceased being used for its converted purpose, but that a canopy of trees has been detected as re-emerging above the identified land use. For example, a canopy may emerge due to the urban landscaping of parks and gardens, or the restoration of riparian vegetation along waterways in cropping regions. The re-emergence of sufficient trees as would meet the definition of a forest gives cause for these lands to be recognised as converted to forest for the purposes of the national inventory. The activity data and emissions methods are the same as those described for *grassland converted to forest land* (6.5.1.1) with respect to the regrowth of forest on previously cleared lands.

Table 6.37 Cumulative area of croplands and settlements converted to forest land 1990–2019

Year	Area of cropland re-converted (ha)	Area of settlement re-converted (ha)
1990	34,659	13,675
1995	64,381	31,424
2000	64,571	41,116
2005	57,184	45,003
2010	63,704	47,423
2011	68,901	51,168
2012	72,816	57,054
2013	76,516	60,604
2014	80,794	63,783
2015	88,725	70,068
2016	92,730	73,376
2017	101,102	77,537
2018	105,173	79,272
2019	108,743	84,460

6.5.1.3 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 and bare tidal flat.

Carbon dioxide emissions and removals are modelled using mangrove-specific parameter values in a Tier 2 spreadsheet-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, Wmax = 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 A6.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 was 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 was 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.

The equation was also used to model the sequestration of soil organic carbon (SOC) during mangrove forest development. As with biomass accumulation, the time to maximum SOC sequestration and to maximum SOC content was set at 23 and 30 years respectively. The simplifying assumption when using this approach was that SOC accumulation was related directly to mangrove forest development. The equation's parameter values for SOC Wo and Wmax at a regional level were derived from the scientific literature that reported on Australian and New Zealand mangrove forest soils (Table 6.J.1). IPCC default values were used if regionally relevant values were not available.

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 6.38). It incorporates observed areas of wetland conversion to mangrove forest from 1972 onwards. Areas of pre-1990 conversion are accounted for from 1990 onwards because these forests are less than 30 years old, the age when maximum forest biomass is attained.

Table 6.38 Cumulative area of wetland converted to forest land 1990–2019

Year	Area (ha)
1990	3,470
1995	4,488
2000	4,985
2005	5,493
2010	6,046
2011	6,171
2012	6,282
2013	6,401
2014	6,508
2015	6,594
2016	6,675
2017	6,837
2018	7,103
2019	7,346

6.5.2 Emission estimates

The annual net emissions for the *land converted to forest land* category for the period 1990 to 2019 are in Table 6.39 below.

Table 6.39 Annual net emissions for land converted to forest land, 1990–2019 (Gg CO_2-e)

Year	Cropland converted to forest land	Grassland converted to forest land	Settlements converted to forest land	Wetlands converted to forest land	Total
1990	-85	-4,232	-18	-161	-4,494
1995	-173	-8,574	-82	-267	-9,095
2000	-299	-21,457	-161	-387	-22,304
2005	-236	-20,257	-207	-378	-21,078
2006	-236	-25,432	-203	-386	-26,258
2007	-226	-22,560	-200	-394	-23,381
2008	-231	-26,409	-186	-397	-27,222
2009	-214	-26,252	-176	-398	-27,040
2010	-217	-30,329	-185	-397	-31,129
2011	-266	-43,539	-174	-393	-44,371
2012	-309	-41,399	-202	-382	-42,292
2013	-291	-36,871	-239	-373	-37,775
2014	-308	-38,444	-267	-363	-39,382
2015	-329	-37,726	-258	-356	-38,670
2016	-375	-43,976	-340	-349	-45,040
2017	-437	-45,750	-319	-347	-46,853
2018	-404	-35,115	-335	-343	-36,196
2019	-345	-28,111	-305	-314	-29,075

6.5.3 Uncertainties and time series consistency

Uncertainty in the *land converted to forest land* sub-category is expected to be 17.3 per cent. 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 per cent to over 200 per cent. 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.

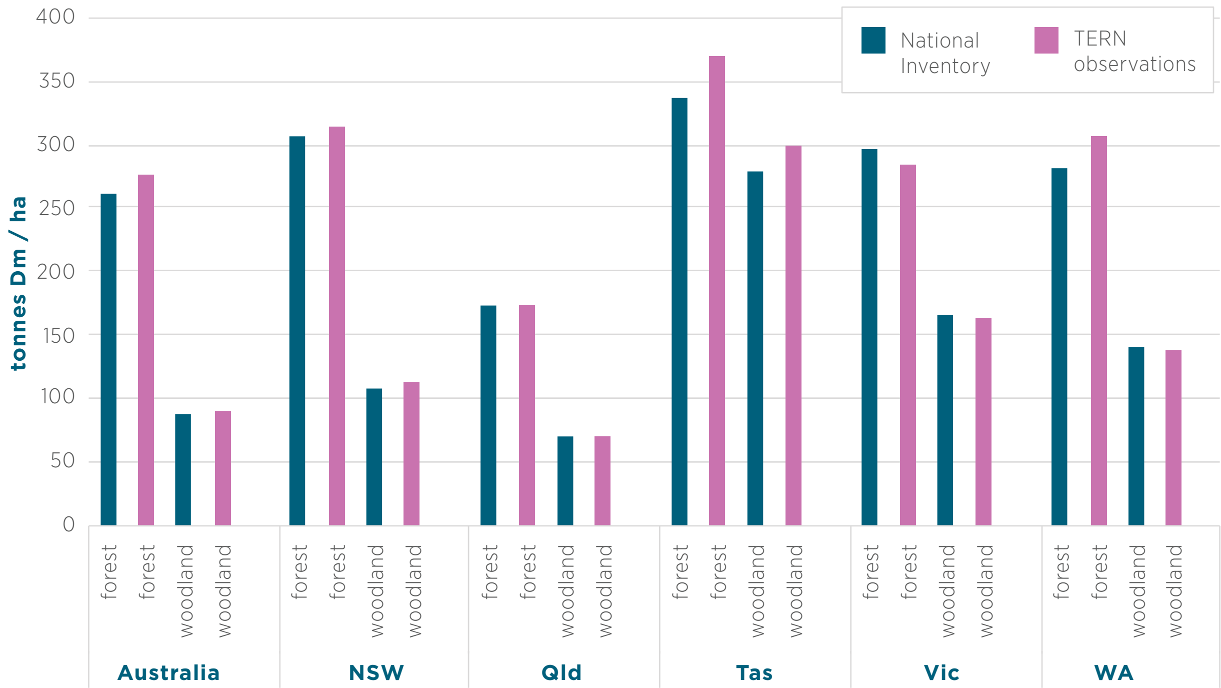
6.5.4 Source Specific QA/QC

In recent years, regeneration of native vegetation has become a significant driver in the trend for LULUCF emissions. To explore the combined impact of recent improvements to the maximum above-ground biomass and rate of growth, a comparison between the 2016 and 2019 publicly released versions of FullCAM was undertaken.

Annual increments in above-ground biomass (AGB) are empirically predicted in FullCAM through the calibration of two key Tree Yield Formula (TYF) parameters: rate of growth (as determined by *G*; the stand age when the annual increment of AGB is at its maximum), which was revised in the 2020 inventory submission; and the maximum above-ground biomass (M), which was updated in the 2017 submission.

The work of Roxburgh (2017) compared FullCAM-modelled maximum biomass estimates with the average maximum biomass data from a sample from the TERN biomass library. He found that for forest cover with more than 50 per cent canopy coverage, at the national level, that the modelled estimates were within 10 per cent of the estimates from the sample from the TERN biomass library. For woodland forests, where the canopy cover was between 20 and 50 per cent, the estimate from FullCAM was within 5 per cent of the estimates from the sample from the TERN library (Figure 6.26).

Figure 6.26 Comparison of maximum biomass layer and empirical data, Australia and by State, (tonnes of dry mass/ha)



The calibrations of the tree yield formula in the 2020 submission are informed by AGB measurements obtained from calibration sites of different types of tree stands. There are currently 1,246 site-based observations on which the revised rate of growth (G) were based (Paul and Roxburgh 2020), and 5,739 site-based observations of maximum above-ground biomass, or calibration sites for *M* (Roxburgh *et al*. 2019).

The TYF parameter calibration process distinguished between regeneration in farmland and in nature conservation areas.

Improved representativeness of calibration sites, achieved through significantly increasing their number and spatial extent (Figure 6.27), has increased confidence in the model predictions. The efficiency of model prediction (Soares *et al*. 1995) of AGB against the 1,246 currently available calibration sites shows that it was 42% for the 2019 version of the model (Figure 6.28b), compared to 25% for the 2016 version (Figure 6.28a).

There is also an increase in the accuracy of estimates. In terms of systematic error, the gains in accuracy using the mean residuals as the index were 98.8% and 73.1% for regenerating stands and mature vegetation respectively (Table 6.40). All of these improvements were highly statistically significant.

In terms of precision (or IQR), the gain in accuracy of site-level AGB prediction in young stands of natural regeneration was of 32.6% (Table 6.40; Figure 6.29a), and of 45.5% in mature stands of natural regeneration (Table 6.40; Figure 6.29b). Again, all of these improvements were highly statistically significant.

Figure 6.27 Location of the TYF calibration sites for Block stands used for different versions of FullCAM; (a) 2016 and (b) 2019.

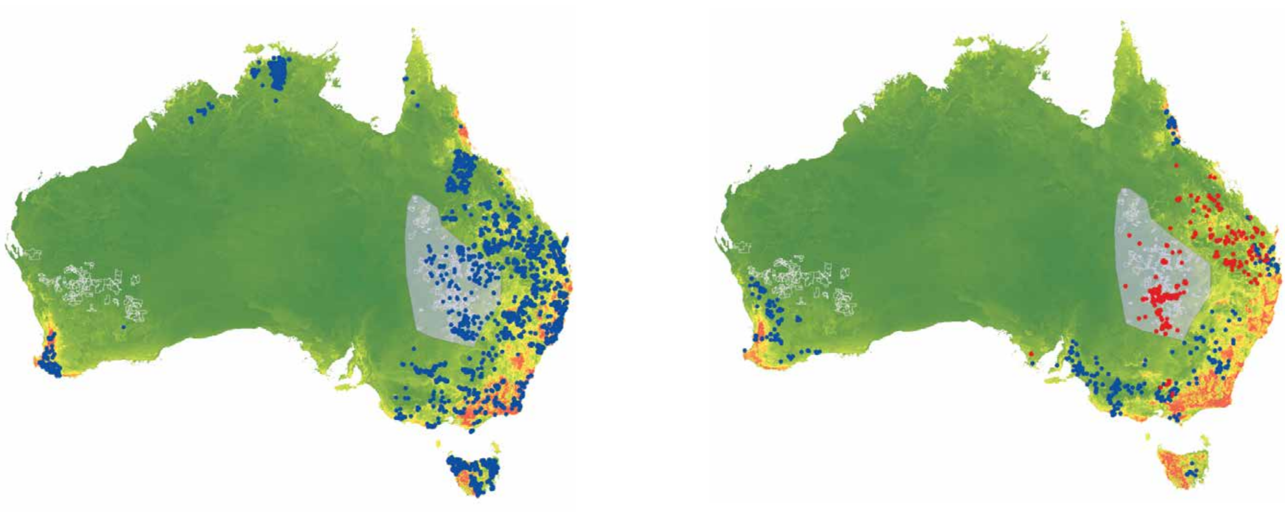


Figure 6.28 Plot of predicted versus observed AGB for different versions of FullCAM; (a) 2016, and; (b) 2019. Blue symbols represent regeneration in nature conservation areas ('Block-Environmental Services'). Red symbols represent the regeneration in farmland ('Block-Regeneration Systems').

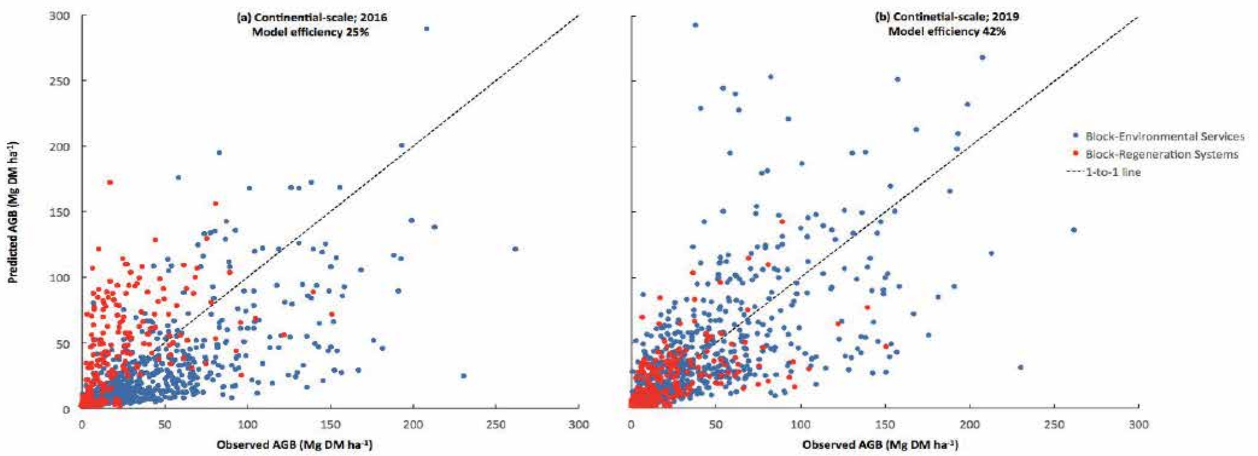


Figure 6.29 Continental-scale results of accuracy analysis for the estimation of site-level biomass for the: (a) regeneration in farmland ('Block-Regeneration System' category); (b) maximum above-ground biomass, and (c) the regeneration in nature conservation areas ('Block-Environmental Service' category).

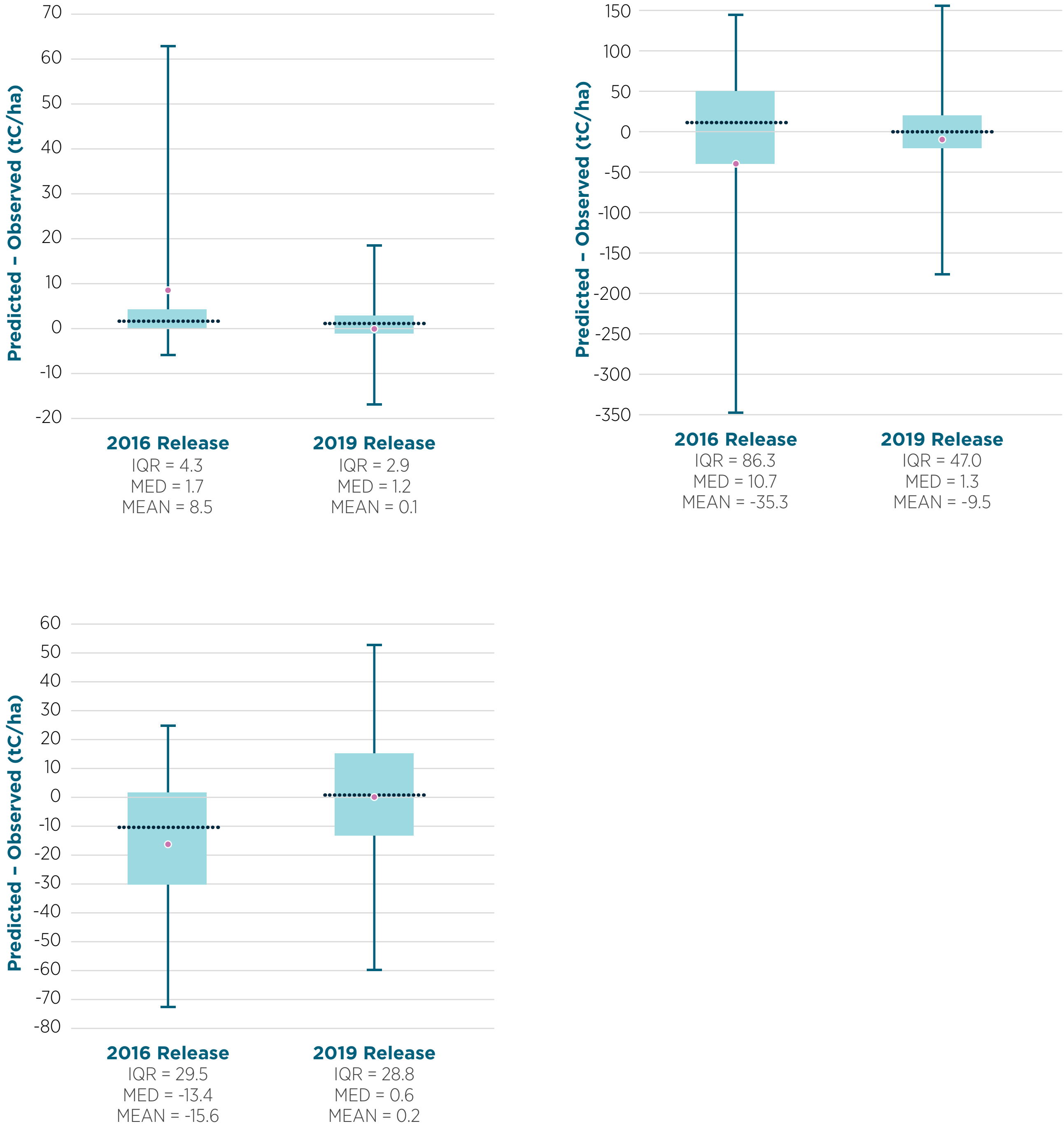


Table 6.40 Summary of results for the analysis of change in systematic error from the FullCAM (2016) release to the FullCAM 2019 release.

			Block – Regeneration	Block – Environmental Services	Maximum Above-ground biomass
Precision	Inter-Quartile range	FullCAM (2016) (tDM/ha)	4.3	29.5	86.3
		FullCAM (2019) (tDM/ha)	2.9	28.8	47.0
		Gain in accuracy (tDM/ha)	1.4	0.7	39.3
		Gain in accuracy (%)	32.6	2.4	45.5
		P	0.020	0.769	<0.000
Systematic error	Median	FullCAM (2016) (tDM/ha)	1.7	-10.4	10.7
		FullCAM (2019) (tDM/ha)	1.2	0.6	1.3
		Gain in accuracy (tDM/ha)	0.5	9.8	9.4
		Gain in accuracy (%)	29.4	94.2	87.9
		P	<0.000	<0.000	<0.000
	Mean	FullCAM (2016) (tDM/ha)	8.5	-15.6	-35.3
		FullCAM (2019) (tDM/ha)	0.1	0.2	-9.5
		Gain in accuracy (tDM/ha)	8.4	15.4	25.8
		Gain in accuracy (%)	98.8	98.7	73.1
		P	<0.000	<0.000	<0.000

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

Up until the 2014 Inventory, 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 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.

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).

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 2017 and subsequent Inventories are well understood and explained, along with their impacts, in section 6.5.5 below. As per the improvement plan, Australia has reviewed and updated the current Tier 2 model to ensure it remains a valid QA check for the current and the future inventories.

A comparison of the yield rate of tree stem mass (Figure 6.30a) 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 2000–2018, the Tier 3 yield rate of stem mass increased and then decreased relative to the Tier 2 models (Figure 6.30a). These variations were due to conditions for plant growth being close to optimal or better during 2000 to 2014 and then becoming less optimal during 2015 to 2018. In 2017 and 2018 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 FullCAM framework.

The results of the Tier 3 soil carbon model (Figure 6.30b) 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 the 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.

Figure 6.30a Yield rate of tree stem mass (t dm/yr) output from Tier 2 and Tier 3 methodology, 1990–2018

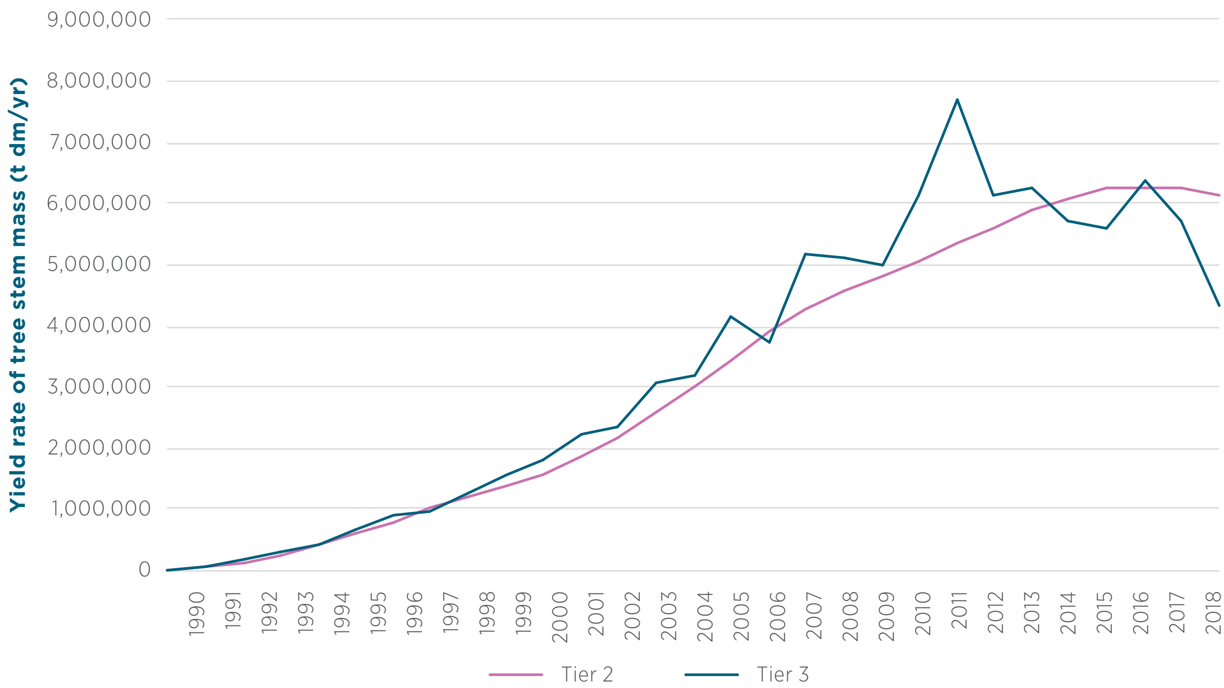
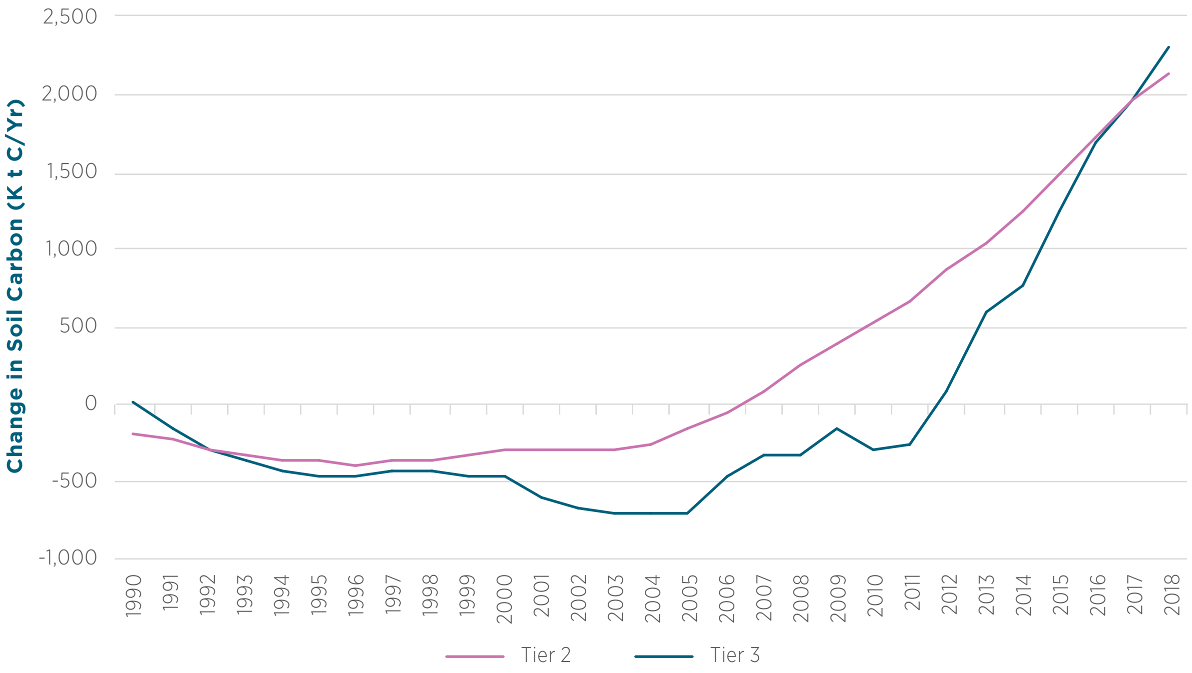


Figure 6.30b Soil carbon (t C/yr) output from Tier 2 and Tier 3 methodology, 1990–2018



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 Industry, Science, Energy and Resources.

6.5.5 Recalculations since the 2018 Inventory

Improvements and updates made to FullCAM relating to simulation of the *grassland and cropland land converted to forest land* sub-categories that have contributed to the recalculations include:

A. Updated spatial observations:

Satellite imagery is analysed each year to update the spatial datasets for forest cover change, including the emergence of forest. This year's update also includes improvements to completeness by incorporating three additional tiles of satellite observations in central Australia.

B. Soil cover on crop and grass species:

Improvements were made to the timing and scope of events determining agricultural plant cover properties in FullCAM, which influence the rate at which organic carbon decays in mineral soils such that decomposition occurs slower in vegetated soil than exposed soil (Jenkinson *et al* 1987). Plant cover changes now more precisely align with events which remove plant residues and establish new plants in agricultural settings, including where they have been converted to forest land. These recalculations are consistent with improvements made in *croplands remaining croplands* and *grasslands remaining grasslands*.

C. Agricultural parameter updates:

For consistency with *croplands remaining croplands* and *grasslands remaining grasslands*, agricultural species databases have been updated for the latest information of yields and perennial growth, for the latest science on the resistant fractions of crop and grass debris, and for an update to the Nitrogen Leeching fraction from 0.3 to 0.24.

D. Non-temperate Fire Updates

Revisions associated with non-temperate fire activity are associated with updated activity data and are further described under *grasslands remaining grasslands.*

Table 6.41 Land converted to forestland: recalculation of total CO_2-e emissions (Gg), 1990–2018

Year	Land converted to forest				Reasons for Recalculations				
	2020 submission	2021 submission	Change	Change	A.		B.	C.	D.
					Spatial Updates		Soil Cover	Agricultural Parameters	Non-temperate Fire Updates
	(Gg CO_2-e)	(Gg CO_2-e)	(Gg CO_2-e)	%	Terrestrial forests	Mangroves			
1990	-4,783	-4,494	288	-6.0%	-122	-15	430	-13	8
1991	-4,936	-4,811	125	-2.5%	-166	-17	285	15	7
1992	-5,663	-5,688	-25	0.4%	-180	-19	159	7	7
1993	-7,259	-7,518	-259	3.6%	-77	-21	-176	8	6
1994	-5,475	-5,792	-316	5.8%	-54	-23	-241	-4	5
1995	-8,413	-9,095	-682	8.1%	-134	-25	-532	4	5
1996	-12,045	-12,741	-697	5.8%	-86	-27	-561	-28	6
1997	-13,931	-14,654	-723	5.2%	-99	-29	-586	-14	5
1998	-16,098	-16,852	-754	4.7%	-11	-30	-712	-6	5
1999	-17,325	-17,994	-670	3.9%	-174	-31	-408	-61	5
2000	-21,506	-22,304	-799	3.7%	-138	-31	-576	-58	5
2001	-17,933	-18,804	-871	4.9%	92	-31	-895	-41	5
2002	-17,885	-18,974	-1,089	6.1%	76	-30	-1,138	-2	5
2003	-17,640	-19,014	-1,374	7.8%	94	-27	-1,423	-22	5
2004	-22,330	-23,851	-1,521	6.8%	-41	-24	-1,450	-12	5
2005	-19,814	-21,078	-1,264	6.4%	380	-21	-1,615	-12	5
2006	-24,593	-26,258	-1,665	6.8%	-317	-21	-1,235	-97	4
2007	-22,221	-23,381	-1,160	5.2%	155	-20	-1,266	-33	4
2008	-25,971	-27,222	-1,252	4.8%	315	-20	-1,391	-159	4
2009	-25,781	-27,040	-1,259	4.9%	457	-19	-1,719	19	3
2010	-29,475	-31,129	-1,654	5.6%	969	-19	-2,477	-130	3
2011	-41,715	-44,371	-2,656	6.4%	-311	-18	-2,160	-170	3
2012	-40,074	-42,292	-2,217	5.5%	569	-18	-2,604	-167	3
2013	-36,254	-37,775	-1,521	4.2%	941	-18	-2,519	73	2
2014	-37,760	-39,382	-1,623	4.3%	832	-18	-2,377	-62	2
2015	-36,993	-38,670	-1,677	4.5%	964	-18	-2,501	-123	2
2016	-43,171	-45,040	-1,868	4.3%	987	-18	-2,744	-95	1
2017	-44,980	-46,853	-1,873	4.2%	852	-17	-2,515	-196	1
2018	-35,091	-36,196	-1,104	3.1%	1,419	-24	-2,400	-100	0

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:

Updates to remaining FullCAM parameters – allocations of biomass, stem wood density, litter fall, and decomposition and CO_2 losses to atmosphere as well as improving the simulation of the creation and loss of carbon stocks in standing dead pools post disturbances such as thinning, harvesting and management burns. Datasets of biomass allocation have been expanded for plantations and native vegetation types in Australia (e.g. Paul & Roxburgh 2017). These datasets were implemented to inform updated defaults for allocation for native vegetation, environmental and mallee plantings. However, for commercial plantation species, the implementation of revised allocation parameters requires further consideration to ensure that harvested stem volumes are also accurately predicted.

Re-calibration of the TYF for commercial plantings and farm forestry will include a thinning response, with parameters derived from field data collected through a literature search and augmented by plantation industry input.

Standing dead in simulation. It is planned to implement standing dead in simulation of both pre-1990 and post-1989 plantations. Datasets of standing dead and coarse woody debris are being collated from Australian field studies of disturbance events such as fire and harvesting. These datasets are currently being applied to improve the accuracy of simulation of the carbon dynamics through standing dead and debris pools post such disturbance events. With the proposed revisions, management options would be available for harvesting of standing dead debris (harvest residues or crop stubble) for biomass or bioenergy, and addition of soil amendments, e.g. biochar etc.

Improved simulation of decomposition of debris. Related to the above work on improvement of standing dead simulation, further refinements will also be required to improve the accuracy of simulation of the carbon stock dynamics in debris (and hence soil).

Improved simulation of decomposition of soil carbon. Fine dead roots will be simulated to directly enter the soil pools as suggested by Farquharson *et al.* (2013). This 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.

Improvements to mangrove modelling. 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. Extension of the remote sensing program is planned to improve spatial and temporal identification and attribution of transitions from tidal marsh and salt pan to mangrove forest.

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 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)[5].

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.

The areas of *cropland remaining cropland* is estimated using ABARES Catchment Scale Land Use of Australia 2017 provided by the Department of Agriculture and Water Resources at the mapping scale of 1:5000 to 1:250 000.

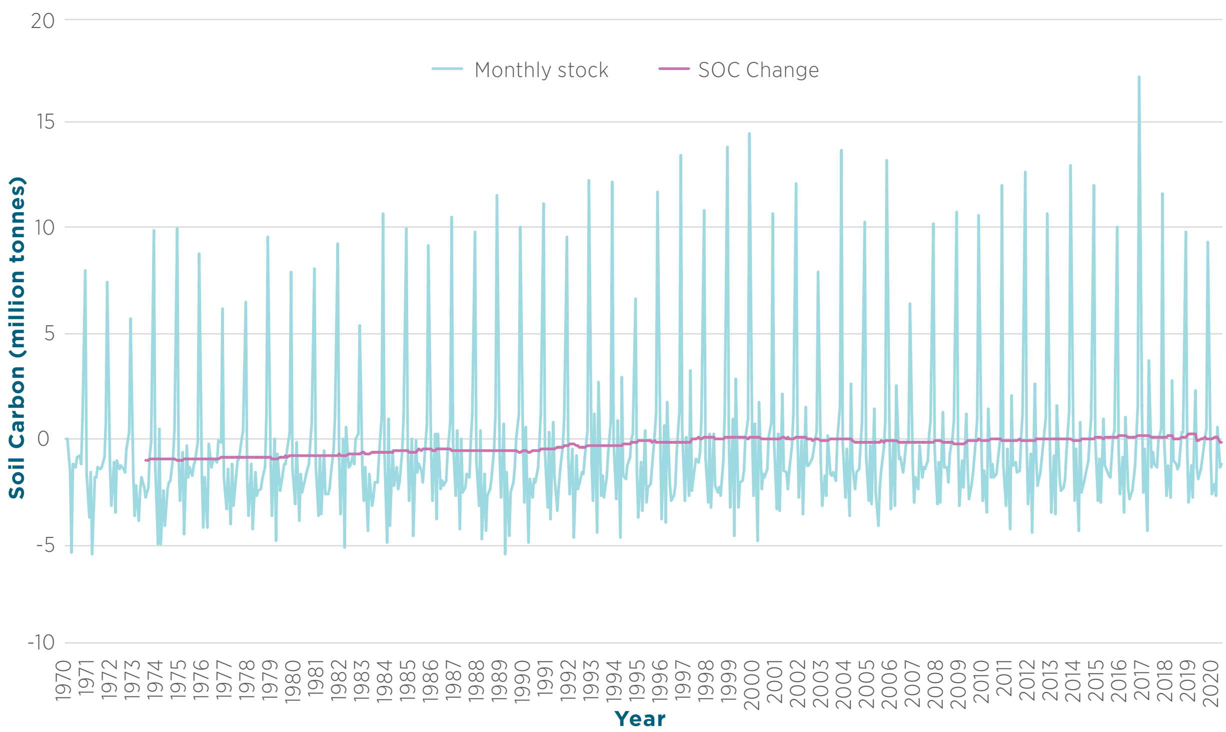
Herbaceous crops

FullCAM is simulated in monthly time steps commencing at the time of first planting in 1970 (Figure 6.31). 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.

All on-site carbon pools (living biomass, dead organic matter (DOM) and soil) are estimated. 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 the *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). Consistent with the method outlined in the *IPCC 2006 Vol 4, 2.3.3.1,* a mean incremental value for the transitions between SOC near steady states is derived, in this case from the simulated monthly data, as shown in Figure 6.31.

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.

Figure 6.31 Carbon stock change from cropland remaining cropland, 1970–2020



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 in the ABS Land Management and Farming (2017a) which provides information on management practices being adopted and utilised by Australian agricultural business. Further details on changes in management practices are provided in Appendix 6.E.

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 literature to calculate CO_2 emissions and removals. The coefficients required are: total biomass carbon stock at harvest[6] (tonnes C ha^{-1}), years to maturity (M), 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 6.42a. Additionally, root to shoot ratios were sourced from the literature and biomass accumulations associated with fruit production were excluded from all calculations. Where parameters were derived from other countries, corrections were made to account for local conditions. For example, for olives, carbon accumulation rates were sourced from Spain where plot density was 408 trees.ha^{-1} whereas in Australia plot density of olives is reported to be 250 trees.ha^{-1}. The Spanish carbon accumulation rate was adjusted relative to the Australian plot density factor.

6 Includes both above and belowground biomass

Table 6.42a 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	M × y	M	y
e.g. (oranges)	5	10	0.5

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 6.42b). 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, 2018)*, which also account for planting and clearing events. Most crop data are provided as tree number values and subsequently were converted to area statistics using crop-specific plot density coefficients (Table 6.42b).

Table 6.42b 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	5	10 [n]	0.5 [a]	556 [b]	0.17 [c]
Nuts					
Macadamias	45	15 [n]	3 [e]	355 [e]	0.25 [e]
Almonds	9.6	8 [n]	1.2 [a]	222 [f]	
Pomes					
Apples	4.9 [g]	7 [n]	0.7	500 [g]	0.17 [c]
Stone fruit					
Peaches	5.2	4 [n]	1.3 [a]	740 [h]	0.17 [c]
Grapes	1.2	4 [n]	0.3 [a]	N/A	0.5 [c]
Kiwifruits	1.5	5 [n]	0.3 [a]	N/A	0.5 [c]
Olives	6.67	10 [n]	0.67 [j]	250 [k]	0.145 [c]
Avocados	6 [l]	10 [n]	0.6	100 [l]	0.125 [l]
Mangoes	13 [l]	10 [n]	1.3	222 [m]	0.125 [l]
IPCC default	63		2.1		

Source and location of study is: *a* = Kroodsma & Field (2006) USA California, *b* = Morgan *etal.* (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, *m* = Western Australian Government Agricultural website (2013), and *n* = Queensland Department of Agriculture, Fisheries and Forestry (2014). 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 6.42a.

6.6.2 Emission estimates

Net annual emissions estimates for *cropland remaining cropland* for the period 1990 to 2020 are shown graphically in Figure 6.32, and a breakdown by sub-category is shown in Table 6.43. While climate has important cyclical effects, the uptake of reduced, minimum and no-till management techniques through the 1980's and 90's is reflected in the tendency towards decreasing emissions during this period as a new soil C state of equilibrium is reached. Further management changes in recent years and their impact on the soil C steady state can be detected in shifts later in the emissions time series.

Figure 6.32 Net CO_2 emissions from cropland remaining cropland, 1990–2020

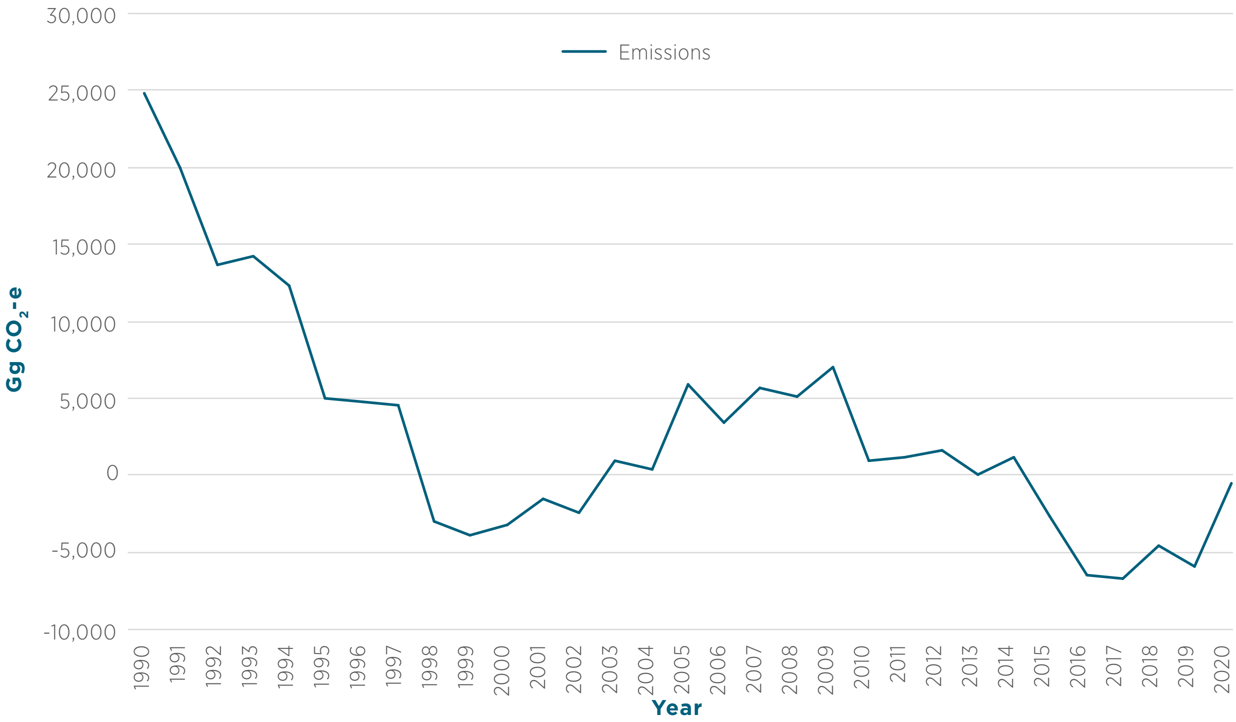


Table 6.43 Net emissions and removals from cropland remaining cropland sub-categories, 1990–2019 (Gg CO_2-e)

Year	Soil carbon	Perennial woody crops (biomass)	Total
1990	24,861	-69	24,793
1995	5,085	-100	4,985
2000	-3,140	-50	-3,190
2005	6,099	-162	5,938
2006	3,614	-175	3,440
2007	5,586	36	5,622
2008	5,232	-122	5,110
2009	7,129	-152	6,976
2010	1,225	-282	943
2011	1,574	-363	1,211
2012	1,782	-109	1,672
2013	-64	94	30
2014	1,137	36	1,174
2015	-2,616	-83	-2,699
2016	-6,225	-225	-6,450
2017	-6,484	-269	-6,753
2018	-4,464	-135	-4,599
2019	-5,698	-187	-5,885

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, 2019) 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

Extensive QA/QC of FullCAM shows that the results closely align to the Tier 2 steady-state soil carbon model (T2SSM) provided in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Volume 4 Chapter 5). This work is described in Appendix 6.B.7.1.

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

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

6.6.5 Recalculations since the 2018 Inventory

The recalculation of the *cropland remaining cropland* time series is presented in Table 6.44, and an explanation of the key influences on the change in estimates follows:

A. Spatial and climate updates

A revision of land areas across the LULUCF sectors has resulted in a recalculation for the cropland time series reflecting this land-use allocation change. Due to the derivation of the mean SOC near steady state, 2016 and 2017 experience recalculations due to longer term variations in the monthly data simulated by FullCAM.

B. Soil cover

Improvements were made to the timing and scope of events determining agricultural plant cover properties in FullCAM, which influence the rate at which organic carbon decays in mineral soils such that decomposition occurs slower in vegetated soil than exposed soil (Jenkinson *et al* 1987). Plant cover changes now more precisely align with events which remove plant residues and establish new plants in agricultural settings (Appendix 6.B.7). This has led to a recalculation across the time series with an increase in emissions in earlier years due to increased decomposition in soil carbon especially during fallow periods following harvest with stubble removal.

C. Agricultural parameter updates

Crop yields were updated using the crop yield model with minor improvements, and a minor adjustment has been made to the ratios of decomposable to resistant plant material for cotton. The 2018 Inventory used a value for DPM/RPM of 1.44 when a ratio of 0.25 should have been used because its woody content makes it more like a woody plant; this is corrected in this inventory (Appendix 6.B.7) and has led to a decrease in emissions across the series.

Table 6.44 Cropland remaining cropland: Recalculation of CO_2-e emissions 1990–2018

	2020 submission (Gg CO_2-e)	2021 submission (Gg CO_2-e)	Change (Gg CO_2-e)	Percent	Reasons for recalculations		
					A. Spatial and climate updates	B. Soil cover	C. Agricultural parameter updates
1990	17,922	24,793	6,871	38.3%	42	7,682	-853
1991	13,535	19,986	6,451	47.7%	36	7,337	-923
1992	6,271	13,619	7,348	117.2%	23	8,078	-753
1993	6,753	14,223	7,470	110.6%	18	8,259	-807
1994	4,665	12,270	7,605	163.0%	22	7,969	-386
1995	-2,592	4,985	7,577	-292.4%	5	7,989	-417
1996	-2,250	4,803	7,054	-313.5%	6	7,363	-316
1997	-1,278	4,600	5,878	-460.0%	10	6,129	-261
1998	-8,165	-2,940	5,225	-64.0%	3	5,607	-385
1999	-8,590	-3,879	4,711	-54.8%	-7	5,558	-839
2000	-7,695	-3,190	4,505	-58.5%	-3	5,281	-773
2001	-5,820	-1,490	4,330	-74.4%	-6	5,396	-1,060
2002	-6,713	-2,443	4,270	-63.6%	-9	5,554	-1,275
2003	-3,296	977	4,273	-129.7%	-4	5,265	-987
2004	-3,774	349	4,123	-109.2%	1	4,838	-716
2005	2,569	5,938	3,369	131.1%	9	4,255	-894
2006	226	3,440	3,214	1424.9%	10	3,603	-399
2007	3,283	5,622	2,339	71.2%	10	2,903	-573
2008	3,599	5,110	1,511	42.0%	15	2,322	-826
2009	6,355	6,976	622	9.8%	26	1,468	-873
2010	710	943	233	32.7%	22	1,207	-996
2011	1,829	1,211	-618	-33.8%	18	1,113	-1,749
2012	3,002	1,672	-1,330	-44.3%	19	503	-1,852
2013	1,269	30	-1,238	-97.6%	13	599	-1,850
2014	2,367	1,174	-1,194	-50.4%	3	658	-1,854
2015	-744	-2,699	-1,956	263.1%	2	-475	-1,483
2016	-3,879	-6,450	-2,571	66.3%	-1	-1,087	-1,483
2017	-4,106	-6,753	-2,647	64.5%	-464	-1,137	-1,046
2018	-3,597	-4,599	-1,002	23.7%	-442	-1,548	988

6.6.6 Source specific planned improvements

The handling of the below-ground debris pool within FullCAM requires investigation to determine the correct behaviour of the relationship of the Roth-C implementation and changing management practices.

The initialisation of soil carbon pools within FullCAM is being investigated to determine the optimal starting values that more accurately reflect the measured carbon soil fractions at any given period in time.

Tillage activities within the FullCAM modelling framework require examination to calibrate the impact that varying tillage practices, such as minimum and no till, have on soil decay functions. Additionally, research will be conducted into options for enabling more accurate modelling of the impacts of management strategies on the entry of crop residues into the soil.

Comparison of FullCAM outputs for croplands with outputs from alternate soil carbon models is under way. Progress is detailed in Appendix 6.B. Results from the tier 2 model will help drive further work such as the calibration and verification of the carbon flows within the FullCAM framework.

Potential areas for research include plant turnover and debris decomposition rates and their rates at the regional level across crop, improved pasture, and native perennial grass lands. Measured sites from the Soil Carbon Research Program (SCaRP) along with additional pasture sites would be used to optimize and run sensitivity analysis to update the FullCAM parameters to better reflect the varying Australian agricultural zones.

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 conversions between croplands and grasslands 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 for each state and territory. 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.

Nationally, 4,000 ha of histosols were previously identified as being cropped. This was primarily in coastal Queensland and involved sugar cane farming (Volume 1, Section 5.6.8 Cultivation of Histosols). As this activity involved the draining of coastal wetland, the concomitant wetland area was considered to represent the national total of organic hydrosols that were drained and converted to cropland. The remaining wetland conversions to cropland involved mineral hydrosols.

In response to an ERT recommendation, several soil-related emission factor values are applied based on stratification with respect to soil type (mineral or organic) and climate zone.

For organic soils, Equation 2.26 from IPCC 2006 Guidelines Vol 4 was used to estimate the annual emissions from Queensland:

$$L_{organic} = A \times EF$$

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

The tropical IPCC default emissions factor was applied (Table 5.6 IPCC 2006 GL, Vol 4), based on tropical north Queensland location of the wetland ecosystems where this conversion occurred.

Conversions involving wetlands on mineral soils were dispersed over several climate zones. A tier 1 approach was used to estimate annual change in organic carbon stock in mineral soils over the 20 year transition period, based on equation 2.25 (IPCC, 206, Volume 4). The exact distribution of the conversions within each state and territory was not known. Consequently averaged climate zone and soil reference values were applied at a state and territory level; Queensland and the Northern Territory comprise Tropical wet and dry climate zones, Tasmania was considered cool temperate moist, and all other states were warm temperate (moist or dry). Australia's soils were considered to be generally weathered (Low activity clay), and were long term cultivated with (on average) reduced tillage and medium inputs. On the basis of these assumptions the following average annual changes in carbon stocks were derived and applied to their respective states to estimate annual emissions:

- Queensland/ Northern Territory: 2.97182 tonnes C / ha / year,
- Tasmania: 0.882 tonnes C / ha / year,
- All other States/Territories: 3.031063 tonnes C / ha / year.

Conversions involving cultivated organic soils are reported for Queensland in the tropical climate zone. The annual emission factor is 20 tonnes C / ha / year (IPCC, 2006, Volume 4, Table 5.6).

Emissions from each state and territory were calculated, based on area, and then aggregated to give the annual national totals for both (Tables 6.45 and 6.46).

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

Table 6.45 below shows the cumulative areas of *forest land* and *wetlands* that were *converted to croplands* over the period 1990 to 2019.

Table 6.45 Cumulative area of land converted to cropland 1990–2019 (ha)

Year	Forest land converted to cropland	Wetlands converted to cropland	Total
1990	1,923,686	12,661	1,936,347
1995	2,062,623	12,661	2,075,284
2000	2,168,738	12,661	2,181,399
2005	2,250,153	12,661	2,262,814
2010	2,284,057	12,661	2,296,718
2011	2,284,211	12,661	2,296,872
2012	2,284,990	12,661	2,297,651
2013	2,286,983	12,661	2,299,644
2014	2,288,214	12,661	2,300,875
2015	2,284,961	12,661	2,297,622
2016	2,285,301	12,661	2,297,962
2017	2,279,313	12,661	2,291,974
2018	2,278,272	12,661	2,290,933
2019	2,276,918	12,661	2,289,579

6.7.2 Emission estimates

As Table 6.46 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 6.46 Net emissions from land converted to cropland by sub-category, 1990–2019 (Gg CO_2-e)

Year	Forest land converted to cropland	Wetlands converted to cropland	Total
1990	18,774	386	19,160
1995	5,792	386	6,178
2000	4,343	386	4,729
2005	4,020	386	4,406
2006	5,580	386	5,966
2007	3,655	386	4,041
2008	3,839	386	4,225
2009	3,536	386	3,922
2010	3,242	386	3,629
2011	3,810	386	4,196
2012	701	386	1,087
2013	4,123	386	4,509
2014	3,492	386	3,878
2015	2,938	386	3,324
2016	1,610	386	1,996
2017	1,760	386	2,146
2018	978	386	1,364
2019	2,346	386	2,732

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 per cent 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 2019. 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 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 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 6.47 provides the recalculation results, including reasons and quantified impacts.

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

Table 6.47 Forest land converted to cropland: Recalculation of CO_2-e emissions 1990–2018

	Forest land converted to cropland				Reasons for recalculation		
	2020 Submission (Gg C02 -e)	2021 Submission (Gg CO -e)	Change (Gg CO -e)	%	A. Updated Spatial Observations	B. Soil Cover on Crop Species	C. Agricultural Parameter Updates
1990	18,450	18,774	324	1.8%	2	264	58
1995	5,825	5,792	-33	-0.6%	1	266	-300
2000	4,456	4,343	-113	-2.5%	2	246	-361
2005	4,031	4,020	-12	-0.3%	2	197	-210
2006	4,539	5,580	1,041	22.9%	2	198	841
2007	3,910	3,655	-255	-6.5%	4	205	-464
2008	3,719	3,839	120	3.2%	5	147	-33
2009	3,288	3,536	248	7.6%	3	155	90
2010	3,540	3,242	-298	-8.4%	1	136	-435
2011	2,678	3,810	1,132	42.3%	3	82	1,048
2012	1,333	701	-632	-47.4%	4	130	-766
2013	3,618	4,123	504	13.9%	4	115	386
2014	3,752	3,492	-261	-6.9%	8	46	-315
2015	2,222	2,938	716	32.2%	14	122	579
2016	1,946	1,610	-337	-17.3%	4	73	-414
2017	958	1,760	802	83.7%	-13	-23	838
2018	1,972	978	-994	-50.4%	-39	21	-976

6.7.5.2 Wetlands converted to cropland

There is a recalculation for *wetlands converted to cropland* over the period 1990 to 2018 in response to ERT recommendations on the application of stratified emission factor values, based on both soil type and climate zone, which are discussed in section 6.7.1.2 above. Table 6.48 is a comparison of the 2021 and 2020 submissions.

Table 6.48 Wetlands converted to cropland: recalculation of CO_2-e emissions 1990–2018

Year	2020 submission (Gg CO_2-e)	2021 submission (Gg CO_2-e)	Change (Gg CO_2-e)	Change (%)
1990	232.1	386.1	154.0	66%
1995	232.1	386.1	154.0	66%
2000	232.1	386.1	154.0	66%
2005	232.1	386.1	154.0	66%
2006	232.1	386.1	154.0	66%
2007	232.1	386.1	154.0	66%
2008	232.1	386.1	154.0	66%
2009	232.1	386.1	154.0	66%
2010	232.1	386.1	154.0	66%
2011	232.1	386.1	154.0	66%
2012	232.1	386.1	154.0	66%
2013	232.1	386.1	154.0	66%
2014	232.1	386.1	154.0	66%
2015	232.1	386.1	154.0	66%
2016	232.1	386.1	154.0	66%
2017	232.1	386.1	154.0	66%
2018	232.1	386.1	154.0	66%

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).

Future work will build on the current spatial and temporal analysis of the relevant activities involved in wetland to cropland conversions, and better resolve the distribution of associated organic and mineral hydrosols. This will improve the stratification of the model and therefore the calculation of the regional emission factors applied.

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, 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 is estimated using the ABARES Catchment Scale Land Use of Australia 2017 at the mapping scale of 1:5000 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.

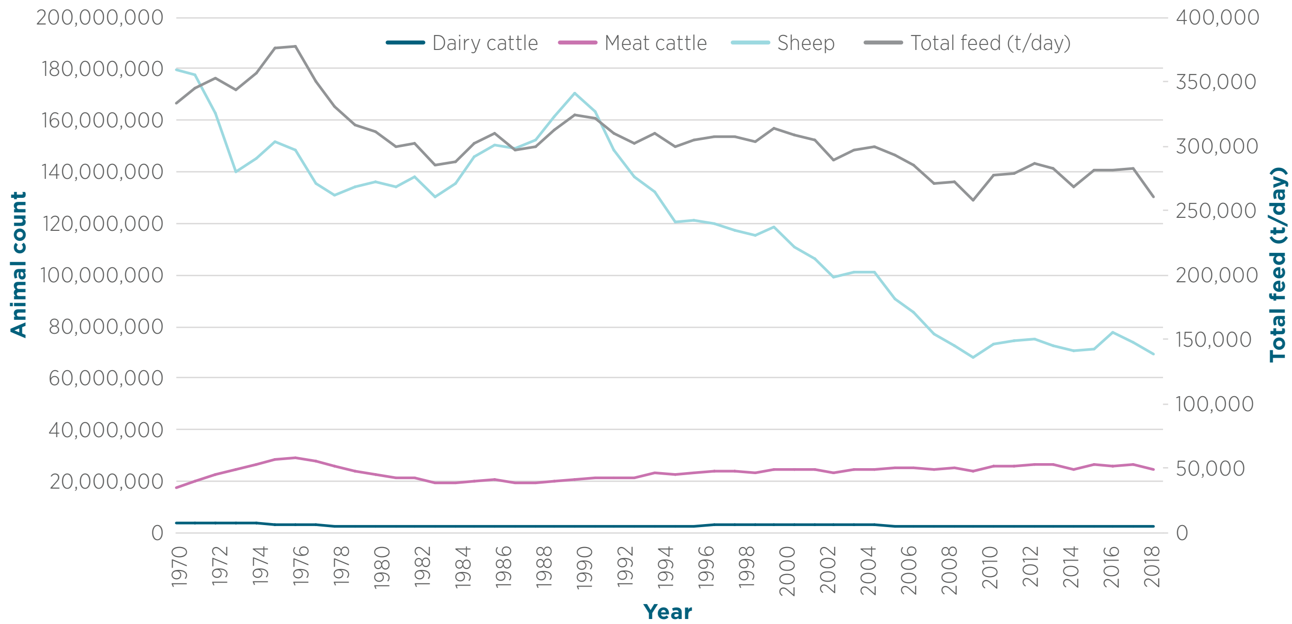
Data

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 in the ABS Land Management and Farming (2017a) which provides information on management practices being adopted and utilised by Australian agricultural business. Further details on changes in management practices are provided in Appendix 6.E.

Grazing pressure for each ABS Statistical Area 2 region across Australia has derived from the ABS Commodity Statistics (Figure 6.33).

Figure 6.33 Grazing pressure by animal type Australia, 1970–2019



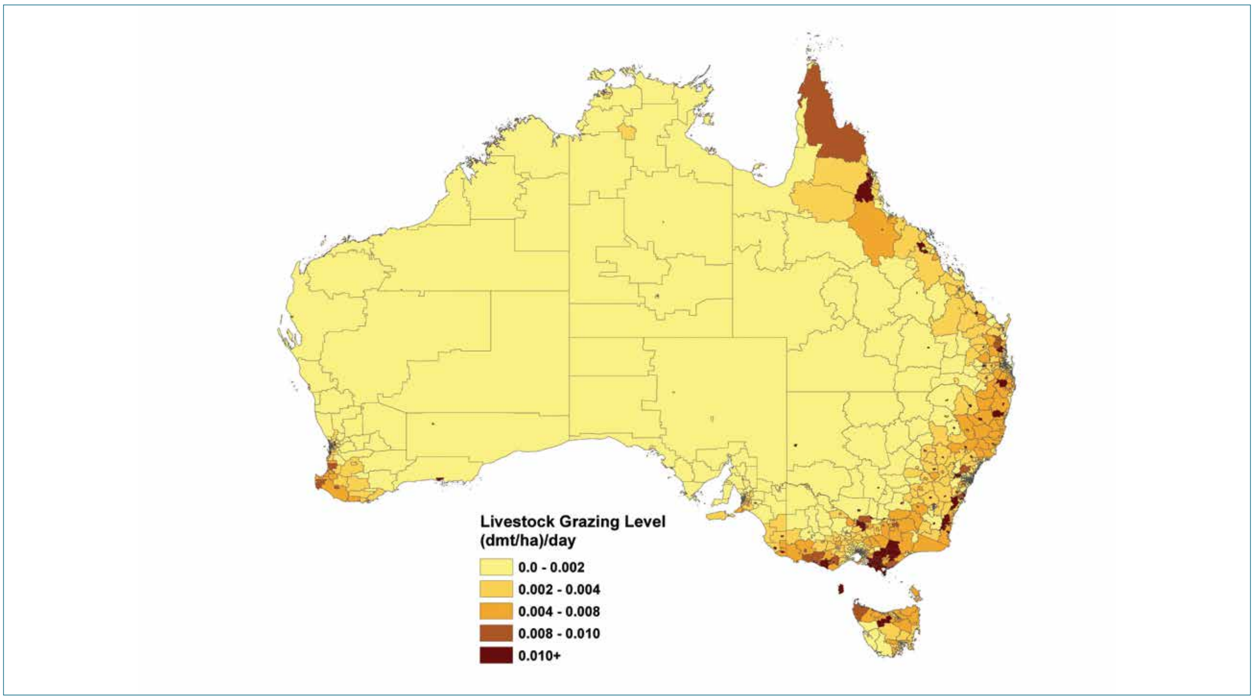
Published beef cattle, dairy cattle, and sheep population and age data from the Australian Bureau of Statistics Agriculture Commodities (ABS 2019) are used to derive average feed amounts for these livestock types.

This data is combined to calculate the grazing pressure for each Statistical area 2 (SA2) which is then inserted into FullCAM as tonnes per hectare of standing dry matter eaten per day.

With respect to unmanaged grazing by native and feral animals such as kangaroos, published data from the Department of the Environment and Energy (DoEE 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 6.34 shows the spatial distribution and levels of biomass eaten in 2010.

Figure 6.34 Livestock grazing pressure levels for Australia (2010) at the SA2 level: tonnes dry matter per hectare of pasture per day

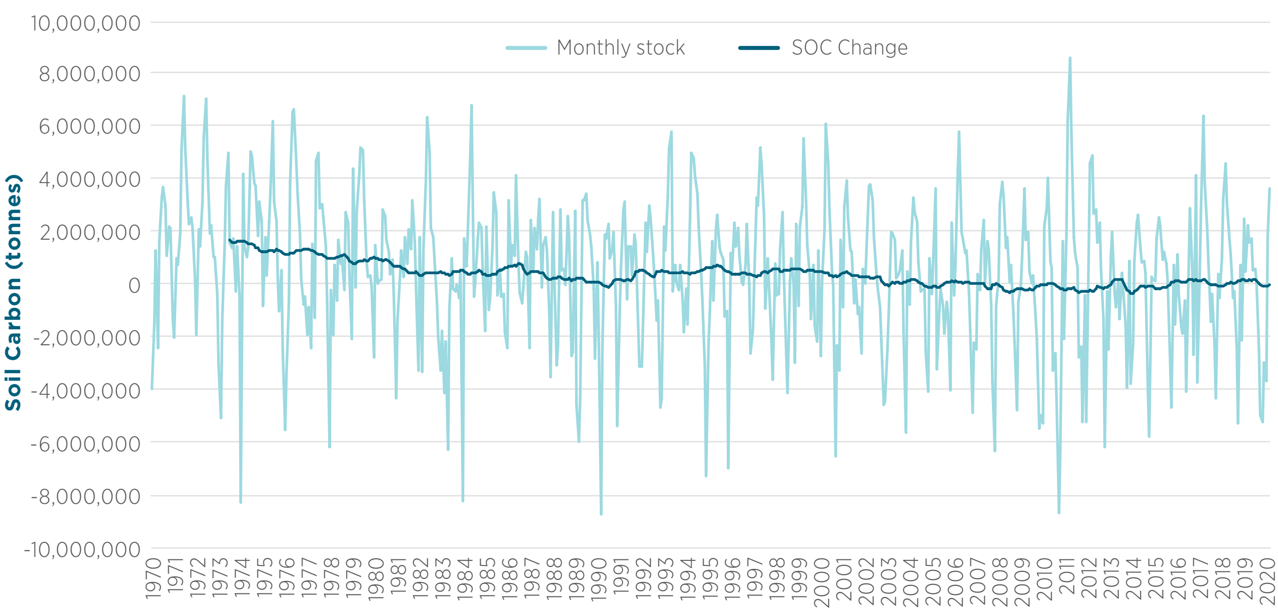


Additional details on data sources for changes in management practices are provided in Appendix 6.E.

Methods

The estimation of emissions from soil carbon from *grassland remaining grassland* is modelled in the same way as for *cropland remaining cropland.* See the discussion on the methodology for herbaceous crops in section 6.6.1.

Figure 6.35 Carbon stock change from grassland remaining grassland, 1970–2020



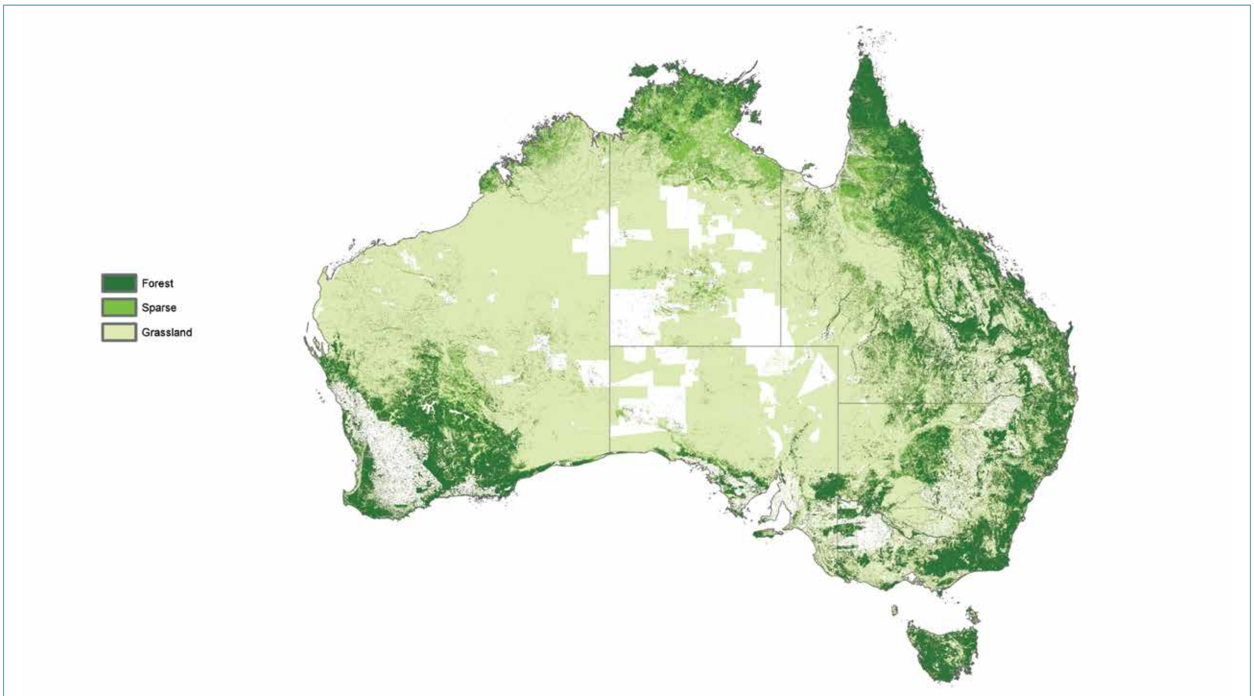
6.8.1.2 Grass and shrub transitions

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 2019 (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 to distinguish between the sparse woody vegetation cover (5–7 per cent to <20 per cent canopy cover) and the forest cover (> 20 per cent canopy cover). Figure 6.36 shows the extent of sparse vegetation in Australia.

Data on sparse woody vegetation extends for the period from 1988 to 2019, except for two interior rangeland tiles, 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 6.36 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 modelled using the same methods, factors and data as described for *other native forests* reported in *forest land remaining forest land* (section 6.4.1.5).

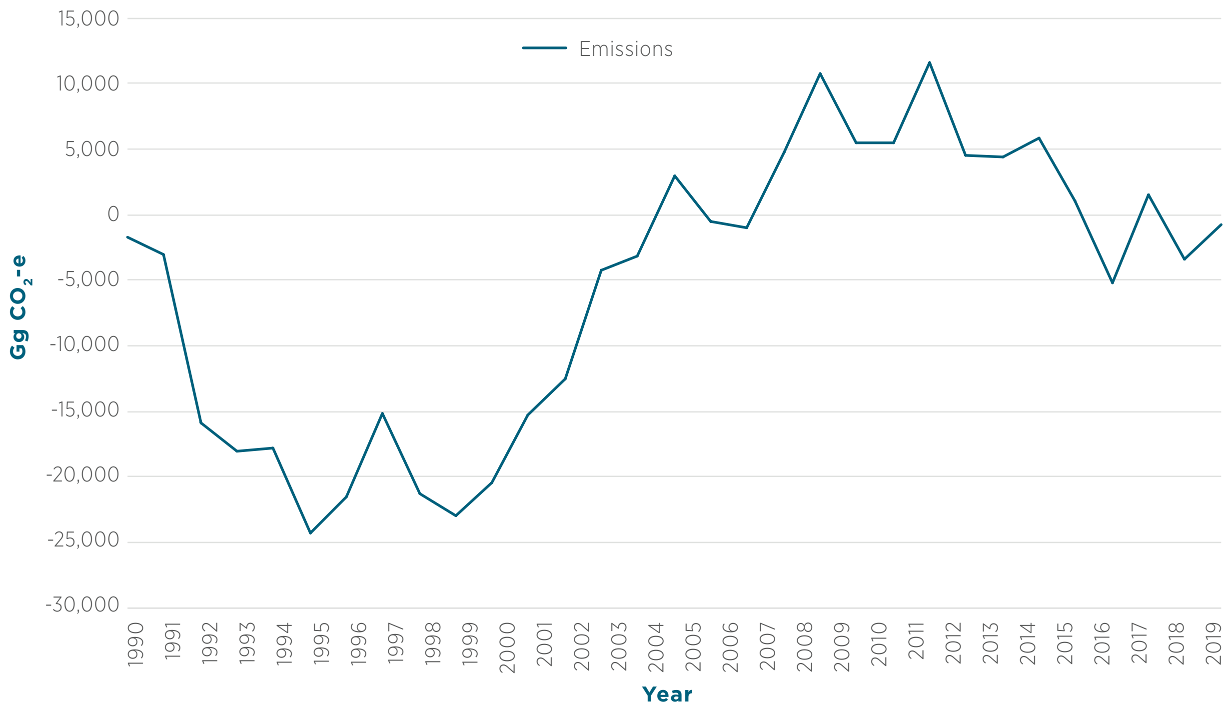
6.8.2 Emission estimates

Emission estimates for the components of *grassland remaining grassland* are reported in Table 6.49.

Table 6.49 Emissions and removals from grassland remaining grassland, by sub-category 1990–2019 (Gg CO_2-e)

Year	Herbaceous grasslands: Soil Carbon and Nitrogen mineralisation and run-off	Perennial woody biomass: Live biomass (Sparse Transitions)	Perennial woody biomass: Dead organic matter (non-temperate fire)	All
1990	-1,337	-3,778	3,642	-1,473
1995	-24,066	702	5,861	-17,503
2000	-20,319	1,676	12,012	-6,632
2005	3,365	3,449	4,990	11,805
2006	-281	3,256	8,513	11,489
2007	-800	2,964	9,221	11,385
2008	5,132	2,224	6,936	14,292
2009	11,258	-364	8,253	19,148
2010	5,918	-2,685	7,366	10,599
2011	5,878	-4,641	6,598	7,835
2012	12,241	-5,868	5,925	12,299
2013	4,893	-5,479	6,407	5,822
2014	4,609	-5,429	6,148	5,328
2015	6,094	-4,803	5,246	6,537
2016	1,243	-4,614	3,286	-85
2017	-4,980	-4,647	3,392	-6,236
2018	1,756	-4,801	2,232	-813
2019	-3,258	-4,957	2,984	-5,231

Figure 6.37 Net CO_2 emissions from soils in grassland remaining grassland, 1990–2020



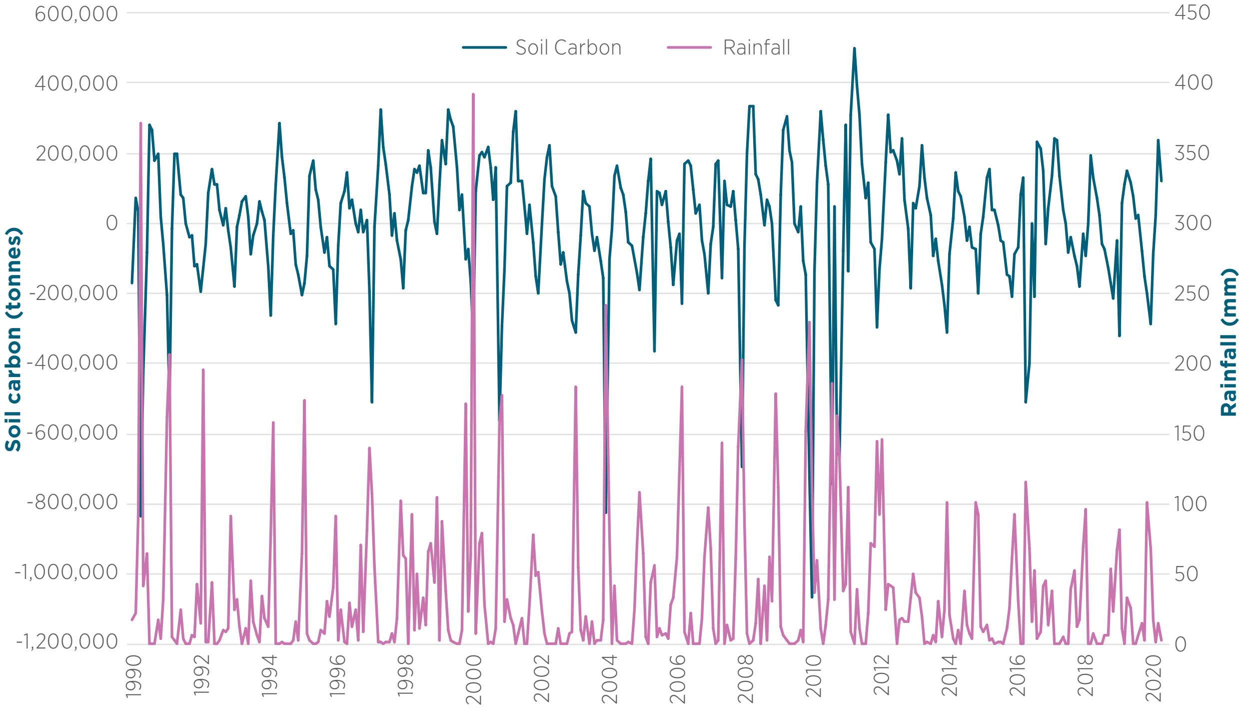
6.8.3 Uncertainties and time series consistency

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 impact of climate data on soil carbon change in pasture lands as simulated in FullCAM has been analysed to assure consistency with modelling expectations. The climate inputs (temperature, rainfall and open-pan evaporation) for selected regions and states have been verified against model outputs as seen below in Figure 6.38.

Figure 6.38 Barcaldine SA2 region, soil carbon stock change charted against rainfall inputs in FullCAM



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 Industry, Science, Energy and Resources.

6.8.5 Recalculations since the 2018 Inventory

Table 6.50a and 6.50b below provide the recalculation results, including reasons and quantified impacts.

A. Changes in area

A revision of land areas across the LULUCF sectors has resulted in a recalculation for the *grassland remaining grassland* time series reflecting this land use allocation change. This led to a very small decrease in emissions across the time series.

Due to the derivation of the mean SOC near steady state, 2018 experiences recalculations due to longer term variations in the monthly data simulated by FullCAM.

B. Non-temperate fire updates

A periodic update was made to the fire spatial layer in FullCAM.

C. Northern pasture lands of Australia

The integration of spatially explicit data for grasslands for Northern Australia pasture lands. A digitised map of these grassland regions (Tothill and Gillies (1992)) was used as an input into FullCAM to provide spatial information on where species grow. (See Figure 6.E.9 and Appendix 6.B.7) This led to a small increase in emissions across the time series.

D. Soil Cover

Improvements were made to the timing and scope of events determining agricultural plant cover properties in FullCAM, which influence the rate at which organic carbon decays in mineral soils such that decomposition occurs slower in vegetated soil than exposed soil (Jenkinson *et al* 1987). Plant cover changes now more precisely align with events which remove plant residues and establish new plants in agricultural settings (Appendix 6.B.7). This results in a small decrease in emissions across the time series.

E. Agricultural parameter updates

An adjustment has been made to the ratios of decomposable to resistant plant material for unimproved grassland species. The 2018 Inventory used a value for DPM/RPM of 1.44 for all grassland species when unimproved grassland species should use a ratio of 0.67 for DPM/RPM (Appendix 6.B.7). Since 20 out of 31 grass species were unimproved and had a reduction in the decomposable component, a large decrease in emissions is observed across the time series.

Table 6.50a Grassland remaining grassland, soil carbon from pasture lands: Recalculation of CO_2 emissions 1990–2018

	2020 submission (Gg CO_2-e)	2021 submission (Gg CO_2-e)	Change (Gg CO_2-e)
1990	10,862	-1,724	-12,585
1991	8,267	-3,030	-11,297
1992	-3,796	-15,923	-12,127
1993	-5,524	-18,002	-12,477
1994	-6,006	-17,836	-11,829
1995	-11,973	-24,294	-12,321
1996	-8,660	-21,572	-12,913
1997	-3,829	-15,147	-11,318
1998	-10,047	-21,247	-11,200
1999	-10,899	-22,895	-11,995
2000	-8,894	-20,403	-11,509
2001	-5,264	-15,304	-10,040
2002	-3,655	-12,523	-8,868
2003	2,993	-4,249	-7,242
2004	2,164	-3,180	-5,343
2005	7,905	3,006	-4,899
2006	3,944	-564	-4,508
2007	4,334	-1,026	-5,360
2008	8,950	4,747	-4,203
2009	13,631	10,760	-2,871
2010	9,275	5,500	-3,775
2011	10,572	5,452	-5,120
2012	15,306	11,647	-3,659
2013	8,621	4,573	-4,048
2014	9,457	4,402	-5,054
2015	8,562	5,842	-2,720
2016	4,625	1,003	-3,621
2017	-1,085	-5,160	-4,075
2018	-1,042	1,542	2,584

Table 6.50b Grassland remaining grassland: Recalculation of CO_2 emissions 1990–2018

				Reasons for recalculation		
	2020 submission (Gg CO_2-e)	2021 submission (Gg CO_2-e)	Total Change (Gg CO_2-e)	A. Soil Carbon and Nitrogen mineralisation and run-off* (Gg CO_2-e)	B. Live biomass (Sparse Woody Transitions) (Gg CO_2-e)	C. Dead organic matter (non-temperate fire management) (Gg CO_2-e)
1990	10,311	-1,473	-11,785	-12,699	899	15
1995	-5,734	-17,503	-11,769	-12,403	629	5
2000	4,521	-6,632	-11,153	-11,556	403	0
2005	16,686	11,805	-4,881	-5,011	121	8
2006	15,924	11,489	-4,435	-4,575	123	16
2007	16,750	11,385	-5,365	-5,460	94	1
2008	18,535	14,292	-4,243	-4,249	14	-8
2009	22,029	19,148	-2,881	-2,929	41	7
2010	14,347	10,599	-3,748	-3,832	84	0
2011	12,887	7,835	-5,052	-5,197	133	12
2012	15,863	12,299	-3,564	-3,755	187	4
2013	9,691	5,822	-3,868	-4,146	252	26
2014	10,202	5,328	-4,874	-5,226	340	12
2015	8,866	6,537	-2,329	-2,801	457	15
2016	2,883	-85	-2,968	-3,655	697	-10
2017	-2,420	-6,236	-3,816	-4,111	982	-687
2018	-3,431	-813	2,617	2,591	967	-941

* Includes soil carbon emissions data in Table 6.50a

6.8.6 Source specific planned improvements

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

Refine and improve the methodology for modelling grazed cereals. Grazed cereals are currently treated as a pasture species within the *grassland remaining grassland* simulation model. Work will be conducted to carry over the parameters from within *cropland remaining cropland* which will more accurately model the biomass levels available for the cereals species.

Further development of the sparse transitions model is planned. For changes in live biomass, the FullCAM modelling system is to be further developed to utilize the spatial information on transitions in sparse woody vegetation and to better calculate carbon stock changes. Growth and decay models will be further developed, exploring options of non-linear transitions and region-specific biomass volumes. This will advance this subcategory to a tier 3 model by taking advantage of information about the distribution of tree species currently used for simulating forests.

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 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.* Lands which are managed for non-agricultural industries, including golf courses, are reported under *forest land converted to settlements.*

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. The carbon removals associated with regrowth are reported in the *grassland converted to forest land* category (section 6.5).

The net emissions associated with fires or with harvesting of forest for timber are reported under *forest land remaining forest land* (as neither fire nor harvesting 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 *cropland remaining cropland* (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 remaining 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 6.3.2. Emissions and removals from *forest land converted to grassland* (and *other land uses)* are estimated using the Approach 3, Tier 3 Full Carbon Accounting Model (FullCAM) as described in Appendix 6.B. The reporting includes all carbon pools (living biomass, dead organic matter (DOM) and soil) other than the agricultural debris of perennial grasses. The model runs in a mixed configuration (i.e., both forest and agricultural systems) using the *CAMFor, CAMAg* and *Roth-C* sub-models. (Table 6.51 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 6.51 FullCAM configuration used for the forest land converted to cropland and forest land converted to grassland sub-categories

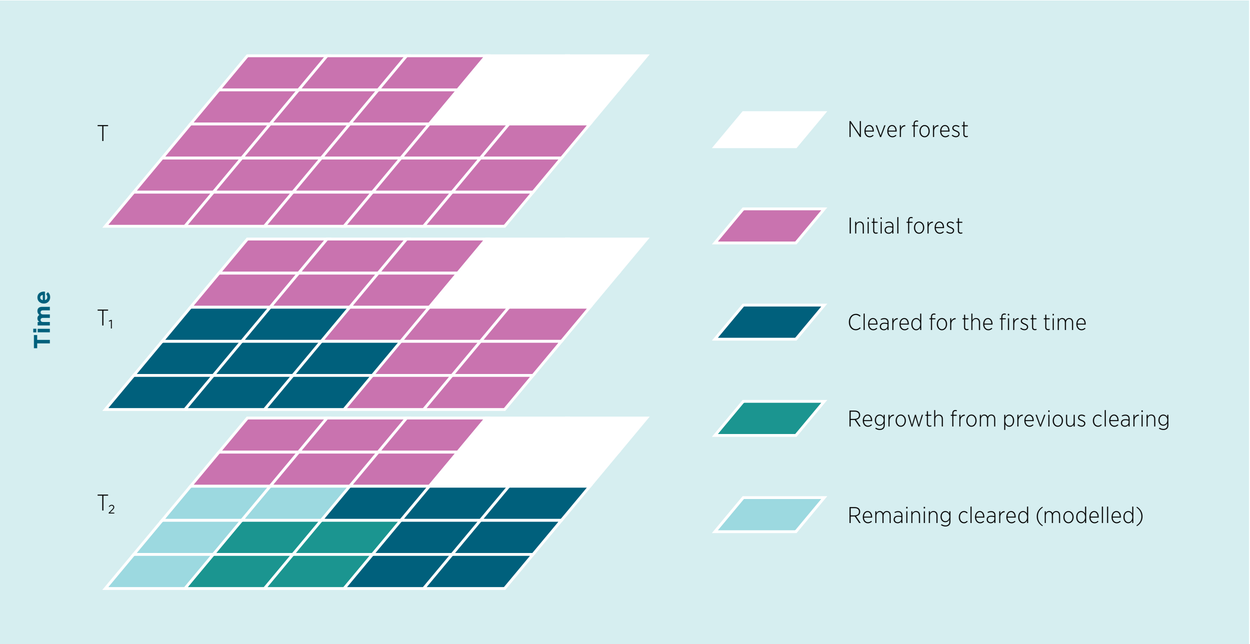
Component	Forest	Agriculture
Living biomass	CAMFor – Forest Productivity Index and Tree Yield Formula	CAMAg – Crop and pasture growth sub-models
Dead organic matter	CAMFor	CAMAg
Soil carbon	Roth-C	Roth-C
Offsite products	NA	NA

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

The fundamental analytic unit of Tier 3, Approach 3 land sector reporting in Australia is the land cover change pixel (25 m x 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 6.39.

The first class of forest pixel is 'inactive' (brown). 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 (T1, dark 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 (T2, light blue and green). These active pixels may remain cleared (light blue) or may temporarily regrow some forest cover as part of a cyclic clearing/re-clearing management system (green).

Figure 6.39 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, other than on flooded lands), FullCAM begins to regrow the forest. The removals associated with this regrowth are reported under land converted to forest (section 6.5). Where this regrowth is subsequently re-cleared, the biomass at re-clearing is based on actual age (through identification of time since regrowth). The emissions associated with the re-clearing along with the subsequent emissions and removals on the converted land are reported under the relevant forest converted to *cropland, grassland or settlements* sub-category.

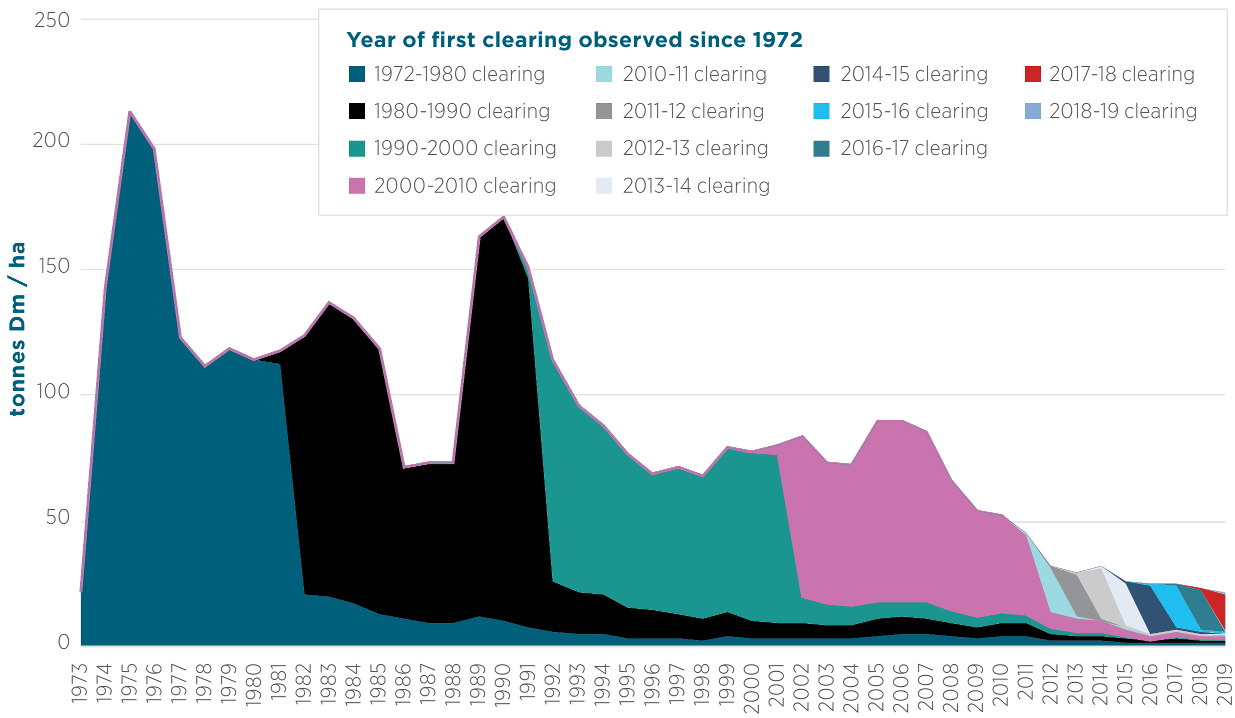
Estimating lagged emissions

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 6.40 shows that the greatest impact of lagged emissions on overall emissions estimates occurs within the first two years following a land clearing event.

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

Figure 6.40 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 6.52) 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 6.52 Partitioning of biomass between the tree components under different rainfall zones. Estimates are for mature stands of assumed stand age 100 years.

Rainfall zone	Fraction of biomass allocated to:					
	Stems	Branches	Bark	Leaves	Coarse Roots	Fine Roots
≥500mm	0.49	0.11	0.09	0.04	0.24	0.03
<500mm	0.28	0.22	0.08	0.07	0.27	0.08

The carbon content of various tree components (Table 6.53) are drawn from an analysis of a range of species across a range of environments by Gifford (2000a, 2000b).

Table 6.53 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 permanently cleared and regenerated forests, decomposition of DOM will be important. The rates of turnover and decomposition (Tables 6.54 and 6.55a and 6.55b) were based on a recent review by Paul *et al.* (2017).

Table 6.54 Tree component turnover rates

Tree component	Turnover % month^{-1}
Branches	0.74
Bark	0.41
Leaves (rainfall ≥500mm)	2.96
Leaves (rainfall <500mm)	1.28
Coarse Roots	0.87
Fine Roots	12.55

Table 6.55a Decomposition rates for standing dead pools used in the forests model

Standing Dead component	Breakdown % month^{-1}
Stems, branches and coarse roots	0.83
Bark	1.25
Leaves and fine roots	1.67

Table 6.55b Decomposition rates for debris pools used in the forests model

Debris component	Breakdown (% month^{-1})
Deadwood	1.25
Bark litter	1.44
Leaf litter, decomposable*	81.20
Leaf litter, resistant*	2.70
Coarse dead roots	2.93
Fine dead roots	81.20

* The fraction of leaf litter that was resistant was 77 per cent.

Forest residue management

For each major vegetation group (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 remaining post-burn. The residual decomposing pool is 'standing dead' of relatively slow decomposition rates (Paul and Roxburgh, 2018b). The standing dead residues burnt is set at 98 per cent, leaving 2 per cent to subsequently decompose on-site. The predictions of post-clearing residues 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. Of residues burnt post-clearing, combustion efficiencies were set at 90% for deadwood, 95 per cent for bark, 95 per cent for leaf litter, 80 per cent for coarse dead roots, and 70% for fine roots (Paul and Roxburgh 2018b).

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:

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

and for total annual emissions for NO and N O are:

$$E_{ijk} = FC_{jk} \times NC_{jk} \times EF_{ijk} \times C_i. \qquad (4.C.2\_2)$$

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 = 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

A review of state-based technical and scientific literature and spatial files (Pressey and Middleton, 1982; Bryant *et al.*, 2008; Qld, NSW and SA spatial files, listed in Table 6.J.13) on wetland soil types and transitions indicated that wetland to grassland transitions involved small areas of organic soil along the Queensland and New South Wales coastal floodplains. In this initial analysis it was determined that organic soils made up 1.23% of all soils involved in Queensland wetland to grassland transitions, and 7.4% in equivalent New South Wales transitions. Transitions recorded elsewhere were considered to involve mineral soils only.

The methodology for activity data collection and modelling of emissions and removals is similar to that underpinning estimates for *wetlands converted to croplands*. This includes a similar analysis of activity data involving wetlands on organic and mineral soils and the use of EF values appropriate to the climate zones in which the conversions occurred. As such, this methodology is covered in detail in section 6.7.1.

Annual changes in carbon stocks for mineral soils were derived, as explained in section 6.7.1, and applied to their respective states to estimate annual emissions:

- Queensland/ Northern Territory: 2.12963 tonnes C / ha / year,
- Tasmania: 0.882 tonnes C / ha / year,
- All other States/Territories: 2.7375 tonnes C / ha / year.

Conversions involving organic soils are reported for Queensland and northern New South Wales in the tropical to sub-tropical climate zones. The annual emission factor for drained grassland organic soils is 5 tonnes C / ha / year (IPCC, 2006, Volume 4, Table 6.3).

Emissions from each state and territory were calculated, based on area, and then aggregated to give the annual national totals for both (Table 6.57).

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 6.56 shows cumulative areas for *land converted to grassland* over the period 1990–2019.

Table 6.56 Cumulative area of land converted to grassland 1990–2019 (ha)

Year	Forest land converted to grassland	Wetlands converted to grassland	Total
1990	6,965,275	48,877	7,014,152
1995	8,797,159	48,877	8,846,037
2000	10,443,837	48,877	10,492,714
2005	12,645,490	48,877	12,694,367
2006	13,074,075	48,877	13,122,952
2007	13,441,750	48,877	13,490,627
2008	13,619,360	48,877	13,668,237
2009	13,620,140	48,877	13,669,017
2010	13,516,889	48,877	13,565,767
2011	13,443,019	48,877	13,491,897
2012	13,394,125	48,877	13,443,002
2013	13,370,795	48,877	13,419,672
2014	13,328,889	48,877	13,377,766
2015	13,220,456	48,877	13,269,333
2016	13,196,040	48,877	13,244,917
2017	13,178,590	48,877	13,227,468
2018	13,306,017	48,877	13,354,894
2019	13,354,096	48,877	13,402,973

6.9.2 Emission estimates

Emission estimates for the components of *land converted to grassland* are reported in Table 6.54.

Table 6.57 Net emissions and removals from land converted to grassland sub-categories 1990–2019 (Gg CO_2-e)

Year	Forest land converted to grassland	Wetlands converted to grassland	All
1990	150,493	456	150,948
1995	69,295	456	69,751
2000	72,606	456	73,062
2005	89,937	456	90,392
2006	87,303	456	87,759
2007	88,591	456	89,046
2008	66,196	456	66,652
2009	53,993	456	54,449
2010	61,313	456	61,769
2011	45,621	456	46,077
2012	43,577	456	44,032
2013	45,116	456	45,572
2014	46,940	456	47,396
2015	39,043	456	39,498
2016	39,038	456	39,493
2017	38,435	456	38,891
2018	42,764	456	43,220
2019	30,848	456	31,303

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 per cent 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 2019. 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

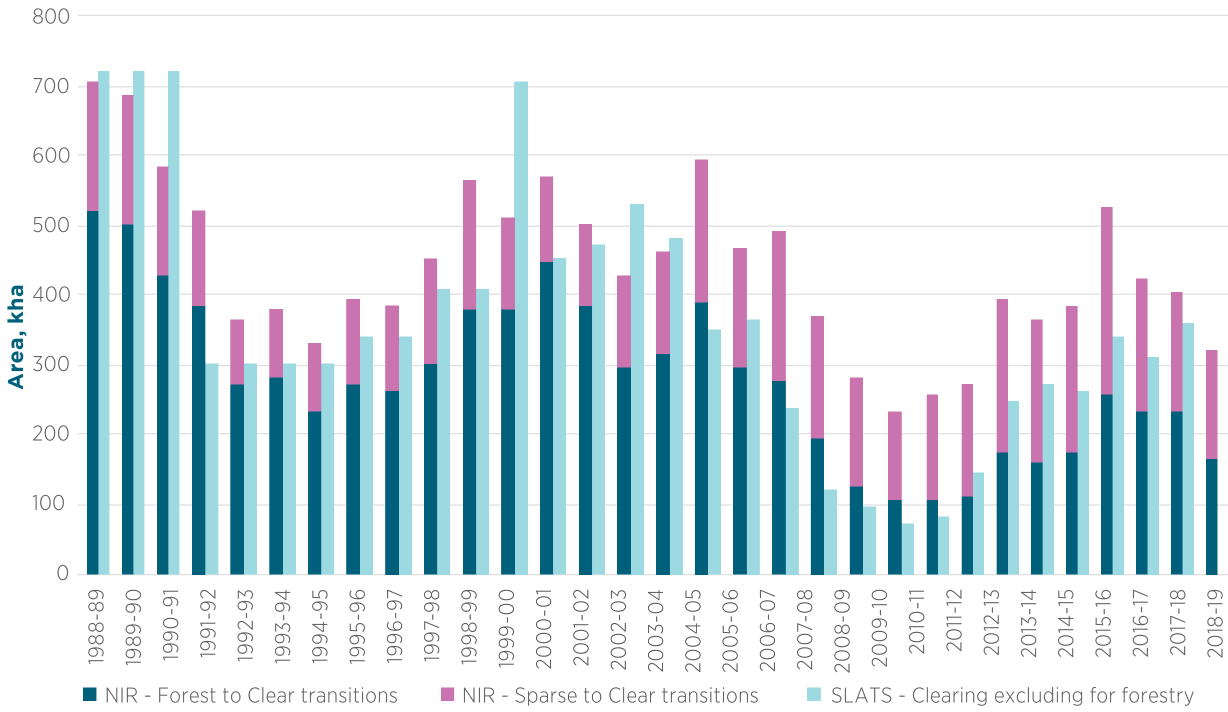
In accordance with the recommendations of an independent review of forest clearing estimates (Federici 2016b), quality control processes were established to compare the remote sensing-based forest change data used in the inventory to similar information published by the Queensland Department of Science, Information, Technology and Innovation (DSITI) in order to verify the quality of the remote sensing programme.

Analysis conducted in collaboration with DSITI discerned that the lands identified as having a history of anthropogenic vegetation removal in the national inventory's datasets are within ±10 per cent of those identified as having been cleared by Queensland's Statewide Landcover and Trees Study (SLATS) over the available time series of 1988–2018. This high level of agreement provides confidence that the areas identified for modelling of anthropogenic forest conversion are accurate. By also including all areas identified by SLATS into the scope of the inventory estimates, this provides additional confidence that they are complete. More information on the analysis and continuous improvement of the remote sensing program is provided in Appendix 6.A.

Due to variations in methodology, the timing of individual events may vary between the Inventory and SLATS datasets, but they follow a similar trend as shown in Figure 6.41.

Since 2005, the inventory's remote sensing programme has identified a greater area of annual clearing activity than in SLATS when including clearing sub-forest woody vegetation in *grasslands*, but slightly less on average when considering only forest clearing.

Figure 6.41 Comparison of land clearing rates in Queensland



Note: DTISI has not yet released a SLATS update for 2018–19.

The comparison shown here uses an alternative presentation of the inventory transition data compared to that used for land transition matrix. The land transition matrix, in accordance with IPCC reporting, identifies losses of forests that meet Australia's national definition of >20% canopy cover and >2m height. SLATS is designed to identify mechanical land clearing. For this comparison, the National Inventory Report area shown in Figure 6.41 uses 3-class vegetation change information in FullCAM to identify transitions of both forests (above 20% canopy cover) or sub-forest woody vegetation (classified as *grasslands*) to a non-woody or "clear" state. Similarly, SLATS data is presented exclusive of activities where the replacement class is "forest" or "thinning" – that is, where the identified clearing is related to native forestry activities which would not constitute a land use change in the inventory.

It is a common for agricultural land managers in Australia to periodically re-clear vegetation on their properties to maintain pastures. This is reflected in the high levels of activity observed in transitions from sparse sub-forest vegetation to clear land. This activity has a very limited impact on emissions trends, because any emissions are functionally limited to the small amount of carbon sequestered since a preceding clearing event.

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).

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 FullCAM).

Further information on FullCAM, 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 2014 Inventory, 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.

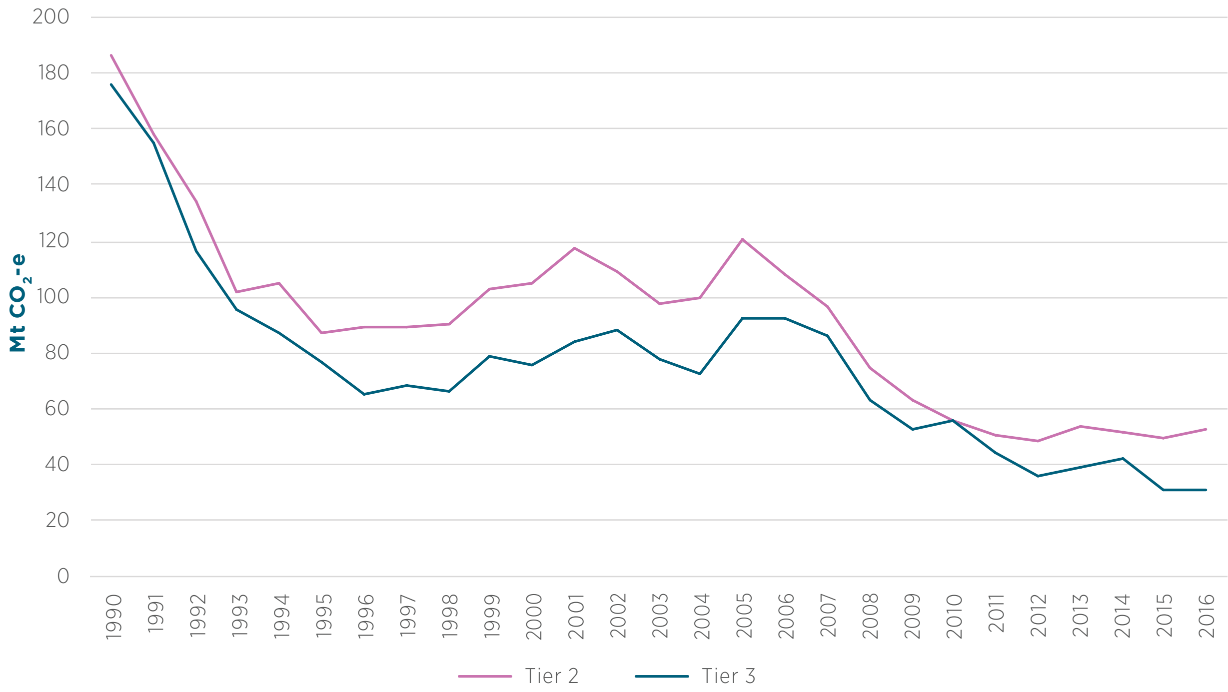
The results from the two models have been largely consistent and followed a similar trend since 1990 (Figure 6.42). The emissions output has not varied substantially between the Tier 2 and Tier 3 models; however, the discrepancies between the two model approaches can be explained further.

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 re-clearing 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 in the 2015 Inventory, 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 2014 and subsequent Inventories are well understood and explained, along with their impacts, in section 6.5.5 of each NIR. As part of the improvement plan, the current Tier 2 model will be reviewed and updated to ensure it remains a valid QA check for future inventories.

Figure 6.42 Emissions from forest land converted to cropland and grassland output from Tier 2 and Tier 3 methodology from 1990–2016

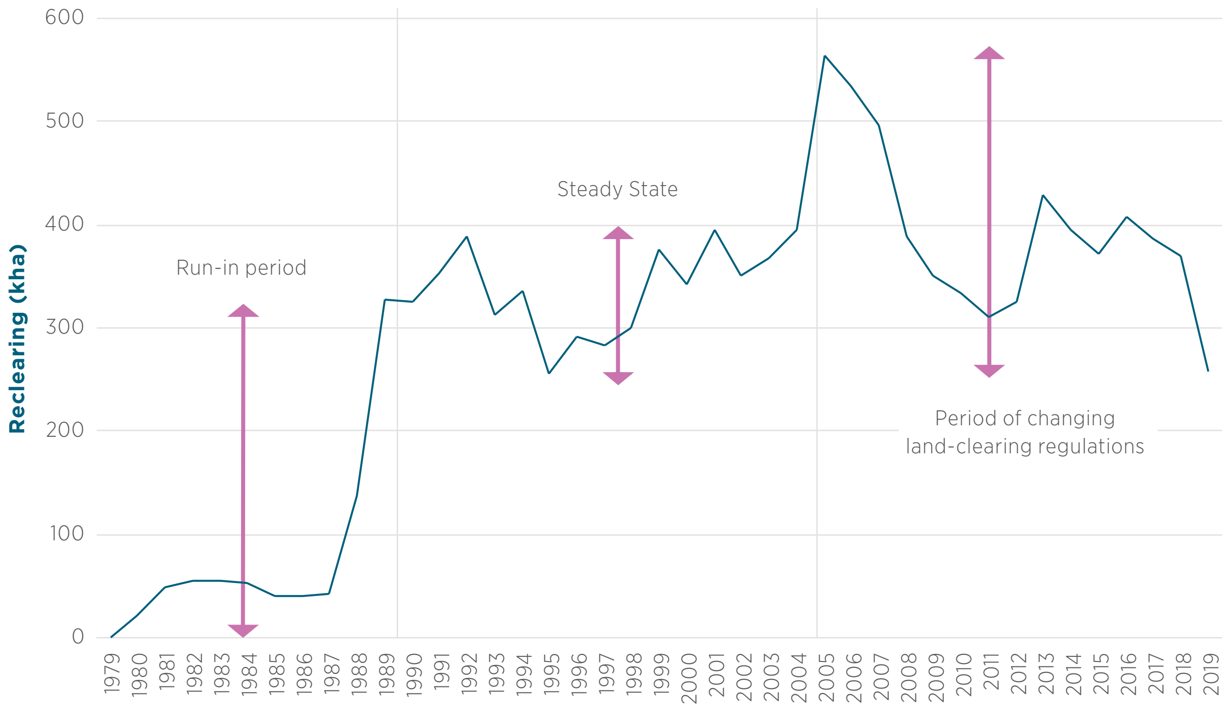


Testing sensitivity of emissions in 1990 to re-clearing prior to 1990

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 6.43). From 2004 re-clearing rates deviate from the steady-state in an apparent response to changes in land clearing regulations.

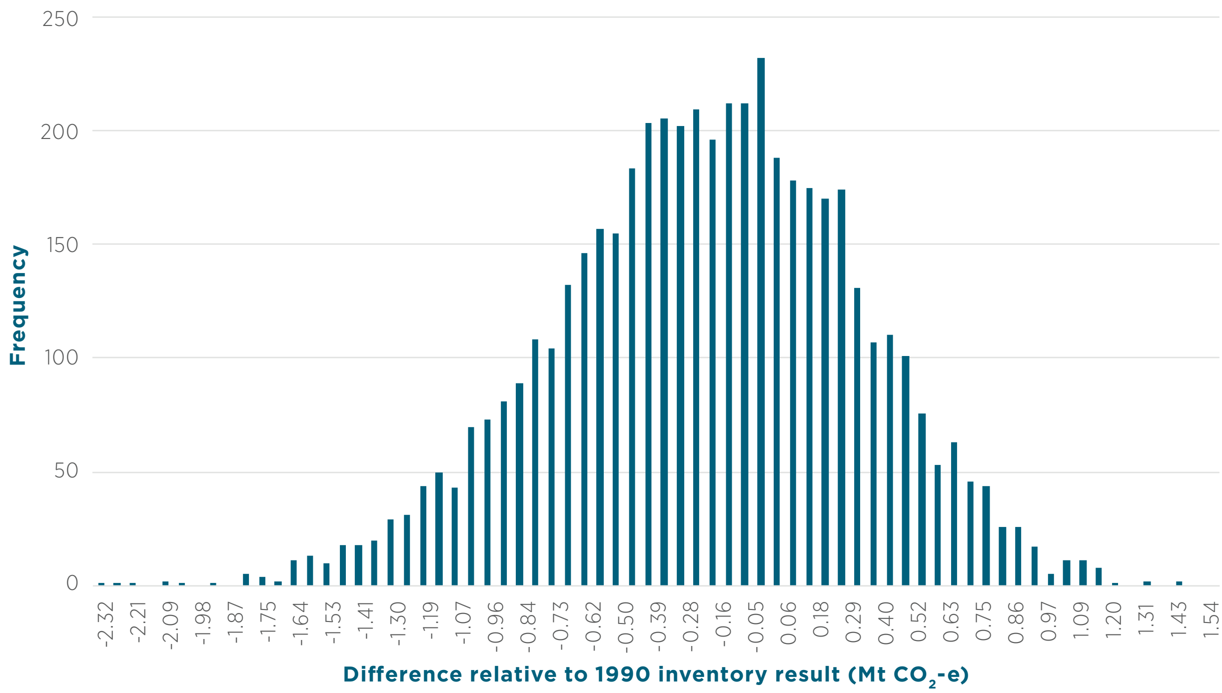
Figure 6.43 Observed re-clearing 1975–2018



While by 1990 re-clearing had reached a steady state, the observed re-clearing during the run-in period 1972–1989 (Figure 6.43) is 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 6.44.

Figure 6.44 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 6.44). 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 6.43), 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 Australian Government 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 2018 Inventory

6.9.5.1 Forest land converted to grassland

Table 6.58 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:

A. Updated spatial observations

Satellite imagery is analysed each year to update the spatial datasets for forest cover change, including the emergence of forest. This year's update also includes improvements to completeness by incorporating three additional tiles of satellite observations in central Australia.

B. Soil cover on crop and grass species

Improvements were made to the timing and scope of events determining agricultural plant cover properties in FullCAM, which influence the rate at which organic carbon decays in mineral soils such that decomposition occurs slower in vegetated soil than exposed soil (Jenkinson *et al* 1987). Plant cover changes now more precisely align with events which remove plant residues and establish new plants in agricultural settings, including where they have been converted to forest land. These recalculations are consistent with improvements made in *croplands remaining croplands* and *grasslands remaining grasslands*.

C. Agricultural parameter updates

For consistency with croplands remaining croplands and grasslands remaining grasslands, agricultural species databases have been updated for the latest information of yields and perennial growth, for the latest science on the resistant fractions of crop and grass debris, and for an update to the Nitrogen Leeching fraction from 0.3 to 0.24.

D. Non-temperate fire updates

Revisions associated with non-temperate fire activity are associated with updated activity data and are further described under *grasslands remaining grasslands.*

Table 6.58 Forest land converted to grassland: recalculation of total CO_2-e emissions, 1990–2018

Year	Forest converted to Grassland				Reason for recalculations			
	2020 submission (GgCO-e)	2021 submission (GgCO-e)	Change (Gg CO -e)	%	A. Updated spatial observations	B. Soil Cover	C. Agricultural Parameters	D. Non-temperate fire updates
1990	149,455	150,493	1,038	0.7%	208	664	137	28
1995	68,131	69,295	1,164	1.7%	105	516	519	24
2000	71,508	72,606	1,098	1.5%	104	505	463	25
2005	88,394	89,937	1,542	1.7%	230	895	391	27
2006	86,755	87,303	548	0.6%	226	953	-658	28
2007	86,160	88,591	2,430	2.8%	254	929	1,218	29
2008	65,128	66,196	1,068	1.6%	1,027	435	-424	30
2009	53,156	53,993	837	1.6%	313	399	96	30
2010	60,837	61,313	476	0.8%	188	316	-59	31
2011	45,223	45,621	399	0.9%	166	355	-152	30
2012	42,856	43,577	721	1.7%	158	277	255	31
2013	43,528	45,116	1,588	3.6%	251	639	668	31
2014	45,676	46,940	1,264	2.8%	399	626	207	32
2015	37,246	39,043	1,797	4.8%	879	382	502	32
2016	37,575	39,038	1,462	3.9%	559	510	358	35
2017	38,116	38,435	319	0.8%	541	323	-579	34
2018	39,524	42,764	3,240	8.2%	2,818	319	71	33

6.9.5.2 Wetlands converted to grassland

There is a recalculation for wetlands converted to grassland over the period 1990 to 2018. Table 6.59a is a comparison of the 2020 and 2021 submissions. The recalculation is due to the application of emission factor values stratified for the first time based on both soil type and climate zone.

Table 6.59 ***Wetlands converted to grassland:*** **Recalculation of CO_2-e emissions 1990–2018**

Year	2020 submission (Gg CO_2-e)	2021 submission (Gg CO_2-e)	Change (Gg CO_2-e)	Change (%)
1990	896	456	-441	-49%
2000	896	456	-441	-49%
2005	896	456	-441	-49%
2006	896	456	-441	-49%
2007	896	456	-441	-49%
2008	896	456	-441	-49%
2009	896	456	-441	-49%
2010	896	456	-441	-49%
2011	896	456	-441	-49%
2012	896	456	-441	-49%
2013	896	456	-441	-49%
2014	896	456	-441	-49%
2015	896	456	-441	-49%
2016	896	456	-441	-49%
2017	896	456	-441	-49%
2018	896	456	-441	-49%

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;
- 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 the *cropland remaining cropland* and *grassland remaining grassland* sections of this chapter.

Improvements are also planned in relation to activity data collection and modelling of emissions and removals associated with conversions of conventional forest to wetlands (flooded lands), of mangrove forest to settlements, and of mangrove forest to grassland or cropland. The additional work on conversions of mangrove forest to settlement, grassland or cropland will address the impact of constructing bunds and other types of barriers that impede tidal flow, whether to affect land use change or to provide coastal protection against tidal intrusion.

Restrictions in tidal flow due to the construction of bunds and other types of barriers also affect tidal marsh. Conversions of tidal marsh to settlement, grassland or cropland may result. Future work will account for this activity where such conversions are observed and recorded.

Conversions of mangrove forest or tidal marsh to ponded pasture, which is grassland on seasonally saturated soils, will also result in methane emissions. Future improvements to the relevant conversion models will enable annual methane emissions to be estimated and reported.

Future work will build on the current spatial and temporal analysis of the relevant activities involved in wetland to grassland conversions, and better resolve the distribution of associated organic and mineral hydrosols. This will improve the stratification of the model and therefore the calculation of the regional emission factors applied.

With respect to mangrove forest conversions and accounting more broadly for emissions and removals associated with wetlands, the Australian Government confers with an informal expert advisory group of academic and government wetland specialists who 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), and Chapter 7: Wetlands in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4 Agriculture, Forestry and Other Land Use. The wetlands inventory, which previously focused on coastal wetlands, includes estimates of methane emissions from certain sub-sectors of *Flooded lands remaining flooded lands* that are provided on a voluntary basis.

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

- Gains and losses of sparse woody vegetation on wetlands (both coastal and inland);
- Emissions from aquacultural production in Australia;
- Emissions from seagrass removal due to capital dredging projects; and
- Methane emissions from *reservoirs* and other constructed freshwater ponds under *Flooded land remaining flooded land,* including an estimate for certain ponded pastures.

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. Emissions are reported in Table H of the CRF tables.

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:

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

Where $N_2O\text{-}N_{AQ}$ = 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)$^{-1}$

N_2O emissions are reported as kilo-tonnes CO_2-e, based on the AR4 100 year N_2O global warming potential of 298.

Seagrass removal

A report (Kettle 2017) was commissioned by the department to capture the timing and extent of current and historical capital dredging activity in Australia that informs the seagrass excavation model. (Appendix 6.J).

The seagrass excavation model has a tier 1 model structure to which country-specific parameter values are applied, elevating it to a tier 2 model (IPCC 2014). Parameter values were estimated from pooled data collected from the scientific literature. Where possible these are based on species-specific values within a regional context (Appendix 6.J.2). The coastal regions applied to the seagrass model are the same as those developed for the mangrove and tidal marsh models (Figure 6.J.1). Species presence and abundance within each coastal region was estimated from available survey data (Table 6.J.6 and Table 6.J.7).

The timing and extent of capital dredging activity in Australian waters was reported for the period 1989 to 2016 (Kettle 2017), noting there was no recorded capital dredging activity for 1990–1995, 2011 and 2016.

The model is populated with area estimates for excavated seagrass meadow obtained by spatial modelling. Kettle (2017) provided dredge-related shapefiles (listed in Table 6.J.10) that are overlaid on seagrass habitat shapefiles to determine the areas of seagrass and underlying sediment removed by dredging activity. Seagrass habitat shapefiles are sourced from State and Territory jurisdictions and the University of Tasmania. (Table 6.J.11).

It is reported in the literature that seagrass habitat takes time to recover after removal or burial, depending on the species involved (Preen, Lee Long, and Coles 1995; Campbell and McKenzie 2004; Smith *et al.* 2016; Vanderklift *et al.* 2017). Some seagrass habitat, including that dominated by temperate, high biomass species, may not re-establish when disturbance is regular, periodic, or catastrophic (Meehan and West 2002; Erftemeijer and Robin Lewis 2006; Wu *et al.* 2015). As navigational channels also undergo scheduled periodic maintenance dredging it is assumed that seagrass habitat is removed permanently when establishing a channel. Also, in keeping with tier 1 assumptions, all excavated plant and soil based organic carbon is mineralised in the year of removal. Finally, an estimation of the soil organic carbon removed by dredging is based on an excavated depth of one meter only.

Freshwater ponds and reservoirs

The publication of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories provides additional guidance in the Wetlands land use category Flooded Land. The Australian Government, in its program to expand implementation of Wetlands on a voluntary basis, includes in this submission methane emissions from *Reservoirs* and *freshwater ponds* that will be reported under *Flooded Land remaining Flooded Land.*

Tier 1 methods for estimating methane emissions from *Reservoirs* and *freshwater ponds* are described here. Reservoirs up to 20 years in age also emit additional CO_2 due to the ongoing decay of woody biomass and soil organic carbon caused by inundation. These CO_2 emissions are reported elsewhere, under *Forest land converted to wetland.*

For *Reservoirs* and *freshwater ponds* within a specific climate zone:

$$F_{CH4} = EF_{CH4} \times A$$

Where F_{CH4} = Annual emission of CH_4 from all *Reservoirs* and *freshwater ponds*

A = Area of water body water surface

EF_{CH4} = Emission factor for CH_4 emitted from the water body surface, which is specific for the type of water body and climate zone in which that waterbody is located.

The refinement provides default values for methane emission factors (EF_{CH4}) for *Reservoirs* that are specific to waterbody age and climate zone (Tables 7.9 and 7.15 in the 2019 Refinement), and which are reproduced in Table 6.60. *Reservoirs,* also emit methane from water released downstream of the reservoir, $F_{CH4\ downstream}$. Emissions from this source, which under Tier 1 may add up to 9% to the total reservoir related emissions, and are estimated in this account for the first time. In Tier 2/3 models, an emission factor adjustment (a) is applied to account for the influence of eutrophication of reservoir waters. This has a default value of one for Tier 1 models, which is applied here and therefore does not influence the emission estimate.

Methane emissions are also estimated from *freshwater ponds,* which are defined as a type of *Other constructed waterbody* in the 2019 Refinement. Unlike with *Reservoirs* however, the 2019 Refinement only provides a global methane emission value for each type of *Other constructed waterbodies* (freshwater ponds, saline ponds, and canals and ditches) under all climate zones. Australia is geographically diverse and experiences a range of climate zones, including wet and dry tropics, warm and cool temperate, as well as arid and montane regions. Recent Australian (Grinham *et al.* 2018) and international work (Baker-Blocker, Donahue, and Mancy 1977; Kelly and Chynoweth 1981; Casper *et al.* 2000; Natchimuthu, Panneer Selvam, and Bastviken 2014; Panneer Selvam *et al.* 2014; van Bergen *et al.* 2019; Zhang *et al.* 2019) on methane emissions from agricultural and urban dams, and small, shallow reservoirs show temperature dependent methane emission rates based on diel and seasonal monitoring, as well as geographical (climate zone) location.

A regression analysis of the reported total methane emissions (diffusive + ebullitive) against the corresponding air temperature reported by the authors above identifies seasonal EF_{CH4} values against the mean daily temperature of each Australian climate zones, for each of the four seasons, as reported by the Australian Bureau of Meteorology (2020). The methane EF value used in this first account is the mean of the four seasonal emission estimates for each Australian climate zone for which the mean annual temperature is known (Table 6.60).

Table 6.60 EF_{CH4} values for Reservoirs and Other constructed water bodies (freshwaterponds)

	Other constructed water bodies (freshwater ponds)	Reservoirs	
Australian Climate Zone	**EF_{CH4} (kg CH_4/ha/year)**	**AGE (Old > 20 years)**	**EF_{CH4} (kg CH_4/ha/year)**
Tropical – wet	697	Young	252
Tropical – dry	581	Young	392
Tropical – moist	381	Young	196
Temperate – warm	238	Young	128
Temperate – cool	152	Young	85
Tropical – wet		Old	141
Tropical – dry		Old	284
Tropical – moist		Old	151
Temperate – warm		Old	151
Temperate – cool		Old	54

Freshwater ponds include stock dams as well as crop dams and farm tanks, which are small to large, shallow impoundments used for crop irrigation. Australian studies (Grinham *et al.* 2018; Ollivier *et al.* 2018) have demonstrated that emissions from the latter not servicing stock water requirements, and not located on grazing land, generally have lower methane emissions. This is presumably because they are not contaminated with manure, either through direct deposit, or as a component of rain runoff into the dam. The freshwater pond emission factor values reported here (Table 6.60) are assigned to stock dams, on the assumption that the relatively high values observed may be attributed to some level of organic fertilization.

Grinham *et al.* (2018) reported on emissions from freshwater ponds, with primary uses including irrigation, stock watering or urban use. They also recorded the primary land use against each individual pond. A comparison of emission rates between ponds used for stock watering on grazing land (assumed high organic input) against ponds used for irrigation or "urban use" on cropland or settlement land (assumed lower organic inputs) resulted in a geometric mean ratio of 0.47 for crop dams and farm tanks relative to stock dams. This ratio is a multiplier, used in conjunction with the EF_{CH4} values in Table 6.60, to estimate the baseline methane emission (lower organic input) for freshwater ponds. The "manure component" of stock dam emissions is then estimated on the basis of (1 – 0.47) X EF_{CH4} values reported in Table 6.60. The manure related methane emissions are reported elsewhere, in *manure management* in Agriculture.

Activity data for methane emissions from reservoirs and agricultural ponds is the aggregated surface area (by state and nationally) for each of these categories of water bodies. The surface area of Australia' major dams and reservoirs was obtained from the satellite based Geoscience Australia data set, Water Observations from Space (WOfS), cross referenced with the Bureau of Meteorology data on Australia's major dams and reservoirs that reflects the waterbodies reported in the Australian National Committee on Large Dams (ANCOLD) list of dams. In this initial analysis of reservoir surface area, and therefore the resulting time series, is based on reservoir areas observed at a single point in time each year. A more comprehensive annual analysis of reservoir surface area change will improve accuracy of this account. This will form the basis for a future improvement of this account.

The "Surface Hydrology Polygon (Regional)" geodatabase, a component of the Australian Hydrological Geofabric (AHG) (Geoscience Australia 2016) provides the location and surface area data of 655,053 farm dams nationally. This represents 33% of the 2 million farm dams estimated to exist nationally by the Australian Water Association, 2006 (cited in Baillie 2008). This data set represents a single time point for each dam, not a time series as required for the NIR. However it has enabled an estimate of each state and territory's contribution to the national dam population, and the distribution of farm dam size classes. Both of these parameters are required in modelling the available annual farm dam surface area (activity data). This was estimated by using the proxy of Australian agricultural water use, which is reported annually by the Australian Bureau of Statistics (e.g. 4618.0 – Water use on Australian Farms, 2017–18, ABS 2019) The ABS agricultural water use data is available for the financial years 2002–03 to 2017–18, and is reported at the level of each state and territory's Natural Resource Management (NRM) regions. The method for estimating the annual available surface area available for emissions is described briefly:

- Estimate the total volume of water available.
  - The ABS data includes *Water taken from on-farm dams or tanks (ML),* which represents all farm dam water usage.
  - Assume this water usage represents 20% of all water stored annually across all farm dams and adjust values to represent total water stored by multiplying the water usage statistic by five.
  - The value of the adjustment multiplier was originally based on that of a Qld study that adopted a water usage value of 50%, based on farmer interviews (Logan and Wiesenfeld 2012). However the calculated surface area of farm dams, when based on this relationship, was a significant under-estimate when compared to the observational data provided by GA's surface hydrology data set.
  - Altering the reported water usage value to 20% gave the best comparable estimate of farm dam surface area.

- Estimate the annual available surface area for farm dams at state/territory and national levels.
  - Water used is reported by the ABS in ML.
  - For each size class of freshwater pond, estimate the total surface area (ha) according to the following equations developed in A South Australian study (McMurray, 2004):
    - For $A < 15{,}000$ m^2, $V = 0.0002\ A^{1.25}$
    - For $A > 15{,}000$ m^2, $V = 0.0022\ A$
      - where A = surface area (m^2); and
      - V = estimated volume (ML).
  - Aggregate the results to a total water surface area for the NRM region
- For each NRM region, estimate the annual baseline methane emissions for freshwater ponds, noting that each NRM region is assigned to one specific climate zone:
  - EF x Area, where
    - EF value is specific to climate zone (Table 6.60) and multiply by the 0.47 to obtain the baseline freshwater pond annual methane emissions
- Aggregate the results for each NRM, and then to state/territory and national levels, which are reported in the NIR.

A proportion of freshwater ponds are used for stock watering. These ponds are subject to additional organic matter inputs due to manure from local stock. A brief description is provided of the methodology to estimate these additional methane emissions.

- Estimate the surface area of dams in each size class that are "stock dams"
  - The ABS reports the statistic *Other agricultural water use,* which is mainly stock watering, and which is attributed 100% to that activity in this model.
  - Based on the assumption that 100% of drinking water for stock is delivered by stock dams, then this reported volume is a subset of the *Water taken from on-farm dams or tanks (ML).*
  - Estimate the surface area of these dams, as described above, based on the volume of water attributed to each NRM region and dam size class.
  - Aggregate the results for each NRM region
  - Estimate emissions for each NRM region, as described above, except that a multiplier is not applied to the corresponding EF_{CH4} values in Table 6.60.
  - Aggregate the results to state/territory and national levels for reporting in the NIR.
  - These results are reported elsewhere, under *Manure management* in the Agriculture sector.

The ABS had not collected Water use on Australian Farms statistics prior to the 2002–03 financial year. To complete the time-line for this first submission, trend analysis was undertaken on the available data (2002 to 2018) to back-cast to 1990.

Ponded pasture

Ponded pastures are ponds constructed in grazing lands in tropical and subtropical regions that experience distinct wet and dry seasons. The ponds are designed to flood seasonally (during the wet), and are sown with water tolerant grasses. The grasses grow during the wet season and become pasture in the dry season, providing highly nutritious fodder for cattle as the ponds dry out.

Australia has an area of 52,500 ha of certain ponded pastures in Australia's dry tropics and subtropics. An estimate of methane emissions from this source is provided in this submission under *Freshwater ponds.*

There is no information on the emission rates from these water bodies. However, as they are vegetated, it is likely that methane emissions are high. The full EF values reported in Table 6.60 are therefore used in this instance.

The Tier 1 method is briefly described here:

- $F_{CH4} = EF_{CH4} \times A \times B$,
  - A = Area of water body water surface (ha)
  - EF_{CH4} = Emission factor for CH_4 emitted from the water body surface, which is based on the dry tropical and subtropical values reported in Table 6.60 climate zone.
  - B is the proportion of the year that are emissive days (when water is present in the pond)
- A total area of 52,500 ha is divided between the dry tropics (35,000ha) and the moist tropics (17,500ha)
- The number of emissive days is assumed to be 240 days annually, so that B = 0.66

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 6.61 below:

Table 6.61 Area and net emissions of sparse woody vegetation transitions, UNFCCC *Wetlands remaining wetlands*

Year	Area gains kha	Area losses kha	Net emissions Gg CO_2
1990	50.8	72.4	397.6
1995	18.0	26.5	442.3
2000	40.4	26.8	304.8
2005	76.4	41.9	159.6
2006	34.7	130.0	245.1
2007	31.4	79.3	279.8
2008	29.6	59.2	288.5
2009	26.7	54.5	247.9
2010	41.0	67.7	252.6
2011	36.9	44.0	235.2
2012	74.6	31.8	87.7
2013	59.4	58.0	65.5
2014	32.6	77.3	85.3
2015	33.0	71.2	112.6
2016	61.2	57.4	113.4
2017	29.9	93.1	175.8
2018	31.4	74.3	225.3
2019	35.5	37.7	249.0

Aquaculture production

Annual emissions for aquaculture over the reporting period 1990–2019 are shown in Table 6.62 below.

Table 6.62 Annual emissions calculated for aquaculture (use) within the *wetlands remaining wetlands* category

Year	Emissions (Gg CO_2-e)
1990	4
1995	10
2000	19
2005	23
2006	28
2007	31
2008	33
2009	36
2010	38
2011	40
2012	47
2013	46
2014	45
2015	52
2016	58
2017	55
2018	63
2019	65

Seagrass removal

Nationally, capital dredging removed 416 ha of seagrass meadow, which represents 4 per cent of the aggregated capital dredging area (11,843 ha), during the period 1989/90 to 2014/15. This resulted in total emissions of 129 Gg CO_2-e generated by the removal and aerobic disposal of plant biomass and soil organic carbon. There were no capital dredging projects identified that removed seagrass habitat in 2015/16, 2016/17, 2017/18, or 2018/19.

Annual emissions for seagrass removal over the reporting period 1990–2019 are shown in Table 6.63 below.

Table 6.63 Annual area and emissions for seagrass removal within the *wetlands remaining wetlands* category

Year	Emissions (Gg CO_2-e)	Area removed (ha)
1990	0	0
1995	0	0
2000	1	1
2005	11	26
2006	10	22
2007	1	3
2008	54	235
2009	0	1
2010	0	1
2011	0	0
2012	1	6
2013	2	7
2014	34	76
2015	1	3
2016	0	0
2017	0	0
2018	0	0
2019	0	0

The key drivers of variation over the time period are increased sparse transitions in wetlands due to climatic impacts that alter wetland hydrology and increased aquaculture production in tidal wetland areas.

Methane from Reservoirs and freshwater ponds

Annual emissions for reservoirs and freshwater ponds, including ponded pasture, over the reporting period 1990–2019 are shown in Table 6.64 below.

Table 6.64 Annual area and CH_4 emissions for *reservoirs and freshwater ponds*

Year	Emissions (Gg CO_2-e)	Area as flooded land (kha)
1990	3,857	683
1995	3,431	686
2000	3,736	745
2005	3,313	669
2006	3,144	644
2007	2,890	633
2008	3,055	636
2009	3,020	680
2010	3,125	711
2011	3,293	753
2012	3,248	739
2013	3,119	720
2014	3,218	761
2015	3,031	700
2016	3,211	722
2017	3,427	759
2018	3,213	717
2019	2,924	661

Key drivers for methane emissions from these sources are the change in area of reservoirs and *freshwater ponds* that reflect annual changes in rainfall and usage.

The methane emissions reported here represent the base-line emissions from waterbodies. *Freshwater ponds* may have additional organic matter (OM) inputs, namely manure from cattle, sheep and other livestock. Methane production from manure inputs in agricultural ponds is reported elsewhere, under manure management in Agriculture.

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 2019 (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. 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.

Under *wetland remaining wetland* the confidence intervals associated with 2013 IPCC guidance values for parameters associated with land use, land use change involving coastal wetlands range from 24 per cent to over 200 per cent. For seagrass removal 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.

Estimates of CH_4 emissions from reservoirs and freshwater ponds are based on the Tier 1 methodology provided in the 2019 Refinement to the 2006 IPCC Guidelines, with some refinement in spatial analysis of activity data and, for freshwater ponds, the development of emission factor values based on regional annual average temperatures.

Based on the summary of emission factor values published in the 2019 Refinement, the 95% confidence interval around the default and modelled emission factor values is large. It is anticipated that the level of uncertainty will reduce as research on methane emissions from waterbodies is continues to be published and the results incorporated into Australia's modelling efforts.

Time series consistency is ensured by the use of consistent methods across the time series.

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 and seagrass removal)* involve internal reviews of data entry and model outputs, including a check on the consistency of aquaculture production statistics across Australian jurisdictions.

The quality control measures employed in estimating methane emission from *reservoirs* and *freshwater ponds* include comparing the applied EF values, which are climate zone based and derived from international data, against Australian values reported in the scientific literature,

Activity data for reservoirs is derived from satellite image analysis to obtain the annual change in their individual surface areas. A subset of these estimates are checked against corresponding water storage levels for major reservoirs as reported annually by each state and territory.

Freshwater pond water storage levels are estimated through modelling. The parameter values in the model are sourced from the Australian Bureau of Statistics (ABS). The quality of the ABS is reflected in the Relative Standard Errors for its published estimates. This varies between 2.5% to 27% for the estimates employed in the current freshwater pond model, with RSEs over 10% to be used with caution. This lowers the confidence level that can be attributed to freshwater pond emissions.

6.10.5 Recalculations

Recalculations for *wetlands remaining wetlands* for 1990 to 2018 are shown in Table 6.65 below. As with *grassland remaining grassland* (section 6.8.5), activity data for grass and shrub transitions (to and from sparse woody vegetation) has been revised due to annual updates in image analysis.

Consistent with the revisions for non-temperate fire management described under *forests remaining forests,* reporting of these emissions has been revised in *wetlands remaining wetlands* to reflect updated activity data.

Downstream CO_2 emissions from reservoirs is introduced in this NIR, as described in Chapter 6.10.2 above.

An ERT recommendation to correct the calculation of the Aquaculture Use emission is implemented, as is the incorporation of an update to Australia's aquaculture production statistics for 2016/17 and 2017/18.

Additional information on *Flooded Land* areas and the age of reservoirs also resulted in a recalculation as the activity data was updated and different EF values applied to reservoirs that were older than 20 years compared to those established within 20 years of a reporting year.

Table 6.65 Wetlands remaining wetlands: recalculation of total CO_2-e emissions, 1990–2018

	Wetlands remaining wetlands				Reason for recalculation			
	2020 submission	2021 submission	Change		Sparse Woody Vegetation	Biomass burning	Constructed Water Bodies	Aquaculture Use
Year	(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	3,761	4,335	574	15%	40	0	532	1
1995	4,008	3,839	-168	-4%	29	1	-202	4
2000	4,969	4,725	-243	-5%	20	1	-271	7
2005	4,618	3,752	-866	-19%	8	1	-883	9
2006	4,138	3,798	-339	-8%	8	2	-360	10
2007	4,261	3,561	-700	-16%	7	1	-719	11
2008	3,986	3,857	-129	-3%	2	1	-144	12
2009	4,746	3,811	-935	-20%	2	1	-951	13
2010	3,300	3,806	506	15%	2	-1	490	14
2011	4,391	3,950	-441	-10%	3	0	-459	15
2012	2,046	3,680	1,634	80%	6	0	1,610	17
2013	4,440	3,570	-871	-20%	10	3	-900	17
2014	5,219	3,691	-1,528	-29%	15	3	-1,562	16
2015	4,757	3,566	-1,191	-25%	20	5	-1,236	19
2016	4,249	3,621	-627	-15%	36	1	-686	21
2017	5,536	3,909	-1,627	-29%	53	-32	-1,668	20
2018	5,098	3,667	-1,431	-28%	54	-61	-1,451	28

6.10.6 Source specific planned improvements

Further development of the sparse transitions model is planned as described for *grassland remaining grassland* (section 6.8.6).

In terms of seagrass removal activity data, the capital dredging report (Kettle, 2017) has catalogued the capital dredging activity associated with port and related infrastructure projects for the current reporting period 1990 to 2016. Acquisition of data on new and on-going capital dredging activity from 2016 continues.

Modelling of methane emissions associated with the reservoirs and other constructed water ponds will undergo improvement in step with the developing scientific literature in this area. Improvements in spatial analysis of small water bodies at a national scale may also improve the confidence limits of future submissions.

A process of continuous improvement regarding regionally based seagrass removal parameter values to underpin the emissions model has been established to incorporate updated values acquired in regular surveys of the scientific literature.

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 implemented 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.

Any emissions arising from the release of methane from constructed water bodies are included in *wetland remaining wetland.*

6.11.2 Emission estimates

The annual area identified, and associated net emissions are in Table 6.66 below.

Table 6.66 Cumulative areas of forest land converted to wetlands (flooded land), and associated net annual emissions 1990–2019

Year	Cumulative National Area (kha)	Net Annual Emissions (Gg CO_2-e)
1990	26	708
1995	33	216
2000	36	26
2005	37	40
2006	38	73
2007	38	32
2008	39	37
2009	39	-5
2010	40	328
2011	43	709
2012	43	4
2013	43	26
2014	43	8
2015	43	2
2016	43	-10
2017	43	2
2018	43	8
2019	43	3

6.11.3 Uncertainties and time series consistency

Uncertainties for *land converted to wetland* at the national scale were estimated to be ±27.3 per cent 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 2018 are shown in Table 6.67 below.

The recalculations are due to improvements in remote sensing of forest cover change and in FullCAM agricultural parameters, as detailed for *forest converted to grassland*.

Table 6.67 Recalculation of total CO_2-e emissions, 1990–2018

Year	Forest land converted to flooded land 2019 submission (Gg CO_2-e)	2020 submission (Gg CO_2-e)	Change (Gg CO_2-e)	%
1990	697	708	11	1.6%
1995	216	216	0	0.1%
2000	27	26	-1	-5.4%
2005	37	40	3	8.2%
2006	72	73	1	1.6%
2007	27	32	5	19.1%
2008	33	37	4	12.8%
2009	-6	-5	1	10.2%
2010	316	328	12	3.9%
2011	689	709	19	2.8%
2012	9	4	-5	-52.2%
2013	22	26	4	17.4%
2014	10	8	-2	-21.1%
2015	0	2	2	323.5%
2016	-9	-10	-1	-11.9%
2017	-1	2	2	285.9%
2018	10	8	-3	25.1%

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 6.68.

Table 6.68 Area and net emissions of sparse woody vegetation, settlements remaining settlements

Year	Area gains kha	Area losses kha	Net emissions kt CO_2
1990	5.9	-11.4	-33.5
1995	3.8	-5.4	2.4
2000	4.2	-4.7	24.7
2005	7.1	-9.8	35.9
2006	8.3	-8.8	36.6
2007	8.1	-9.1	38.5
2008	7.8	-9.8	42.3
2009	11.0	-9.9	31.8
2010	11.0	-9.3	25.2
2011	17.6	-6.7	10.9
2012	20.3	-6.2	-7.0
2013	15.0	-9.3	-13.4
2014	16.4	-9.9	-19.1
2015	12.7	-9.5	-23.5
2016	14.3	-10.0	-30.1
2017	20.8	-7.8	-44.7
2018	26.0	-5.7	-65.1
2019	16.6	-5.1	-77.0

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 Appendix 6.A.4.

6.12.5 Recalculations

Recalculations for *settlements remaining settlements* for 1990 to 2018 are shown in Table 6.69. Like for *grassland remaining grassland* (section 6.8.5), activity data for grass and shrub transitions has been revised due to annual updates in image analysis.

Table 6.69 Settlements remaining settlements: recalculation of total CO_2-e emissions, 1990–2018

Year	Settlements remaining settlements			
	2019 submission	2020 submission	Change	
	(Gg CO_2 -e)	(Gg CO_2 -e)	(Gg CO_2 -e)	%
1990	-33.6	-33.5	0.2	0.5%
1995	2.2	2.4	0.1	6.3%
2000	24.7	24.7	-0.1	-0.3%
2005	36.2	35.9	-0.3	-0.7%
2006	36.9	36.6	-0.2	-0.6%
2007	38.8	38.5	-0.3	-0.8%
2008	42.8	42.3	-0.4	-1.1%
2009	32.2	31.8	-0.4	-1.2%
2010	25.4	25.2	-0.2	-0.8%
2011	11.2	10.9	-0.3	-2.6%
2012	-6.7	-7.0	-0.3	-4.9%
2013	-13.3	-13.4	-0.1	-0.7%
2014	-18.9	-19.1	-0.2	-1.0%
2015	-23.3	-23.5	-0.2	-0.9%
2016	-30.1	-30.1	0.0	0.1%
2017	-45.0	-44.7	0.3	0.7%
2018	-63.6	-65.1	-1.5	-2.4%

6.12.6 Source specific planned improvements

Further development of the sparse transitions model is planned as described for *grassland remaining grassland* (section 6.8.6).

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, 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 territories (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 bio-geomorphology 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 6.70 Cumulative area of land converted to settlements 1990–2019 (ha)

Year	Terrestrial forest converted to settlements	Mangrove forest converted to settlements	Wetlands converted to settlements	Total
1990	148,809	1,306	1,571	151,686
1995	216,124	1,796	2,198	220,118
2000	277,544	2,117	2,651	282,312
2005	344,728	2,471	3,126	350,325
2006	362,789	2,583	3,259	368,631
2007	376,146	2,669	3,377	382,192
2008	388,108	2,747	3,518	394,373
2009	396,733	2,798	3,634	403,165
2010	400,828	2,865	3,737	407,430
2011	401,210	2,922	3,817	407,949
2012	399,621	2,979	3,897	406,497
2013	399,736	3,051	3,997	406,784
2014	399,643	3,148	4,086	406,877
2015	396,452	3,190	4,133	403,775
2016	396,357	3,232	4,183	403,772
2017	394,394	3,257	4,215	401,866
2018	394,249	3,280	4,241	401,770
2019	389,946	3,292	4,256	397,494

6.13.2 Emission estimates

Identified land category transitions and associated annual emissions are in Table 6.71 below.

Table 6.71 Net emissions from land converted to settlements 1990–2019 (Gg CO_2-e)

	Land converted to settlements			
Year	Mangrove forest	Terrestrial forest	Wetlands (tidal marsh)	All
1990	216	4,672	89	4,978
1995	102	2,842	72	3,016
2000	102	2,825	72	2,999
2005	171	3,442	80	3,693
2006	191	3,390	98	3,679
2007	130	3,111	82	3,324
2008	108	3,043	91	3,241
2009	68	2,586	85	2,739
2010	103	2,478	75	2,656
2011	103	2,106	59	2,268
2012	95	1,895	67	2,057
2013	133	1,693	107	1,933
2014	156	1,582	72	1,810
2015	73	1,445	34	1,552
2016	71	1,328	34	1,433
2017	42	1,268	21	1,331
2018	49	1,098	17	1,165
2019	21	813	9	843

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 per cent 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 per cent to over 200 per cent. 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 settlements* are reported in Table 6.72 below.

These include:

A. Updated spatial observations on terrestrial forests – as detailed in section 6.9.5.1, recalculation of *forest land converted to grassland*.

B. Updated spatial observations on mangrove and tidal marsh converted to settlements areas.

C. Soil cover on grass species – as detailed in section 6.9.5.1, recalculation of *forest converted to grassland.*

D. Agricultural parameter updates – as detailed in section 6.9.5.1, recalculation of *forest converted to grassland.*

Table 6.72 Land converted to settlements: recalculation of total CO_2-e emissions, 1990–2018

Year	Land converted to settlements							
	2020 submission	2021 submission	Change		Reasons for change			
					A.	B.	C.	D.
	(Gg CO_2 -e)	(Gg CO_2 -e)	(Gg C02 -e)	%	Updated Spatial Observations		Soil Cover	Agricultural Parameters
					Terrestrial forests	Mangroves and Tidal Marshes		
1990	4,915	4,978	63	1%	32	-1	24	7
1995	2,956	3,016	60	2%	20	0	28	12
2000	2,930	2,999	69	2%	28	-2	25	18
2005	3,554	3,693	139	4%	72	7	49	11
2006	3,546	3,679	134	4%	64	7	57	6
2007	3,195	3,324	129	4%	61	0	48	20
2008	3,141	3,241	100	3%	62	3	29	7
2009	2,595	2,739	145	6%	111	-3	21	16
2010	2,173	2,656	483	22%	459	6	6	13
2011	2,190	2,268	78	4%	89	-3	-10	2
2012	2,013	2,057	44	2%	34	4	-8	14
2013	1,865	1,933	68	4%	32	14	5	17
2014	1,771	1,810	39	2%	30	-11	4	17
2015	1,490	1,552	62	4%	50	2	1	8
2016	1,384	1,433	49	4%	31	-8	5	22
2017	1,294	1,331	37	3%	34	-5	-2	10
2018	1,037	1,165	128	12%	89	27	-2	14

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 accommodate the 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 regions.
- 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 (ABARES, 2020a). 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” percentage 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 (2020a) 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 6.73) 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 6.73 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

Carbon Fractions	
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 m3)

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.

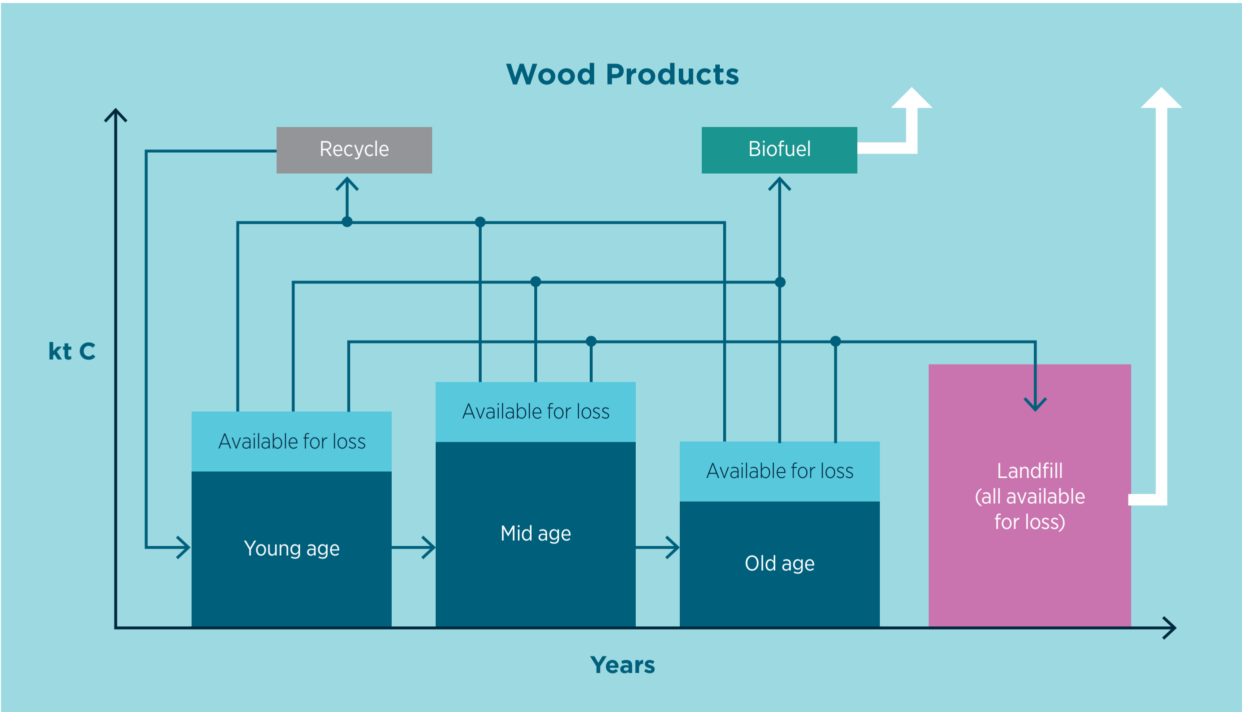
Life span of timber products (recycling and landfill)

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 6.45). The destination of material lost from service life is shown in Table 6.74.

Table 6.74 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	1,241	1,908	461	539
1995	1,264	2,336	531	333
2000	1,278	2,682	550	296
2005	1,294	2,897	544	434
2006	1,145	2,959	536	544
2007	1,056	2,981	546	708
2008	992	3,021	570	847
2009	940	2,997	438	926
2010	734	3,058	413	1,141
2011	763	3,022	392	1,139
2012	662	3,013	420	1,065
2013	623	2,965	311	1,196
2014	577	3,016	346	1,120
2015	584	3,071	355	1,054
2016	581	3,098	350	1,081
2017	555	3,171	350	1,212
2018	575	3,210	350	1,162
2019	549	3,335	350	1,052

Figure 6.45 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 6.75 and 7.5 (in Chapter 7).

Table 6.75 Decomposition rates and maximum possible loss

	YOUNG		MEDIUM		OLD	
Pool	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 6.76).

Table 6.76 Carbon stock and emissions outcomes (kt C)

Year	Domestic Production of Wood Products kt C	Imports of Wood Products kt C	Exports of Wood Products kt C	Increase Due to Wood Products kt C	Carbon Pool (excl. landfill) kt C
1990	2,905	854	786	2,972	64,063
1995	3,503	989	1,181	3,311	69,853
2000	4,401	1,063	1,770	3,694	75,531
2005	4,932	1,166	2,192	3,905	81,811
2006	4,883	1,115	2,169	3,829	83,049
2007	5,045	1,153	2,386	3,812	84,244
2008	5,128	1,222	2,374	3,976	85,538
2009	4,701	1,073	2,152	3,622	86,491
2010	4,608	1,143	2,167	3,583	87,547
2011	4,694	1,247	2,335	3,607	88,631
2012	4,414	1,177	2,153	3,438	89,622
2013	4,145	1,176	1,965	3,355	90,591
2014	4,605	1,175	2,485	3,295	91,567
2015	4,989	1,188	2,787	3,390	92,642
2016	5,404	1,144	3,104	3,444	93,749
2017	5,798	1,122	3,420	3,500	94,928
2018	5,917	1,189	3,559	3,547	96,167
2019	5,860	1,133	3,524	3,473	97,358

6.15.2 Emission estimates

Table 6.77 Net emissions from harvested wood products 1990–2019 (Gg CO_2-e)

Year	Emissions
1990	-7,417
1995	-7,550
2000	-7,753
2005	-7,645
2006	-6,758
2007	-6,269
2008	-6,409
2009	-4,990
2010	-4,628
2011	-4,885
2012	-4,207
2013	-4,027
2014	-3,934
2015	-4,341
2016	-4,476
2017	-4,710
2018	-5,061
2019	-4,815

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, 2020a). 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 2018 Inventory

Table 6.78 Recalculations of the HWP inventory

Year	2020 submission (Gg CO_2-e)	2021 submission (Gg CO_2-e)	Change (Gg CO_2-e)	Change (%)
1990	-7,417	-7,417	0	0.0%
1995	-7,550	-7,550	0	0.0%
2000	-7,753	-7,753	0	0.0%
2005	-7,645	-7,645	0	0.0%
2006	-6,758	-6,758	0	0.0%
2007	-6,269	-6,269	0	0.0%
2008	-6,409	-6,409	0	0.0%
2009	-4,990	-4,990	0	0.0%
2010	-4,628	-4,628	0	0.0%
2011	-4,885	-4,885	0	0.0%
2012	-4,207	-4,207	0	0.0%
2013	-4,027	-4,027	0	0.0%
2014	-3,934	-3,934	0	0.0%
2015	-4,341	-4,341	0	0.0%
2016	-4,477	-4,476	2	0.0%
2017	-4,715	-4,710	4	-0.1%
2018	-5,078	-5,061	17	-0.3%

Recalculations as shown in Table 6.78 are due to revisions in the Waste sector, which impact harvested wood products in solid waste disposal sites.

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.

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 for non-CO_2 gases from this voluntary reporting category. CO_2 emissions associated with the drainage of organic soils, where relevant, are reported in their respective land use change categories.

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 matter

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 (0.0021 (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:

$$E_{ij} = M_{ij} \times FracWET_{ij} \times Frac_{LEACH} \times EF \times C_g \quad \text{(4IV\_1)}$$

Where M_{ij} = mass of N mineralised due to a loss of soil carbon (Gg N)

$FracWET_{ij}$ = fraction of N available for leaching and runoff (Appendix 5.J.I)

FracLEACH = 0.24 (Gg N/Gg applied) IPCC (2019) default fraction of N lost through leaching and runoff

EF = 0.0075 (Gg N_2O-N/Gg N) IPCC (2006) default EF

C_3 = 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 has assembled a series of national coverages of Landsat satellite data (MSS, TM, ETM+ and OLI sensors) across 29 time epochs from 1972 to 2020 which are analysed to identify where and when land use change occurs.

The archive of time series of historic land cover and land 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 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 data processing stages have been streamlined since the development of the Australian Geoscience Data Cube in 2014 (now referred as Digital Earth Australia). Migration of legacy data processing methods to the Data Cube environment has been completed including use of machine learning algorithms for change detection. The process to produce the assessment of Australia-wide land cover change consists of:

- image compositing of 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;
- perform a single-epoch 3-class classification using the Random Forests classifier;
- conditional probability network (CPN) analysis (Kiiveri *et al.,* 2001), each year over the entire time series; and
- attribution[9] 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.

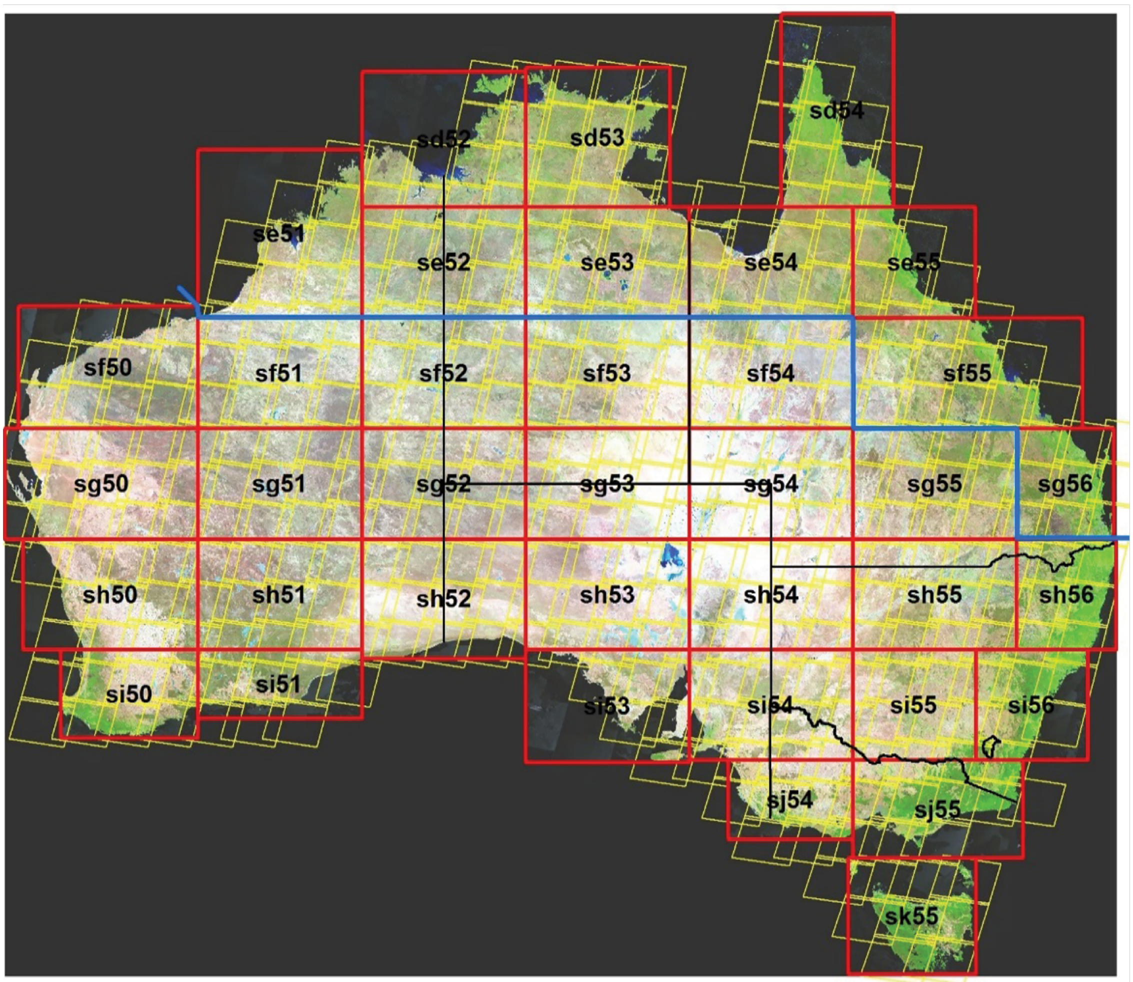
9 Attribution uses a combination of automation and visual inspection of the image sequence to determine the cause of land cover change and determine subsequent land use.

Image acquisition and selection

The time series of available Landsat images extends from 1972 to 2020. 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 2004 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 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. 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.

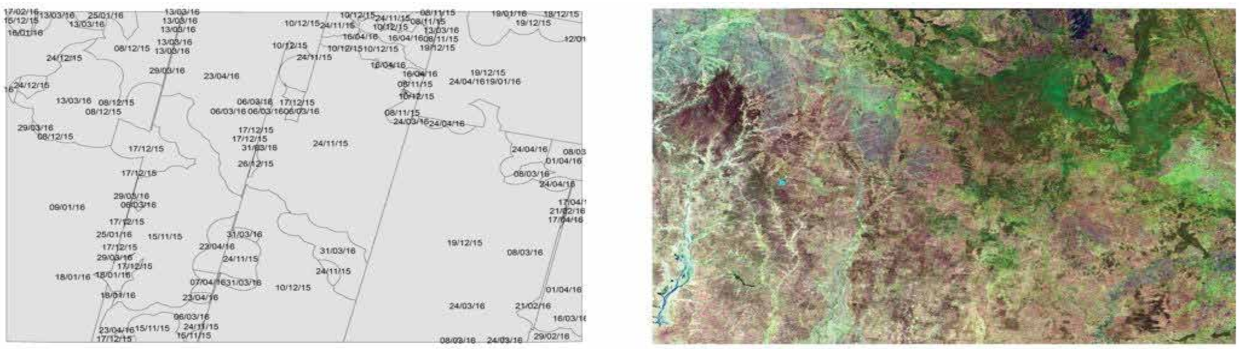
Table 6.A.1 Landsat Image sequence

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	1
1995, 1998	25	3
2000, 2002, 2004	25	2
2005–2020	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 x 79 m) is resampled to a 50 x 50 m pixel.

The 30 x 30 m native resolution of the Landsat TM, ETM+ and OLI data available after 1985 is produced as 25 x 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 25 m 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 resampling 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.

Resampling Landsat TM, ETM+ and OLI sensor data to 25 m pixels is 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 resampled 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.

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.

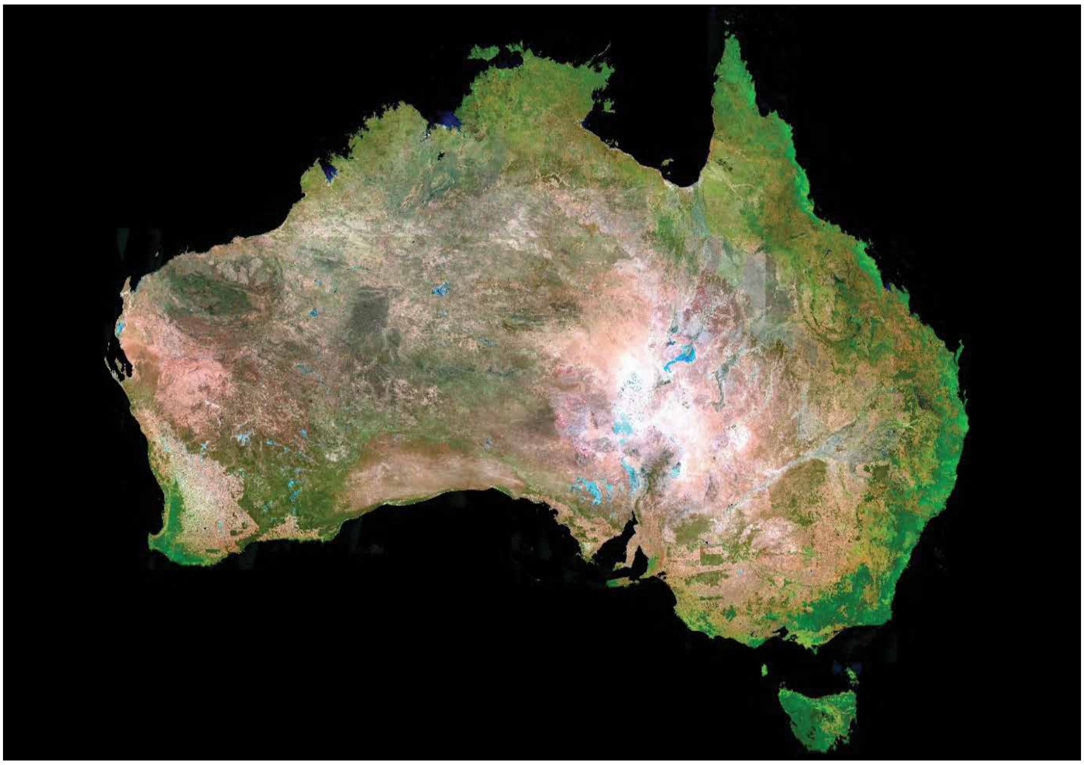
The second step was to assess the radiometric consistency between the ARG25 and LCCP products using 339 image pairs from the 2005 continental coverage. The two products were paired up based on Landsat path and row, and image acquisition date. Null pixels in either image were discarded. Pixels located 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 x 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. 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, from 2015 the 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 2020 Landsat 8 surface reflectance image of Australia

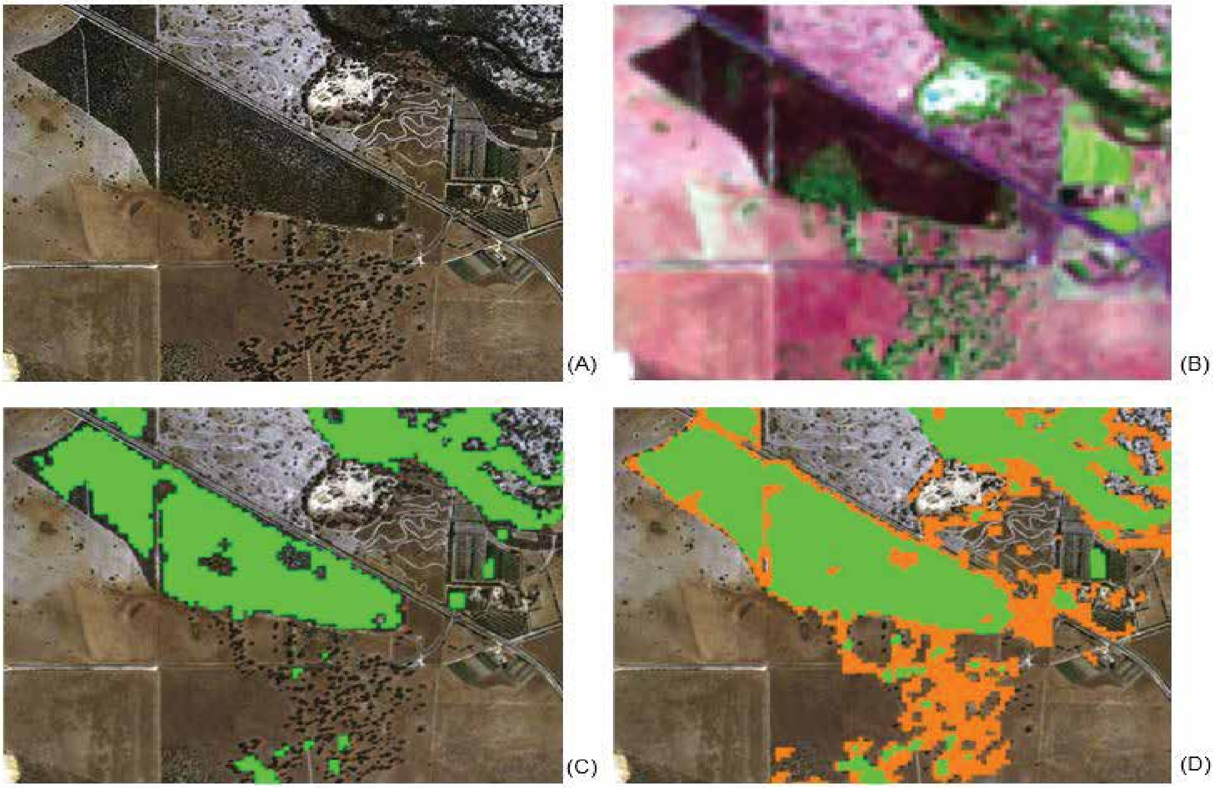


3-class Random Forests classifier

A new method of classifying woody vegetation has been adopted in the National Inventory update since 2019. The method has changed from a thresholding approach using simple decision boundaries, to a Random Forests (RF) classifier (Breiman, 2001). The RF classifier uses a sophisticated decision-tree approach, building a large number of trees from samples of training or reference data to create a class prediction. For a given pixel, the average prediction across all the trees is taken. It also allows class membership probabilities to be undertaken concurrently, requires minimal manual intervention and is readily extended to any number of classes of interest.

This method incorporates previous National Inventory innovations such as the move from a 2-class (forest, non-forest) classification to a 3-class classification (forest, sparse, non-woody). Figure 6.A.4 compares the previous 2-class product with the current 3-class outputs. Background image is from UrbanMonitorTM 2014 (Figure 6.A.4 (A)), and a Landsat false colour composite 2014 (B). Forest is highlighted green and Figure 6.A.4 (D) shows sparse vegetation (in orange) that was detected using the 3-class algorithm. 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 (Figure 6.A.5).

Figure 6.A.4 Comparison of traditional 2-class forest and non-forest product with the 3-class product



The Random Forests classification was performed on Landsat 8 imagery for the current epoch in a semi-automated manner, to investigate the parameter settings required to optimize the performance of the algorithm. The classifier was fitted independently to each of the stratification zones used in the previous method, which encompass local soil, vegetation and land use types. The relative importance of the individual input variables (ie spectral bands 1–6, spectral indices 7–8, texture bands 9–10, texture index 11) are tracked per stratification zone, and results can be used to modify the variables used in future updates.

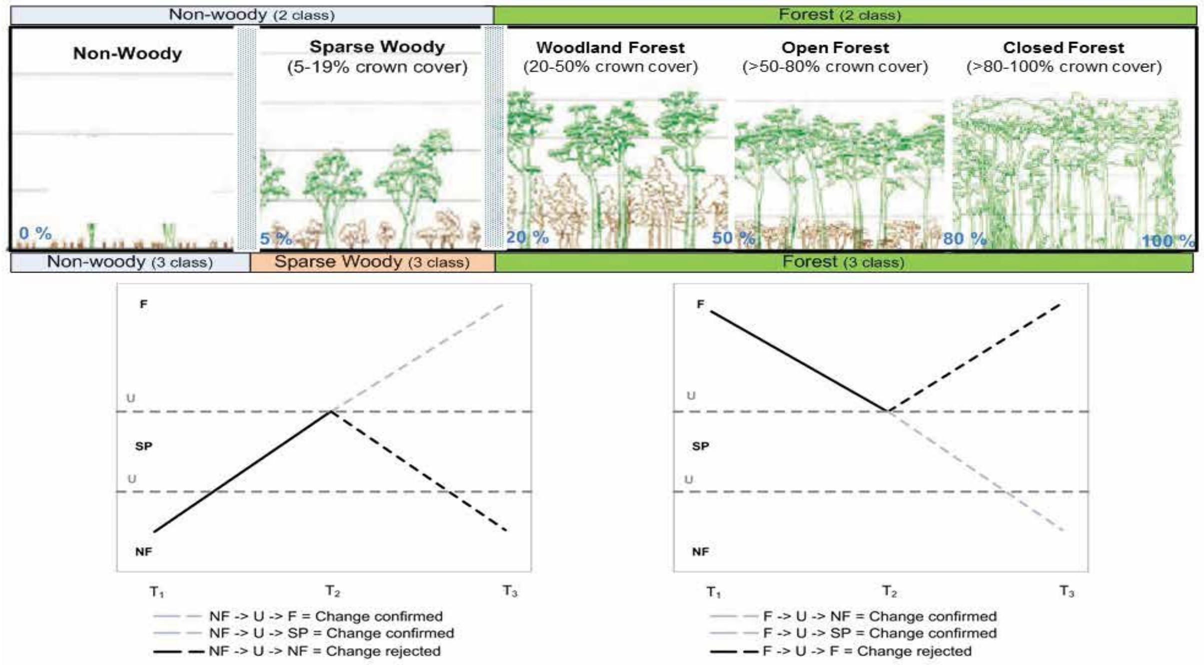
The Conditional Probability Network (CPN) outputs for 2018 were used as the training sample or "base" to train the RF classifier for the new update. Twenty percent of this data is extracted randomly and reserved to calculate an independent accuracy assessment. Early testing indicated that woody extent and change classifications were very sensitive to the choice of training samples, and the RF classifier produced much higher probabilities of class membership than the previous thresholding approach. This is most noticeable in the sparse class, which has historically experienced the greatest uncertainty. As a result, training samples were restricted to more pure examples of each class to enable the classifier to determine the boundary between them.

Early results also showed that the RF classifier could classify an area cleared in the latest epoch as having experienced a reduction in the probability of forest, but not necessarily reduce the probability enough to enable the CPN to correctly identify the change, given multiple years of high forest cover probabilities before the change event. To correct this problem for this update, a change mask was created by comparing the spectral index values between 2019 and 2020. Any pixels that fell under the change mask were excluded from the training sample.

Ultimately a combination of reduced error rates for sparse in 2019 and 2020, the use of a change masks and temporal rules restricting forest to sparse conversion leading up to 2020 were employed, resulting in products more consistent with earlier versions.

In future, the single-epoch classification will be refined to enable a multi-temporal classification to be performed across all epochs, to ensure consistency across the time series. Once all refinements have been made and automation is fully implemented, this should assist in moving towards the planned use of Sentinel 1 and 2 imagery.

Figure 6.A.5 3-class algorithm to detect entire range of woody vegetation.



Source: Adapted from *Australia's State of the Forests Report 2013*

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; 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.

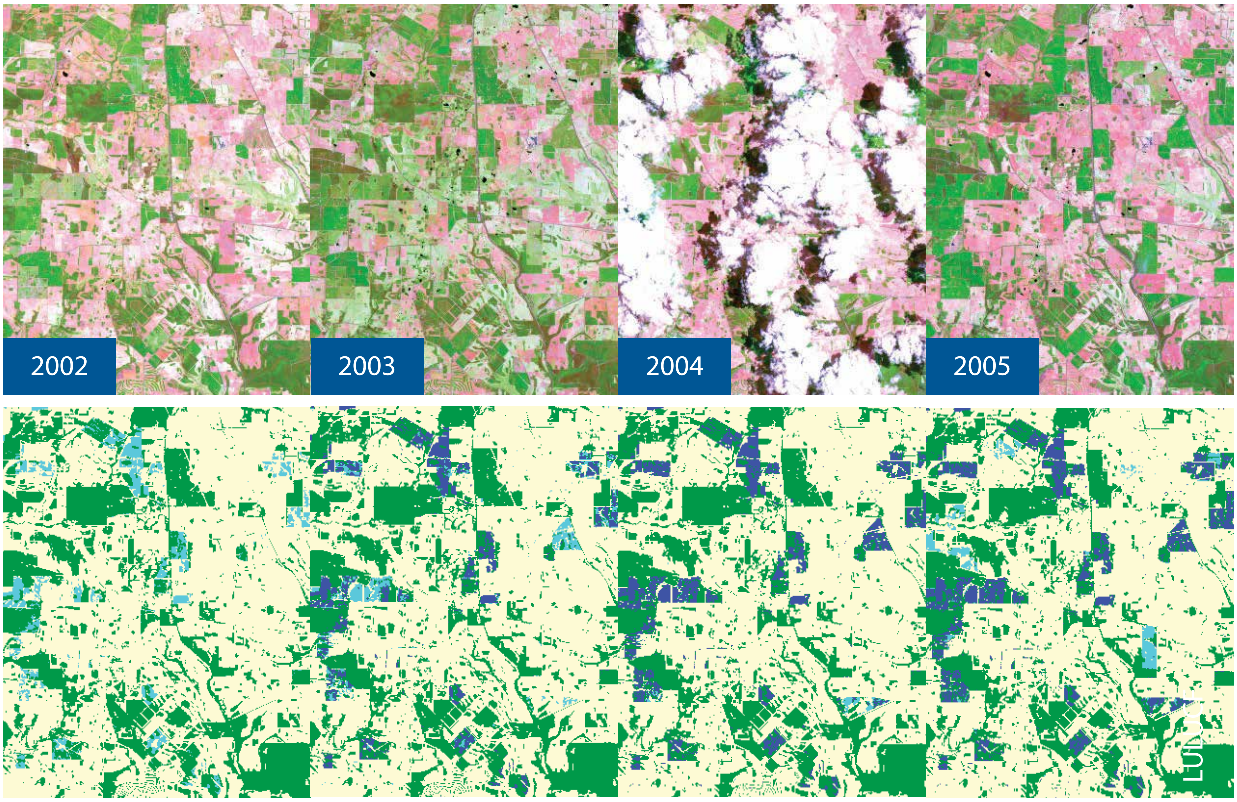
The spatial rules consider the labelling of a pixel in the context of its spatial surroundings, where labels that are consistent with the neighbouring labels are reinforced as opposed to those that are inconsistent (e.g., isolated pixels). This method evaluates the status of adjoining pixels as well 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 to provide 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 that could have 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



Green: forest 2000	Green: forest 2000	Green: forest 2000	Green: forest 2000
Blue: new forest 2000-02	Dark Blue: new 2000-02	Dark Blue: 2000-04	Dark Blue: 2000-05
	Light Blue: new 2002-04	Light Blue: 2004-05	Light Blue: 2005-06

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 minimises 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-woody to sparse
- non-woody to forest
- sparse to forest
- sparse to non-woody
- forest to non-woody, 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

A spatial analysis 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 identified 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. This 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 Sentinel Hub™ 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 series of 'masks' 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 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 from non-forest to forest follows the same general approach and same remote sensing data as described above. Plantation classes are identified by discrimination against regionally specific ground 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 Australia's land cover change methods are summarised below – see also Furby (2002, 2016). 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 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 since NIR 2016. Each data set is checked to ensure completeness and consistency of the composite images (Furby, 2016).

3-class Random Forests classifier

The Random Forests classifier is a relatively new process introduced in 2019. The classifier was run in a semi-automated manner as there are a number of variables that can be tuned to optimize the performance of the classification algorithm. In future, the aim is to fully automate the implementation of the classifier.

Semi-automation allowed QA/QC to be undertaken to investigate a number of elements:

- methods of training sample selection, i.e. using default automated settings versus using modified training samples to remove all omission and commission errors
- use of a more 'typical' base year from which to create training samples, for individual stratification zones
- the use of change masks to exclude areas with a change in spectral index values between 2019 and 2020 from the training sample
- setting of suitable probability thresholds of change within indices, per map sheet and stratification zone
- tracking of the relative importance of individual input variables to probabilities for individual map sheets and stratification zones; and
- monitoring of prediction accuracies per stratification zone.

Undertaking all these investigations led to a greater understanding of how the RF classifier performed, and the impact of certain parameters on the probability predictions. As the choice of training sample data was found to greatly influence the results, this remains a major focus of the QA process.

After extensive testing, it was determined that the threshold for inclusion in the training sample should be allowed to vary by class, dependent on the dominant vegetation cover of each map sheet.

CPN products for the current epoch were then compared to the cover class probabilities of previous epochs, to identify the impact from the change in classification methodology. This change has generally resulted in a shift in woody extent and change statistics which has implications for the emission calculations derived from this data. To compensate for the different nature of the 2019 and 2020 RF probabilities, experiments were performed to adjust the CPN parameters to compensate for the observed shifts and produce a result more consistent with previous updates.

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 and whether any further data review is required.

CPN products

When the CPN datasets are supplied to the Department's Geospatial team, they undergo a supplementary QA review process. The purpose of this review is to provide an independent check to ensure supplied products are fit for the purpose.

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 for each tile the CPN dataset's individual components for the time series contain pixel values that are within the acceptable range for that component.
- Check that for each tile the 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 requiring further investigation.
- A sample visual review is undertaken of the distribution of pixel 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, the CPN datasets are proceeded for spatial attribution prior to submitting to the FullCAM for emissions modelling.

Continuous Improvement and Verification Programme

Periodic review of the CPN products, to ensure human-induced vegetation change is not being omitted, is conducted separately to the NIR. This review is undertaken within a continuous improvement and verification programme (CIVP).

The CPN products identify woody vegetation cover and change, and undergo expert geospatial review using high resolution imagery and external datasets to isolate areas of human-induced change. This attribution of human-induced change is a vital part of each NIR. The ongoing verification programme provides an assessment of the CPN products prior to attribution, while attribution by expert operators ensures that errors of omission and commission related to human-induced clearing and regrowth are minimised in the inventory.

Figure 6.A.7 shows the history of the CIVP and the relevant details for each iteration. CIVP-3 was established as an extension of CIVP-2 in response to an ERT recommendation, to determine the commission and omission errors associated with using the CPN algorithm to assess land cover change.

Figure 6.A.7 The series of continuous improvement and verification programmes

Program: Year:	CIVP-1 2004	CIVP-2 2012	CIVP-3 2014	CIVP-4 2017
Coverage:	37 tiles	19 tiles	19 tiles	11 tiles
Number of points:	12,564	7,680	1,214	4,520
Time series:	1972-2000	2002-2010	2001-12	2011-2014
Products assessed:	Forest & non-forest	Forest & non-forest	Change product only	Forest, sparse & non-woody, change products
Resources used for verification:	Aerial photos, satellite imagery	High resolution satellite imagery	High resolution satellite imagery	Very high resolution satellite imagery

For CIVP-4 the new CPN 3-class woody vegetation product (forest, sparse and non-woody) was assessed across 11 tiles that contribute the most emissions to the national inventory, to determine the accuracy of the product and to identify areas for improvement. The method established during CIVP-2 was followed in CIVP-4, where 400 points were created across each tile using a stratified random sample. The vegetation classification at each point was cross-tabulated against the visual assessment of vegetation type undertaken by experienced operators using very high resolution satellite imagery (see table 6.A.2).

At points where the CPN identified change in vegetation cover between 2011–2014, an assessment of the likelihood of change during that period was also undertaken. As the CPN algorithm uses data from earlier and later years to determine vegetation change for each pixel, the time period for assessment of change in CIVP-4 was selected to ensure the change classification had stabilized using data from later years. In the latest assessment, the CPN land cover change product was verified using very high resolution satellite imagery acquired between 2009 and 2014. Imagery earlier than 2011 was consulted in case there was a lag between change being detected by the CPN in 2011 and change occurring prior to that year.

Of the 4520 points assessed across 11 tiles, 88 per cent had experienced no change (NC) across the time period. Based on the CPN classification, these points were identified as forest throughout (FT), sparse throughout (SPT), or non-woody throughout (NWT). The operator determined if these classifications were definitely correct, or probably correct, if imagery was not clear or not available at the right time. Probably non-woody throughout was not assessed as this category was considered to be difficult to distinguish from probably sparse. Table 6.A.2 shows the CPN product identified forest and non-woody areas consistently better than the identification of sparse vegetation. Commission errors indicate where the classification is deemed incorrect, while omission errors are where points should have been given the classification but weren't.

Table 6.A.2 CIVP-4 verification results for the 3-class woody vegetation product where no change was indicated

	CPN classification			
Verification	**Number of points**	**% correct**	**% Commission error**	**% Omission error**
Forest	1546	98	2	2
Sparse	685	66	24	13
Non-woody	1722	96	6	4

As sparse was a new class of woody vegetation and due to the difficulties detecting it remotely using medium resolution data, it was expected that the errors would be moderate. Despite these errors, the 3-class product has improved the prediction of woody and non-woody vegetation when compared to the previous forest and non-forest classes. Forest was predicted as correct for 96 per cent of the points in CIVP-2 compared to 98 per cent in CIVP-4, while non-forest was definitely correct 76 per cent of the time for CIVP-2 compared to 96 per cent for CIVP-4 (Lowell *et al.* 2012). Point data records from the verification programme could be used as extra sites to train the CPN algorithm and further improve the woody vegetation product.

The results for the points that had experienced change during 2011–2014 are shown in table 6.A.3, with the number of sample points for each classification cross-tabulated against the operators' assessment. Green cells indicate correct detection of change or no change (NC), red cells are erroneously detected change, lavender cells are undetected deforestation and blue cells are undetected regeneration. Of the points where the CPN had identified change (n = 550), 26 per cent were classified by the CPN as deforestation (DEF), 63 per cent were regeneration (REG) and 11 per cent indicated cyclic change (CYC). In this report DEF and REG refer to all cleared or regeneration pixels as indicated by imagery and associated processing. This is not to be confused with deforestation as used in the Kyoto Protocol that specifically refers to human-induced land conversion. A small number of points were uncertain (U) due to poor imagery available to confirm the classification. Pixels classified as CYC suggest errors in the classification given that rapid change, such as forest to non-woody and back to forest, is unlikely to occur over such a short time.

It is imperative that errors of omission related to human-induced change are minimised to give confidence that the inventory has captured all true clearing and regeneration within the given year.

Results of the operator assessment in table 6.A.3 take into account transitions such as forest to sparse and vice versa. For the purpose of this exercise such transitions were included as the verification programme was undertaken to assess the implications of introducing a new sparse category into the vegetation classification and its impact on the change product. Therefore the 71 DEF points shown in the table are inclusive of these transitions which do not reflect vegetation clearing.

The 27 DEF points and 11 REG points that were incorrectly classified by the CPN in table 6.A.3 were subject to further evaluation by additional operators. Initial investigation indicated that 73 per cent of these points had no evidence of clearing or regrowth, however they reflected the classification and operator uncertainty between the forest-sparse and sparse-non-woody decision boundaries

Combined errors of omission for DEF and REG were 0.4 per cent of the total 4520 points, while errors of commission were 7 per cent. These results are comparable to those of previous verification programmes (see table 6.A.4), with 0.3 per cent omission errors over 7680 points and 3 per cent commission errors. The higher commission errors in CIVP-4 are related to the addition of the sparse category into the woody vegetation product, as almost all points incorrectly identified as change had been classified by the CPN as sparse at some time in the change period. Errors may also be partly explained by the smaller sample size in CIVP-4.

The commission error of 7 per cent within the CPN change products identified by CIVP-4 justifies the continuation of the attribution process by geospatial experts to ensure that non-human induced change (i.e. false positive change) does not enter the inventory accounts.

Once the Random Forests classifier has been extended back through the time series, further verification of the 3-class CPN products produced using this new methodology will be undertaken.

Controls

Omission errors are addressed by using external clearing and revegetation data obtained from state agencies (such as Queensland Statewide Landcover and Trees Study data) and other anecdotal evidence to identify and monitor any areas where change may have been missed. In addition, the CPN algorithm revises the last few years of data each time it is processed, based on the latest probability information. Therefore, pixels with uncertain probabilities are reassessed so omitted change is detected in the following iteration of the process and included in the subsequent NIR submission.

Table 6.A.3 Outcomes of operator assessment of CPN classification for CIVP-4

CIVP-4		Operator assessment					
		NC	DEF	REG	CYC	Uncertain	TOTAL
CPN classification	NC	3953	10	6	0	1	3970
	DEF	94	44	3	0	0	141
	REG	209	14	121	1	4	349
	CYC	42	3	2	12	11	60
	TOTAL	4298	71	132	13	6	4520

Table 6.A.4 Outcomes of operator assessments in previous verification programmes

		Operator assessment					
		NC	DEF	REG	CYC	Uncertain	TOTAL
CPN classification	NC	7213	11	12	na	na	7236
	DEF	136	124	0	na	na	260
	REG	87	0	97	na	na	184
	CYC	na	na	na	na	na	na
	TOTAL	7436	135	109	na	na	7680

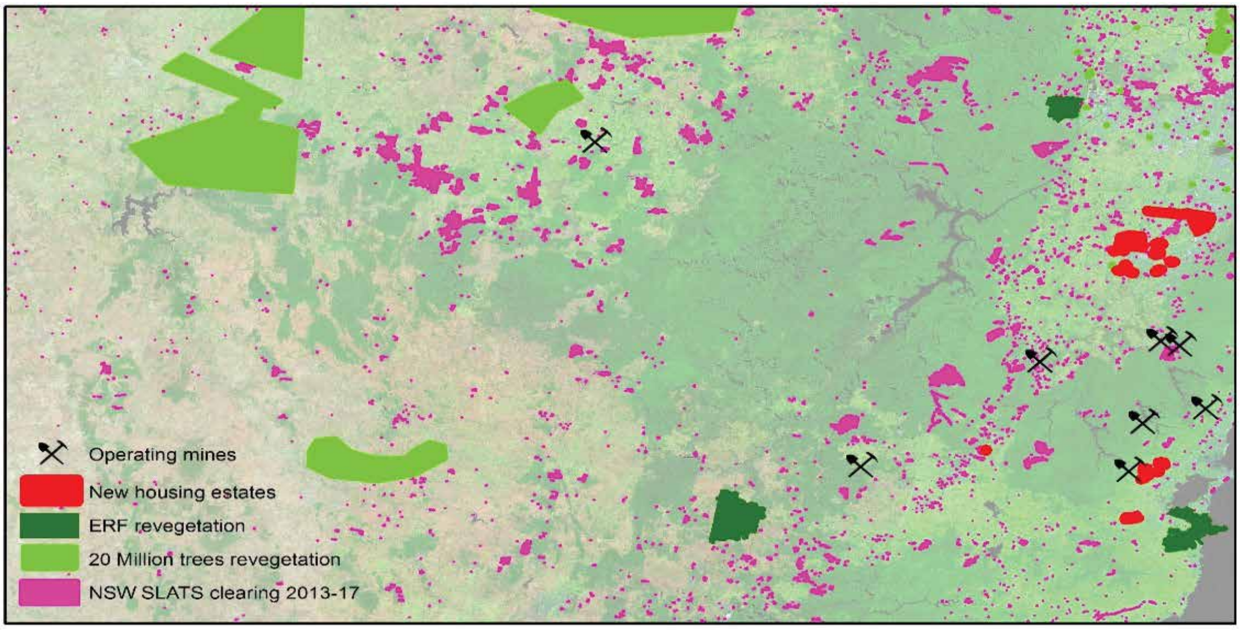
The results of the different verification programmes highlight the continued value of the attribution process, discussed below, which was essentially designed to remove false positive pixels and focus upon human-induced change only. Use of external datasets and rule based machine learning techniques currently being explored would also reduce the uncertainty in the activity data.

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. Departmental staff use high resolution imagery such as Landsat, Google Earth™ or Sentinel Hub™ 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 of commission and omission that were identified in the continuous improvement and verification programme discussed in the previous section.

An ongoing 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.8). The database is continually being updated and the information is used for attribution and QA/QC of satellite derived activity data. The Department has 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.8 Example of ancillary datasets in the Attribution Reference Database that are used to confirm human induced changes



Examples of the QA/QC undertaken using external datasets stored in the ARD are outlined below.

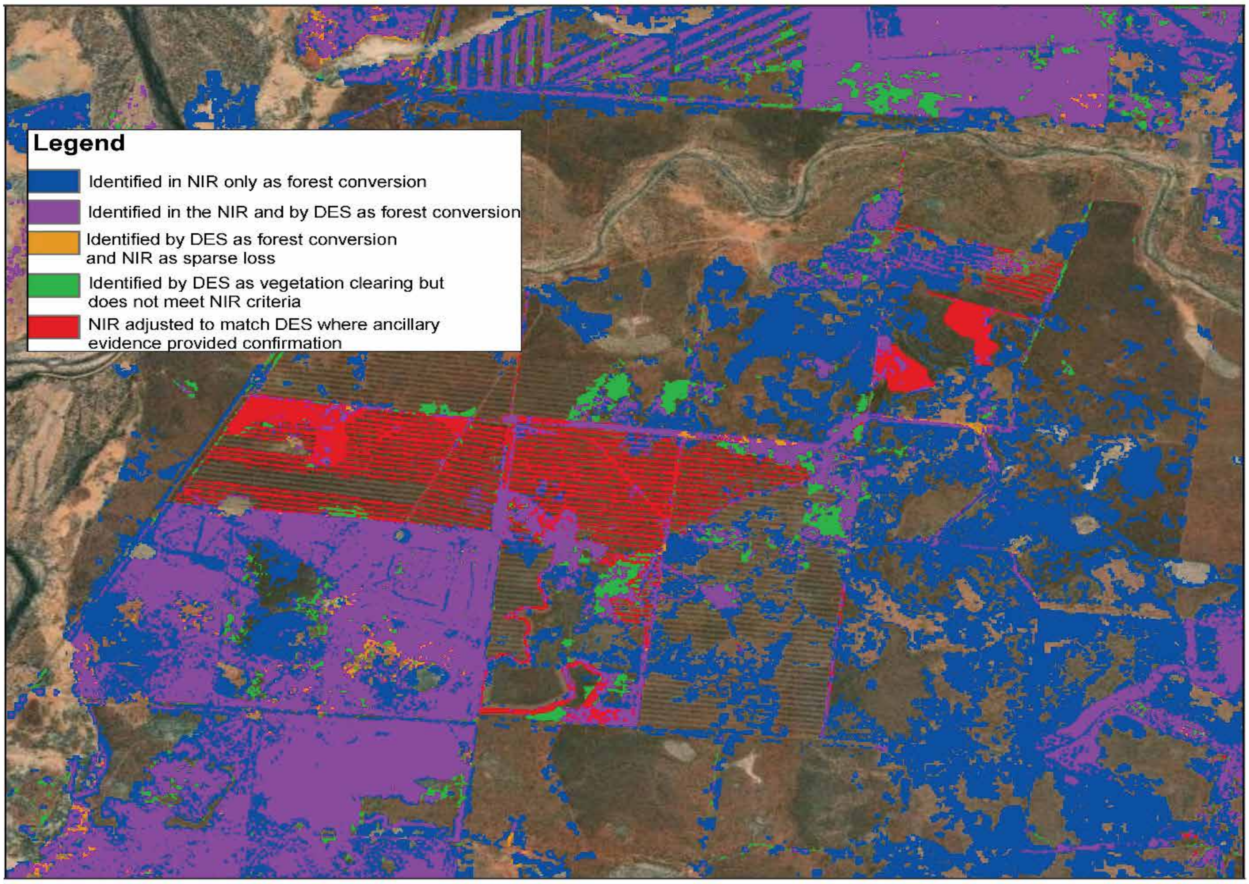
Pixel level comparisons were undertaken of woody vegetation loss between the national inventory data and the Queensland Government Department of Environment and Science (DES) vegetation monitoring system. An assessment was made of the level of agreement between the two datasets for the period 1988 to 2018 (see Figure 6.A.9). Using the improved 3-class change data, there is a high level of agreement (within 10 per cent) 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 DES clearing is post-1990. At a few places, clearing is detected only in the DES 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 of 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.

In the 2018 NIR, 2017–18 SLATS data was used to include additional clearing areas not detected by the national inventory system, where ancillary evidence provided confirmation of clearing.

Figure 6.A.9 Pixel level comparison of the clearing data of the two systems – national inventory and Queensland DES

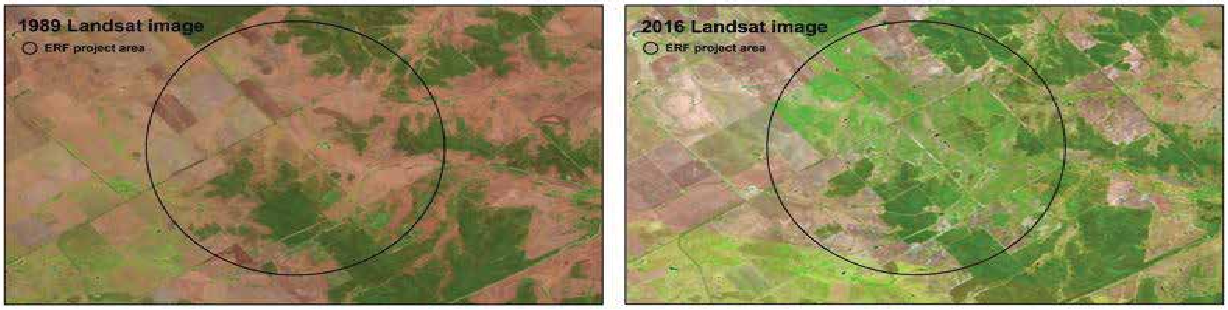


A similar process was also undertaken using vegetation monitoring data for NSW from 1988 to 2014. All areas identified by NSW Department of Planning, Industry and Environment (DPIE) as cleared in the past were checked to determine if they were already part of the national inventory. This analysis showed 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 DPIE.

Additional verification of land clearing is 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 per cent were already included in the national inventory while the remaining 25 per cent 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. Primary reference data such as these are continually updated and are used as part of the standard procedure in attribution and QA/QC.

Reforestation attribution also undergoes a series of QA/QC checks using data collected for the ARD. Figure 6.A.10 shows an area reforested under the Emissions Reduction Fund (ERF). Landsat imagery shows how the area had no forest cover in 1989, and a revegetation signal is visible in the 2016 image.

Figure 6.A.10 ERF data used to identify reforestation across the time series



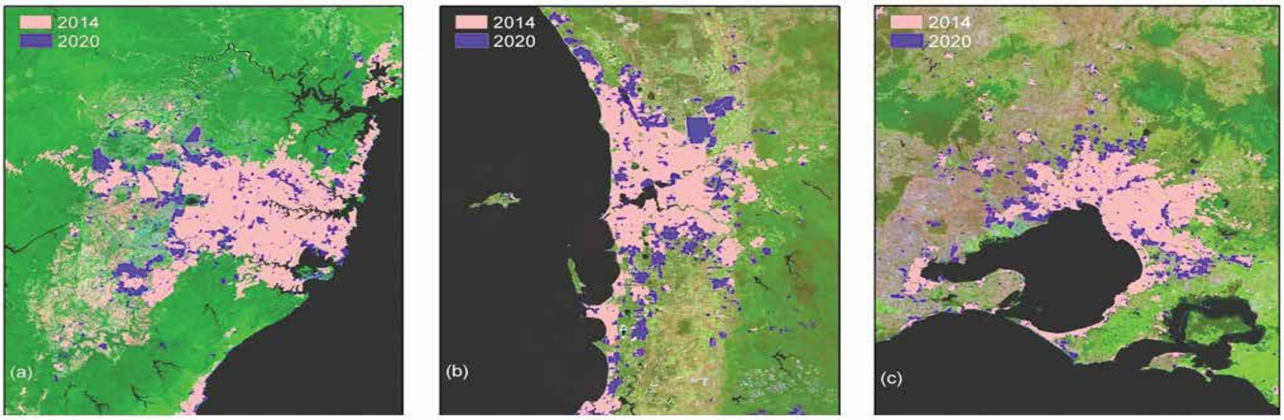
Updates to Settlements dataset

One of the land use categories required by the IPCC 2006 Guidelines is the location of human settlements, and the transitions that occur between settlements and other land use categories. For the National Inventory Report, settlements include areas of residential and industrial infrastructure, including cities, towns, and transport networks (within settlements).

An updated settlements layer was incorporated in the 2019 NIR to take account of the expansion in settlement areas that have occurred since the preceding update in 2014 (see figure 6.A.11). The dataset was derived from the 2017 ABARES catchment scale land use data, unpublished sources and visual assessment of high resolution imagery.

The updated settlement dataset was added as a base land use layer for FullCAM spatial simulations. In future submissions, this will allow modelling of emissions and reporting of land conversions such as grasslands or croplands converted to settlements, which is one of the ERT recommendations. Further work is planned to develop a time series of base land use data for all IPCC land use categories.

Figure 6.A.11 Settlement expansion around (a) Sydney, (b) Perth and (c) Melbourne, between 2014–2020.



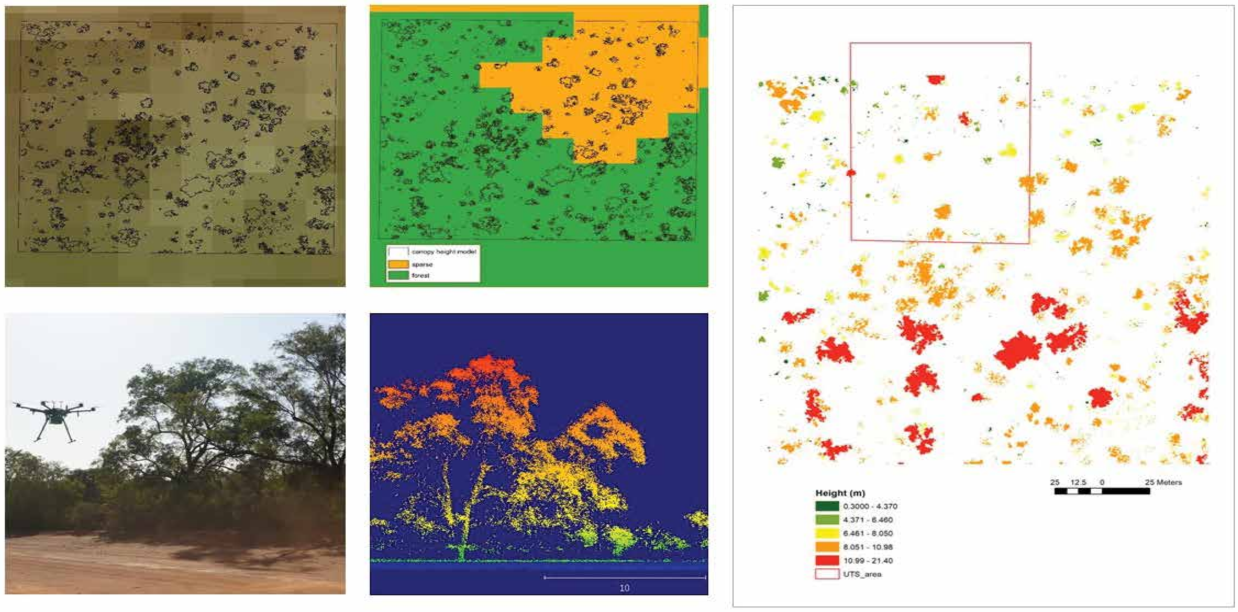
6.A.5 Refining the CPN algorithm

To address the errors of commission and omission related to the sparse classification identified in the CPN woody vegetation products (see continuous improvement and verification programme section in 6.A.4), it is necessary to refine the CPN algorithm.

Since the publication of the 2016 National Inventory Report, the Department has undertaken fieldwork to collect woody vegetation data using a LiDAR (light detection and ranging) drone and optical sensors over national parks in the Bourke region of NSW. The vegetation in this area is difficult to classify as the landscape is highly modified through clearing and grazing, vegetation responds to climatic cycles such as drought, and high resolution imagery is not always available. There are also numerous ERF projects in the area where human-induced revegetation is occurring and being monitored using the woody vegetation data.

Processing of data collected during the fieldwork is ongoing and will result in point-cloud images, canopy height models, vegetation structural data and site statistics. These will act as new regionally specific training data, used to refine the algorithm and during the training of the random forest classifier for the production of the full time series. Figure 6.A.12 gives examples of the outputs from the LiDAR analysis, showing the outline of the canopy height model overlaying (L-R) 25m Landsat 2018 imagery, 3-class woody vegetation classes 2018, LiDAR canopy height model classes, fieldwork photo of vegetation structure and a height profile of the LiDAR scan. This also illustrates the issues associated with classifying sparse woody vegetation from 25m Landsat imagery, where trees are clustered and the algorithm looks to nearest neighbours to confirm a classification. LiDAR canopy height model data will also be utilised as training data for other locations across the country, where available.

Figure 6.A.12 Examples of outputs from LiDAR drone analysis



6.A.6 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 per cent 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 per cent of the error, with only 4 per cent being incorrect for both location and type.

The planned transition to Sentinel 1 and 2 data may provide an opportunity to further improve the accuracy and outputs for plantation typing.

6.A.7 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.

Appendix

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[10], with the area of forest cover cleared since 1788 estimated to be around 100 million hectares. A study by Barson *et al.* (2000)[11] 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.

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)[12] and Henzell (2007)[13].

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.13).

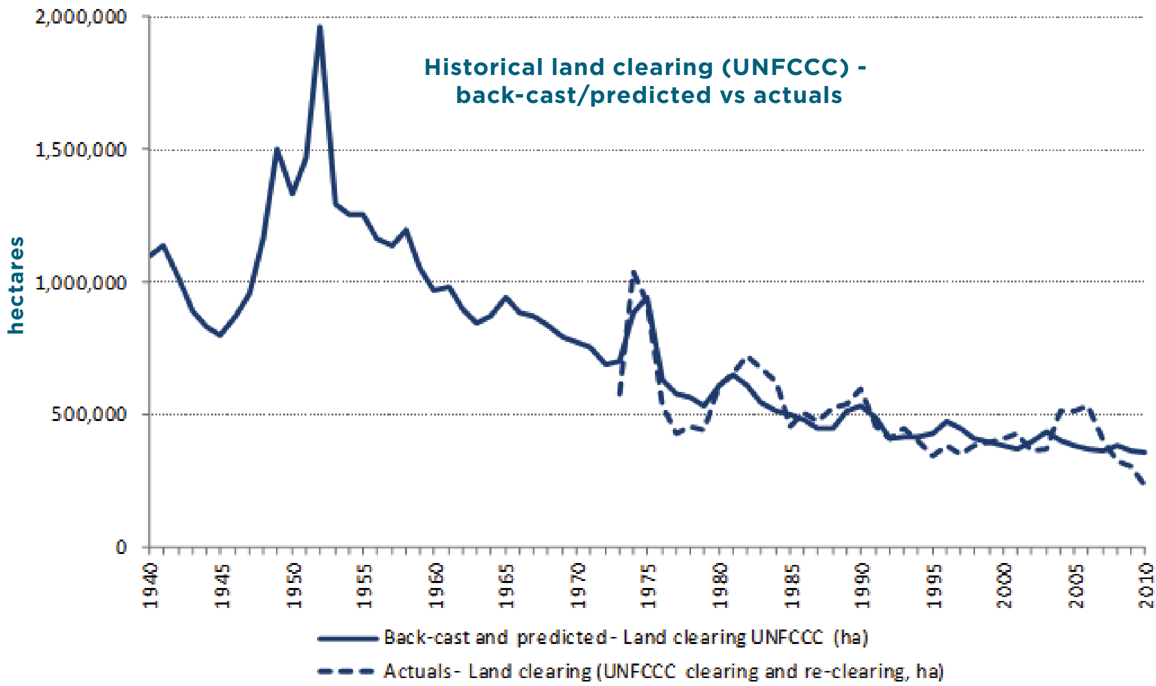
10 State of the Environment 2011 Committee. Australia state of the environment 2011. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. Canberra: DSEWPaC, 2011.

11 Barson, M., Randall, L. And Bordas, V. (2000) Land cover change in Australia, Bureau of Rural Sciences, Australian Government, Canberra.

12 Hamblin, A.P. (2001) *Land, Department of the Environment and Heritage, Canberra.*

13 Henzell, T. (2007) Australian agriculture: Its history and challenges, CSIRO publishing, Collingwood.

Figure 6.A.13 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.

Table 6.A.5 Estimated land clearing 1940–1972: comparison of extrapolation methods

	1940–1972 Extrapolation		1973–1990 Landsat imagery
Extrapolation method	Cumulative land clearing (ha)	Annual clearing (ha)	Annual clearing (ha)
Graetz *etal.* 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.

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 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.

- 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.

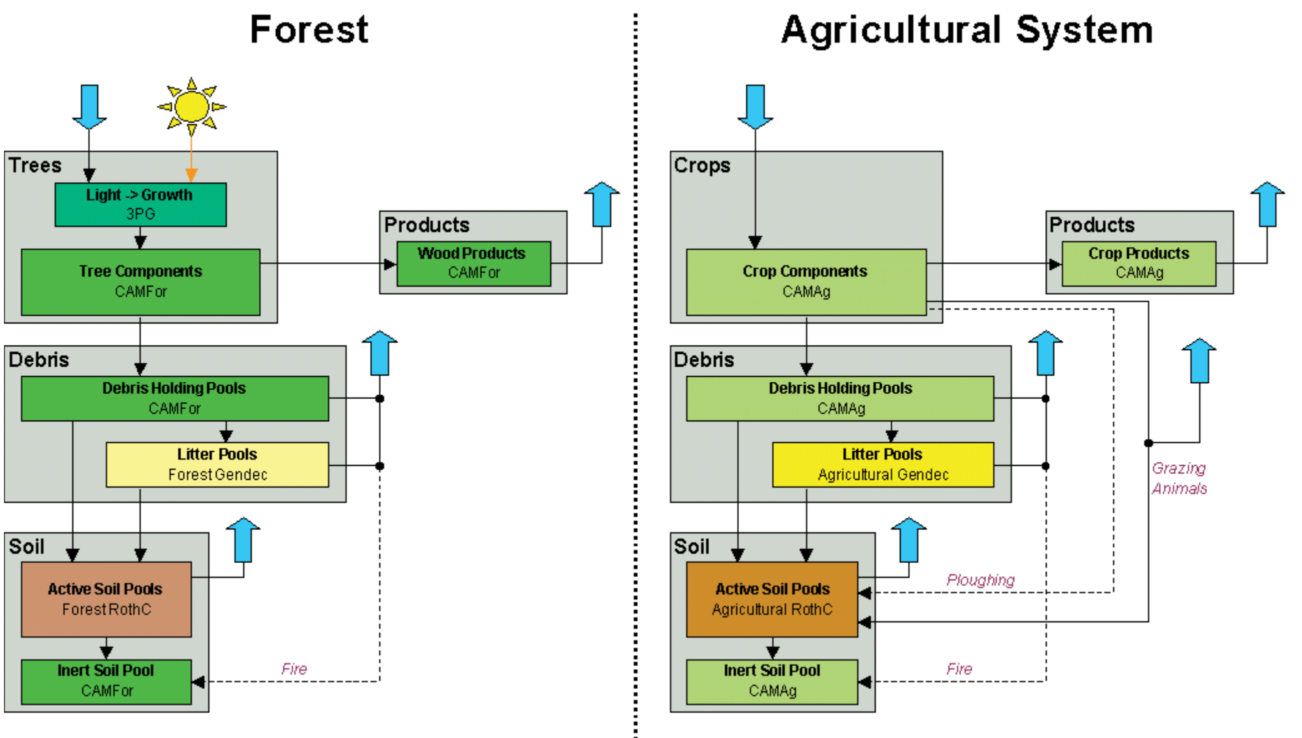
Appendix

6.B.1.1 FullCAM Sub-Models

FullCAM has been developed as an integrated compendium model that provides the linkage between various sub-models (Figure 6.B.1). 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. *CAMFor* is used to model carbon mass and transfers between the living tree, standing dead 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).
- 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 pool structure



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[14]. 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.

14 The change in pixel output is also strongly affected by climate variability and disturbance history on that pixel (fire, forest cover changes, harvesting). 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.

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 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 FullCAM help guide (http://www.fullcam.com/FullCAMServer2020/Help). 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. 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 2004; Brack *et al.* 2006; Waterworth *et al.* 2007; Roxburgh *et al.* 2019; Paul and Roxburgh 2020); and
- direct entry of biomass increment data.

Tree yield formula

The tree yield formula (TYF) is embedded within 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 spatial simulations of forests in FullCAM.

The tree yield formula is provided in Equation 6B_1:

$$\text{Aboveground Tree Mass at age } a = M\, e^{(-k/a)} \qquad \text{(6B\_1)}$$

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 $k = 2\, BI_a - 1.25$, 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*) for a stand can be estimated from the long-term average productivity (P) (see Appendix 6.C):

$$I_a = M\,(e^{(-k/a)} - e^{(-k/(a-1))}) \qquad \text{(6B\_2)}$$

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 (P_a) as a ratio with the long-term average productivity *(Pav):*

$$I_a = I_a\, P_a/P_{av} \qquad \text{(6B\_3)}$$

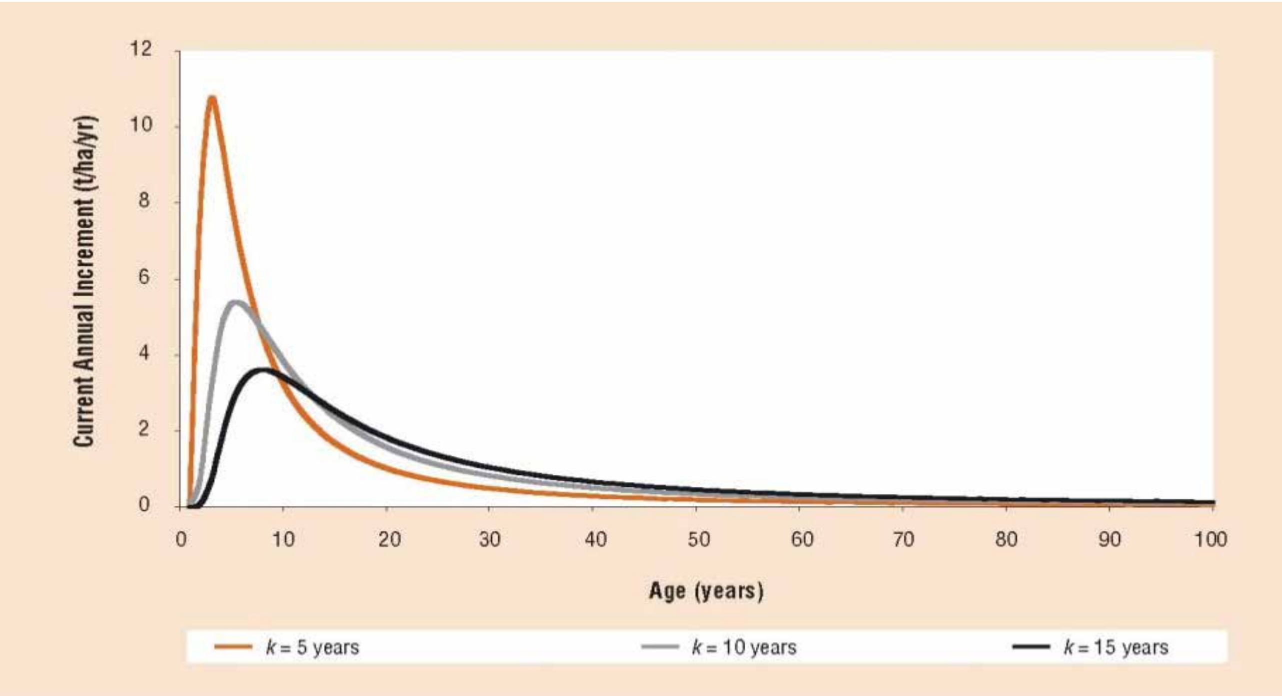
The average increment multiplier (P/P_{av}) in Eqn. 6B_3 needs to be close to 1.0 to enable the attainment of the long-term maximum above-ground biomass of the stand; M. Due to the formulation of FullCAM's TYF, M will not be achieved if the mean of the P's for the years across which the simulation is run is less than P_{av}. This was an issue for some regions of Australia when P_{av} was calculated using climatic data from the years 1925–2000. As outlined by Roxburgh and Paul (2019), recent improvements to FullCAM have included the more NIR-relevant P_{av} based on the climatic data from the years 1970–2015. This refinement in the definition of P_{av} contributed to a slight increase in yields of woody biomass in many regions of Australia.

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 BLa= 3.1, 5.6 and 8.1 years, respectively



Available national data and literature sources were analysed to estimate BI_a for commercial plantations (Roxburgh *et al.* 2019), environmental and mallee plantings of various configurations (Paul and Roxburgh 2020), and natural regeneration or re-growth of woodlands or forests occurring on land that is either set aside for conservation, or managed for grazing (Paul and Roxburgh 2020).

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 tree yield formula calculation of biomass increment within FullCAM.

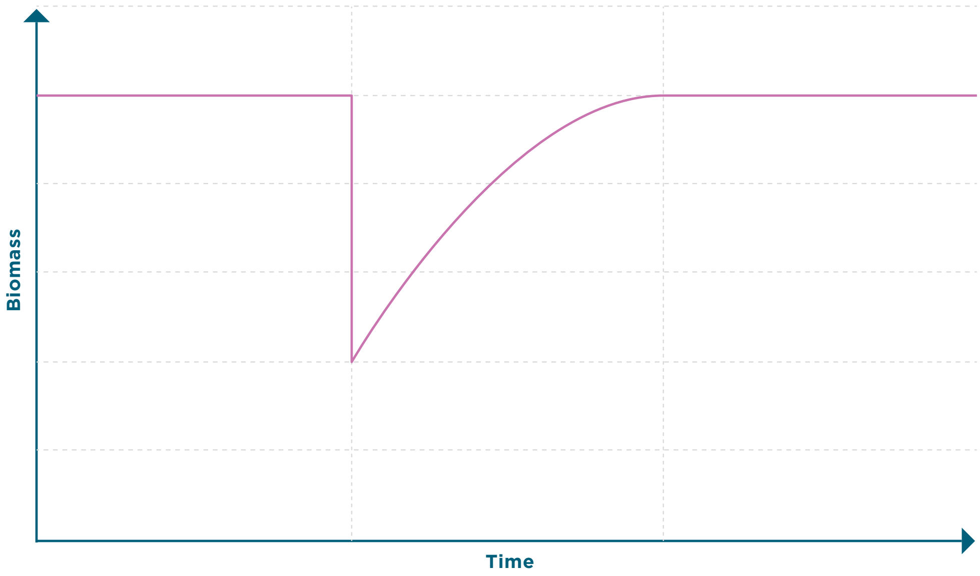
The direct entry of biomass increment data component of FullCAM is applied in the source category *forest land remaining forest land* in the estate-model for Harvested Native Forests in chapter 6.4.1.1.

Biomass recovery function

A thin response or recovery function has been developed account for disturbance events that affect live biomass (e.g. fire, thinning) but do not reset stand age. The biomass recovery function is based on the calculated amount of biomass lost from disturbances (fire, thinning). As the forest recovers from the disturbance, the lost biomass is added back as an addition to the TYF annual increment over a number of years. Hence, if the thin occurs in a young stand, the post-thin biomass increment will be the sum of the TYF increment at age t plus the Annual Recovery calculated by the recovery function.

Appendix

Figure 6.B.3 Fire recovery function



$$R_a = (t_r - t + 1) / (t_r \times (1 + t_r) / 2) \times (AGB_{pre\ disturbance} - AGB_{post\ disturbance}) \quad (6B\_4)$$

Where

R_a is the annual amount of biomass recovered

t is the time since disturbance in years

t_r is the total time to recover from the disturbance

$(t_r - t + 1)$ is the remaining years till fully recovered

The amount of biomass lost through fire or thinning is $(AGB_{pre\ disturbance} - AGB_{post\ disturbance})$

The total time to recover (t_r) depends on the proportion of biomass lost due to fire or thinning, so that the recovery is shorter where less than half the biomass is lost. The calculation of t_r is as follows:

$t_{r\ max}$ is the maximum time to recover, in years

proportion biomass lost = $1 - (AGB_{post\ disturbance} / AGB_{pre\ disturbance})$

where proportion biomass lost > 0.5 $\quad t_r = t_{r\ max}$

where proportion biomass lost <= 0.5 $\quad t_r = 2\ t_{r\ max}$ ^{x} proportion biomass lost

This thin response and recovery function is applied at the level of individual pools in FullCAM, reflecting the differential impacts of disturbances and recovery periods for leaves, branches, bark and stems.

6.B.2.2 Partitioning 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 (Equation 6B_1). In contrast, predicted belowground biomass (BGB) is determined by allocation to coarse roots (BGBC) and fine roots (BGBF) 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 BGBC to AGB, where BGBC is the biomass of coarse roots (>2 mm diameter). For all forest type, BGBF 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; woodland 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 sources, depending on the biomass component being measured, as described by Paul and Roxburgh (2017). 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).

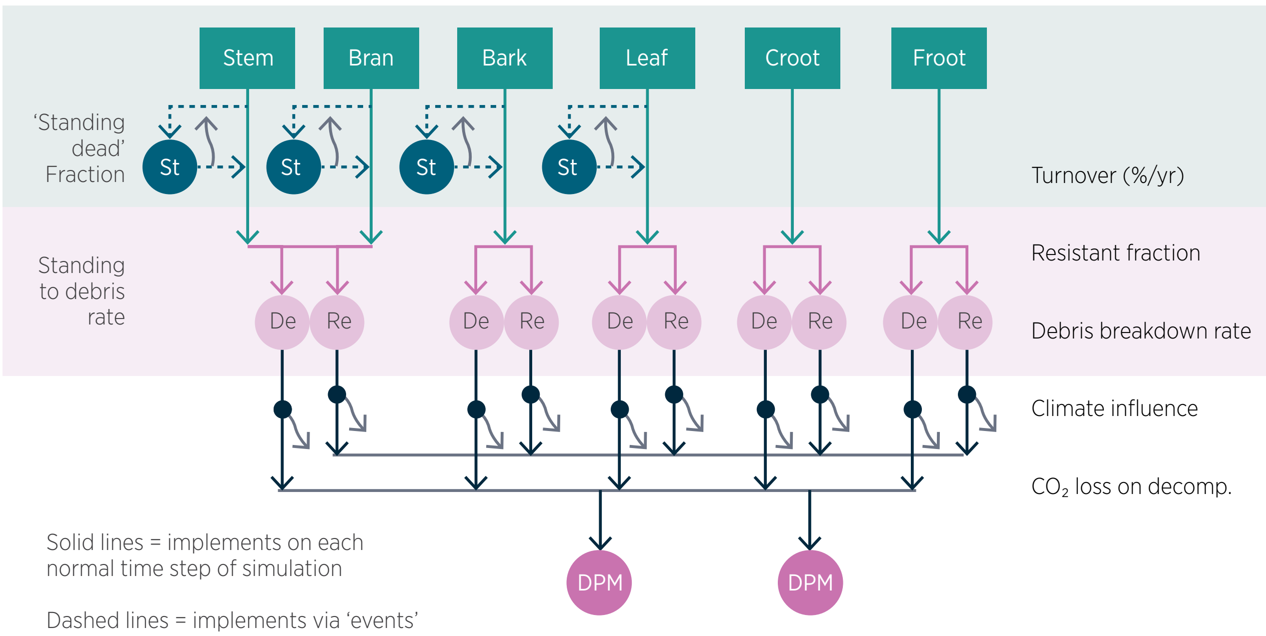
Table 6.B.1 Mean (± SD) observed and predicted biomass ratios for native forest

Ratio of biomass components	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	0.19–0.39

6.B.3 Estimating changes in forest standing dead

FullCAM allows for the modelling of standing dead pools following disturbance events such as wildfires, prescribed burns, management burns (e.g. slash burns and site preparation burns), clearing or commercial harvesting (Paul and Roxburgh 2019b). At each such event, a proportion of each pool of live biomass may be assumed to be disturbed to such an extent that it will slowly die. The rates of such senescence will be relatively slow when compared to the relatively fast rates of breakdown of pools of debris, which were calibrated to litter bag decomposition studies.

Figure 6.B.4 FullCAM structure with regard to standing dead (st) pools, and how these may be created from live biomass pools following disturbance events, and their slow transfer of carbon into the decomposable (De) and resistant (Re) pools of debris due to the slow process of standing dead senescence



Appendix

Based on data presented in Table 6.B.2 below, it was also assumed that rates of senescence were 0.83 per cent mo^{-1} for standing dead stem or branch wood, 1.25 per cent mo^{-1} for standing dead bark, and 1.67 per cent mo^{-1} for standing dead foliage. In contrast to live biomass pools above-ground, it is assumed that any coarse or fine roots below-ground affected by disturbances are converted to debris, not standing dead pools. There is a paucity of data on the fate of biomass decomposed from standing dead pools; namely the split between atmospheric emissions (CO_2-C loss) and material passed into the debris pools. Given standing dead pools generally have poor contact with soil and hence, decomposers, the assumption made was that the carbon use efficiency during senescence of standing dead pools was be relatively poor, with 90 per cent of the material being lost as CO_2-C and only 10 per cent being converted to debris carbon. This assumption was consistent with that applied by Paul and Roxburgh (2019a).

Table 6.B.2 Collation of decomposition constants (k) fitted to a single exponential decay model of observed in situ decay of coarse woody debris, from South-West, Western Australia

Species	Component (& diameter, cm)	In situ decomposition time (years)	k	Source
Eucalyptus diversicolor	Twigs (<0.5)	1.5	-0.120	O'Connell *et al.* (1987)
E. diversicolor	Stem (2.5)	2	-0.046	O'Connell *et al.* (1997)
E. diversicolor	Stem (4.3)	2	-0.030	O'Connell *et al.* (1997)
E. diversicolor	Stem (8.4)	2	-0.022	O'Connell *et al.* (1997)
E. diversicolor	Twigs (0.8)	2	-0.107	O'Connell *et al.* (1997)
E. diversicolor	Twigs (1.1)	2	-0.120	O'Connell *et al.* (1997)
E. diversicolor	Twigs (1.4)	2	-0.094	O'Connell *et al.* (1997)
Acaia urophylla	Stem (1.9)	2	-0.115	O'Connell *et al.* (1997)
Acaia urophylla	Stem (3.7)	2	-0.109	O'Connell *et al.* (1997)
Bossiaea laidlawiana	Stem (1.7)	2	-0.114	O'Connell *et al.* (1997)
Bossiaea laidlawiana	Stem (4.3)	2	-0.093	O'Connell *et al.* (1997)
Trymalium spathulatum	Stem (1.8)	2	-0.123	O'Connell *et al.* (1997)
Trymalium spathulatum	Stem (4.0)	2	-0.081	O'Connell *et al.* (1997)
E. diversicolor	Stem (10–15)	5	-0.174	Brown *et al.* (1996)
E. marginata	Branch (3–5)	5	-0.067	Brown *et al.* (1996)
Pinus pinaster	Branch (3–5)	5	-0.049	Brown *et al.* (1996)
Allocasurian fraseriana	Branch (3–5)	5	-0.072	Brown *et al.* (1996)
Banksia grandis	Branch (3–5)	5	-0.133	Brown *et al.* (1996)
E. calophylla	Branch (3–5)	5	-0.215	Brown *et al.* (1996)

6.B.4 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.4.1 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 per cent foliage, per cent twig and per cent 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 of 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.

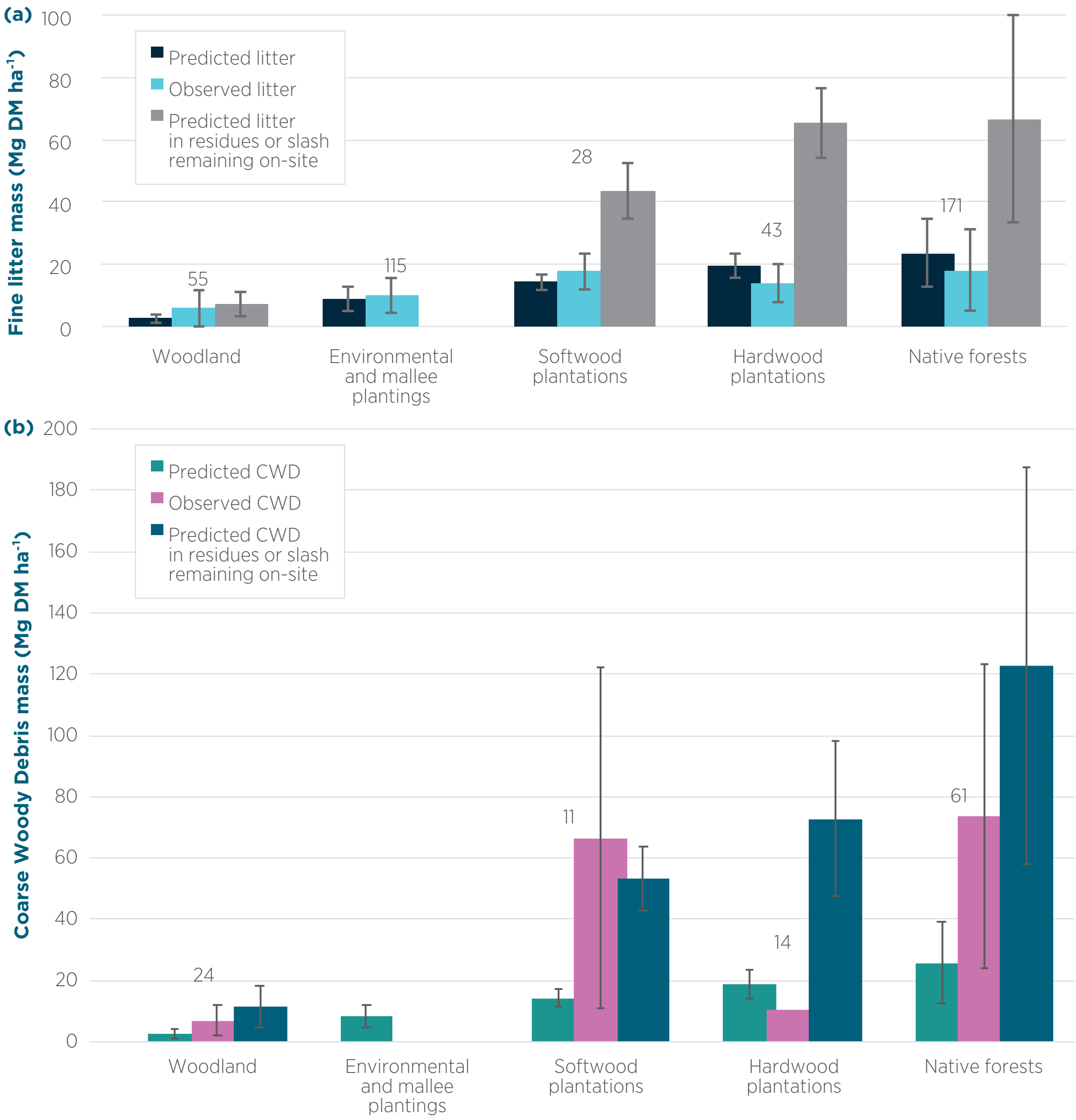
Simple double- or single-pool decay functions are commonly calibrated to datasets obtained from litterbag studies. On review of these, it was found that single-pool models were justified for deadwood and bark litter, while two-pool double models were justified for foliage litter. Hence for all forest types, FullCAM inputs of the fraction of debris that was resistant was set to 100 per cent 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 per cent) for softwood plantations than all other forest types (set at 77 per cent). 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 sensitivity 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.5 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).

Appendix

Figure 6.B.5 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 are 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 calculate 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).

6.B.5 Estimating changes in forest soils

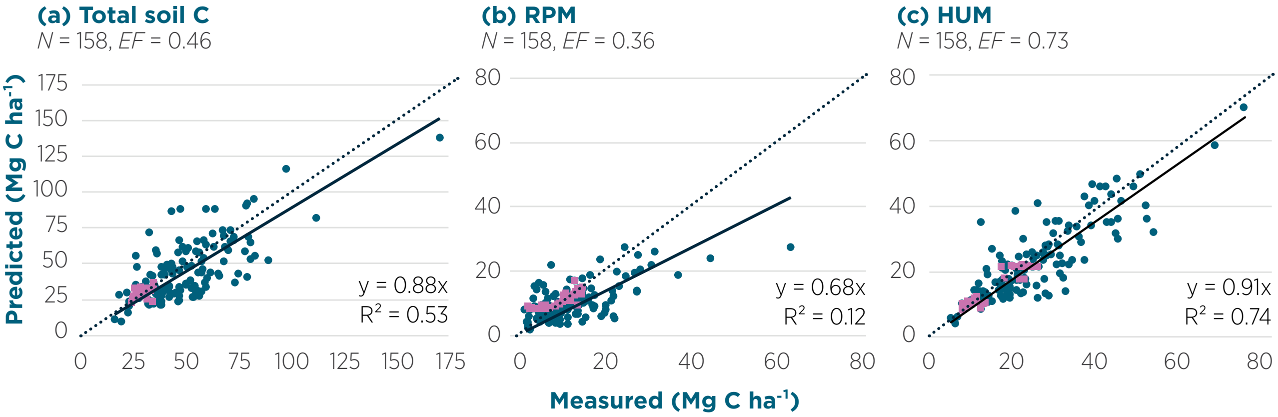
Soil can often be the largest storage of C in forests, and many pools of soil C significantly change in response to land use change, or changes in management. However, the modelling of stocks of soil C is complicated given: stocks are the balance of C inputs from debris decomposition, and outputs from turnover of soil pools, and; 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 FullCAM's RothC sub-model (e.g. RPM, HUM etc., Baldock *et al* 2013, Chappell and Baldock 2017), together with measurements of biomass and litter mass, has been useful to constrain the calibration of some of these parameters (e.g. Paul and Polglase 2004b; Paul *et al.* 2017b; Paul *et al.* 2018).

6.B.5.1 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 constraints, obtaining high efficiencies of calibration of pools of soil C was challenging. Nonetheless, efficiencies of prediction of total soil C pools was still 43 per cent (and 31 per cent for RPM and 69 per cent for HUM) (Figure 6.B.6).

Figure 6.B.6 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.6 are described by Paul and Polgase (2004a) and Paul *et al.* (2017b). Dark circles represent the paired-site environmental plantings. Pale squares represent the hardwood and softwood repeated-measured forestry trials.

6.B.6 Estimating changes in crop and pasture biomass and debris

6.B.6.1 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.3) at the Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (ABS 2010).

Table 6.B.3 Field crops accounting for >95 per cent (I), and additional crops for >99 per cent (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)*	I	I	I	I	I	I	I
Barley *(Hordeum vulgare)*	I	I	I	I	I	I	I
Narrow-leaf lupin *(Lupinus angustifolius)*	I	O	O		O	I	
Canola *(Brassica napus)*	I	I	I		I	I	
Oat (*Avena sativa*)	I	I	I	O	I	O	I
Sorghum (*Sorghum vulgare*)	I	I		I			
Sugarcane *(Saccarum officinarum)*	I	O		I			
Cotton (*Gossypium hirsutum*)	I	I		I			
Triticale *(Triticum durum xSecale cereale)*	I	I	I		I		I
Chickpea *(Cicer arietinum)*	O	O	O	I			
Field Pea *(Pisum sativum)*	O		I		I	O	
Faba bean *(Vicia faba)*	O	O	O		O		
Rice *(Oryza sativa)*	O	I					
Sunflower *(Heliantus annus)*	O	O		I			
Lentil *(Lens culinaris)*	O		I				
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)*							I

The available data has 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 allocations of dry matter to plant components were determined from estimates by expert field agronomists and includes allocations 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.4.

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.4 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	0.53	0.00	0.47
Annual grass	0.00	0.00	0.53	0.00	0.47
Annual legume	0.00	0.00	0.53	0.00	0.47
Annual legume irrigated	0.00	0.00	0.53	0.00	0.47
Aristida-Bothriochloa	0.00	0.00	0.53	0.00	0.47
Barley	0.30	0.00	0.47	0.00	0.23
Black speargrass	0.00	0.00	0.53	0.00	0.47
Blady grass	0.00	0.00	0.53	0.00	0.47
Blue lupin	0.00	0.00	0.53	0.00	0.47
Bluebush/Saltbush	0.00	0.00	0.53	0.00	0.47
Bluegrass-browntop	0.00	0.00	0.53	0.00	0.47
Canola	0.21	0.00	0.56	0.00	0.23
Chickpea	0.28	0.00	0.49	0.00	0.23
Cotton – irrigated	0.33	0.10	0.13	0.22	0.22
Cotton – rainfed	0.33	0.10	0.13	0.22	0.22
Faba bean	0.23	0.00	0.54	0.00	0.23
Field pea	0.28	0.00	0.49	0.00	0.23
Grass only – brigalow/ gidyea	0.00	0.00	0.53	0.00	0.47
Grazed cereal	0.00	0.00	0.53	0.00	0.47
Grazed cereal – irrigated	0.00	0.00	0.53	0.00	0.47
Grazed vetch	0.00	0.00	0.53	0.00	0.47
Lentil	0.26	0.00	0.51	0.00	0.23
Lucerne	0.00	0.00	0.53	0.00	0.47
Lucerne irrigated	0.00	0.00	0.53	0.00	0.47
Maize	0.38	0.31	0.08	0.00	0.23
Millet	0.20	0.00	0.57	0.00	0.23
Mitchell grass	0.00	0.00	0.53	0.00	0.47
Monsoonal annual	0.00	0.00	0.53	0.00	0.47
Monsoonal perennial	0.00	0.00	0.53	0.00	0.47
Mung bean	0.23	0.00	0.54	0.00	0.23
Narrow-leaf lupin	0.22	0.00	0.55	0.00	0.23
Native annual	0.00	0.00	0.53	0.00	0.47
Native annual improved	0.00	0.00	0.53	0.00	0.47
Oat	0.16	0.00	0.61	0.00	0.23
Oil poppies	0.385	0.00	0.385	0.00	0.23
Peanut	0.25	0.00	0.52	0.00	0.23
Perennial grass	0.00	0.00	0.53	0.00	0.47

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	0.53	0.00	0.47
Perennial grass/clover	0.00	0.00	0.53	0.00	0.47
Perennial legume	0.00	0.00	0.53	0.00	0.47
Queensland bluegrass	0.00	0.00	0.53	0.00	0.47
Rice	0.31	0.00	0.46	0.00	0.23
Samphire	0.00	0.00	0.53	0.00	0.47
Sorghum	0.352	0.00	0.418	0.00	0.23
Soybean	0.23	0.00	0.54	0.00	0.23
Spinifex	0.00	0.00	0.53	0.00	0.47
Sugarcane	0.00	0.64	0.13	0.00	0.23
Sunflower	0.31	0.31	0.15	0.00	0.23
Triticale	0.26	0.00	0.51	0.00	0.23
Tropical grass	0.00	0.00	0.53	0.00	0.47
Vetch	0.30	0.00	0.47	0.00	0.23
Wheat	0.275	0.00	0.495	0.00	0.23

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 are sourced from Roth-C (https://www.rothamsted.ac.uk/rothamsted-carbon-model-rothc). These values are a ratio of 1.44 for DPM/RPM for agricultural crops and improved grassland, and a ratio of 0.67 for unimproved grassland.

6.B.6.2 Debris

The amount of plant residue generated and available onsite 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 parameters describe how much of the crop mass becomes litter residue, the rate of residue decomposition, and how much of the decomposed residue is incorporated into the soil carbon pools.

Initial crop litter mass and decomposition rates and carbon use efficiency

The initial mass of litter assigned, decomposition rates and carbon use efficiency for each decomposable and resistant plant pool are shown in Table 6.B.5.

Table 6.B.5 Initial litter mass and decomposition rates and carbon use efficiency for crop systems

Plant Component	Initial Mass t ha^{-1}	Decomposition Rate yr^{-1}	Carbon Use Efficiency
Grains, Buds, Fruit (Resistant)	0.01	0.1	60%
Grains, Buds, Fruit (Decomposable)	0	0.3	60%
Stalks (Resistant)	0.01	0.1	60%
Stalks (Decomposable)	0.01	0.3	60%
Leaves (Resistant)	0.01	0.1	60%
Leaves (Decomposable)	0.01	0.3	60%
Coarse Roots (Resistant)	0.01	1	60%
Coarse Roots (Decomposable)	0.01	1	60%
Fine Roots (Resistant)	0.01	1	60%
Fine Roots (Decomposable)	0.01	1	60%

Crop turnover rates

Turnover represents the natural shedding of material by the plant. Turnover moves directly to the debris pool. All parts of a plant are subject to turnover, including roots. Root sloughing in response to grazing is included in the model which maintains the relative ratio of aboveground to belowground plant mass when grazed. Table 6.B.6 shows the monthly turnover rates applied to crop and pasture systems.

Table 6.B.6 Turnover rates applied to crop and pasture systems

	Turnover Rates month^{-1}	
Plant Component	**Pasture species**	**Annual crop species**
Grains, Buds, Fruit	0	0
Stalks	0	0.008
Leaves	0.07	0.07
Coarse Roots	0	0.008
Fine Roots	0.125	0.125

6.B.7 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.

The 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 utilises clay content and the initial topsoil moisture deficit as inputs to carry out soil carbon simulations.

Resistant fractions revision

Within FullCAM, resistant fractions are set for above and below ground components of crops and grasses and correspond to DPM/RPM ratios within RothC. Previously, resistant fractions for crops and grasses were set uniformly to 0.41. Minor changes have been made this year to cotton and unimproved pastures. The previous resistant fraction for cotton 0.41 did not account for its woody nature and has been revised to 0.8 because it behaves more like woody plants and trees. Unimproved pasture species had their resistant fractions revised to 0.6 in line with the original RothC recommendations, since these grass species decompose more slowly than improved grass species. The changes are summarised in the table below.

Table 6.B.7 Resistant Fractions applied to agricultural regimes

Species	Account	20_18 NIR resistant fraction*	Revised resistant fraction*
Cotton - irrigated	CrC	0.41	0.8
Cotton - rainfed	CrC	0.41	0.8
Annual & perennial (incl. Mulga)	GrG	0.41	0.6
Annual grass	GrG	0.41	0.6
Aristida-Bothriochloa	GrG	0.41	0.6
Black speargrass	GrG	0.41	0.6
Blady grass	GrG	0.41	0.6
Bluebush/Saltbush	GrG	0.41	0.6
Bluegrass-browntop	GrG	0.41	0.6
Grass only - brigalow/gidyea	GrG	0.41	0.6
Lucerne	GrG	0.41	0.6
Mitchell grass	GrG	0.41	0.6
Monsoonal annual	GrG	0.41	0.6
Monsoonal perennial	GrG	0.41	0.6
Native annual	GrG	0.41	0.6
Native perennial	GrG	0.41	0.6
Perennial grass	GrG	0.41	0.6
Perennial grass/clover	GrG	0.41	0.6
Queensland bluegrass	GrG	0.41	0.6
Samphire	GrG	0.41	0.6
Spinifex	GrG	0.41	0.6
Tropical grass	GrG	0.41	0.6

*applied to FullCAM parameters rFracGbfrA, rFracStlkA, rFracLeafA, rFracCortA, rFracFirtA

Soil Cover Factor revision

The soil cover factor (*c*) applies a modifier to the decomposition rate in RothC depending on whether the soil is covered (*c* = 0.6) or bare (*c*= 1) in agricultural systems. Changes were made to several regimes to more precisely define the behaviour of the soil cover factor. Specifically, the bare soil cover factor value now applies at plot initialisation (where no plant exists) and where 100% of the plot is affected by harvest (where stubble removed), herbicide, and fallow. Since fire events affect less than 100% of the plot, their soil cover value now changes to the covered value. The planting events for tree species associated with *cropland converted to forest land* have also been updated to ensure that cover is correctly applied. The changes are summarised in the table below:

Table 6.B.8 Cover factor changes applied to agricultural soils

Event	NIR20-18	Revised value
Plot initialisation default	0.6	1.0
Herbicide	0.6	1.0
Harvest (clearing+stubble removed)	0.6	1.0
Fallow	0.6	1.0
Fire	1.0	0.6
Plant trees	previous factor	0.6

Pasture Lands of Northern Australia

In FullCAM pasture species are randomly allocated based on species frequency and management data frequency tables generalised at the SA2 level. This can lead to pasture species being selected for regions unsuitable for their growth and impact carbon flows. To overcome this the pasture lands of northern Australia (PLNA) map was implemented in FullCAM to enable precise selection of species at specific plots in spatial simulations. 606 SA2s were identified that had 100% coverage by the PLNA map. For these SA2s, the activity table in FullCAM was updated with a related code to enable species selection and event queue building.

6.B.7.1 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 per cent (Janik *et al.* 2002), whereas the coefficient of variation for measured soil carbon is 15–40 per cent (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 (2017) 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.9.

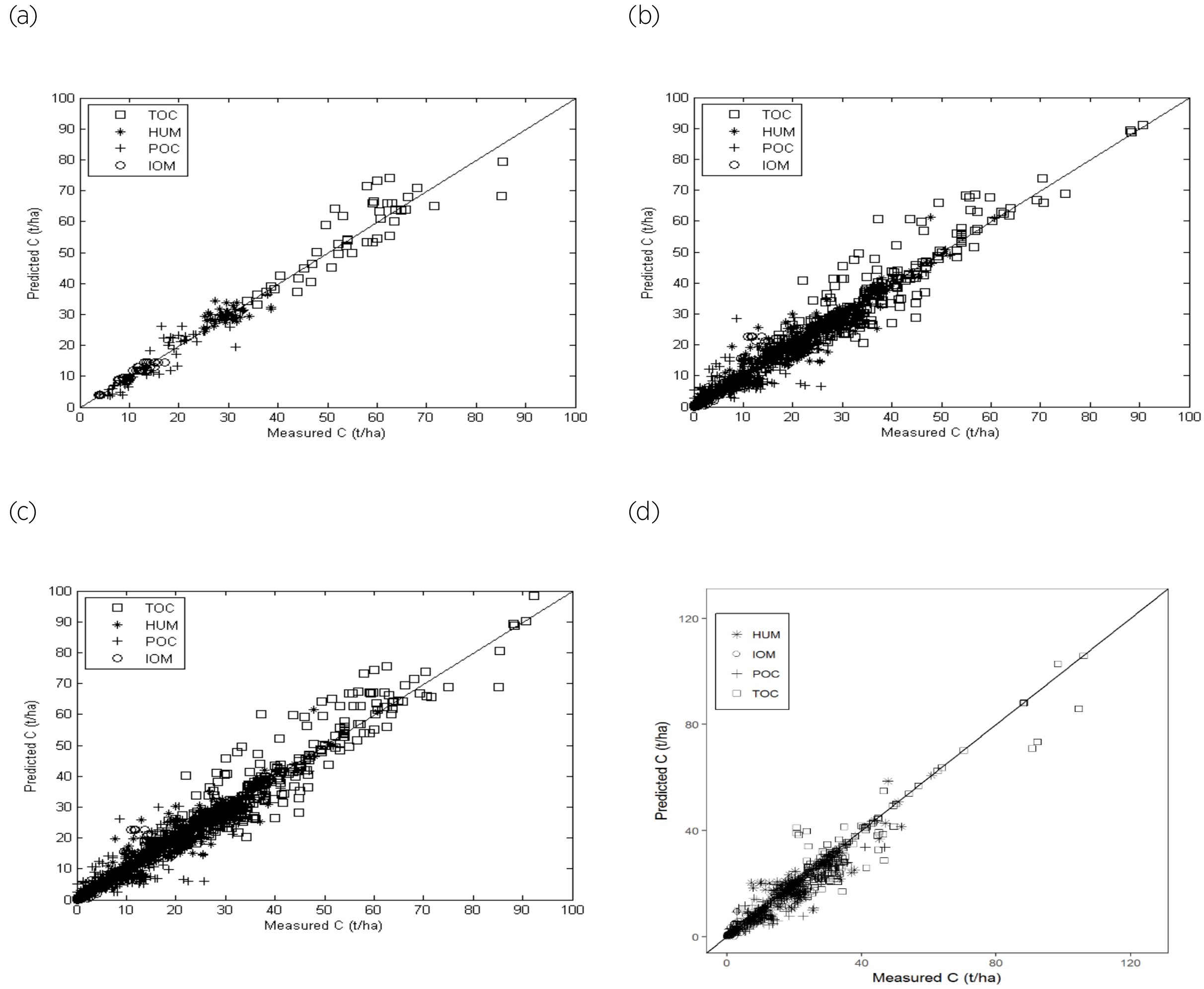
Table 6.B.9 Roth-C model including soil redistribution globally fitted decomposition rates and their goodness of fit

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 (2017)

Figure 6.B.7a (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.7 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 verification sites combined (c) and verification of selected sites using FullCAM (d)

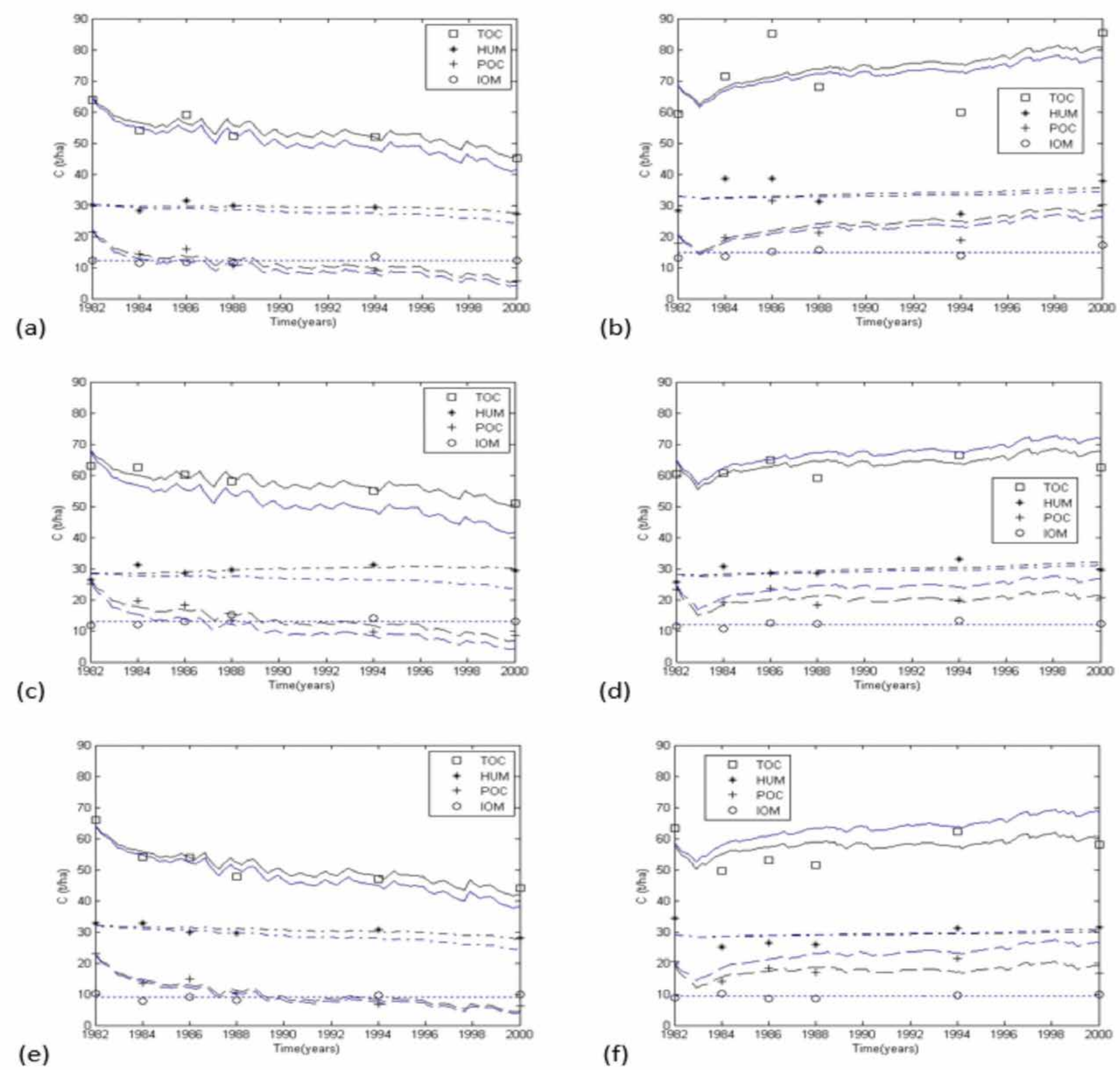


Source: Chappell and Baldock (2017) and the unpublished work carried out by the DoEE (2017)

Figure 6.B.7b 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.7c 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. Further verification using FullCAM revealed that correlation between measured and simulated total soil carbon reported 0.94 correlation while RMSE value was reported as 5.74 C t/ha.

Figure 6.B.8 shows the behaviour 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.8 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



Source: Chappell and Baldock (2017)

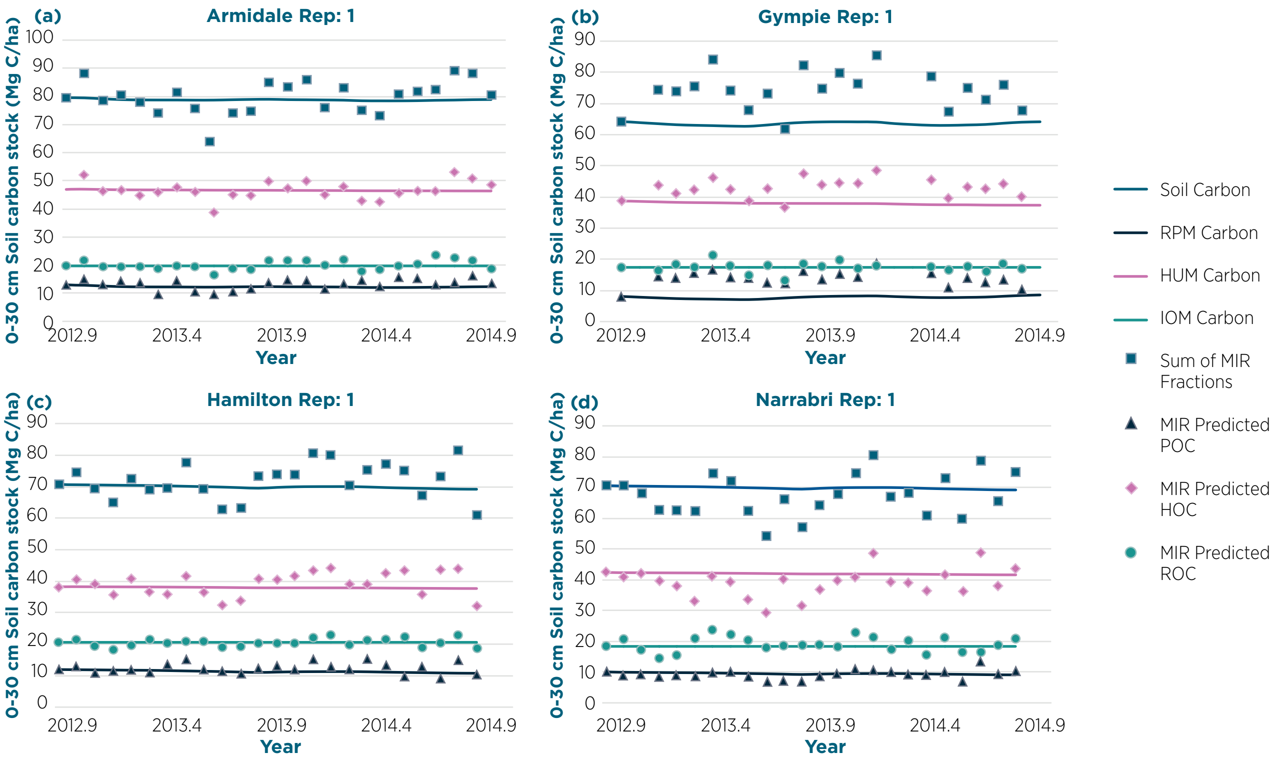
Verification of FullCAM Outputs

Independent soil carbon measurements undertaken through the Filling the Research Gap (FtRG) program, funded by the Australian Government Department of Agriculture and Water Resources, were used to verify the FullCAM simulations.

Figure 6.B.9 shows comparison of selected FullCAM plot simulations with field data (MIR predicted) collected by CSIRO Agriculture and Food, under the FtRG program. These sites represent the major cropping regions of the country. For this verification, we used site specific climate data, soil carbon fractions measured using mid-infrared spectroscopy, while temporal carbon inputs were added based on the cropping regimes included in the FullCAM database.

This verification exercise confirmed the reliability of FullCAM estimates as indicated by overall RMSE value of 9.21 C t/ha and correlation value of 0.60 for the temporal values recorded for 20 sites.

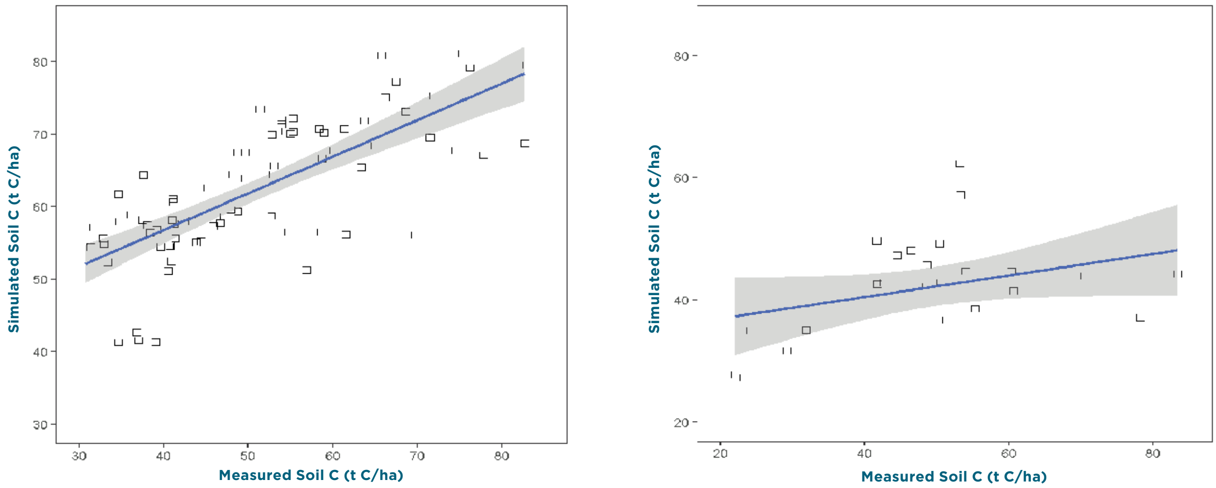
Figure 6.B.9 FullCAM outputs (solid lines) using global decompositions parameters with field measured (MIR predicted) (dotted points) total soil carbon and its fractions for the selected sites Armidale, (b) Gympie, (c) Hamilton and (d) Narrabri



Additionally, FullCAM outputs were assessed using a second of set of independent field data collected by the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) – Victoria State Government (n=77 sites) and CSIRO Agriculture and Food (n=25 sites). In this case, soil fractions data was not available and total soil carbon measurements were obtained for one time only. The results showed an RMSE error of 14.4 C t/ ha and 16.8 C t/ha and correlation between measured and simulated soil carbon values as 0.73 and 0.36 for the DEDJTR and CSIRO Agriculture and Food respectively (Figure 6.B.9).

Figure 6.B.10 Verification of FullCAM estimates using measured soil carbon data from the DEDJTR (a) and CSIRO Agriculture and Food (b)

(a) (b)

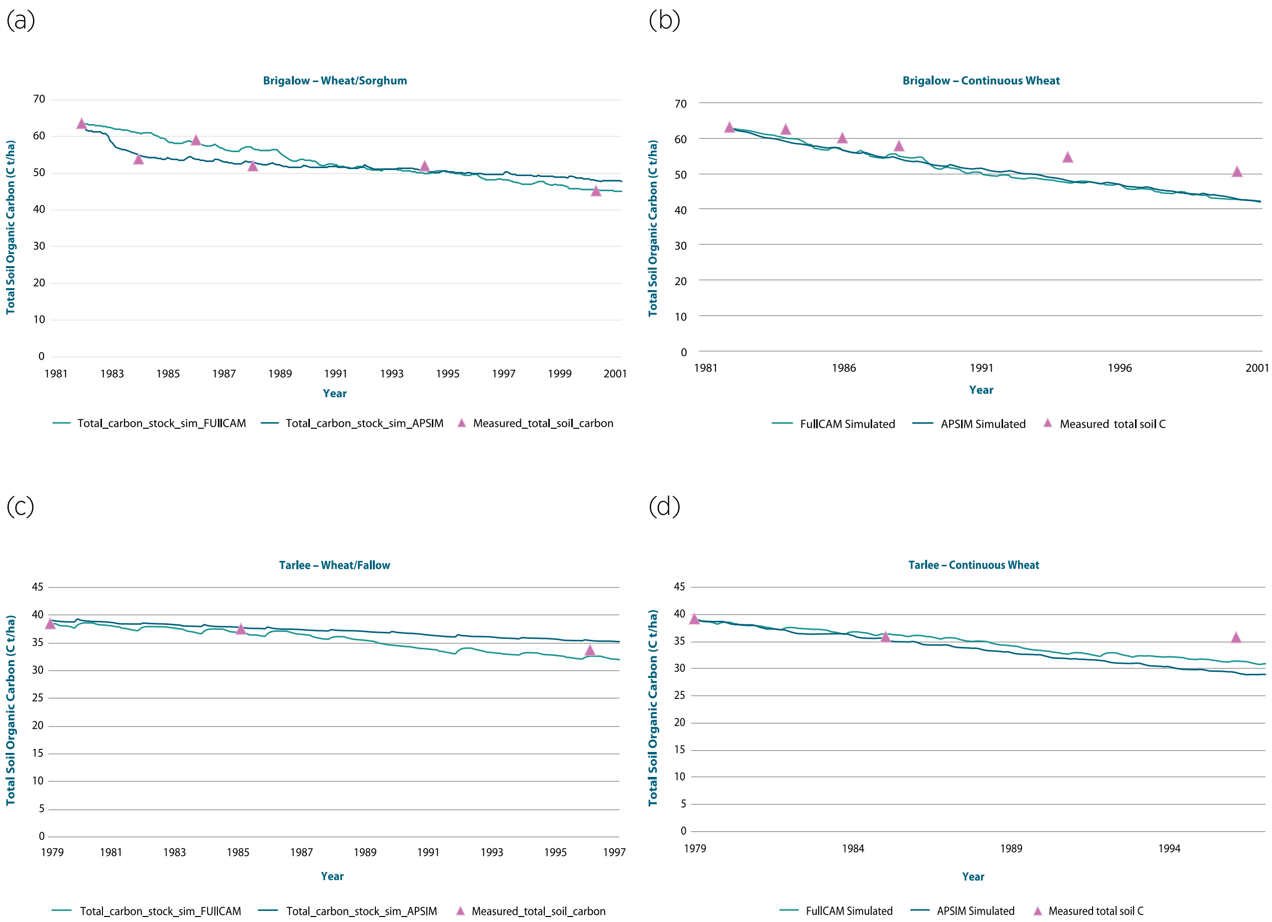


Comparison of the FullCAM estimates with APSIM outputs

FullCAM outputs were also compared with the Agricultural Production Systems siMulator model (APSIM) version 7.0 as shown in Figure 6.B.11. APSIM is internationally recognized as a highly advanced simulator of agricultural systems. It contains a suite of modules which enable the simulation of systems that cover a range of plant, animal, soil, climate and management interactions (Keating *et al.,* 2003). For this comparison, APSIM results for four sites were provided by CSIRO Agriculture and Food (Luo *et al.,* 2015). Both FullCAM and APSIM were run using the same set of field measurements.

The correlation analysis for the temporal simulations between FullCAM and APSIM for each month reported 0.92, 0.99, 0.98, 0.99 for four sites in Brigalow – Wheat/Sorghum, Brigalow – Continuous Wheat, Tarlee – Wheat/Fallow and Tarlee – Continuous Wheat respectively indicating high level of confidence in the outputs. FullCAM, which is specifically designed for carbon accounting purposes, was able to replicate the APSIM, which was designed for agricultural system modelling.

Figure 6.B.11 Comparison of FullCAM simulations with APSIM simulations for the selected sites (a) Brigalow – Wheat/Sorghum, (b) Brigalow – continuous Wheat, (c) Tarlee – Wheat/Fallow and (d) Tarlee – continuous Wheat



Comparison of soil carbon response to changes in management practices

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 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 (ABS 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.

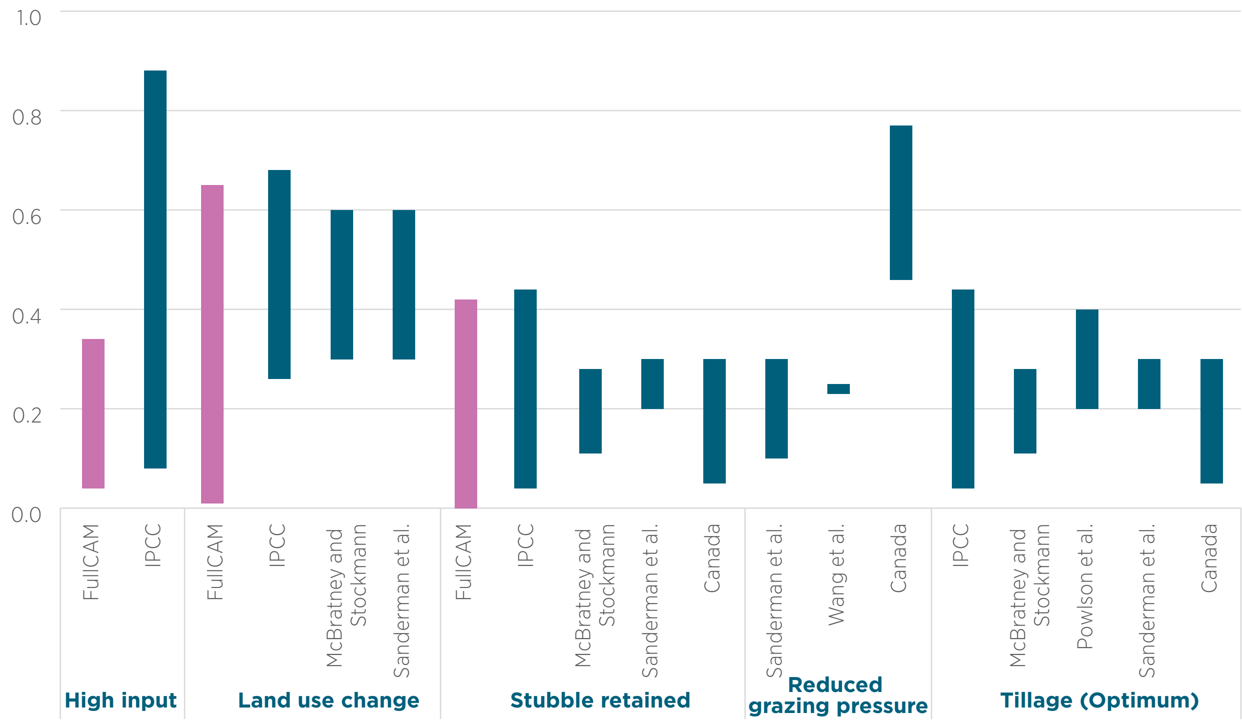
A truncated normal distribution was applied to the Monte-Carlo simulations to ensure the probability distribution of the output value for soil carbon stock is bounded above and below by the minimum and maximum values for the input risk variables.

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.12. 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 modelled by FullCAM, mainly reflecting spatial variations in soil quality, which is entirely expected from empirical experience across Australia. Figure 6.B.12 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.12 Comparison for soil carbon response to changes in management practices for FullCAM and from domestic empirical literature and international practice



Comparison of the FullCAM estimates with IPCC Tier 2 Soil Carbon Method

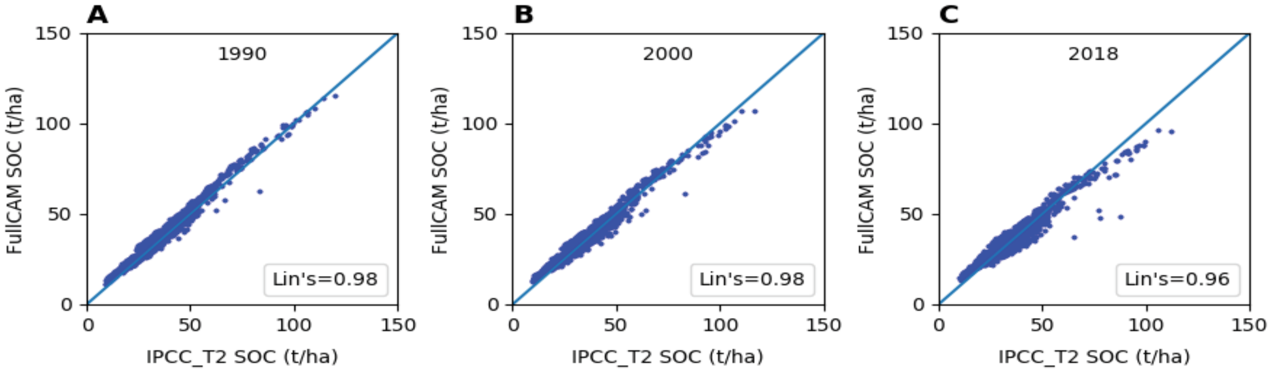
The Tier 2 steady-state soil carbon model provided in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 4 Chapter 5) was compared with FullCAM outputs for croplands. Detailed analysis of the application of the IPCC Tier 2 steady-state soil carbon model to Australian croplands is provided in Baldock et al. (2021).

The IPCC Tier 2 model (IPCC_T2) is based on the Century model with three conceptual carbon sub-pools, while the Inventory's Tier 3 FullCAM, with a soil module is based on the RothC model, has five conceptual sub-pools. In addition, the FullCAM model has been calibrated and verified with measured data points for Australian conditions, and includes variable land management practices such as stubble and tillage events, while the IPCC_T2 has been calibrated with global datasets that overwhelmingly represents the northern hemisphere.

The same land management, yield data (to generate carbon inputs) and climate datasets were used for both FullCAM and IPCC_T2, and the IPCC_T2 model was initialised with measurable fractions considering FullCAM RPM (Resistant Plant Material) stock as the initial slow pool stock and the HUM (humus) and IOM (inert) stock as the initial passive pool stock. The initial stock of the IPCC_T2 active organic carbon was set to zero.

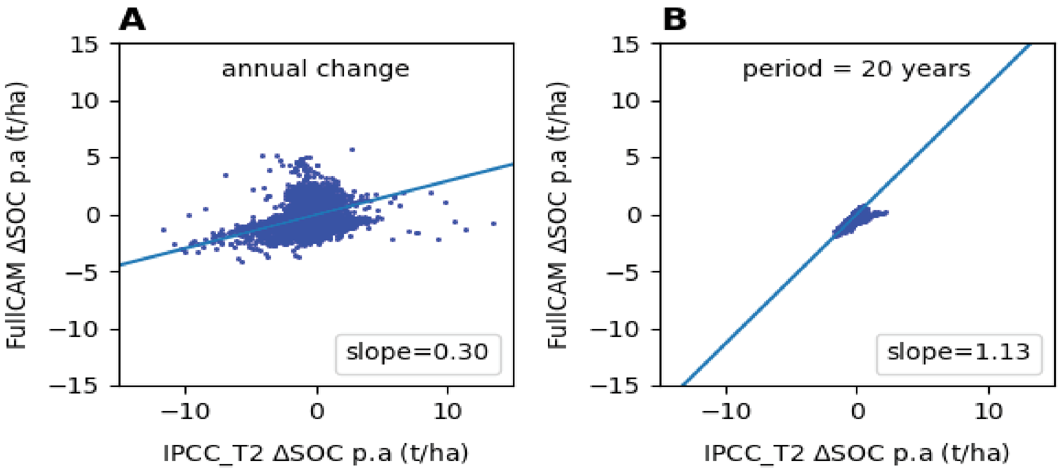
Simulations were carried out from 1970–2018 using 1818 cropland sites collated from the Australian Soil Carbon Research Program (SCaRP), covering the main cropping regions of Australia. Figure 6.B.13 shows the relationship between soil carbon stocks in 1990, 2000, and 2018; good agreement between the two approaches is indicated by a Lin's concordance correlation coefficient of 0.96–0.98.

Figure 6.B.13 Comparison of soil carbon stocks for 1818 SCaRP sites generated using the IPCC Tier 2 steady-state model and FullCAM in (A) 1990, (B) 2000, and (C) 2018.



Plotting the annual change in soil carbon for the two models as a scatter plot (Figure 6.B.14(A)) shows that the IPCC_T2 is more volatile, with changes greater than ±10 t/ha in some cases, while FullCAM changes up to ±5 t/ha. (Figure 6.B.14(A)). This difference in annual changes is not reflected in long-term carbon stock changes – over longer periods, the two models showed average annual stock changes with lower magnitude (±2.5 t/ha/year) and in close agreement, particularly over an interval of 20 years (Figure 6.B.14(B)).

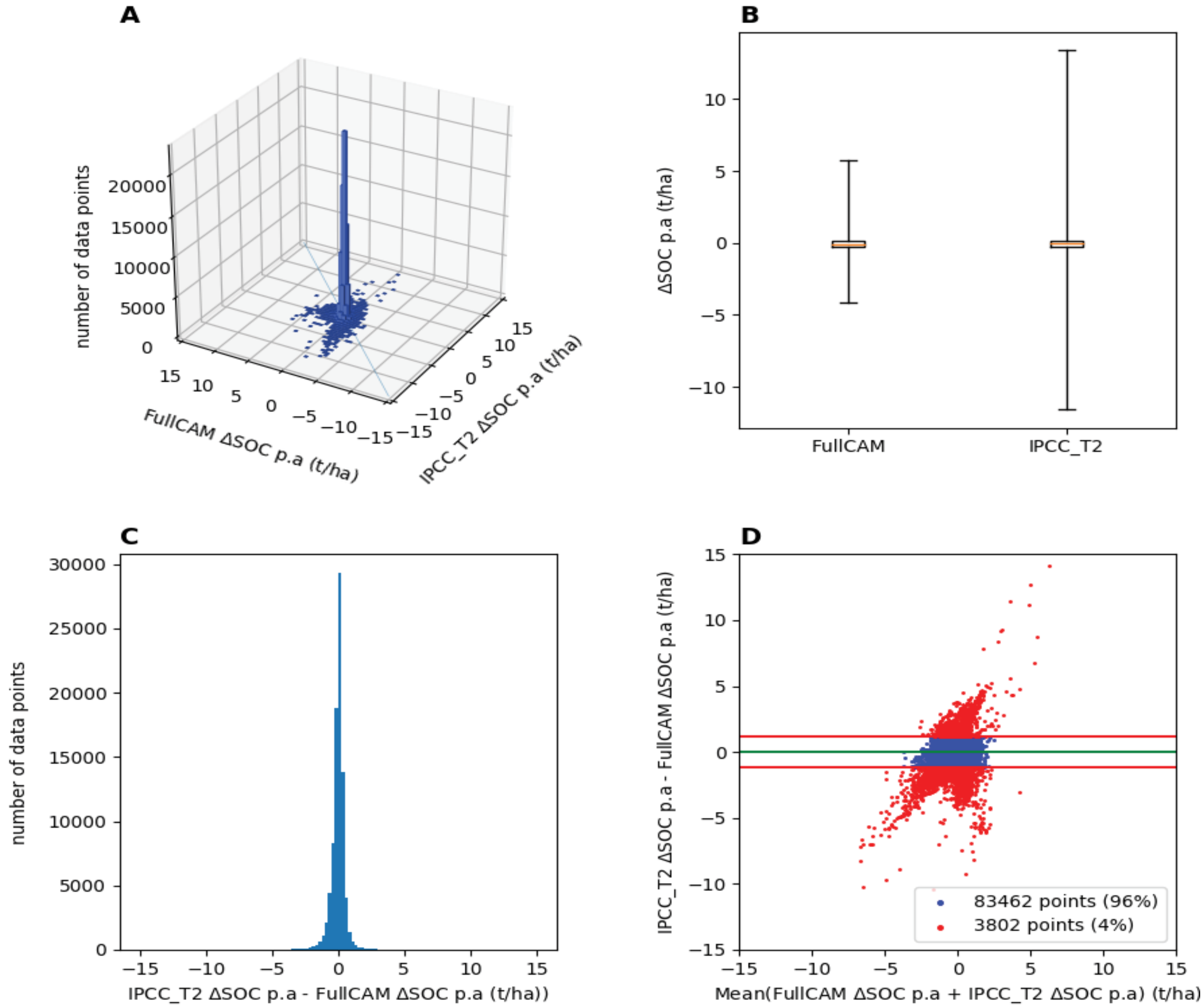
Figure 6.B.14 (A) Annual changes in soil carbon stocks 1970–2018 across all sites using the IPCC_T2 and FullCAM models. (B) Averaged over a 20-year interval (p.a: per annum).



The scatter plot in Figure 6.B.14 (A) also obscures the intense clustering of data, therefore further analysis of the annual changes in soil carbon stocks was undertaken. A 3D bar plot (Figure 6.B.15 (A)) indicates the vast majority of data points fall on the concordance line close to zero. Box and whisker plots (Figure 6.B.15 (B)) indicate that the annual stock changes generated from the two models have similar distributions, means and quartiles. This is further corroborated by a difference analysis (Figure 6.B.15 (C)), which shows the differences between the models displaying a normal distribution with a mean centred near zero (0.0024 t/ha/year) and low variance (s.d. 0.587). Finally, a Bland-Altman analysis (Figure 6.B.15 (D)) indicates that 96% of the data points lie within 2 standard deviations of the mean difference, where 95% is considered good agreement between two methods.

The new IPCC_T2 model provided a valuable opportunity to compare estimates of soil carbon change with those produced by the FullCAM model used in the National Inventory. There is statistically good agreement even between annual changes, and this agreement becomes very good over longer periods, including the 20-year period noted by the IPCC Guidelines as the typical time to achieve new equilibrium following a change in management conditions.

Figure 6.B.15 Analysis of annual carbon stock changes from the IPCC_T2 and FullCAM. (A) 3D barplot of data from Fig 6.B.14 (A) (bins = 0.5 t/ha). (B) Box and whisker plots showing similar means and interquartile ranges for the two models, but greater spread for IPCC_T2. (C) Histogram (nbins =120) of difference in annual stock changes modelled using Tier 2 steady state model and FullCAM (mean 0.0024 t/ha/year, s.d. 0.587). (D) Bland-Altman plot (green line: mean difference, red lines: ±2 standard deviations from mean difference, blue points within ±2 s.d. of mean difference, red points > 2 s.d. from mean difference).



Appendix

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[15]) 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 provide 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 /n(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 ion products (gross primary production) and the loss of a proportion of those products by respiration to give NPP. The value of the conversion factor (e, 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 e 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).

15 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.

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 e 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).

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:

$$\mathrm{VPDmod} = e^{(-005 \times \mathrm{VPD})} \qquad \text{(6C\_2)}$$

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; 79), modified by feed-back from current soil water content, and a conventional water balance equation (Equation 6C_5):

$$\mathrm{EqEvapn} = ((0.67 \times \mathrm{NetRadn} \times (1\text{-}0.05)) / 2.47) \times \text{days in month} \qquad \text{(6C\_3)}$$

$$\mathrm{Transpiration} = \mathrm{EqEvapnj} \times \mathrm{SWmodj\text{-}1} \qquad \text{(6C\_4)}$$

$$\mathrm{WaterBal} = (\mathrm{Rain} \times (1\text{-}\mathrm{interception})) - \mathrm{Transpiration} \qquad \text{(6C\_5)}$$

$$\mathrm{SoilWaterContent}_j = \mathrm{SoilWaterContent}_{j-1} + \mathrm{WaterBal}_j \qquad \text{(6C\_6)}$$

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).

$$\mathrm{MoistRatio} = \mathrm{SoilWaterContent}/\mathrm{SWcapacity} \qquad \text{(6C\_7)}$$

$$\mathrm{SWmod} = 1 / (1 + ((1\text{-}\mathrm{MoistRatio})/0.6)^{0.7}) \qquad \text{(6C\_8)}$$

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:

$$T_{mod} = ((T_{av} - T_{low}) / (T_{opt} - T_{low})) \times ((T_{high} - T_{av}) / (T_{high} - T_{opt})) \qquad \text{(6C\_9)}$$

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 0°C, 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 0°C). 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 T_{max}. Consequently, T_{mod} generally had relatively small effects on the calculation of NPP.

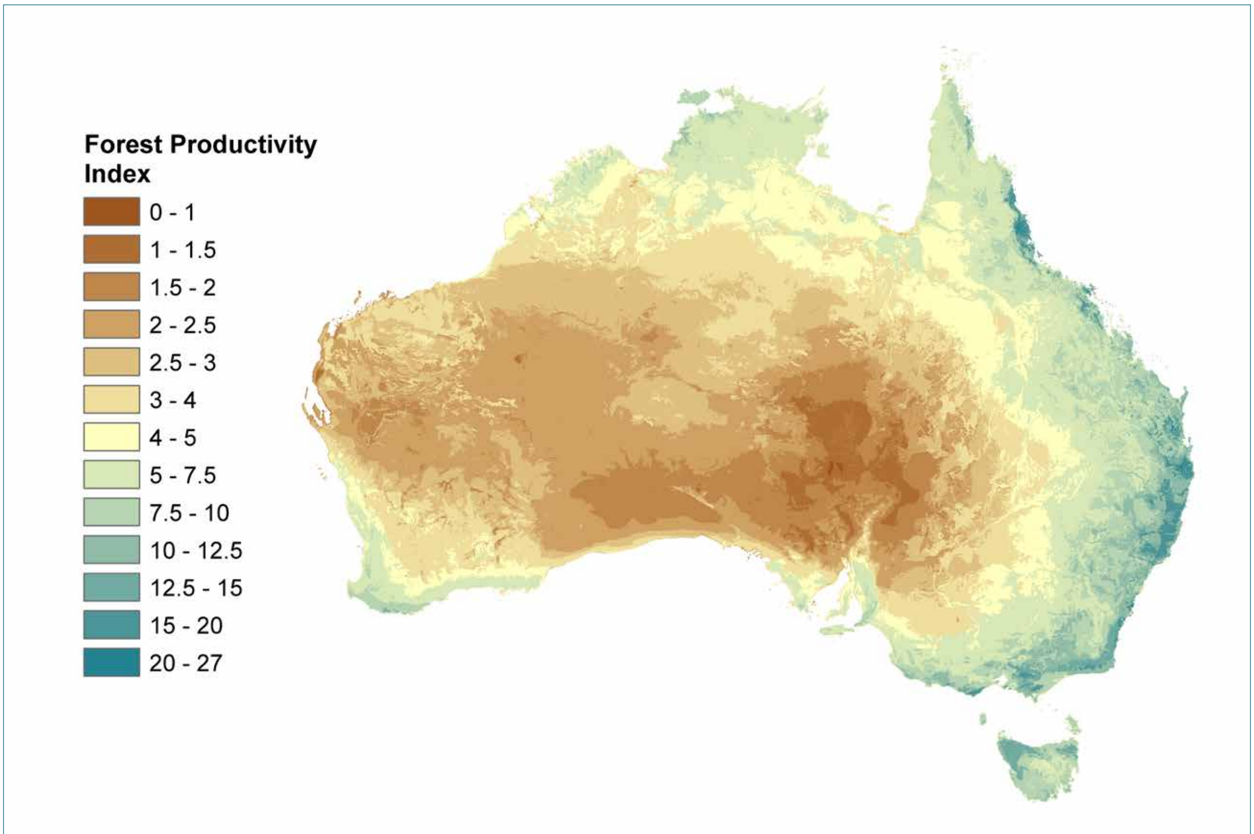
A frost modifier is included, using the simple assumption that frost temporarily inactivates the photosynthetic mechanism in foliage, so there is no growth on a frost day. The modifier is, therefore, simply the ratio of number of frost days/month to the number of days in the month.

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 6.E. A further 250 m long-term average FPI is also calculated using yearly average data from 1970–2017, 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;
- Forest land converted to Grassland;
- Forest land converted to Wetlands (flooded lands); and
- Forest land (terrestrial) converted to Settlements.

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.* (2019) (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.* (2019) 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.

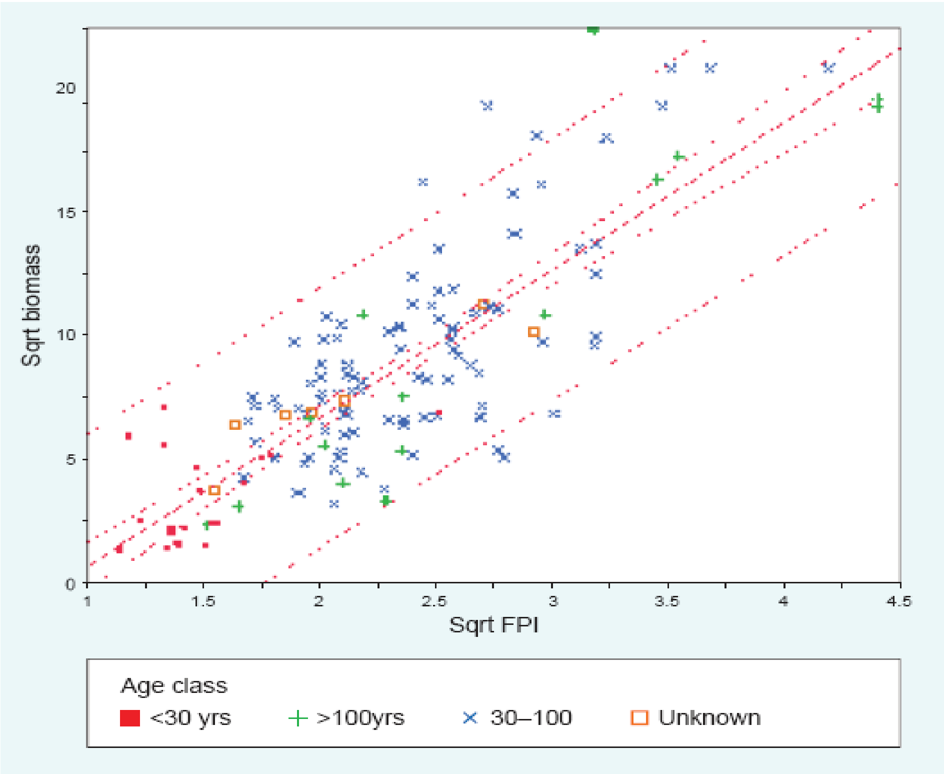
Assumed initial biomass relationship

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).

$$M = (6.011 \times \sqrt{P} - 5.291)^2 \qquad (6D\_1)$$

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 per cent confidence limits (outer pair of dotted lines) show the reliability for predicting biomass at any individual site, and the inner 95 per cent 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.

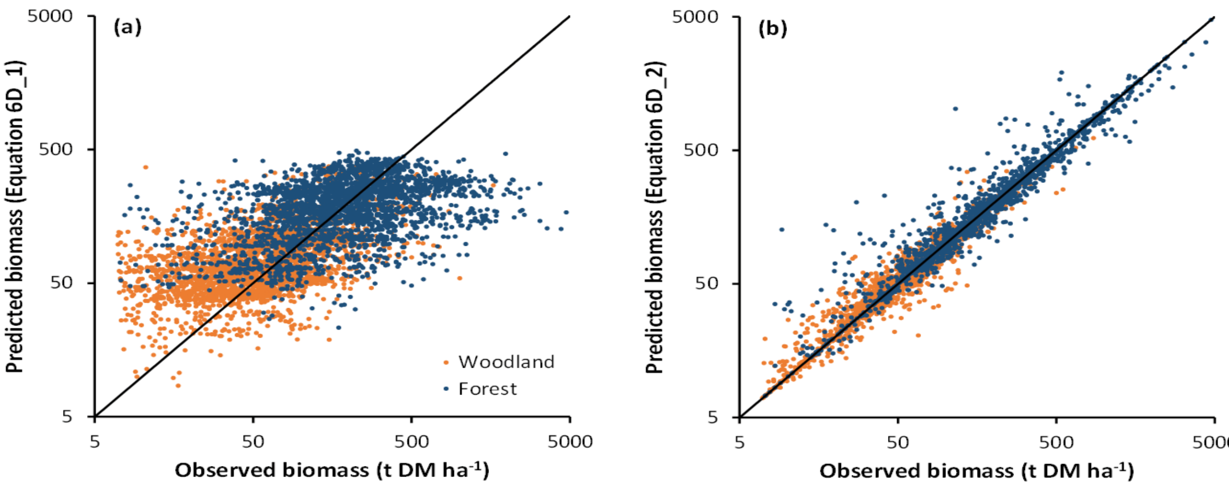
Applying Equation 6D_1 to the data from the TERN/AusCover National Biomass Library suggested the biomass predictions were accurate up to approximately 300–400 t DM ha^{-1}, after which point there was a strong tendency for the equation to under-predict actual biomass, such that all biomass observations greater than 500 t DM ha^{-1} are predicted to be less than 500 t DM ha^{-1} (Figure 6.D.2a). To correct for this bias, a spatially-explicit modifier (X) 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 machine learning algorithm was used to estimate X, 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:

$$Mi = \lambda_i \times (6.011 \times \sqrt{P_i} - 5.291)^2 \qquad (6D\_2)$$

For regions in which the current model (Equation 6D_1) is consistent with the new data then I is expected to be close to 1.0; for regions where biomass is being under-predicted then X is expected to be >1, and for regions where biomass is being over-predicted then X is expected to be <1.

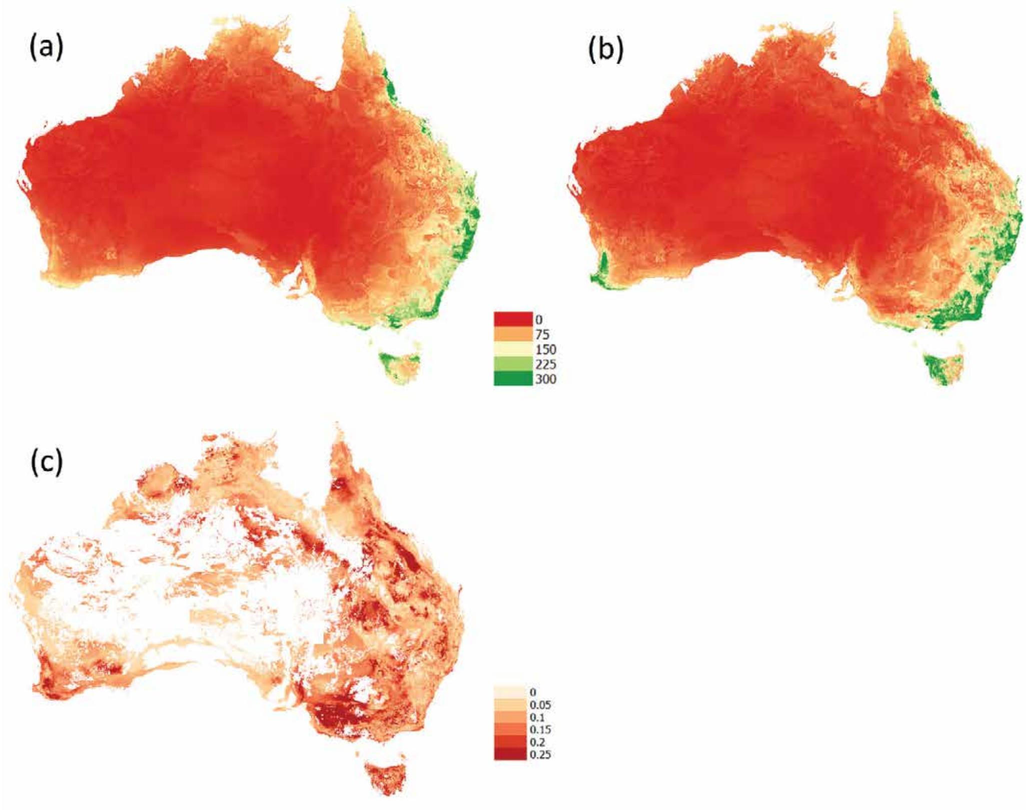
Under Equation 6D_1, and when applied to the full biomass database, the overall root mean square error (RMSE) was 239 t DM ha^{-1}, with a model efficiency (EF) of 0.14 and a mean error (ME) confirming an overall bias of -35 t DM ha^{-1} (Figure 6.D.2a). Under Equation 6D_2, which includes the modifier X, 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 per cent (i.e. including some sites classified as sparse woody vegetation with canopy cover 5–20 per cent). 'Forest' indicates sites with a canopy cover >50 per cent. 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.



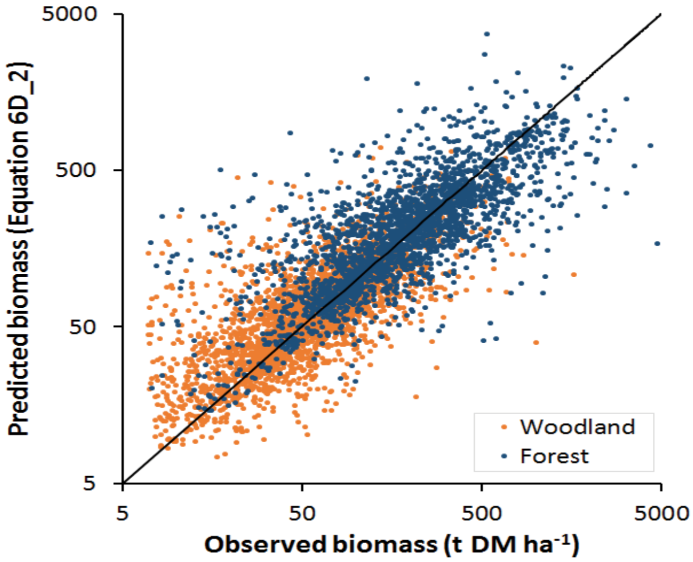
While the goodness of fit and lack of bias in error estimates (Figure 6.D.2b) provides confidence in the application of Equation (6D_2) as a model to predict biomass at maturity, there is an obvious scatter in the data which is somewhat masked by the logarithmic scales on which the figures are displayed. 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 modelling procedure to predict I the empirical database of 5,739 records was split at random into a 70 per cent model fitting (calibration) subset and a 30 per cent 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 per cent 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 per cent (i.e. including some sites classified as sparse woody vegetation with canopy cover 5–20 per cent); 'Forest' indicates sites with a canopy cover >50 per cent. Lines are 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 per cent, 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 per cent, 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 forests (48 t DM ha^{-1} using Equation 6D_1 and 49 t DM ha^{-1} using Equation 6D_2), and increases in the >50 per cent 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 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.

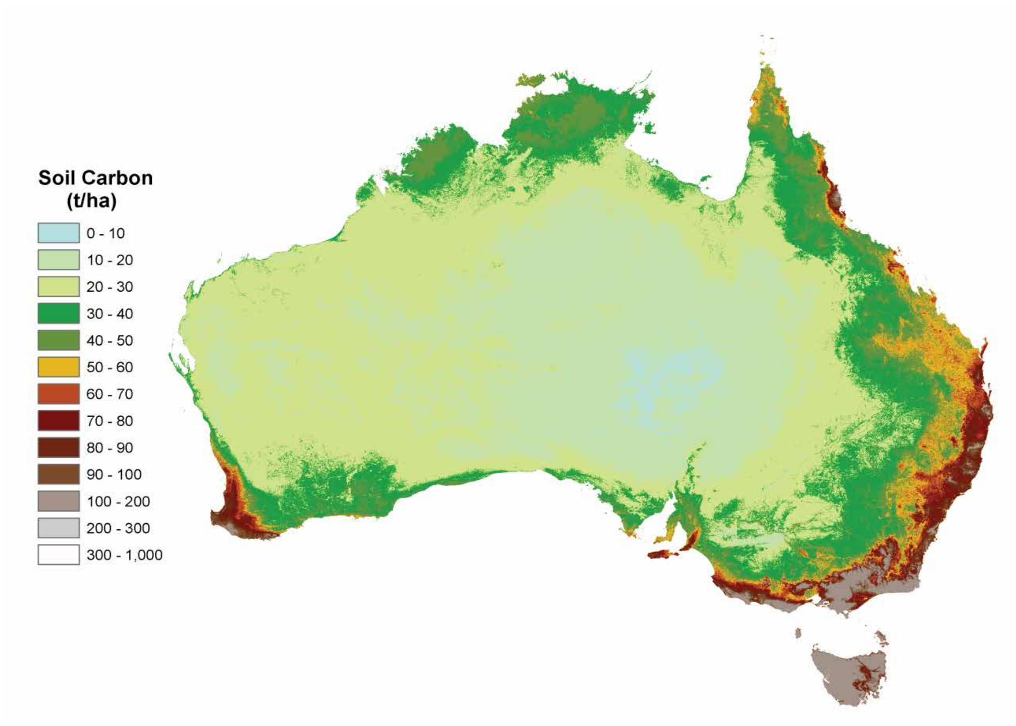
A fine spatial resolution baseline map of organic carbon at the continental scale was produced by combining the bootstrap, a decision tree with piecewise regression on environmental variables, and geostatistical modelling of residuals. Values of stock were predicted at the nodes of a 3-arc-sec (approximately 90 m) grid and mapped 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 per cent 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 per cent 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.

Appendix

Figure 6.E.1 Baseline map of organic carbon in Australian Soil (Viscarra-Rossel et al. 2014)



Soil carbon fractions

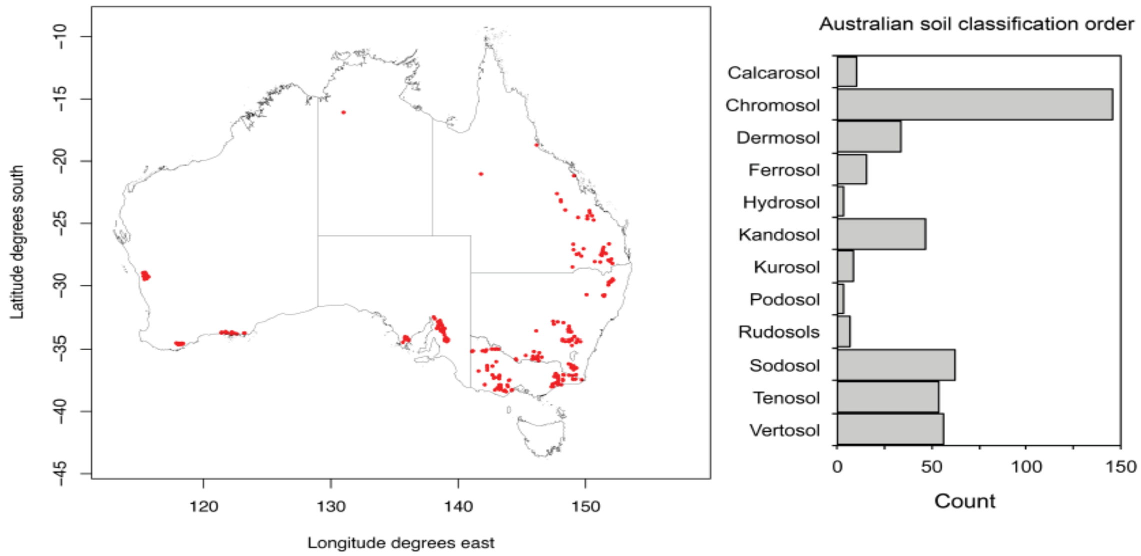
Measureable soil carbon fractions that can replace the conceptual pools of the Roth-C model which are used to simulate soil carbon changes within FullCAM are used to initilise FullCAM. These fractions are defined by their differences in turnover times and biological significance (Baldock *et al.,* 2013).

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

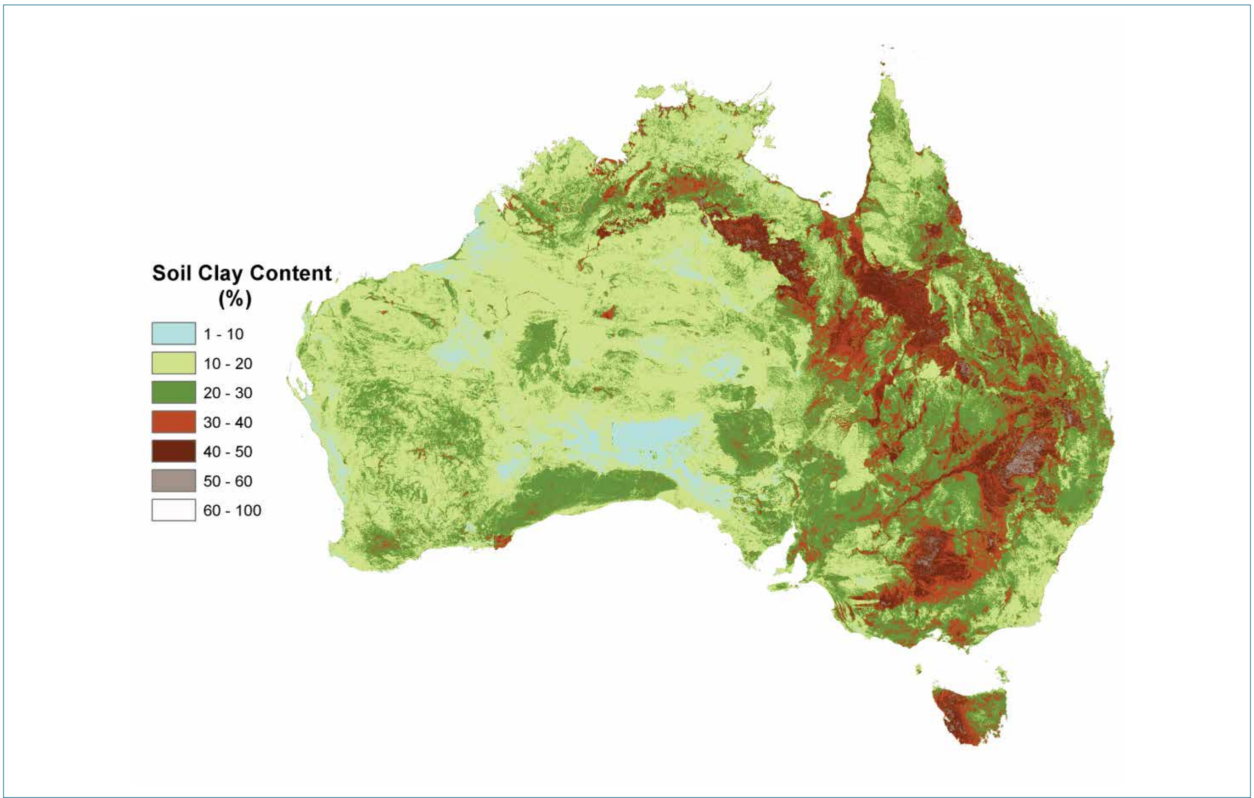


Once the spectroscopic predictions were made, the spatial modelling of the data was performed by combining the bootstrap, a decision tree with piecewise regression on environmental variables and geostatistical modelling of residuals. The spatial models were validated with an independent data set and 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 per cent 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, 2015)



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 average and regionally 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, 1970–2018, weather station data from the Bureau of Meteorology for rainfall, minimum and maximum temperature, evaporation and solar radiation were obtained. Monthly climate surfaces at 1 km resolution for each variable were then derived using ANUSPLIN (Hutchinson and Xu, 2013; McMahon *et al.* 2000) surface interpolation techniques.

Climate data are produced on an annual basis to incorporate new data captured by the Bureau of Meteorology, and updated processing methods as new technology becomes available. ANUSPLIN Version 4.6 was used to derive climate surfaces as it encompasses new developments that improve surface accuracy. These methods significantly improve on the spline based methods described by Kesteven *et al.* (2004). The revised methods incorporate the use of mean background fields based on the full historical climate data network to reduce interpolation error and facilitate reliable detection and removal of source data errors.

Raw data

Within the Bureau of Meteorology database there are approximately 700 weather stations recording temperature, over 4,000 stations recording rainfall, 150 stations recording evaporation and 700 stations recording frost days. Solar radiation surfaces were calculated as a function of monthly minimum and maximum temperature and rainfall using a model calibrated on historical solar radiation data for 40 stations. Precise location and elevation data were available all 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 elevation and proximity to the coast information to support the calculation of the interpolating spline functions by the ANUSPLIN 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 and proximity to the coast. Climate grids are derived at a grid spacing of 0.01 degrees longitude/latitude (approximately 1 km) using the ANUSPLIN software (Hutchinson and Xu 2013). 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 surfaces generated from the data produced using the ANUSPLIN software.

The surface interpolation from weather station data provides climate mapping which is both temporally and spatially relevant to the application of FullCAM.

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 1968–2019
Temperature	1 km resolution min., max., and average continentally, monthly 1968–2019
Evaporation	1 km resolution continentally, monthly 1968–2019
Frost Days	1 km resolution continentally, monthly 1968–2019
Long-term productivity	250 m resolution
Annual productivity	(sum of monthly) 1 km resolution (1970–2019)

Figure 6.E.4 Long-term average annual evaporation

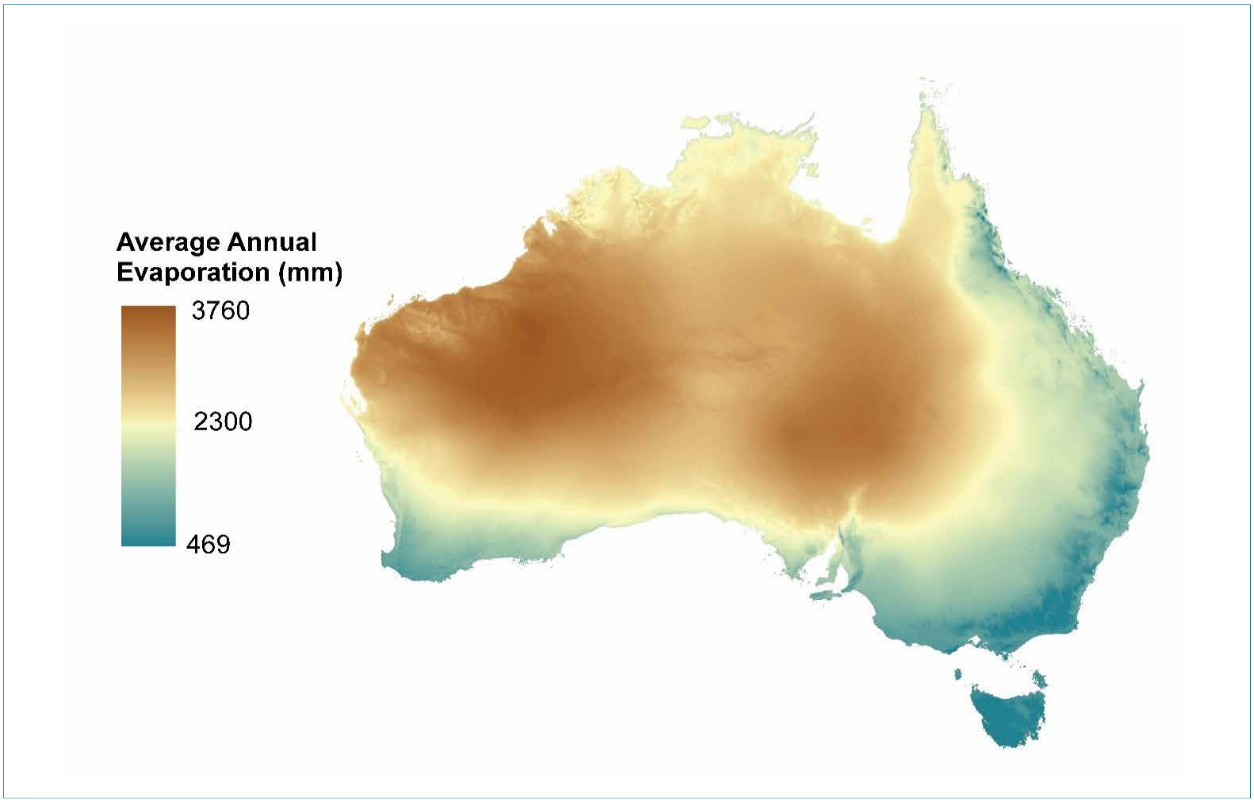
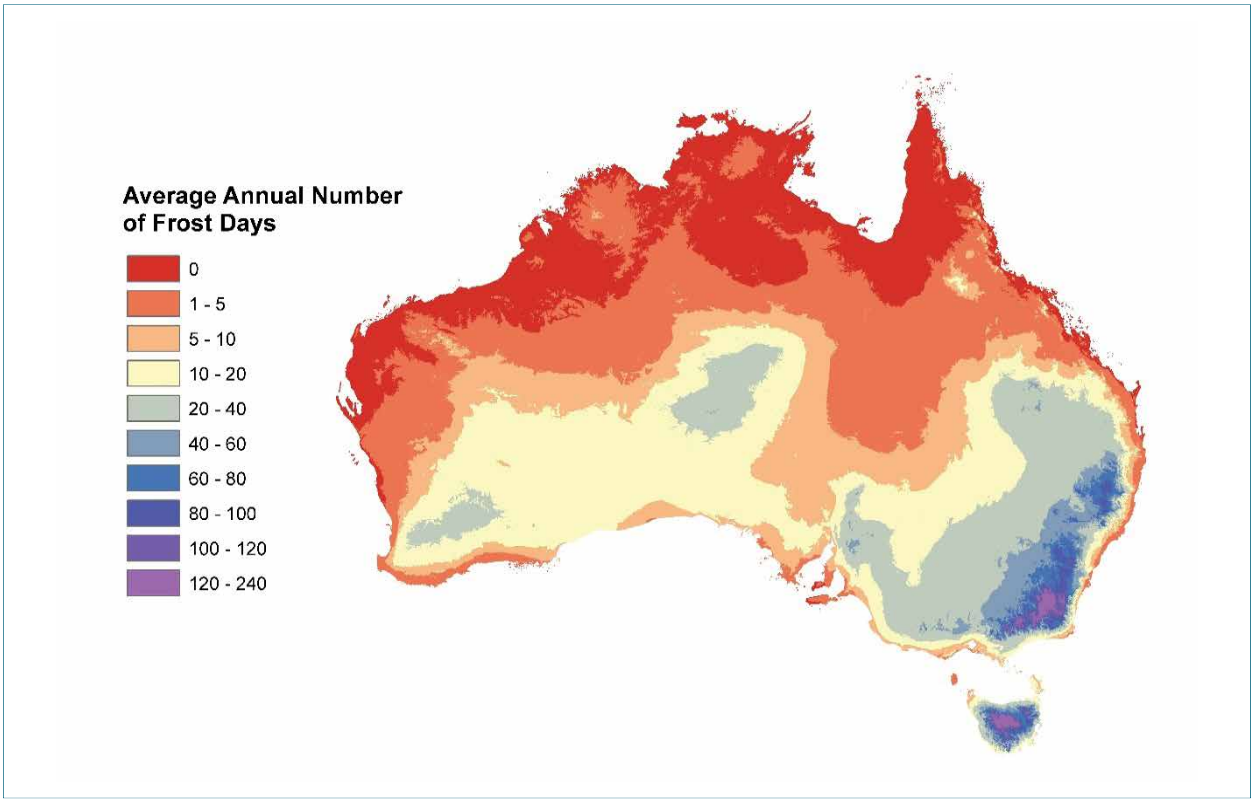


Figure 6.E.5 Long-term average number of frost days per year



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 and Energy 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 program, 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 (ABS 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 per cent 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	2010–2014
2016	2015–2020

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.

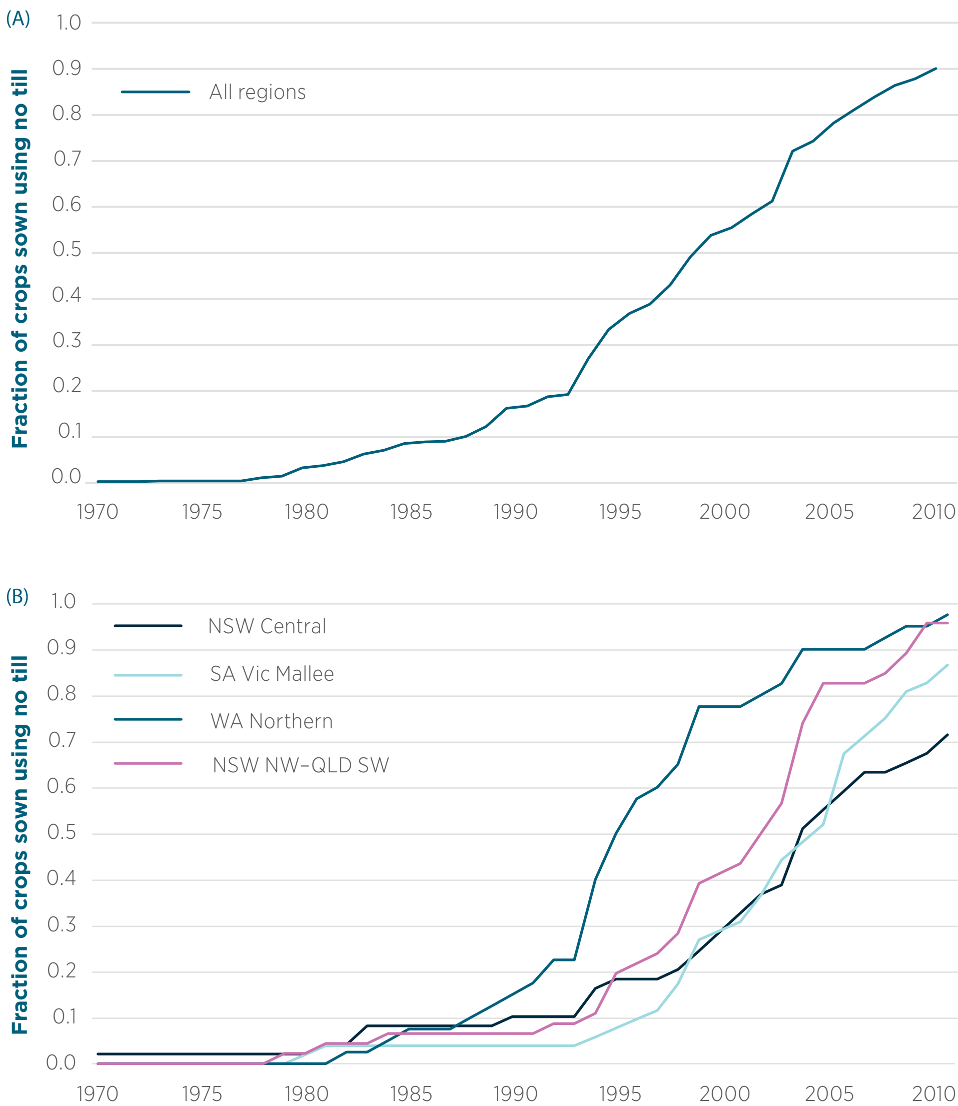
Cropping systems have evolved over time with the use of herbicides to control weeds instead of tillage and sowing machinery adapted to sow into standing stubble of antecedent crops. This means that there has been a significant change over time in the extent of tillage and the incorporation of crop residues 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[16]. 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.

16 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.

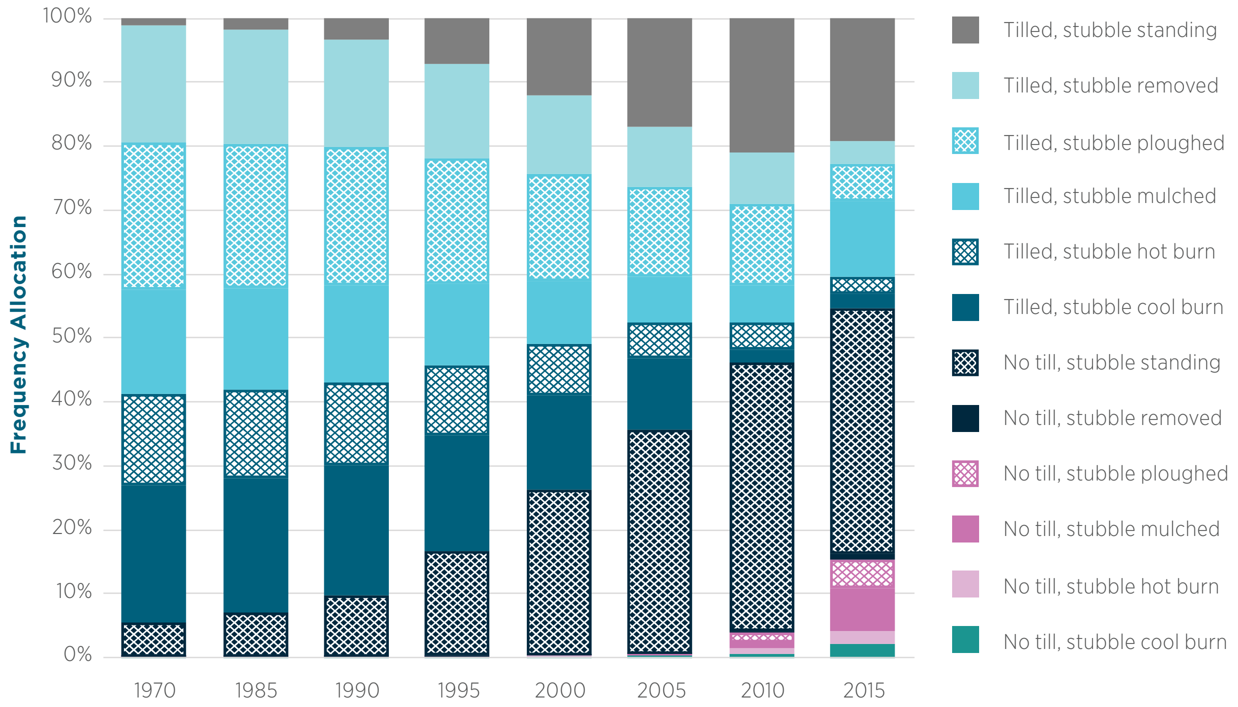
Appendix

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 all crop species in Australia since 1970 for each epoch taken from Table 6.E.2. The benefit of changing management practices seen within the first 10 years and the diminishing returns afterwards, are a result of the soil carbon stock attempting to reach a new equilibrium. Peaks in net gains or removals attributed to SOC generally are not caused by management change, but are experienced during regional drought or flood events in which the net balance between C inputs and C losses is altered.

Figure 6.E.8 Changing allocation of management practices for cropland since 1970, generated from the management crop management frequency database embedded in 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.

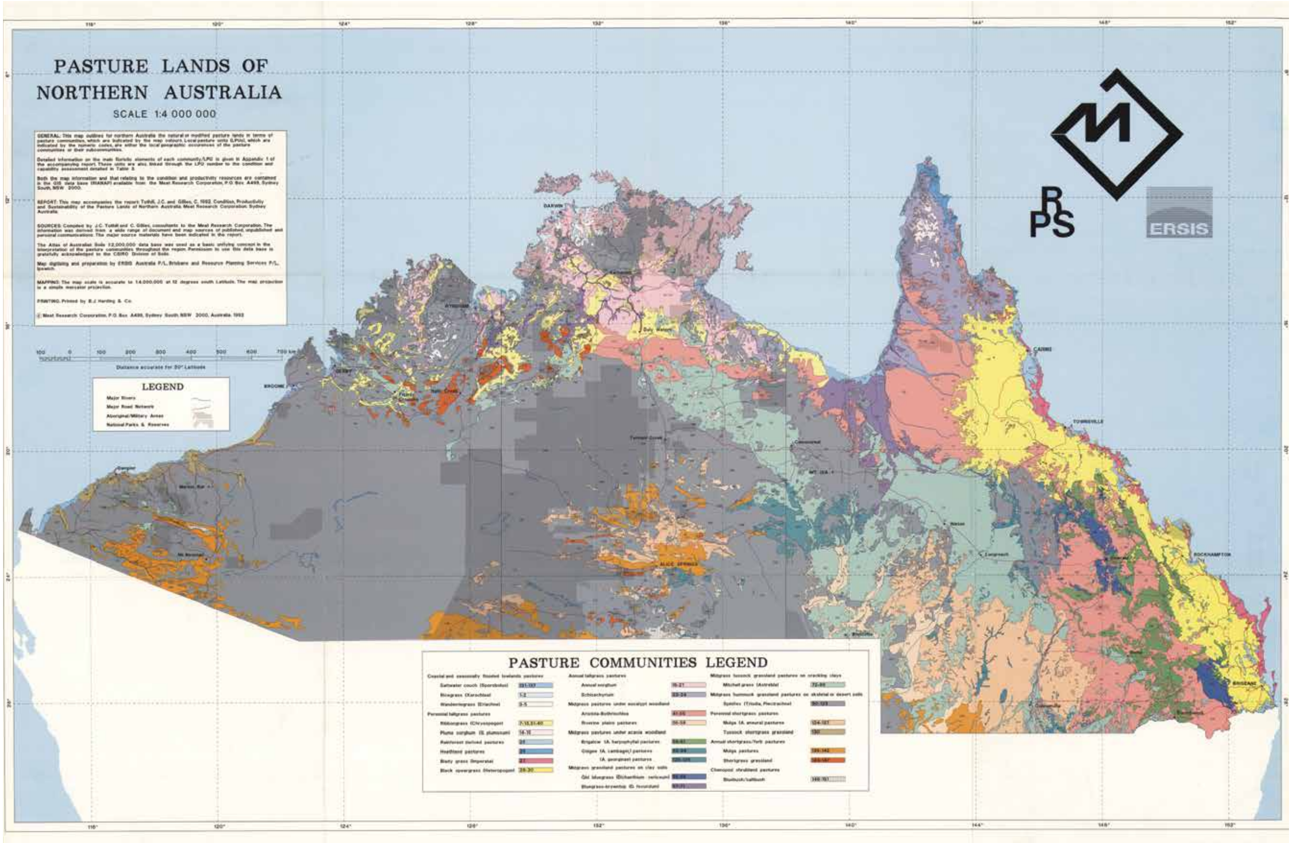
Based on the information collected by Llewellyn and D'Emden (2009) and Llewellyn *et al.* (2012) and using farmer estimates of the historical use of no-till seeding systems back to 1960 clearly shows that there is an increasing trend in adoption of no-tillage practices in Australian grain growing regions (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 (ABS 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

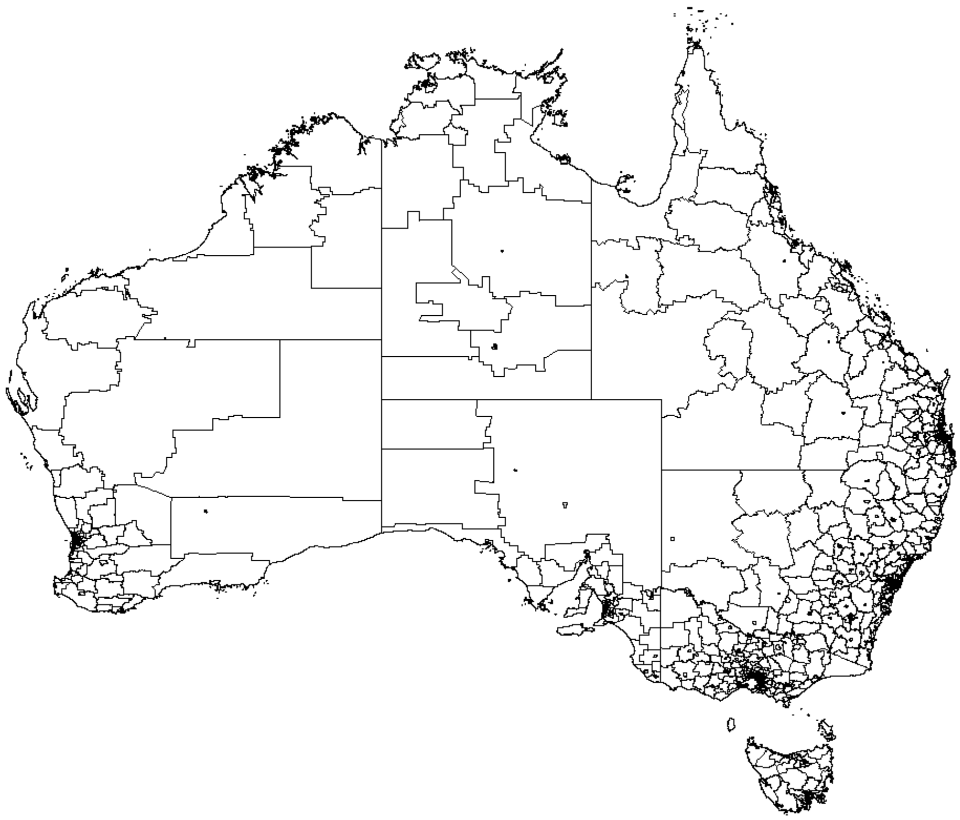


The information collected describes 527 grazing and cropping systems, with associated management practice data also held within FullCAM relational database. Table 6.E.3 provides an example of the data collected. Allocation to a land use and management system is designated according to the relative frequency 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, 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, 1 burn
71050	1990	1994	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 122, 2y, 0 burns
71055	1990	1994	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 244, 2y, 0 burns
31177	2010	2014	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 244, 5y, 1 burn
31503	1985	1989	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 30, 1y, 0 burns
51207	1990	1994	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 305, 2y, 0 burns
71068	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 305, 2y, 0 burns
71065	2005	2009	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 305, 2y, 0 burns
71068	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 335, 10y, 8 burns
31406	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 335, 10y, 8 burns
71055	2000	2004	Aristida-Bothriochloa	Aristida-Bothriochloa, Estab 335, 10y, 8 burns
11238	2000	2004	Barley	Barley, No till, stubble cool burn
11238	2010	2014	Barley	Barley, No till, stubble hot burn
11238	1990	1994	Barley	Barley, No till, stubble mulched
11238	1995	1999	Barley	Barley, No till, stubble ploughed
11238	2005	2009	Barley	Barley, No till, stubble removed
11238	2000	2004	Barley	Barley, No till, stubble standing
11238	2005	2009	Barley	Barley, Tilled, stubble cool burn
11238	1995	1999	Barley	Barley, Tilled, stubble hot burn
11238	2005	2009	Barley	Barley, Tilled, stubble mulched
11238	1990	1994	Barley	Barley, Tilled, stubble ploughed
11238	1990	1994	Barley	Barley, Tilled, stubble removed
11238	2010	2014	Barley	Barley, Tilled, stubble standing

Figure 6.E.10 Australian Statistical Geography Standard, statistical area level 2 (SA2) boundaries (ABS 2010)



6.E.4 Native forest harvesting spatial data

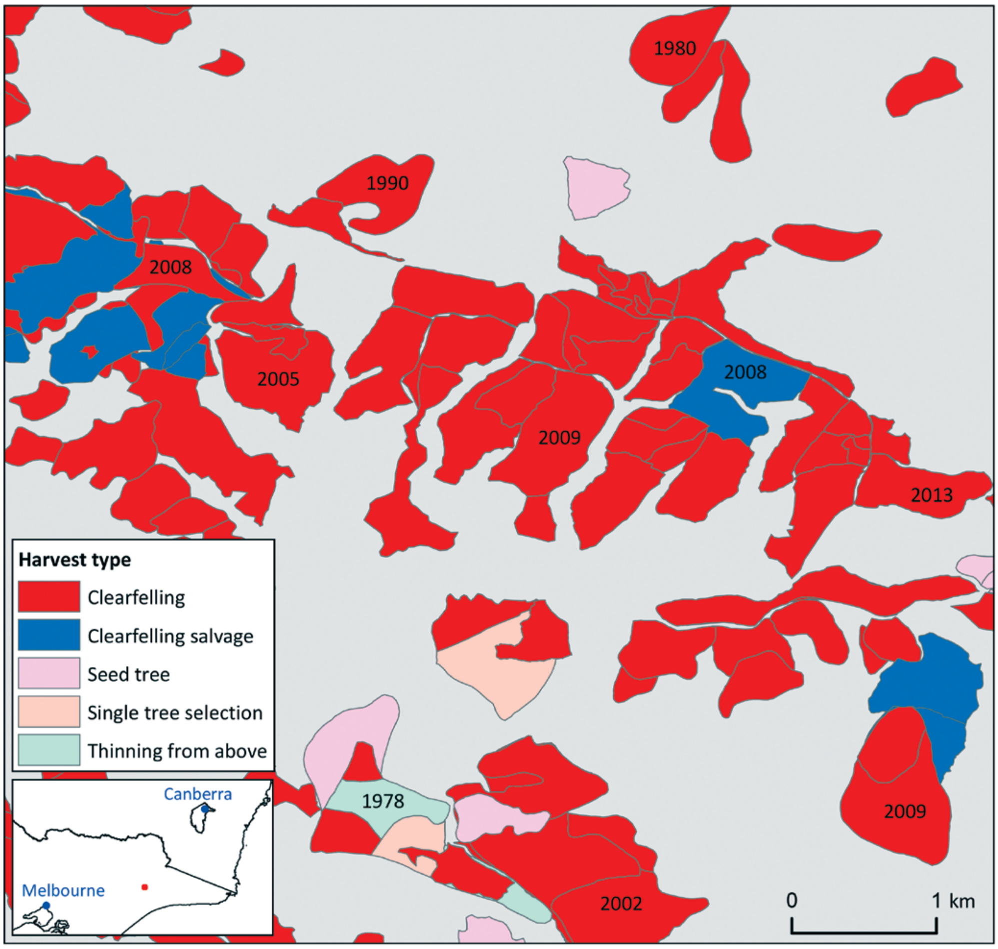
The FullCAM spatial method for *harvested native forests* uses spatial datasets provided by state forest management agencies to specify the area, date and type of timber harvesting events. Within a FullCAM *harvested native forests* simulation, this data triggers timber harvesting, associated management and subsequent forest regrowth at the appropriate times and locations. For the current inventory, spatial data on native forest harvesting was provided for Victoria and New South Wales. In each case a spatial dataset was provided in which polygons define the discrete areas, or logging coupes, where harvest has occurred.

For Victoria, the Harvested Logging Coupes dataset, accessed from data.gov.au, maps Victorian commercial logging events for each season, including silvicultural operation type and start/end dates of logging events. After filtering for valid dates there were approximately 30,000 mapped harvest events for the period 1932 to June 2019, each assigned to one of 12 harvest types, as listed in Table 6.15.

For New South Wales harvest polygons were provided by Forestry Corporation of NSW, with 25,000 events covering the period from July 1950 to June 2019. Harvest and operation type were grouped, with advice from the Forestry Corporation, to derive 13 harvest types for NSW as listed in Table 6.15.

These harvest data polygons were converted to a 25m x 25m grid, which matches the resolution used for other land use and land-cover change data in FullCAM. For each 25m pixel the year, month and type of each harvest event were encoded.

Figure 6.E.11 Example of forest harvest data from Gippsland, Victoria



Multiple use forest extent

The *harvested native forest* model covers areas of public land which are available for commercial timber harvesting, typically described as *multiple use forest*. Areas defined as multiple use forest in FullCAM include areas currently managed for uses including timber production, such as state forests. As well as areas currently available for harvesting, multiple use forests in FullCAM also include areas which were previously available for timber harvesting after 1990. Typically such areas were transferred from state forests to national parks or other protected tenures.

The spatial data which defines multiple use forest in FullCAM was prepared by the *Australian Bureau of Agricultural and Resource Economics and Sciences* (Mutendeuzi *et al.* 2014) based on an analysis which selected from forest areas using the following criteria:

- land tenure (public land which has been available for harvest at some time since 1990);
- commerciality (sufficient forest productivity and presence of merchantable species);
- distance from wood processing facilities (< 200km);
- slope (< 50%); and
- not rainforest in mainland areas.

6.E.5 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 using a crop/pasture growth model developed by *CSIRO Land and Water* 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 second for perennial pasture systems (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.12 Conceptual model of annual crop growth module

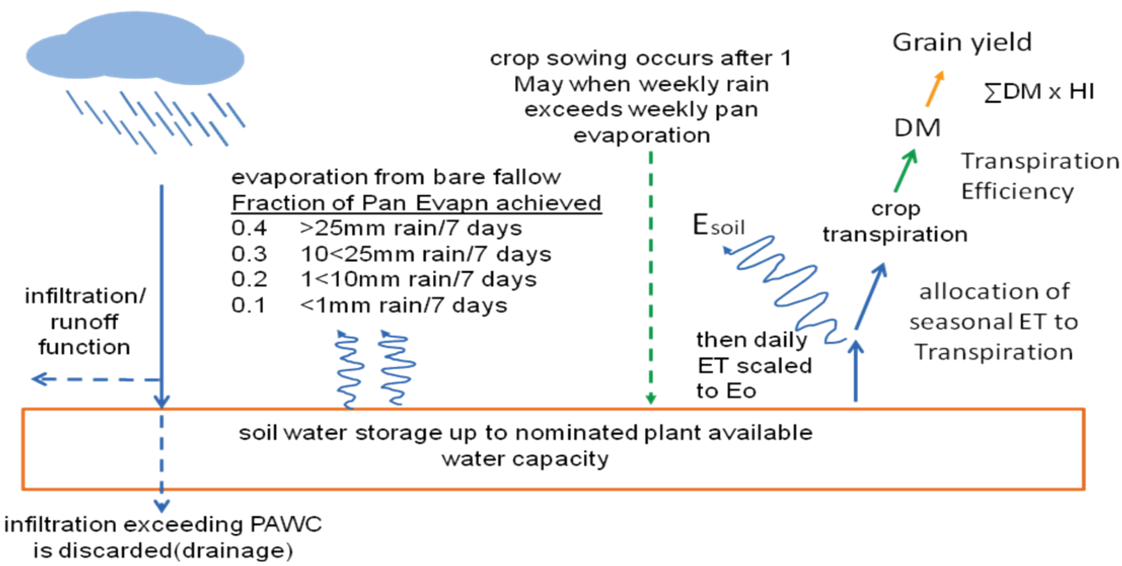
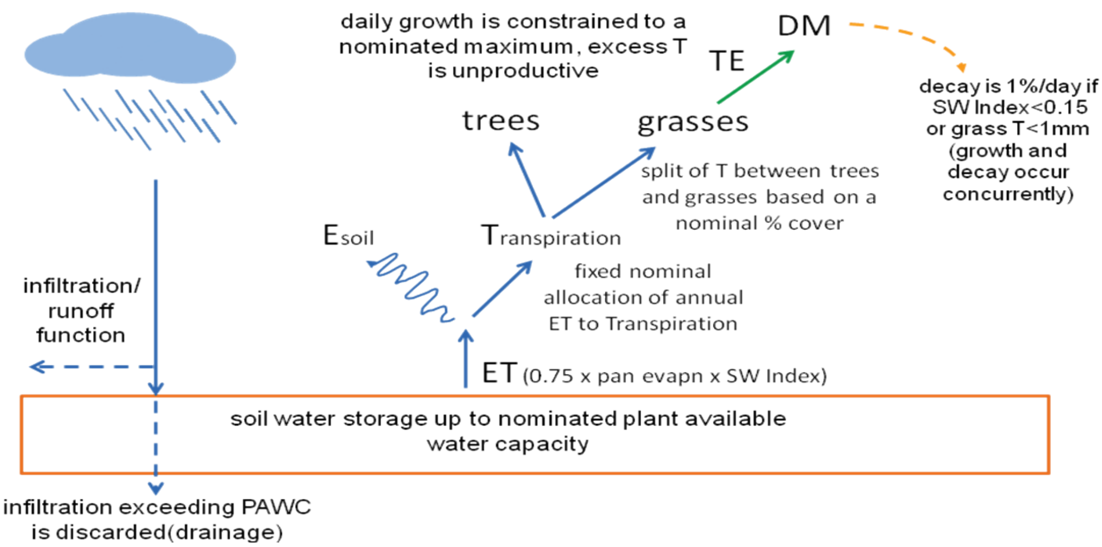


Figure 6.E.13 Conceptual model of perennial grass/pasture module



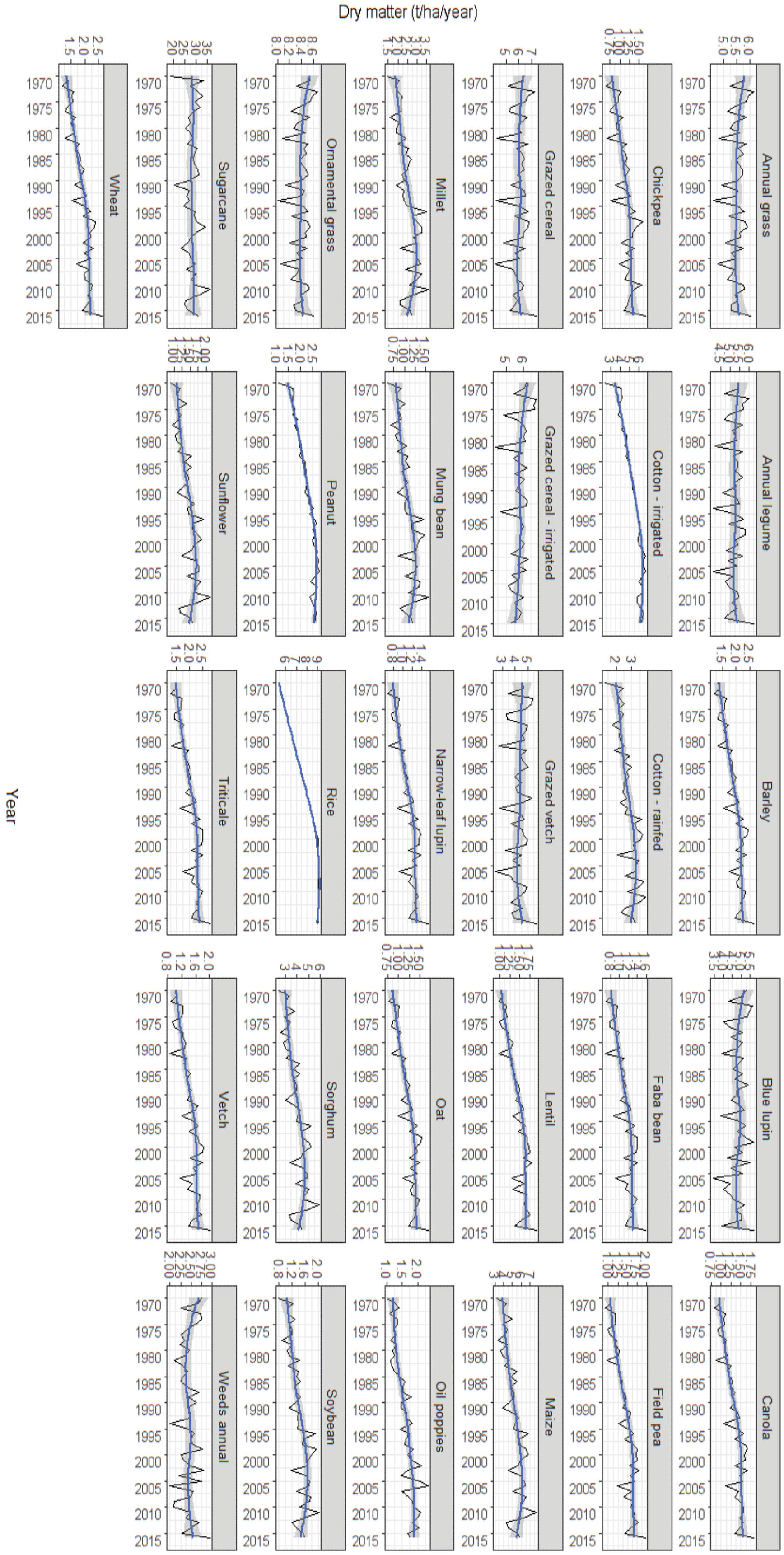
Productivity improvement trends

As the model of crop growth is based on recent agricultural management practices it is necessary to scale the modelled dry matter production through time according to long term trends in farm crop productivity. Taking 2000 as the base year, modelled yields have been scaled from this time at the indicative rate (1.36 per cent pa) for the 1970–2000 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 average annual yield for major crops. The yields show high fluctuations due to factors such as climate with the blue line denoting the general trend of the yields for considered crops from 1970 – 2016. Annual yield data plays a major role in the flow of carbon masses within FullCAM, with residues incorporated into soil over the growing period and after the harvest event. Most crops show an increasing trend from 1970 with a slight decline post 2010.

Figure 6.E.14 Australian average crop yields for crop, tonnes dry matter/ha/year, 1970–2016



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 per cent 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 per cent of the variance in crop yield.

Annual species growth model

The annual growth model is designed to model annual crop growth. Crop growth being for a plant that is planted, grown and then harvested in an annual rotation. 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.15 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

$$\textit{Daily fraction} = \frac{1}{1 + e^{\left(\frac{\textit{An\_season\_day}\ \text{sigmoidal GrowthA}*\textit{An\_max\_days}}{\text{sigmoidal GrowthB}*\textit{An\_sow\_day}*\textit{An\_max\_days}}\right)}}$$

Perennial species growth model

Running model simulations with perennial species under the annual growth model is unrealistic as it has no ability to simulate an ongoing growth cycle. This has an impact on the fidelity of grassland simulations, producing results that do not represent perennial growth and produce less soil carbon capture than generally expected from a perennial pasture species.

The CSIRO has provided monthly data for perennial grass species in Australia. Combined with a perennial growth model in FullCAM, this data is used 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.

Appendix 6.F Post-1990 Plantations – forest growth model

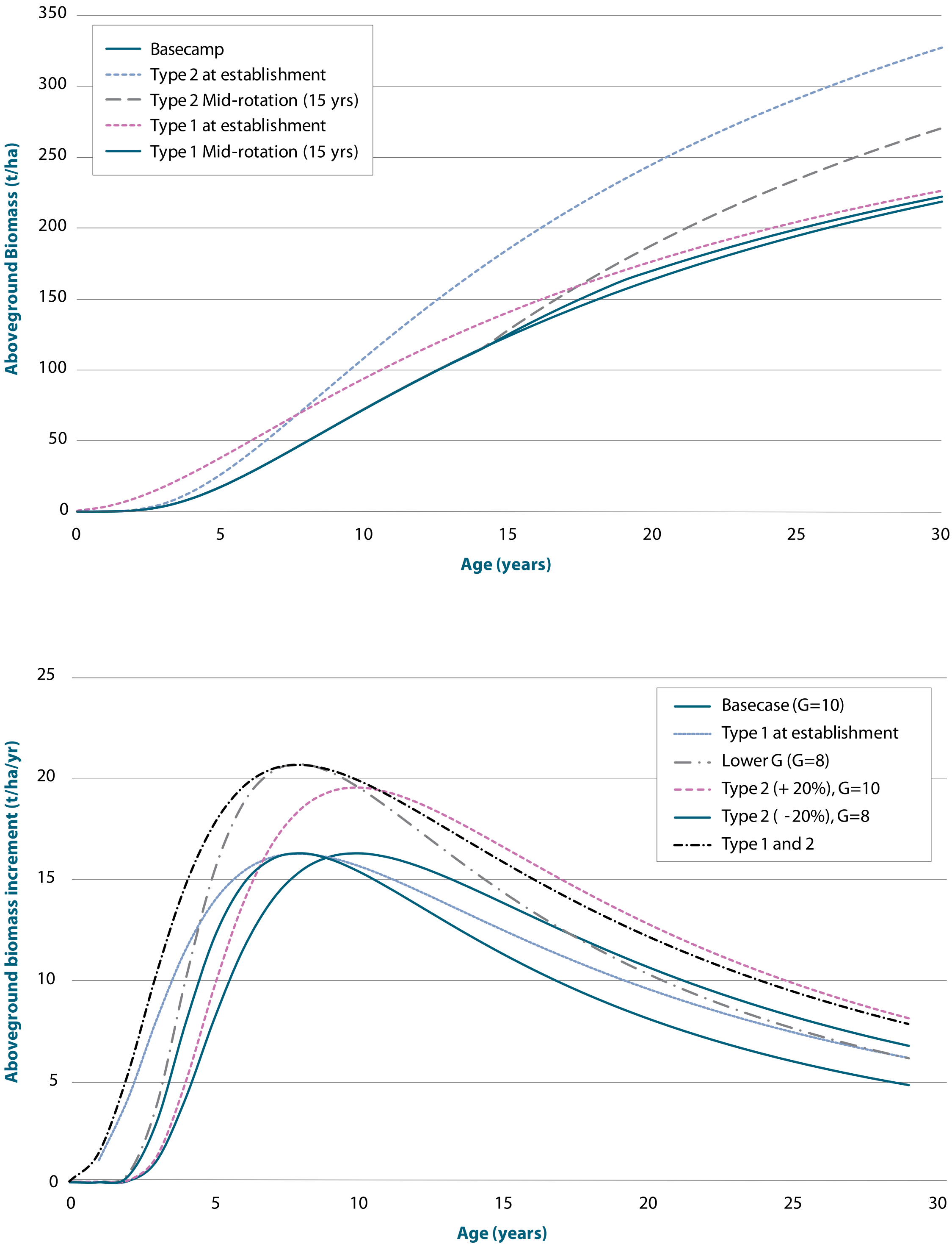
Forest growth model

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 per cent more biomass compared to 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 (effective 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



Appendix

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 FullCAM. 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 (Waterworth *et al.* (2007); Roxburgh *et al,* 2019). 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 m3 ha^{-1} yr^{-1} in long rotation systems and 35 m3 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) (Paul and Roxburgh 2020). 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 per cent and 95 per cent 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 per cent 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, m3 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

NPI	Plantation Type	Species	FPI low	FPI mean	FPI high	Min MAI	Average MAI	Max MAI	Rotation length
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	Southern Pines	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	Southern Pines	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	Southern Pines	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 spp.*	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

$$r = (\text{MAVI x Rotation Length x Basic Density x Expansion Factor}) / M \quad (6F\_1)$$

A model was then fitted to the *r* and *M* data by plantation type (hardwood/softwood) and rotation length (short or long) (Figure 6.F.2) (Equation 6F_2). A separate model based on state was also developed using the same regression to allow predictions for the small area (< 5 per cent) 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.

$$r = ar \times (M_i)^{br} \quad (6F\_2)$$

Where *r* = non-endemic species multiplier

ar and ar0 = area specific growth parameters

M_i = maximum above-ground biomass of relative undisturbed native vegetation (Roxburgh *et al.* 2019)

The results of the original calibration are shown in Waterworth *et al.* (2007). However these were recently updated in accordance with the revised *M* input layer (Roxburgh *et al.* (2019). These analyses showed that plantation forests established on sites with high *P* values require lower *r* values than those on sites with lower *M* 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 *IB*) varies with species, site productivity and management. The age of Max *IB* 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 *IB* 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 *IB*. Where a Type 1 response is applied prior to *G* (i.e. between ages 0 and G), the effective age of Max *IB* 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 *IB* and the sum of Type 1 effects on early age growth due to management (Equation 6F_3):

$$G = G_{man} + T1_{pre\text{-}g} \tag{6F\_3}$$

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 original calibration are shown in Waterworth *et al.* (2007). However these were recently updated in accordance with the revised *M* input layer (Roxburgh *et al.* (2019)).

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

$$G = ag + bg \times M \qquad \text{(6F\_4)}$$

Where G = age of maximum biomass increment of unaffected stand

bg = multiplier to account for site productivity

M = unadjusted maximum above-ground biomass of relative undisturbed native vegetation (Roxburgh *et al.* 2019)

ag = region/species dependent intercept

The modified tree yield formula that is used to calculate forest growth for the post-1990 *plantations* sub-category is therefore:

$$I_a = r \times M \times ((y_2 \times e^{-k/d}) - (y_1 \times e^{-k/d-1})) \times (P/P_{av}) \qquad \text{(6F\_5)}$$

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 (Roxburgh *et al* 2019)

y_1 =Type 2 site multiplier at age, a

y_2 = Type 2 site multiplier at age, a^{-1}

$k = 2 \times G$

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 da to da.

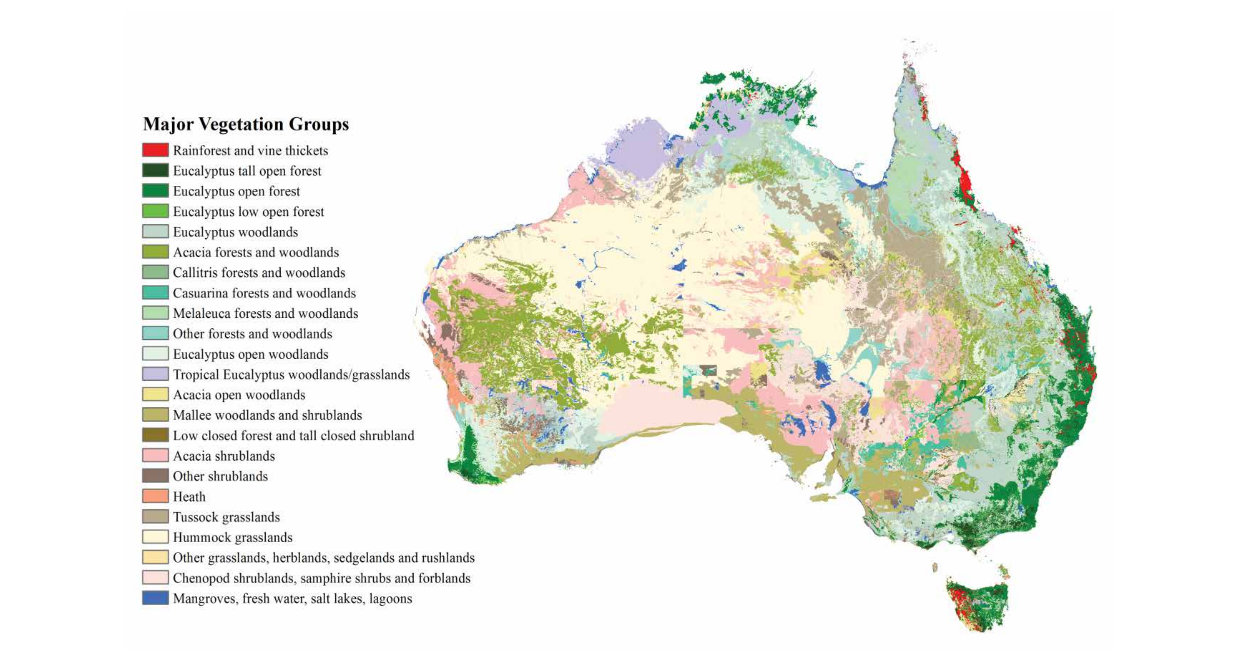
P_{av}=Long term (1970–2018) average FPI value

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 spp*. 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 (salt-tolerant, non-woody plants) 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.

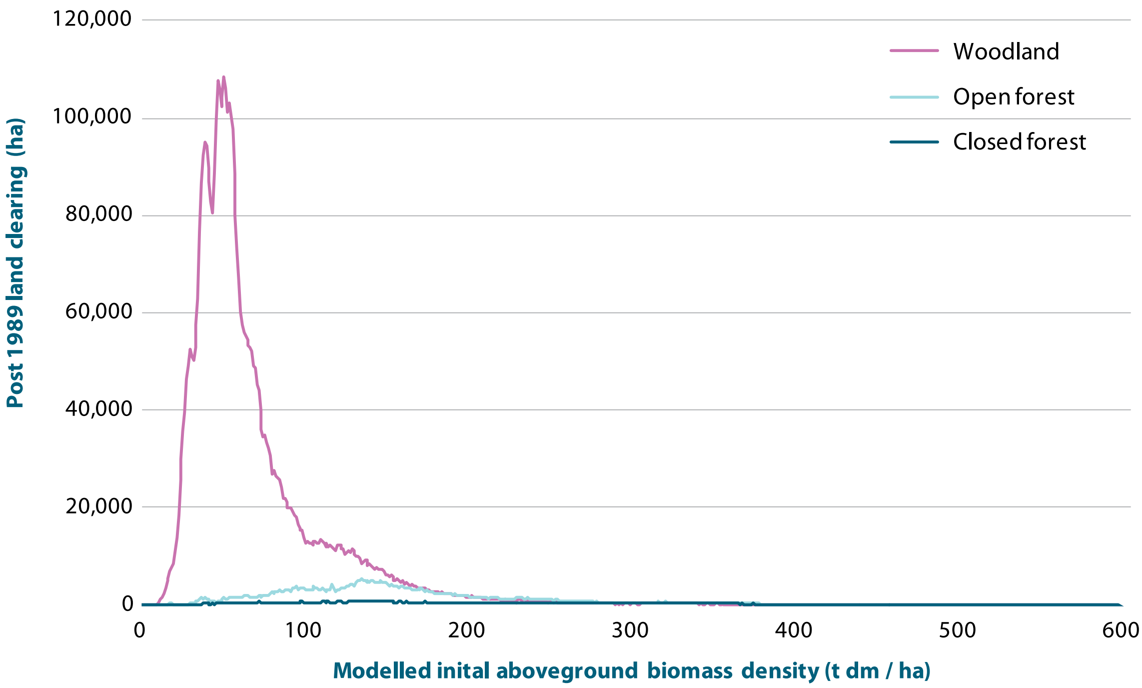
In the Tier 2 model land clearing is stratified into three broad forest classes:

- 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 per cent 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.I. 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

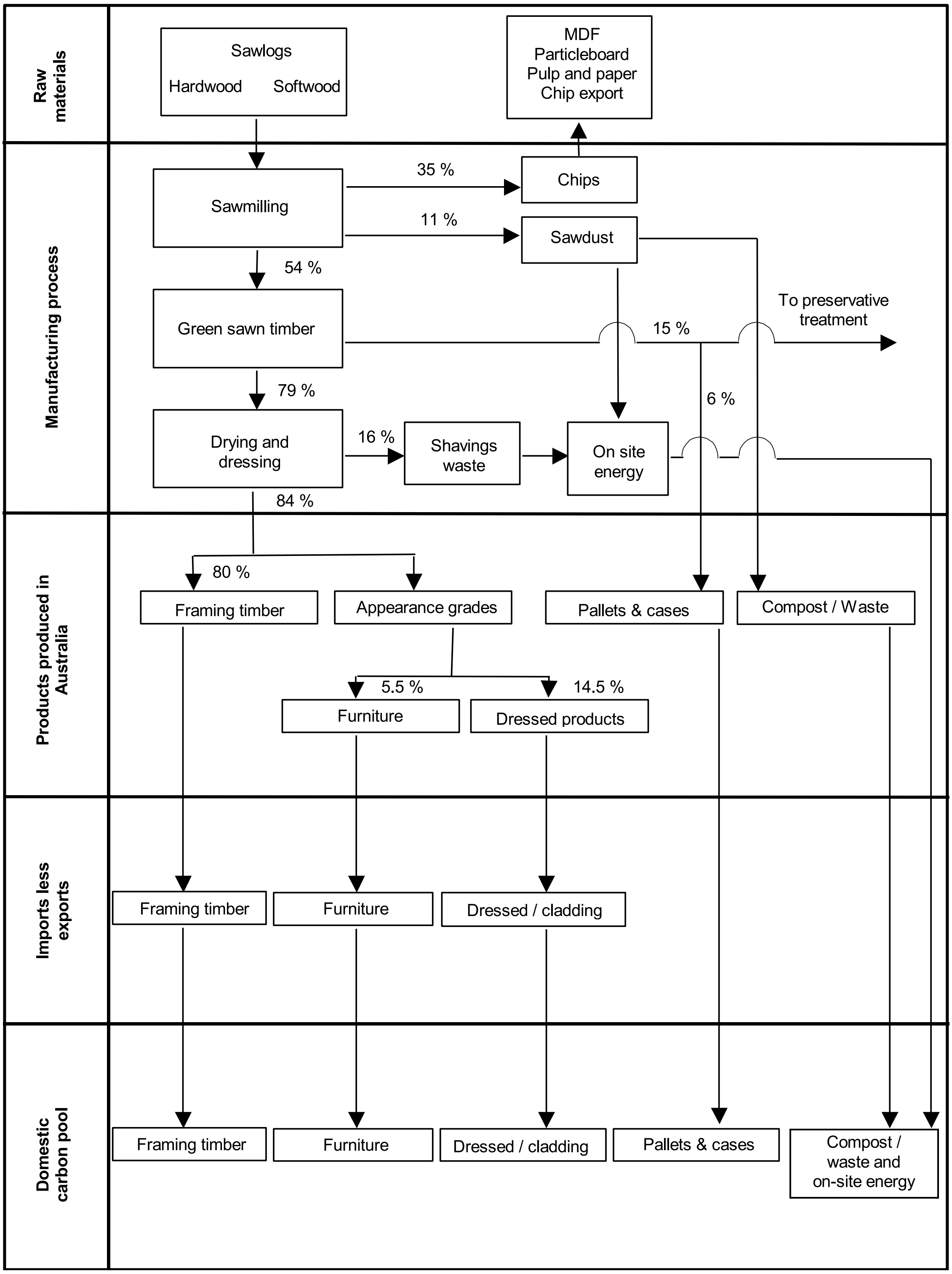
Emissions of soil carbon following conversion are estimated by applying the Roth C model for all first time cleared land (See Appendix 6.B). The Roth C model was parameterised with climate data (rainfall, temperature, open pan evaporation) from a representative site in central Queensland.

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

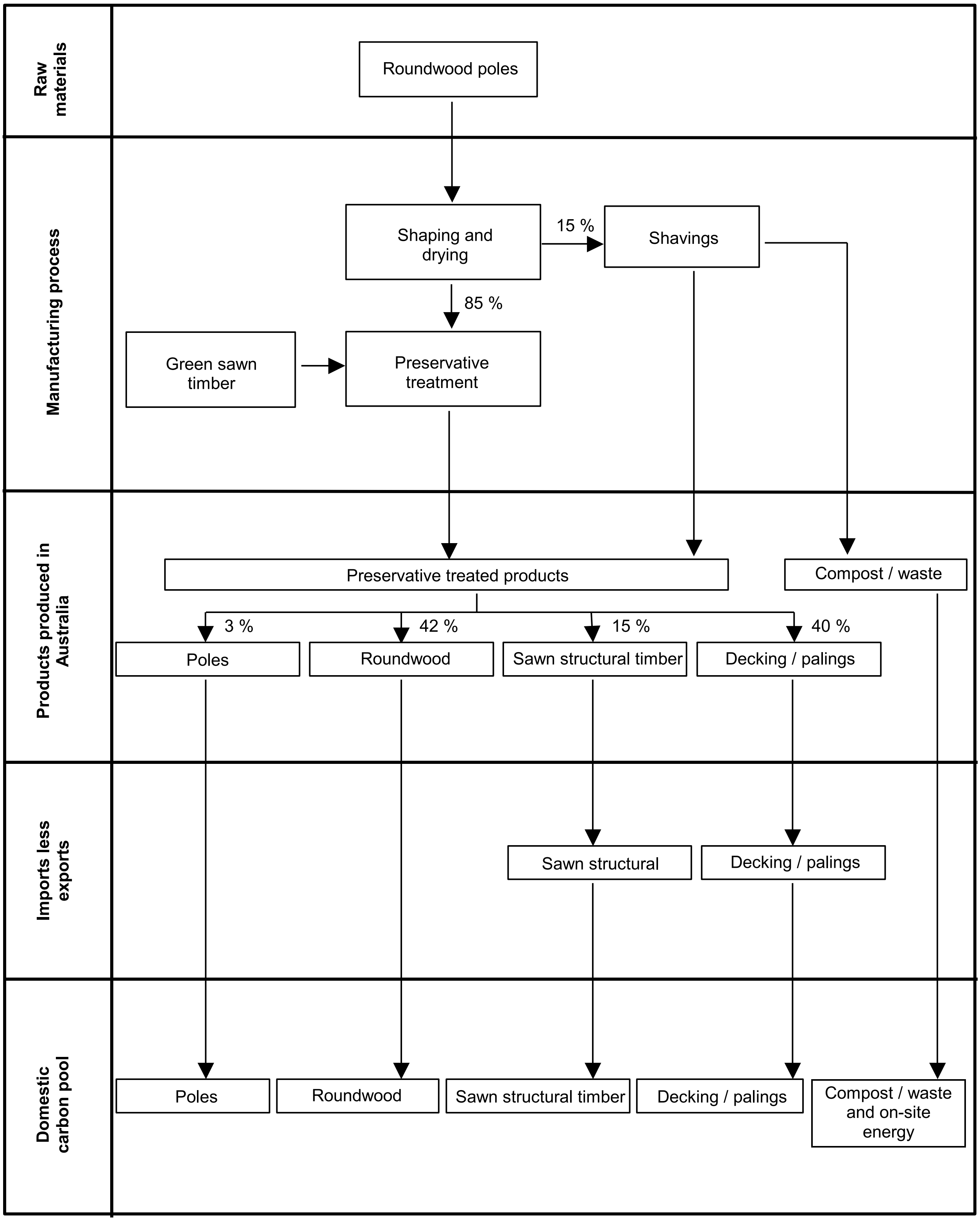


Figure 6.I.3 National Carbon Accounting Model for Wood Products – Wood Flows in plywood production

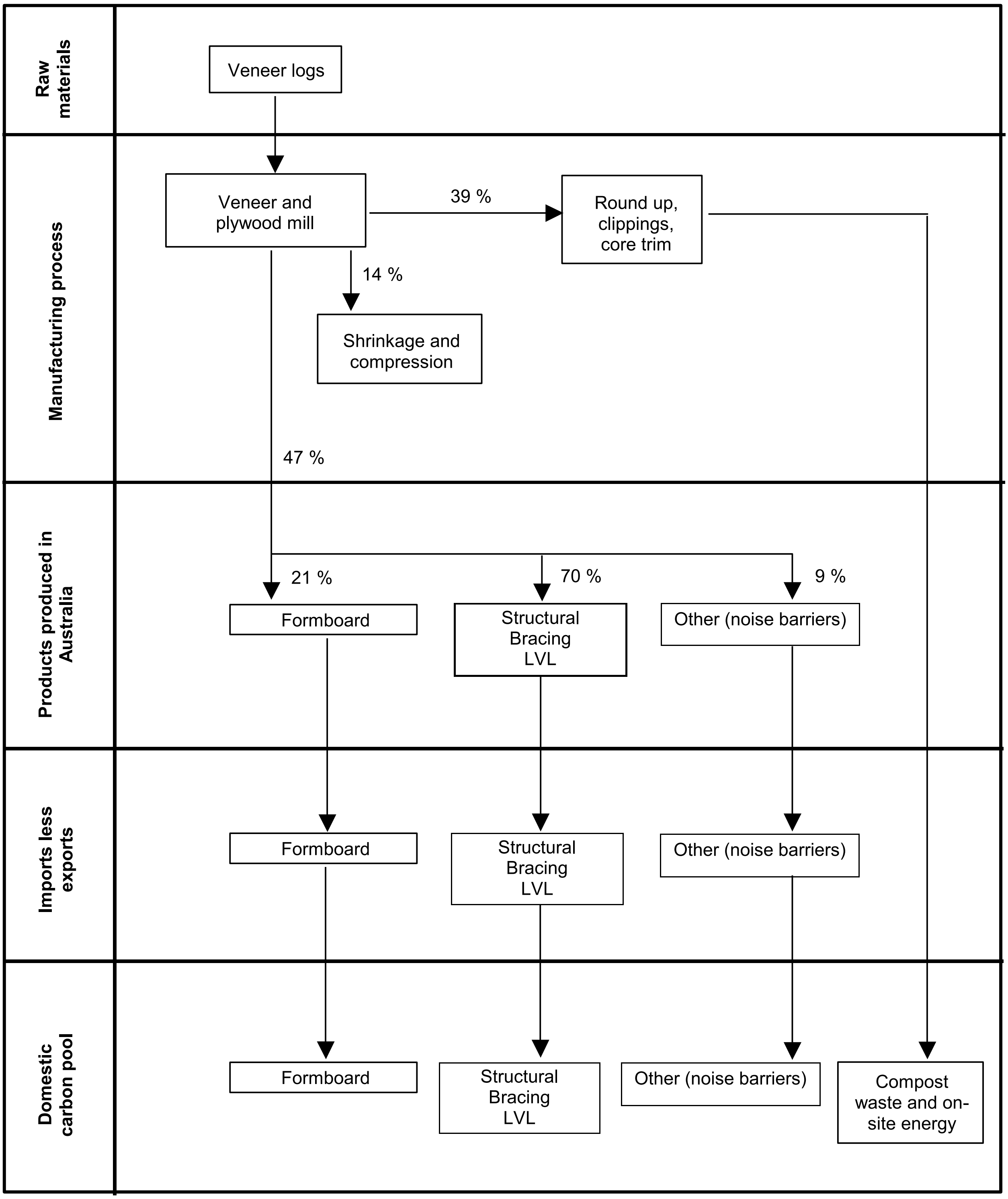


Figure 6.I.4 National Inventory Model for Wood Products – Wood flows in plywood production

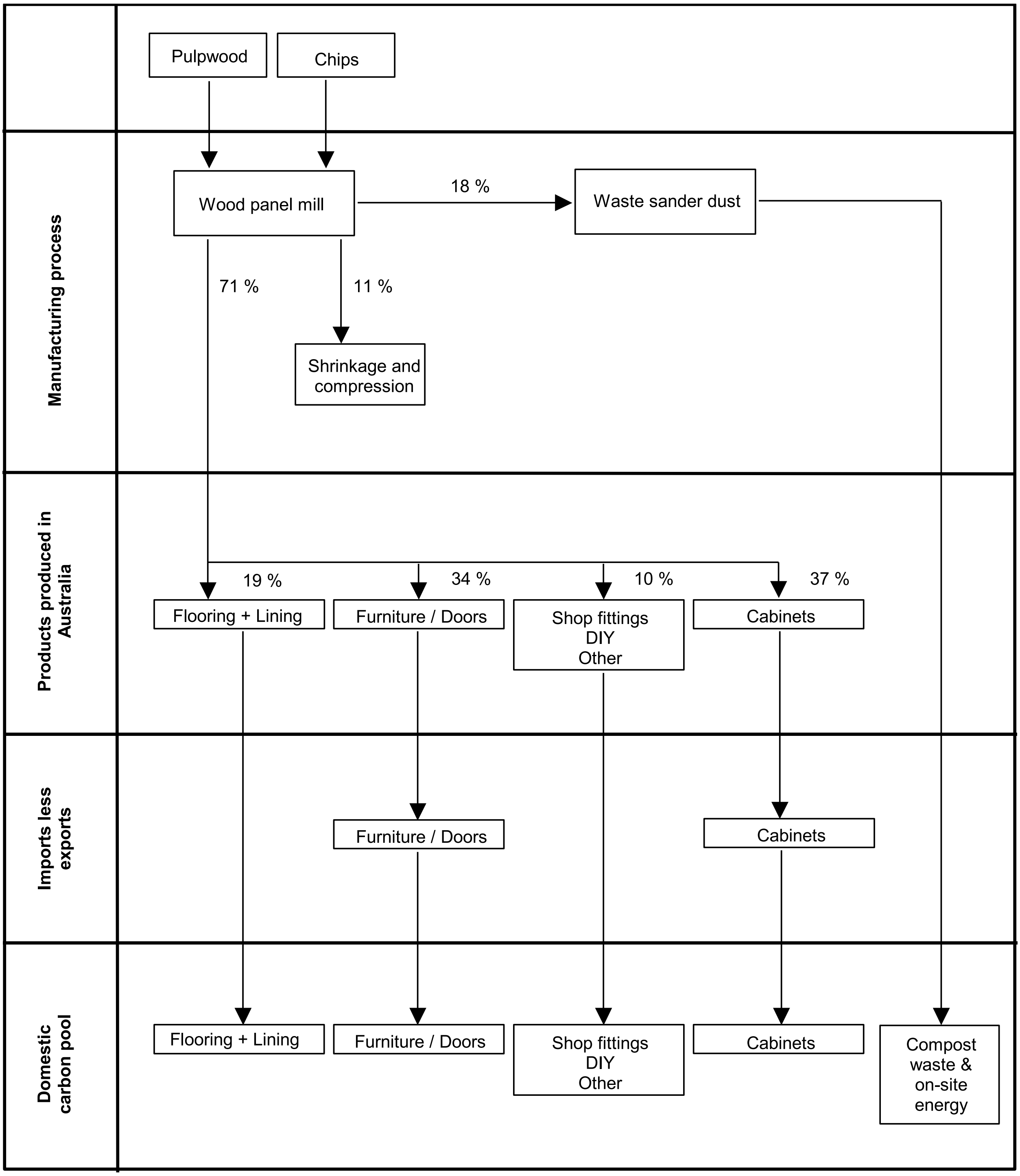
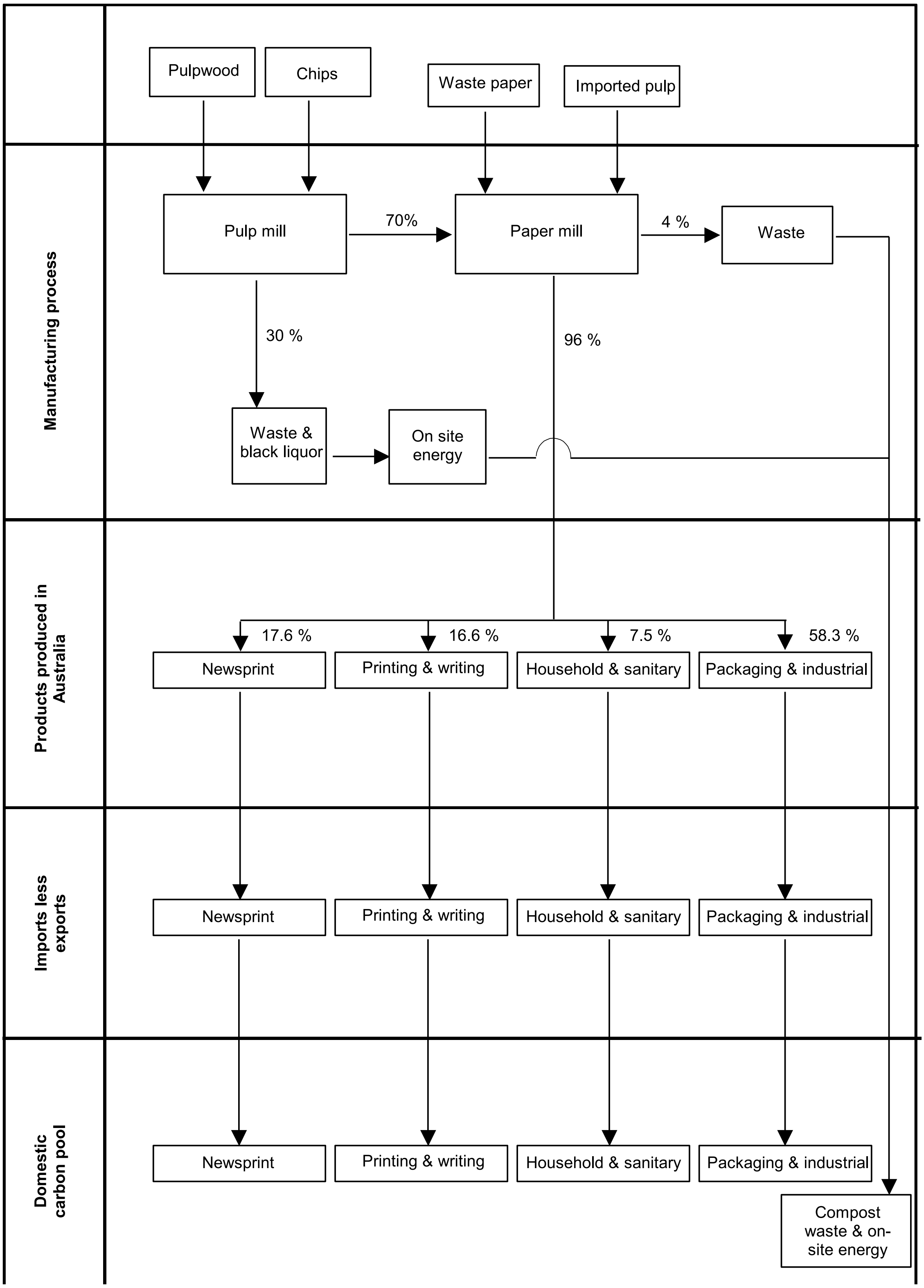
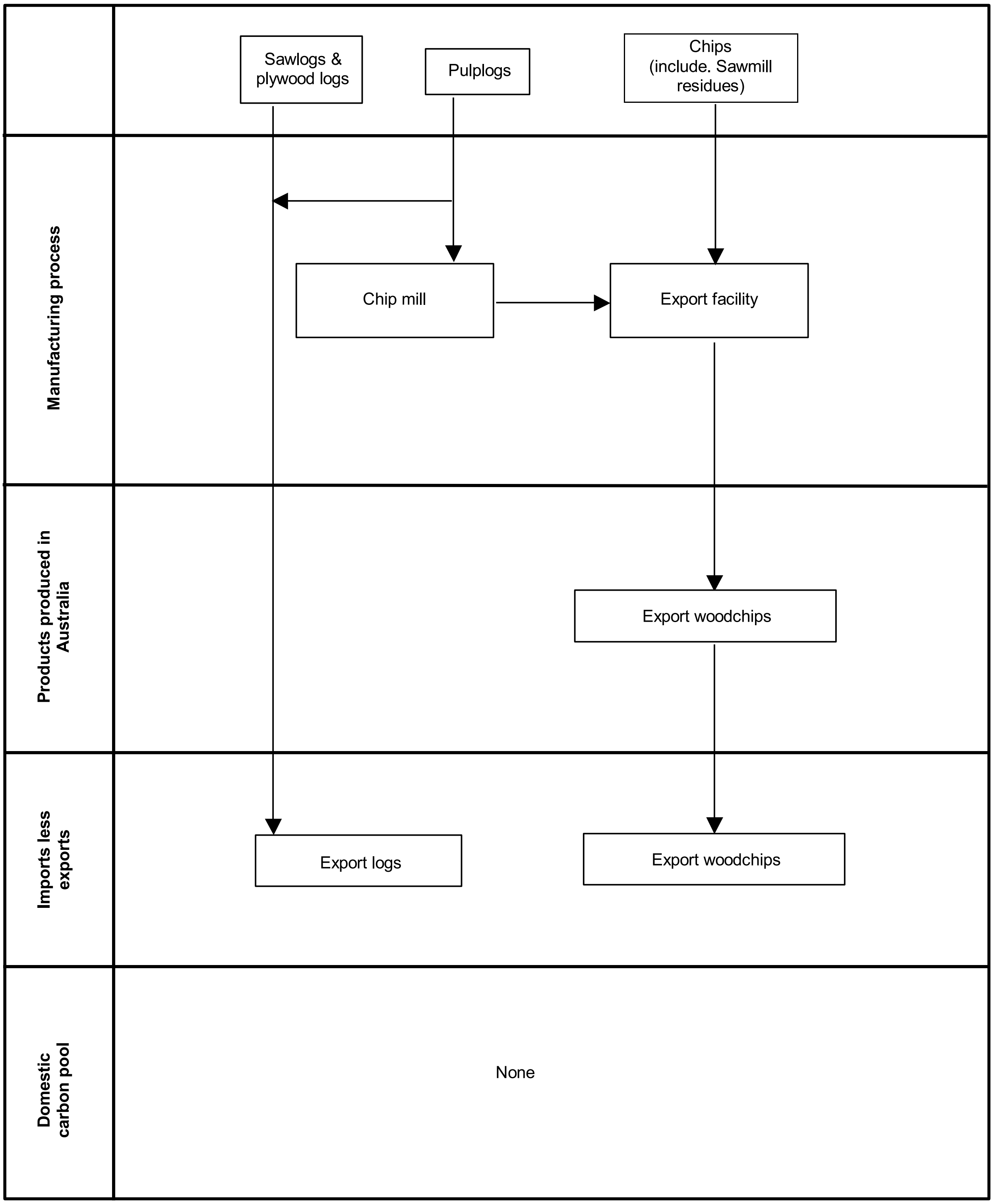


Figure 6.I.5 National Inventory Model for Wood Products – Wood flows in MDF and particleboard manufacture*



* percentages shown for particleboard manufacture – see model for details on MDF

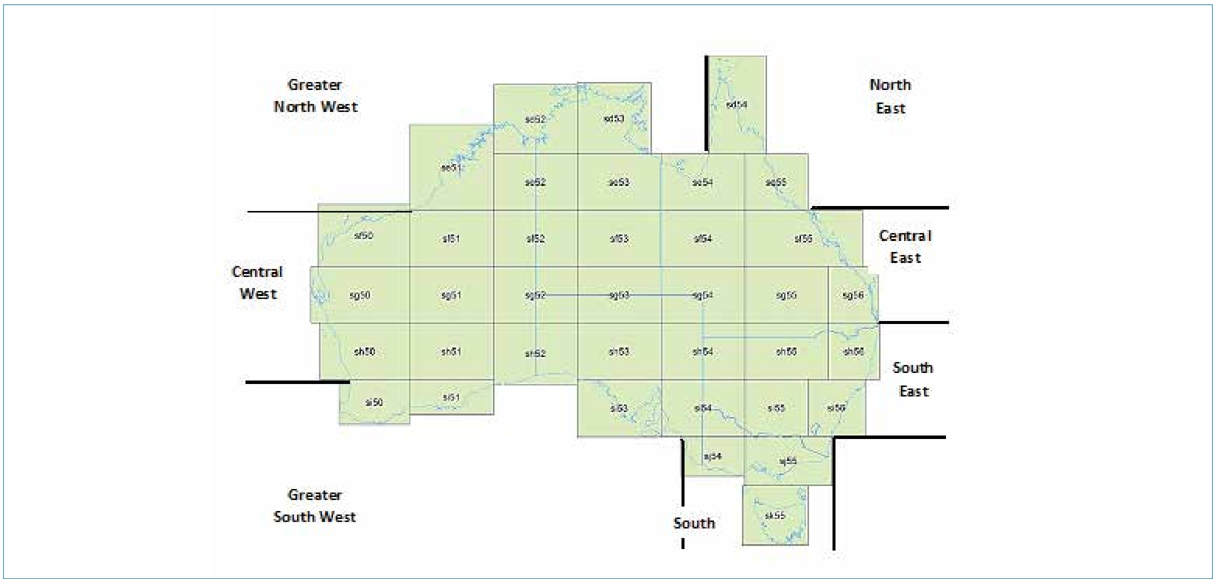
Figure 6.I.6 National Inventory Model for Wood Products – Wood flows in pulp and paper manufacture



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 (Tables 6.J.3 and 4 below).

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}	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	31.3	621
MG, Central E	0.48	0.68	1.2	90.08	0.8	60.05	0.01	9.44	0.01	1.98	31.3	343
MG, SE	0.46	0.68	0.9	92.87	1.1	114.38	0.01	0.76	0.01	0.16	31.3	285
MG, South	0.45	0.77	0.87	121	1.13	157	0.01	0.76	0.01	0.16	31.3	145
MG, Greater SW	0.45	0.77	0.3	101	1.7	238	0.01	0.76	0.01	0.16	31.3	205
MG, Central W	0.45	0.77	0.3	101	1.7	238	0.01	0.68	0.01	2	31.3	118
MG, Greater NW	0.47	0.76	1.34	406.19	0.66	199.34	0.01	0.68	0.01	2	31.3	367
TM, NE	0.41	0	0	6.4	0	18	0	0	0	0.02	n/a	125
TM, Central E	0.41	0	0	6.4	0	18	0	0	0	0.02	n/a	125
TM, SE	0.41	0	0	7	0.00	5	0	0	0	0.02	n/a	191
TM, South	0.41	0	0	7	0	5	0	0	0	0.02	n/a	169
TM, Greater SW	0.41	0	0	6.4	0	18	0	0	0	0.02	n/a	147
TM, Central W	0.41	0	0	6.4	0	18	0	0	0	0.02	n/a	413
TM, Greater NW	0.41	0	0	6.4	0	18	0	0	0	0.02	n/a	413

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 spp.	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
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 6.11. 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 *etal.* 2015), (Bulmer, Schwendenmann, and Lundquist 2016b), (Bulmer, Schwendenmann, and Lundquist 2016a), (Bhattacharyya, Mitra, and Raha 2015), (Rodrigues *etal.* 2015), (Patil *etal.* 2014), (Perera and Amarasinghe 2014)	(Duke, Mackenzie, and Wood 2013), (Santini *et at.* 2013)	(Alongi *etal.* 2003), (Alongi, Clough, and Robertson 2005), (Mackey 1993), (Burchett *etal.* 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 *etal.* 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 *etal.* 1996), (Goulterand Allaway 1979), (Woodroffe *etal.* 1988), (Murray 1985)	(Carnell *etal.* 2015), (Livesley and Andrusiak 2012), (Saintilan *etal.* 2013), (Lovelock ef *al.* 2013), (Page and Dalai 2011), (Matsui 1998), (Howe, Rodriguez, and Saco 2009), (Brown *et al.* 2016), (KELLEWAYefa/. 2015), (Salmo, Lovelock, and Duke 2013), (Kaly, Eugelink,and Robertson 1997)
Aegiceras spp.	(Hossain *etal.* 2016)	(Duke, Mackenzie, and Wood 2013)	(Lichacz, Hardiman,and Buckney 2009), (Saintilan 1997b), (Saintilan 1997a)		
Ceriops spp.	(Binh and Nam 2014), (Slim *et at.* 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 spp.	(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 spp.	(Rodrigues *etal.* 2015), (Kauffman *etal.* 2011), (Perera and Amarasinghe 2014), (Slim *etal.* 1996), (Duke, Burrows, and Mackenzie 2015)	(Clough and Scott 1989), (Duke, Mackenzie, and Wood 2013)	(Alongi *etal.* 2003), (Alongi, Clough, and Robertson 2005), (Duke, Burrows, and Mackenzie 2015), (Robertson and Daniel 1989), (Comley and McGuinness 2005), (Tamooh *etal.* 2008)		
Sonneratia spp.	(Kauffman *etal.* 2011), (Bhattacharyya, Mitra, and Raha 2015),	(Duke, Mackenzie, and Wood 2013)	(Ball and Pidsley 1995), (Tamooh *etal.* 2008)		
Bruguiera spp.	(Kauffman *etal.* 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)		

Species / habitat type	Carbon fraction	Wood density	AGB/BGB	Litter production and Litter standing stock	soc
Excoecaria spp.	(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)		
Tidal marsh	(Hemminga *etal.* 1996), (Cartaxana and Catarino 1997)	n/a	(Clarke and Jacoby 1994), (Lichacz, Hardiman, and Buckney 2009), (Macreadie, Hughes, and Kimbro 2013)	(Van DerValkand Attiwill 1983)	(Carnell *etal.* 2016), (Carnell *etal.* 2015), (Kelleway *etal.* 2016), (Macreadie, Hughes, and Kimbro 2013), (Macreadie *etal.* 2017), (Livesley and Andrusiak , (Saintilan *etal.* 2013), (Lovelock *etal.* 2013), (Page and Dalai 2011), (Howe, Rodriguez, and Saco 2009), (Brown *etal.* 2016), (KELLEWAY *et al.* 2015), (Salmo, Lovelock, and Duke 2013)
U-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 in Table 6.J.12 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)

Table 6.J.6 Relative abundance of major seagrass species within each Coastal Region. within each Coastal Region. References are listed in Table 6.J.8

Species	North East Coast	Central East Coast	South East Coast	South Coast	Greater South West Coast	Central West Coast	Greater North West Coast
Amphibolis antarctica	0	0	0	0.1	0.35	0.84	0
Cymodocea spp.	0.1	0.1	0	0	0	0.07	0.3
Enhalus acroides	0	0	0	0	0	0.01	0.05
Halodule uninervis	0.35	0.35	0	0	0.05	0.01	0.1
Halophila spp.	0.45	0.4	0.13	0.1	0.05	0.01	0.45
Posidonia spp.	0	0	0.46	0.1	0.5	0.05	0
Thalassia hemprichii	0.05	0.05	0	0	0	0.01	0.1
Zostera muelleri	0.05	0.1	0.41	0.7	0.05	0	0

Table 6.J.7 Seagrass model parameter values obtained from the scientific literature. References are listed in Table 6.J.9

Parameter	Species	North East Coast	Central East Coast	South East Coast	South Coast	Greater South West Coast	Central West Coast	Greater North West Coast
Carbon fraction	*Amphibolis antarctica*	0	0	0	0.3	0.3	0.3	0
	Cymodocea spp.	0.3	0.3	0	0	0	0.3	0.3
	Enhalus acroides	0	0	0	0	0	0.3	0.3
	Halodule uninervis	0.3	0.3	0	0	0.3	0.3	0.3
	Halophila spp.	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Posidonia spp.	0	0	0.3	0.3	0.3	0.3	0
	Thalassia hemprichii	0.3	0.3	0	0	0	0.3	0.3
	Zostera muelleri	0.3	0.3	0.3	0.3	0.3	0	0
BGB (t ha^{-1})	*Amphibolis antarctica*	0	0	0	2.77	2.77	2.77	0
	Cymodocea spp.	0.6	0.6	0	0	0	0.6	0.6
	Enhalus acroides	1.52	1.52	0	0	0	1.52	1.52
	Halodule uninervis	0.07	0.07	0	0	0.07	0.07	0.07
	Halophila spp.	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Posidonia spp.	0	0	3.4	3.4	3.4	3.4	0
	Thalassia hemprichii	3	3	0	0	0	3	3
	Zostera muelleri	1.8	1.8	1.8	1.8	1.8	0	0
SOC (t ha^{-1})	*Amphibolis antarctica*	0	0	0	28	28	38	0
	Cymodocea spp.	63	63	0	0	0	63	63
	Enhalus acroides	51	51	0	0	0	51	51
	Halodule uninervis	52	52	0	0	52	52	52
	Halophila spp.	86	86	86	86	86	86	86
	Posidonia spp.	0	0	60	200	200	60	0
	Thalassia hemprichii	24	24	0	0	0	24	24
	Zostera muelleri	81	31	151	182	182	0	0

Table 6.J.8 Sources of biogeographical and relative abundance data for seagrass species within Australian state waters. Full details are provided in the source documents list in Table 6.J.12 below.

State/Territory	Source documents
National	(Short *et al.* 2007)
Queensland	(Lee Long, Mellors, and Coles 1993; Lee Long, McKenzie, and Coles 1997; Lee Long *et al.* 1998; Lee Long *et al.* 2002; Campbell *et al.* 2002; Abal and Dennison 1996; Carruthers *et al.* 2002; Poiner, Staples, and Kenyon 1987; Coles *et al.* 1994; Coles *et al.* 1996)
New South Wales	(Astles *et al.* 2010; Fyfe 2004; King 1988; Larkum and West 1990; Meehan and West 2002; Sanderson 1997; West 2010; Williams and Meehan 2004)
Victoria	(Roob and Ball 1997; Roob, Werner, and Morris 1998; Blake, Roob, and Patterson 2000; Blake and Ball 2001; O'Hara, Norman, and Staples 2002; Ball and Blake 2007b, 2007a; Walker 2011; Monk *et al.* 2011; Pope, Monk, and Ierodiaconou 2013; Ball 2013)
Tasmania	(Barrett *et al.* 2001)
South Australia	(Edyvane 1999; Bourman, Maurray-Wallace, and Harvey 2016)
Western Australia	(Carruthers *et al.* 2007; Walker, Kendrick, and McComb 1988; Hillman, McComb, and Walker 1995; McMahon *et al.* 1997)
Northern Territory	(McKenzie 2008; Roelofs, Coles, and Smit 2005; Poiner, Staples, and Kenyon 1987; Kenyon, Conacher, and Poiner 1997)

Table 6.J.9 Sources of seagrass model parameter values. Full details are provided in Table 6.J.12.

Carbon fraction	BGB	SOC
(Duarte 1990; Moore and Wetzel 2000)	(McKenzie 1994; Duarte *et al.* 1998; Paling and McComb 2000)	(Lavery *et al.* 2013; Brown *et al.* 2016; Carnell *et al.* 2015)

Table 6.J.10 List of locations subject to capital dredging projects recorded for the period 1990 to 2016. Shapefiles (Kettle, 2017) of each project provide a polygon representing the dredge footprint and area excavated.

State	Location name	Commencement Year	Polygon Area (km2)
NSW	Port Macquarie Marina	2001	0.0392
NSW	Newcastle Port	2005	3.08
NSW	Port Macquarie Marina	2008	0.136
NSW	Port Macquarie Marina	2008	0.0392
NT	Bing Bong	1994	0.238
NT	Port Darwin	2000	2.44
NT	Port of Groote Eylandt	2010	0.07
NT	Port Darwin	2011	0.27
Qld	The Jetty Precinct	1993	0.14
Qld	Port Hinchinbrook Marina	1995	0.206
Qld	Laguna Quays Marina	1995	0.114
Qld	Port of Karumba	1996	0.75
Qld	Nelly Bay Marina	2002	0.148
Qld	Abell Point Marina	2003	0.252
Qld	Hay Point Harbour	2006	0.4
Qld	Port of Hay Point	2007	6.25
Qld	Ephraim Island Marina	2007	0.4764

State	Location name	Commencement Year	Polygon Area (km2)
Qld	Gladstone Marina	2009	0.514
Qld	Keppel Bay Marina	2010	0.227
Qld	Port of Gladstone	2011	11.9
Qld	Port of Gladstone	2011	4.38
Qld	Port of Brisbane	2011	3.46
Qld	Port Denison	2011	0.26
Qld	Port of Weipa	2012	2.94
Qld	Brisbane Airport Middle Banks	2014	6.07
Qld	Port of Cooktown	2014	0.11
SA	Port Vincent Marina (CYSA)	1996	0.09
SA	Copper Cove Marina	2005	0.25
SA	Port of Whyalla	2013	0.466
SA	Whyalla Marina	2013	0.076
SA	Whyalla Wharf	2013	0.06
Vic	Port Melbourne	2007	25.3
Vic	Port Melbourne	2007	8.27
Vic	Portland Marina	2012	0.902
Vic	Queenscliff Harbour	2012	0.158
Vic	Yaringa Marina	2014	0.05
WA	Port of Bunbury	1994	0.92
WA	Port Dampier	1995	7.76
WA	Exmouth Harbour	1997	0.282
WA	Albany Waterfront Marina	2000	0.093
WA	Port of Geraldton	2003	1.45
WA	Port of Geraldton	2003	1.05
WA	Hillarys Boat Harbour	2004	0.265
WA	Fremantle Harbour	2005	1.53
WA	Jurien Bay Boat Harbour	2005	0.152
WA	Emu Point Boat Harbour	2006	0.049
WA	Rous Head Harbour	2007	0.183
WA	Cockburn Marine Complex	2009	7.44
WA	Barrow Island	2009	1.4
WA	Barrow Island	2009	0.271
WA	Casuarina Boat Harbour	2009	0.04
WA	Port Walcott	2010	14.4
WA	Port Dampier	2010	0.408
WA	Wheatstone LNG Port	2011	0.167
WA	Casuarina Boat Harbour	2015	0.04

Table 6.J.11 Seagrass habitat extent shapefiles

State or national seagrass extent	Source Credit	Date accessed	Accessed at
Australia, base layer	World Imagery: DigitalGlobe (2016) Vivid – Australia	28/08/2017	http://goto.arcgisonline.com/maps/World_Imagery
Australia, national seagrass set	CSIRO (2015): Seagrass Dataset – CAMRIS. v1. CSIRO. Data Collection Lucieer V, Walsh P, Flukes E, Butler C, Proctor R, Johnson C (2017). Seamap Australia - a national seafloor habitat classification scheme. Institute for Marine and Antarctic Studies (IMAS), University of Tasmania (UTAS).	28/08/2017 12/04/2021	https://metadata.imas.utas.edu.au/geonetwork/srv/eng/metadata.show?uuid=4739e4b0-4dba-4ec5-
NSW	NSW Department of Primary Industries, New South Wales Government (2013). Estuarine Macrophytes of NSW	05/09/2017	http://metadata.imas.utas.edu.au/geonetwork/srv/en/metadata.show?uuid=281FAA64-F6F3-400C-A48F-D342E4ABCA83
NT	Mount, R.E. and PJ. Bricher, 2008. Estuarine, Coastal and Marine (ECM) National Habitat Map Series Project – National Intertidal-Subtidal Benthic Habitat (NISB) Map (Original dataset not available, see "Australia, National seagrass set" above)	31/08/2017	https://demo.ands.org.au/northern-territory-national-mapplus/644037?source=suggested_datasets
NT	Smit, N (2011). Darwin Harbour marine habitats. Department of Environment and Natural Resources, Northern Territory Government	31/08/2017	http://metadata.imas.utas.edu.au/geonetwork/srv/eng/metadata.show?uuid=2e754ed7-caab-4640-a133-5ead9e077edb
QLD	James Cook University (2014). Torres Strait Seagrass Mapping Consolidation	05/09/2017	http://metadata.imas.utas.edu.au/geonetwork/srv/eng/metadata.show?uuid=e7ea913e-2528-4ece-847c-a25722e11c1f
QLD	Department of National Parks, Sport and Racing, Queensland Government (2008). Moreton Bay broadscale habitats 2008	05/09/2017	http://metadata.imas.utas.edu.au/geonetwork/srv/eng/metadata.show?uuid=806decf7-1260-44b8-b5a0-cc96a746cedc
QLD	TropWATER, JCU: NESP TWQ 3.1 – Collation of spatial seagrass data (meadow extent polygons, species presence/ absence points) from 1984-2014 for the Great Barrier Reef World Heritage Area (GBRWHA)	05/09/2017	http://eatlas.org.au/data/uuid/77998615-bbab-4270-bcb1-96c46f56f85a
QLD	Mount, R.E. and PJ. Bricher, 2008. Estuarine, Coastal and Marine (ECM) National Habitat Map Series Project – National Intertidal-Su btidal Benthic Habitat (NISB) Map (Original dataset not available, see "Australia, National seagrass set" above)	05/09/2017	https://demo.ands.org.au/queensland-national-intertidal-map-plus/644047?source=suggested datasets
SA	Mount, R.E. and PJ. Bricher, 2008. Estuarine, Coastal and Marine (ECM) National Habitat Map Series Project – National Intertidal-Su btidal Benthic Habitat (NISB) Map	30/09/2017	https://demo.ands.org.au/south-australia-national-map-plus/644036?source=suggested_datasets
Vic	The State of Victoria, Department of Economic Development, Jobs, Transport and Resources, 2017, Port Phillip Bay seagrass mapping at nine aerial assessment regions in April 2011	26/09/2017	https://www.data.vic.gov.au/data/dataset?q=seagrass
Vic	The State of Victoria, Department of Economic Development, Jobs, Transport and Resources, 2017, Port Phillip Bay 1:25,000 Seagrass 2000	26/09/2017	https://www.data.vic.gov.au/data/dataset?q=seagrass

State or national seagrass extent	Source Credit	Date accessed	Accessed at
Vic	Mount, R.E. and PJ. Bricher, 2008. Estuarine, Coastal and Marine (ECM) National Habitat Map Series Project – National Intertidal-Subtidal Benthic Habitat (NISB) Map	26/09/2017	http://geonetwork-dev.tern.org.au/geonetwork/srv/eng/catalog.search#/metadata/DEC149CF-9C87-469F-A041-894C76941048
WA	Mount, R.E. and PJ. Bricher, 2008. Estuarine, Coastal and Marine (ECM) National Habitat Map Series Project – National Intertidal-Su btidal Benthic Habitat (NISB) Map	05/09/2017	http://geonetwork-dev.tern.org.au/geonetwork/srv/eng/catalog.search#/metadata/58215F4D-7E0A-4B66-8D3FDBCA95EF6FCD

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Appendix

Appendix 6.K Biomass burning

There are six different types of biomass burning events (Table 6.K.1). With the exception of prescribed burns, biomass burning events are monitored via monthly Advanced Very High Resolution Radiometer imagery (AVHRR, 1988–present, with 1970–1987 gap-filling as per Meyer 2016). The FullCAM-predicted impacts of fire were predicted at the pixel resolution of 25 x 25 m, with the fire events only being applied to a proportion of cells randomly selected within the fire scar in accordance with the assumed fire patchiness, *P*. *P* has been shown to vary between the six different burning events (Table 6.K.1).

For historical fire events not detected using AVHRR imagery, assumptions were made in order to simulate spatial and temporal variations in fires. These assumptions were based on available estimates of typical fire return intervals, time of year fires occur, area of the fire scar, and the proportion of early dry season (EDS) to late dry season (LDS) burns in tropical savanna fire zones where available from previous studies and expert opinion (Table 6.K.2)(Meyer *et al.* 2009; Murphy *et al.* 2013). To introduce variation in the simulated fire events, uniform probability distribution functions were applied to vary these assumptions between what was deemed to be their upper and lower bounds.

Areas of land where prescribed burns were conducted are identified either through;

1. the supply of digitised, spatially explicit mapping of prescribed burning treatment areas from state or territory fire authorities (spatial data); or
2. tabular reports of the sum of land areas treated with prescribed burning from state or territory fire authorities (tabular data).

For this report, New South Wales, Victoria, the Australian Capital Territory and South Australia provided spatial data to allow a Tier 3 modelling approach for prescribed burning. The remaining states, Western Australia, Queensland, Tasmania and the Northern Territory, are modelled using a Tier 2 approach. It is anticipated prescribed burning estimates in the future will be created using a nationally consistent Tier 3 approach once complete spatial data becomes available from all states and territories and quality assurance has been completed.

Table 6.K.1 Assumed patchiness (P, varying between 0 and 1) in various fire zones of Australia. Data sources: Meyer *et al.* (2015) and Roxburgh *et al.* (2015).

Fire zone	Fire type	Patchiness (P)
Southern Australian forests & woodlands	Prescribed	0.650
	Wildfire	0.800
Tropical savanna Woodland; > 1000 mm MAR	EDS	0.709
	LDS	0.889
Tropical savanna Woodland; < 1000 mm MAR	EDS	0.790
	LDS	0.970

Table 6.K.2 'Rules' applied when simulating prescribed fires or wildfires prior to 1988; including, typical return intervals, Julian days at which fires occur, area of the fire scar, and relative proportion of EDS and LDS fires in the tropical savanna woodlands. All wildfires were assumed to have scar areas of 3000x3000 m while all other fires were assumed to have scar areas of 1500x1500 m. Based on empirical evidence and expert option as outline by Murphy *et al.* (2013) and Meyer *et al.* (2015).

		Wildfires		Prescribed burns or savanna fires[1]		
Region	Vegetation subclass	Fire return interval (yrs)	*Julian day at which fire occurs*	Fire return interval (yrs)	*Julian day at which fire occurs*	Proportion of EDS (or LDS) fires
Temperate	Tall eucalypt forest (B)	31–185	15±30	5–15	105±30[2]	~
	Eucalypt forest (C)	8–147	334±60	5–15	105±30[2]	~
	Rainforest (D)	154–318	105±30	5–15	105±30[2]	~
	Heath (E)	31–154	344±60	5–15	105±30[2]	~
	Eucalypt woodland[3] (H)	31–182	15±30	5–15	105±30[2]	~
	Mallee (N)	31–182	344±60	5–15	105±30[2]	~
Arid & Semi-arid	Tussock grassland (K)	31–182	344±60	5–15	105±30[2]	~
	Acacia shrubland (mulga) (P)	27-156	344±60	5–15	105±30[2]	~
	Tussock grassland (T)	27–156	344±60	5–15	105±30[2]	~
	Acacia woodland (Brigalow) (J)	31–182	344±60	5–15	105±30[2]	~
Tropical Semi-arid	Acacia woodland (O)	31–154	288±30	5–15	105±30[2]	~
	Eucalypt woodland (Q)	8–147	344±60	5–15	105±30[2]	~
	Chenopod shrubland (R)	27–156	344±60	5–15	105±30[2]	~
	Hummock grassland (S)	7–125	288±30	5–15	105±30[2]	~
Tropical	Rainforest (tropical) (A)	154–308	288±30	5–15	105±30[2]	~
	Eucalypt forest & woodland[3] (I)	8–147	288±30	5–15	105±30[2]	~
Monsoonal Savanna Woodland	Melaleuca Woodland (Other)	~	~	5–8	166±60 (258±30)	0.41 (0.59)
		~	~	5–8	166±60 (258±30)	0.20 (0.80)
		~	~	3–7	166±60 (258±30)	0.30 (0.70)
	Open Forest Mixed (hOFM)	~	~	3–6	166±60 (258±30)	0.31 (0.69)
		~	~	15–18	166±60 (258±30)	0.06 (0.94)
		~	~	1–5	166±60 (258±30)	0.41 (0.59)
	Shrubland Hummock (hSHH)	~	~	2–6	166±60 (258±30)	0.58 (0.42)
		~	~	6–9	166±60 (258±30)	0.08 (0.92)
		~	~	3–6	166±60 (258±30)	0.36 (0.64)

Appendix

Region	Vegetation subclass	Wildfires: Fire return interval (yrs)	Wildfires: *Julian day at which fire occurs*	Prescribed burns or savanna fires[1]: Fire return interval (yrs)	Prescribed burns or savanna fires[1]: *Julian day at which fire occurs*	Prescribed burns or savanna fires[1]: Proportion of EDS (or LDS) fires
Monsoonal Savanna Woodland *(continued)*	Woodland Hummock (hWHu)	~	~	2–6	166±60 (258±30)	0.43 (0.57)
		~	~	6–9	166±60 (258±30)	0.14 (0.86)
		~	~	2–6	166±60 (258±30)	0.36 (0.64)
		~	~	1–5	166±60 (258±30)	0.51 (0.49)
	Woodland Mixed (hWMi)	~	~	3–6	166±60 (258±30)	0.15 (0.85)
		~	~	1–5	166±60 (258±30)	0.41 (0.59)
	Open woodland, mixed (IOWM)	~	~	4–8	135±60 (288±30)	0.34 (0.66)
		~	~	4–7	135±60 (288±30)	0.22 (0.78)
		~	~	3–6	135±60 (288±30)	0.34 (0.66)
	Shrubland Hammock (ISHH) WA	~	~	4–8	135±60 (288±30)	0.40 (0.60)
		~	~	4–7	135±60 (288±30)	0.21 (0.79)
		~	~	3–6	135±60 (288±30)	0.38 (0.62)
	Woodland Hammock (IWHu) WA	~	~	4–7	135±60 (288±30)	0.32 (0.68)
		~	~	5–8	135±60 (288±30)	0.11 (0.89)
		~	~	2–6	135±60 (288±30)	0.40 (0.60)
	Woodland, Mixed grass (IWMi)	~	~	3–7	135±60 (288±30)	0.28 (0.72)
		~	~	9–12	135±60 (288±30)	0.18 (0.82)
		~	~	11–14	135±60 (288±30)	0.37 (0.63)
	Woodland, Tussock grass (IWTu)	~	~	2–6	135±60 (288±30)	0.41 (0.59)
		~	~	11–14	135±60 (288±30)	0.18 (0.82)
		~	~	2–6	135±60 (288±30)	0.37 (0.63)

1 Fire return intervals reported by Meyer *et al.* (2015) were divided by *P*as described in the text.

2 Exception is 243±30 in WA, and 151±30 in Qld.

3 When simulating wildfires prior to European settlement, it was assumed that areas of cleared land deemed by Murphy *et al.* (2013) to be 'temperate pasture' or 'tropical and subtropical pasture' were 'temperate eucalypt woodland' and 'tropical eucalypt forest and woodland'.

For all biomass burning events simulated by FullCAM, it is assumed that the live biomass recovers post-burning. As outlined in detail by Paul and Roxburgh (2019), for wildfire simulations (which were not assumed to be stand-replacing fires, and hence only had relatively small impacts on live biomass pools), recovery of live woody biomass was assumed to take 12 years, with the exception of foliage, which took only 3 years. For all other biomass burning simulations, it was assumed that recovery of live woody biomass took 2 years, with the exception of foliage, which took only 0.5 years.

Grass under woody vegetation can be a key component of fine fuel pools. Hence, when simulating biomass burn events, FullCAM is configured to simulate woody vegetation as well as a perennial grass understorey, with the assumed growth rates and die-off rates provided in Table 6.K.3. The proposal area occupied by grass is given by the parameter, A_{grass} (Table 6.K.4).

As outlined in detail by Paul and Roxburgh (2019), the model was calibrated to ensure that the overall emissions and fuel dynamics were consistent with previous estimates under typical conditions. This gave litterfall rates and A_{grass} estimates as shown in Table 6.K.4, and estimates of C loss from live biomass and debris are provided in Tables 6.K.5 and 6.K.6, respectively. Generally, by the time of a return fire event, all of the standing dead material was assumed to have decomposed. However, for any remaining stem, branch or bark standing dead material, the total C lost on burning was assumed to be 31 per cent for intense fires and 14 per cent for less intense fires. For any remaining foliage standing dead material, the total C lost on burning was assumed to be 85 per cent for intense fires and 70 per cent for less intense fires. Of the C lost on burning standing dead pools, there was an assumed 0.90:0.10 split of CO_2-C-to-debris loss of C.

Table 6.K.3 Average growth and die-back (Tonnes DM) simulated for the three different grasses simulated within the fire zones; Perennial grasses in southern fire zones, Monsoonal perennial grass in the high rainfall savanna fire zones, and spinifex in the low rainfall savanna zones.

Month	Perennial grass		Monsoonal perennial grass		Spinifex	
	Growth	Die-off	Growth	Die-off	Growth	Die-off
Jan	5.4057	0.6705	2.0179	0.1355	1.6832	0.1668
Feb	5.3894	0.5999	2.4964	0.1593	2.0796	0.2167
Mar	5.2980	0.7154	2.9649	0.2361	2.2741	0.3767
Apr	5.1781	0.7528	3.1075	0.4244	2.0318	0.4742
May	5.0460	0.7874	2.7842	0.6468	1.7083	0.4086
June	4.9243	0.7369	2.3243	0.5667	1.4555	0.3085
July	4.8606	0.7315	1.9136	0.4512	1.2583	0.2482
Aug	4.9193	0.7143	1.5874	0.3364	1.0939	0.1936
Sept	5.0720	0.6554	1.3596	0.2407	0.9713	0.1436
Oct	5.2462	0.6400	1.2091	0.1882	0.9076	0.1152
Nov	5.4136	0.6020	1.1927	0.1483	0.9775	0.1071
Dec	5.4677	0.6624	1.5185	0.1307	1.2547	0.1421

Appendix

Table 6.K.4 Values applied in FullCAM for rates of litterfall of foliage, bark and branches (L, per cent month^{-1}), and the proportional area occupied by grasses (A_{grass}). Note, rates of litterfall for southern fire regions were based on litterfall studies as reviewed by Paul and Roxburgh (2017).

Region		Vegetation subclass	State	L (% month^{-1}) Foliage	Bark	Branch	A_{grass}
Southern	-	-	NSW	2.708	0.409	0.738	0.05
			TAS	2.708	0.409	0.738	0.40
			WA	2.708	0.409	0.738	0.00
			SA	2.708	0.409	0.738	0.35
			Vic	2.708	0.409	0.738	0.20
			Qld	2.708	0.409	0.738	0.50
			ACT	2.708	0.409	0.738	0.10
Savanna	> 1000 mm MAR	Open Forest mixed (hOFM)	NT	2.083	0.375	0.375	0.28
			QLD	0.604	0.125	0.108	0.30
			WA	1.917	0.392	0.358	0.25
		Woodland Mixed (hWMi)	NT	3.083	0.350	0.233	0.15
			QLD	1.667	0.233	0.167	0.15
			WA	2.667	0.300	0.200	0.15
		Woodland Hummock (hWHu)	NT	3.333	0.708	0.708	0.20
			QLD	1.333	0.333	0.350	0.20
			WA	2.667	0.583	0.583	0.20
		Shrubland Hummock (hSHH)	NT	3.333	0.283	0.308	0.30
			QLD	1.250	0.042	0.117	0.40
			WA	2.167	0.150	0.267	0.35
		Melaleuca woodland (Other)	NT	0.750	0.250	0.125	0.25
			QLD	1.333	0.267	0.167	0.35
			WA	1.750	0.458	0.250	0.20
	< 1000 mm MAR	Woodland with tussock grass (lWTu)	NT	2.833	0.667	0.167	0.75
			QLD	0.917	0.375	0.108	0.70
			WA	0.267	0.833	0.208	0.80
		Woodland with mixed grass (lWMi)	NT	2.250	0.433	0.267	0.01
			QLD	1.167	0.250	0.167	0.01
			WA	2.667	0.433	0.267	0.01
		Woodland with hummock grass (lWHu)	NT	1.667	0.625	0.100	0.65
			QLD	1.583	0.583	0.100	0.65
			WA	2.333	0.750	0.100	0.65
		Open woodland with mixed grass (lOWM)	NT	2.500	0.333	0.042	0.35
			QLD	2.917	0.333	0.042	0.35
			WA	2.000	0.250	0.042	0.35
		Shrubland with hummock grass (lSHH)	NT	2.500	0.333	0.042	0.35
			QLD	2.917	0.333	0.042	0.40
			WA	2.000	0.250	0.042	0.35

Table 6.K.5 Values of calibrated FullCAM parameters for the percentage of live biomass-C that was assumed to be converted to either CO_2-C or the standing dead pool (t ha^{-1}) as a result of fire. Two pairs of values are provided. The first pair represents percentage C loss to CO_2-C & standing dead (t ha^{-1}) in low intensity fire types (prescribed or EDS). The second pair, given in parenthesis, represents percentage C loss to CO_2-C & standing dead in high intensity fires type (wildfire or LDS).

Region		Vegetation subclass	State	Stem	Branches	Bark	Foliage
Southern forests and woodlands	~	~	ACT	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
			NSW	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
			Qld	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
			SA	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
			TAS	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
			Vic	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
			WA	4.5&0.5 (9&1)	4.5&0.5 (9&1)	4.5&0.5 (9&1)	2.5&0.5 (5&5)
Savanna Woodland	> 1000 mm MAR	Open Forest Mixed (hOFM)	NT	1&0 (2&0.5)	1&0 (2&1)	2&0 (3&3)	2&0 (3&10)
			QLD	1&0 (2&0.5)	1&0 (2&1)	2&0 (3&3)	2&0 (3&3)
			WA	1&0 (2&1)	1&0 (2&3)	2&0 (3&3)	2&0 (3&5)
		Woodland Mixed (hWMi)	NT	1&0 (2&1)	1&0 (2&1)	2&0 (3&5)	2&0 (3&10)
			QLD	1&0 (2&0.5)	1&0 (2&1)	2&0 (3&5)	2&0 (3&10)
			WA	1&0 (2&1)	1&0 (2&1)	2&0 (3&5)	2&0 (3&7)
		Woodland Hummock (hWHu)	NT	1&0 (2&1)	1&0 (2&5.5)	2&0 (3&5.5)	2&0 (3&10)
			QLD	1&0 (2&1)	1&0 (2&2.5)	2&0 (3&2.5)	2&0 (3&3)
			WA	1&0 (2&2)	1&0 (2&5)	2&0 (3&5)	2&0 (3&10)
		Shrubland Hummock (hSHH)	NT	1&0 (2&1)	1&0 (2&2)	2&0 (3&2)	2&0 (3&10)
			QLD	1&0 (2&0)	1&0 (2&0)	2&0 (3&1)	2&0 (3&5)
			WA	1&0 (2&1)	1&0 (2&2)	2&0 (3&2)	2&0 (3&10)
		Melaleuca woodland (Other)	NT	1&0 (2&0)	1&0 (2&2)	2&0 (3&5)	2&0 (3&7)
			QLD	1&0 (2&1)	1&0 (2&1)	2&0 (3&5)	2&0 (3&5)
			WA	1&0 (2&1)	1&0 (2&1)	2&0 (3&3)	2&0 (3&3)
	< 1000 mm MAR	Woodland with tussock grass (lWTu) 11	NT	1&0 (2&1)	1&0 (2&1)	2&0 (3&7.5)	2&0 (3&15)
			QLD	1&0 (2&1)	1&0 (2&0)	2&0 (3&1)	2&0 (3&1)
			WA	1&0 (2&1)	1&0 (2&1)	2&0 (3&10)	2&0 (3&10)
		Woodland with mixed grass (lWMi)	NT	1&0 (2&0.5)	1&0 (2&1)	2&0 (3&2)	2&0 (3&5)
			QLD	1&0 (2&0)	1&0 (2&1)	2&0 (3&2)	2&0 (3&7)
			WA	1&0 (2&0)	1&0 (2&2)	2&0 (3&4)	2&0 (3&10)
		Woodland with hummock grass (lWHu)	NT	1&0 (2&0)	1&0 (2&1)	2&0 (3&10)	2&0 (3&10)
			QLD	1&0 (2&0)	1&0 (2&0)	2&0 (3&3)	2&0 (3&8)
			WA	1&0 (2&0)	1&0 (2&2)	2&0 (3&10)	2&0 (3&10)
		Open woodland with mixed grass (lOWM)	NT	1&0 (2&0)	1&0 (2&1)	2&0 (3&5)	2&0 (3&5)
			QLD	1&0 (2&0)	1&0 (2&1)	2&0 (3&5)	2&0 (3&10)
			WA	1&0 (2&0)	1&0 (2&1)	2&0 (3&5)	2&0 (3&10)
		Shrubland with hummock grass (lSHH)	NT	1&0 (2&0)	1&0 (2&1)	2&0 (3&5)	2&0 (3&5)
			QLD	1&0 (2&0)	1&0 (2&1)	2&0 (3&5)	2&0 (3&15)
			WA	1&0 (2&0)	1&0 (2&1)	2&0 (3&5)	2&0 (3&10)

Table 6.K.6 Values of calibrated FullCAM parameters for the percentage of debris-C that was assumed to be converted to CO_2-C as a result of fire. Two values are provided. The first represents low intensity fire types (prescribed or EDS). The other, given in parenthesis, represents high intensity fires type (wildfire or LDS). For all fire types, it was assumed that no debris-C was converted to inert soil C as a result of fire.

Region		Vegetation subclass	State	Deadwood	Bark litter	Foliage litter
Southern forests and woodlands	-	-	ACT	18 (55)	25 (65)	55 (90)
			NSW	18 (55)	25 (65)	53 (85)
			Qld	18 (50)	28 (65)	40 (90)
			SA	18 (50)	25 (65)	30 (90)
			TAS	18 (50)	25 (65)	30 (90)
			Vic	18 (50)	25 (65)	50 (85)
			WA	18 (55)	25 (65)	55 (85)
Savanna Woodland	> 1000 mm MAR	Open Forest mixed (hOFM)	NT	20 (35)	35 (50)	75 (99)
			QLD	20 (40)	20 (70)	70 (99)
			WA	25 (55)	25 (60)	75 (99)
		Woodland Mixed (hWMi)	NT	20 (50)	20 (70)	75 (99)
			QLD	30 (60)	40 (75)	75 (90)
			WA	20 (50)	20 (70)	75 (99)
		Woodland Hummock (hWHu)	NT	20 (45)	25 (65)	75 (99)
			QLD	15 (45)	20 (55)	70 (95)
			WA	20 (50)	25 (70)	75 (99)
		Shrubland Hummock (hSHH)	NT	20 (50)	25 (75)	70 (95)
			QLD	25 (30)	30 (55)	75 (99)
			WA	25 (60)	25 (75)	75 (95)
		Melaleuca woodland (Other)	NT	20 (45)	25 (60)	70 (95)
			QLD	25 (55)	25 (60)	80 (95)
			WA	25 (50)	30 (60)	80 (90)
	< 1000 mm MAR	Woodland with tussock grass (lWTu)	NT	15 (40)	20 (40)	80 (99)
			QLD	13 (25)	13 (40)	75 (90)
			WA	22 (40)	22 (40)	80 (90)
		Woodland with mixed grass (lWMi)	NT	15 (30)	25 (30)	80 (90)
			QLD	15 (30)	20 (30)	90 (99)
			WA	10 (30)	20 (30)	85 (99)
		Woodland with hummock grass (lWHu)	NT	25 (50)	25 (50)	75 (99)
			QLD	20 (30)	20 (30)	80 (99)
			WA	5 (30)	10 (30)	80 (99)
		Open woodland with mixed grass (lOWM)	NT	25 (30)	25 (30)	80 (90)
			QLD	25 (30)	30 (40)	80 (95)
			WA	20 (30)	20 (30)	80 (95)
		Shrubland with hummock grass (lSHH)	NT	25 (30)	25 (30)	80 (90)
			QLD	25 (30)	25 (30)	80 (95)
			WA	25 (30)	25 (30)	80 (99)

The calibrated parameters given in Tables 6.K.4–6 ensured that FullCAM-predicted pre-fire fuel loads, and emissions on burning, were consistent with NIR estimates under typical conditions (Paul and Roxburgh 2019).

Figure 6.K.1 Comparison between FullCAM-predicted: (a) fuel loads, and (b) emissions of CO_2-C and that expected based on previous NIR-based estimates for coarse and fine fuels for the 37 fire zones and under both intense fires (wildfires in southern fire zones; LDS burns in savanna fire zones) and less intense fires (prescribed burns in southern fire zones, or EDS burns in savanna fire zones).

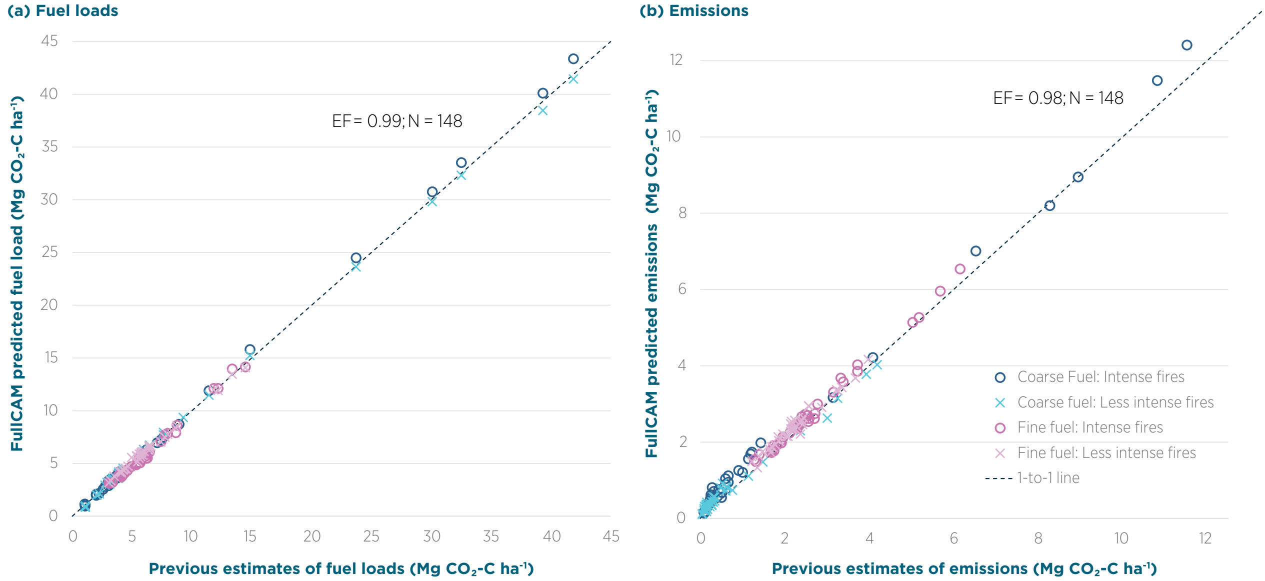


Table 6.K.7 Nitrogen to Carbon ratio in fuel burnt (C)

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

Vegetation class	Vegetation subclass	Rainfall zone	Fuel Size	Percent
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.8 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 NOX	46/14
C to CO	28/12
C to NMVOC	14/12

Table 6.K.9 CH_4 Emission Factors (Gg CH_4-C/Gg C)

Vegetation class		Rainfall Zone	Aggregated	CH_4 EF (Gg CH_4-C/Gg C) 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 *etal.* (2015)

(b) Meyer and Cook (2011)

(c) Roxburgh *et al.* (2015)

(d) Hurst *et al.* (1994 a, b)

Table 6.K.10 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 *etal.* 2009; Lynch *etal.* (2015).

(b) Meyer and Cook (2011)

(c) Roxburgh *et al.* (2015)

(d) Hurst *et al.* (1994 a, b)

Table 6.K.11 Emission Factors (CO, NMVOC and NOX)

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
NOX	Gg NOx-N/Gg N	0.21	0.15

Hurst *et al.* (1994 a, b)

Table 6.K.12 Prescribed burning spatial data sources

State	Source	License
New South Wales	Department of Planning, Industry and Environment NSW Rural Fire Service	Creative Commons 4.0
Australian Capital Territory	Environment, Planning and Sustainable Development Directorate	Creative Commons 4.0
South Australia	Department for Environment and Water	Creative Commons 3.0
Victoria	Department of Environment, Land, Water and Planning	Creative Commons 4.0

Tier 2 Prescribed burning model parameters

Table 6.K.13 Fine Fuels – fuel accumulation model parameters

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0	L	D	Gc
TAS	Temperate Zone	Temperate Forests	NA	Controlled burning	5.3436	2.3389	0.267	1.00
WA	Temperate Zone	Temperate Forests	NA	Controlled burning	7.2163	2.2004	0.186	1.00
Qld	Temperate Zone	Temperate Forests	NA	Controlled burning	8.8267	11.1130	0.768	1.00
NT	Temperate Zone	Temperate Forests	NA	Controlled burning	2.5010	1.2177	0.297	1.00

Table 6.K.14 Coarse Fuels – fuel accumulation model parameters

State	Vegetation class	Vegetation subclass	Rainfall zone	Fire variant	FL_0	L	D
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
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

Table 6.K.15 Burning Efficiency (BEF)

Vegetation class	Fuel Size	Fire variant	Rainfall zone	Percent
Temperate Zone	Fine	Controlled burning	NA	60.0%
Temperate Zone	Coarse	Controlled burning	NA	30.0%

Table 6.K.16 Carbon Content in fuel burnt (C)

Vegetation class	Vegetation subclass	Rainfall zone	Fuel Size	Percent
Temperate Zone	Temperate Forests	NA	NA	50.0%

Appendix

Appendix 6.L Activity Data – Annual areas of forest conversions and sparse woody transitions

The following tables provide National and State/Territory time series (1990–2019) of annual areas of:

- primary forest conversion to other land uses and secondary conversion (re-clearing) of forest that has emerged on previously cleared land (Table 6.L.1.a);
- for each year, the area of identified regrowth on previously cleared land and the resultant net clearing of forest when combined with the previous table, (kha) (Table 6.L.1.b);
- gain and loss of sparse woody vegetation across grasslands, wetlands and settlements (Table 6.L.5)

Tables 6.L.2–6.L.4, show primary and secondary conversion and cleared forest regrowing – by ABARES land use region; Bureau of Meteorology river region; and Natural Resource Management region for each of the years from 2015–2019.

These tables show actual changes in the year of observation, whereas the land representation matrix (Chapter 6.3.3) allocates regrowth events to the year after which they are observed. This ensures that, where there is doubt in the satellite image interpretation causing the forest state to swap between a forested and non-forested state in annual intervals, any 'false' regrowth event will occur in the same year as a subsequently 'false' re-clearing event. This is consistent with the timing in which for which such parcels of land are identified as sustained regrowth and allocated to *land converted to forest land* and ensures a more reliable time series of territorial forest areas.

Showing the changes in the year of observation allows for greater transparency, and for the tables in this appendix to be a more reliable comparison with other independently-produced datasets on forest change observations.

Tables 6.L.6 to 6.L.15 provide disaggregated information on areas of forest clearing and regrowth in the observed year of transition, and the associated carbon emissions and removals, nationally and by state/territory across the time period from 1990 to 2019. The area of sustained regrowth, prepared on the inventory-basis, is also shown for comparison.

Table 6.L.1.a Annual areas of forest cleared over the period 1990 to 2019 (kha)

Year	National		NSW		NT		QLD		SA		TAS		VIC		WA		ACT	
	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing	Primary Conversion	Re-clearing
1990	598.5	325.5	67.7	63.7	2.3	2.2	426.4	214.4	13.4	7.0	12.1	3.9	17.1	14.2	59.2	19.7	0.2	0.3
1991	482.4	353.3	52.6	74.7	2.0	2.0	343.7	220.2	9.6	7.2	14.3	7.5	13.4	17.7	46.8	23.6	0.1	0.4
1992	379.7	389.7	40.4	82.2	3.0	3.0	284.9	250.1	6.8	8.3	6.6	7.0	10.7	19.5	27.2	18.9	0.1	0.5
1993	269.4	312.5	26.4	55.7	1.0	1.5	203.8	212.8	4.3	5.8	5.5	5.0	7.1	15.9	21.3	15.6	0.1	0.2
1994	274.7	335.5	27.3	57.8	1.0	1.6	209.6	230.7	3.6	5.8	4.8	4.2	6.1	18.9	22.2	16.4	0.1	0.2
1995	218.7	256.7	20.0	48.1	0.9	1.4	165.5	168.9	3.1	4.7	4.8	4.1	5.4	14.7	19.0	14.7	0.1	0.2
1996	223.9	291.1	18.2	56.5	1.3	2.2	174.7	193.6	2.7	5.1	3.8	3.5	5.5	13.9	17.6	15.9	0.1	0.3
1997	222.6	282.6	18.5	55.2	1.4	2.3	172.2	186.2	2.7	5.1	4.3	4.2	5.8	13.8	17.6	15.5	0.1	0.3
1998	226.4	299.6	17.4	54.5	1.0	1.7	181.5	207.7	2.6	5.5	3.8	3.7	5.5	12.7	14.7	13.4	0.1	0.3
1999	263.9	375.5	19.9	71.9	0.9	1.9	218.2	262.8	2.8	7.3	3.3	4.1	5.8	14.3	12.9	12.9	0.1	0.3
2000	270.6	342.1	17.7	58.6	0.8	2.0	229.2	245.8	2.5	6.8	3.1	3.1	4.6	11.3	12.6	14.2	0.1	0.3
2001	313.7	394.3	18.4	61.9	0.8	2.6	269.8	287.6	3.2	8.5	3.3	3.1	4.2	9.4	13.8	20.9	0.0	0.4
2002	281.8	350.8	16.5	53.4	0.8	2.4	233.0	249.8	2.9	8.2	3.1	3.1	11.4	13.2	13.9	20.3	0.1	0.5
2003	227.0	368.1	15.7	60.3	0.8	2.4	161.3	237.1	2.6	8.9	3.8	6.4	26.5	27.3	16.1	24.8	0.2	0.9
2004	236.6	395.6	17.7	66.9	0.9	2.5	177.4	254.6	3.0	11.3	4.3	6.3	16.9	26.6	16.4	26.6	0.2	0.9
2005	294.6	565.1	20.9	91.7	1.5	5.5	237.7	371.7	3.7	16.8	5.2	7.7	7.5	34.7	18.0	36.1	0.1	0.9
2006	249.1	534.9	18.0	104.0	1.3	6.8	192.1	311.0	4.0	17.8	4.5	7.6	9.9	43.0	19.2	43.8	0.1	0.8
2007	208.7	497.2	17.1	100.2	1.7	5.6	156.5	299.0	3.7	14.1	4.4	7.6	6.8	30.2	18.3	39.8	0.1	0.7
2008	144.9	389.7	11.9	66.4	1.5	4.1	106.4	242.5	2.1	9.3	4.5	10.4	5.4	23.8	13.1	33.0	0.0	0.3
2009	108.5	349.9	10.2	72.7	0.9	3.7	73.1	195.5	2.2	9.7	3.9	8.1	7.0	27.5	11.2	32.0	0.0	0.7
2010	85.0	333.0	9.3	78.7	0.7	3.8	52.4	170.7	2.0	11.1	3.8	8.7	5.0	26.3	11.8	33.4	0.0	0.4
2011	68.7	311.4	9.4	78.4	0.5	2.3	42.0	169.0	1.5	11.2	2.7	6.8	1.8	15.7	10.7	27.7	0.0	0.2
2012	60.0	325.2	9.7	76.5	0.4	2.8	38.1	192.8	1.5	11.8	1.5	4.7	1.3	13.2	7.4	23.2	0.0	0.2
2013	64.1	429.1	9.3	77.6	0.5	3.1	42.3	280.8	1.8	15.7	1.6	4.9	1.6	21.9	7.0	25.0	0.0	0.1
2014	64.8	394.3	9.1	61.7	0.6	2.9	41.7	255.6	2.1	16.9	1.9	5.3	2.1	26.1	7.2	25.8	0.0	0.1
2015	64.3	371.5	9.0	51.0	0.7	3.1	41.1	252.3	1.3	12.3	1.6	5.7	1.9	20.3	8.7	26.6	0.0	0.1
2016	66.4	407.6	10.6	53.2	0.8	5.2	42.3	292.8	0.6	8.0	1.3	5.6	1.3	15.9	9.4	26.9	0.0	0.1
2017	58.2	387.8	13.1	62.0	0.3	2.8	38.0	278.3	0.6	6.8	1.1	5.0	0.9	13.1	4.2	19.6	0.0	0.1
2018	61.6	370.2	13.6	68.1	0.2	2.1	41.8	258.0	0.6	6.7	1.0	4.5	0.7	12.3	3.7	18.4	0.0	0.1
2019	39.3	258.9	11.8	55.4	0.2	1.7	23.2	168.5	0.3	5.9	0.7	3.0	0.5	10.9	2.5	13.5	0.0	0.1

Table 6.L.1.b Annual areas of identified regrowth and resultant net clearing of forest over the period 1990 to 2019 (kha)

Year	National		NSW		NT		QLD		SA		TAS		VIC		WA		ACT	
	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing	Identified regrowth	Net forest clearing
1990	234.5	689.5	45.9	85.5	1.3	3.3	150.4	490.4	4.7	15.8	3.8	12.3	8.6	22.6	19.6	59.3	0.2	0.3
1991	254.5	581.3	54.7	72.6	1.5	2.5	154.7	409.2	5.9	10.9	5.6	16.2	10.1	21.0	21.8	48.5	0.2	0.4
1992	269.6	499.8	64.7	57.9	2.4	3.7	153.8	381.2	6.3	8.9	4.6	9.1	13.4	16.8	24.2	21.9	0.2	0.4
1993	232.5	349.4	51.1	31.0	1.7	0.8	139.4	277.1	8.3	1.8	3.8	6.7	12.4	10.5	15.5	21.4	0.2	0.0
1994	253.9	356.2	53.4	31.7	1.9	0.7	153.7	286.6	12.1	-2.7	4.2	4.8	13.1	11.9	15.4	23.2	0.2	0.0
1995	191.0	284.4	39.8	28.4	1.8	0.5	113.7	220.7	9.3	-1.5	4.0	4.9	8.8	11.2	13.5	20.2	0.2	0.0
1996	188.9	326.1	38.1	36.7	1.7	1.8	117.6	250.7	7.0	0.8	2.8	4.5	7.5	11.9	14.1	19.4	0.1	0.2
1997	182.8	322.4	37.6	36.0	1.8	2.0	111.7	246.8	7.2	0.7	3.2	5.2	7.4	12.1	13.8	19.3	0.1	0.2
1998	192.1	333.9	38.3	33.6	2.0	0.7	115.6	273.6	5.8	2.2	3.0	4.4	9.1	9.2	18.2	9.9	0.1	0.2
1999	245.2	394.2	51.8	40.0	2.5	0.3	135.6	345.4	5.5	4.6	6.2	1.2	14.8	5.3	28.5	-2.7	0.3	0.1
2000	194.7	417.9	43.6	32.7	1.9	0.8	101.4	373.6	5.3	4.0	5.0	1.2	12.5	3.4	24.7	2.2	0.3	0.1
2001	206.1	501.9	48.5	31.8	2.0	1.4	103.8	453.6	8.5	3.2	5.2	1.1	13.3	0.4	24.6	10.1	0.2	0.2
2002	201.9	430.7	48.7	21.2	1.9	1.3	106.3	376.6	7.6	3.5	4.7	1.5	11.5	13.1	21.1	13.1	0.2	0.4
2003	244.2	350.8	68.9	7.1	3.0	0.2	125.4	273.0	7.8	3.7	5.6	4.6	12.5	41.3	20.8	20.1	0.1	0.9
2004	257.3	374.9	73.3	11.2	3.1	0.3	130.0	302.0	9.0	5.3	6.2	4.3	14.2	29.3	21.3	21.7	0.2	0.9
2005	331.4	528.3	87.5	25.1	3.2	3.8	176.9	432.6	11.9	8.6	9.2	3.7	18.3	24.0	24.3	29.8	0.2	0.8
2006	320.9	463.1	79.3	42.7	3.0	5.2	174.1	329.0	11.0	10.9	10.4	1.7	18.2	34.6	24.7	38.3	0.2	0.8
2007	347.1	358.7	77.6	39.7	2.9	4.4	195.9	259.6	10.9	6.9	6.8	5.3	24.0	13.0	28.7	29.4	0.3	0.5
2008	455.4	79.2	91.0	-12.8	2.8	2.7	281.3	67.7	14.0	-2.6	6.8	8.1	28.8	0.3	30.1	16.0	0.6	-0.3
2009	526.0	-67.5	100.6	-17.7	2.7	2.0	340.2	-71.6	19.2	-7.3	6.9	5.1	25.9	8.6	30.3	12.9	0.2	0.5
2010	464.3	-46.3	93.1	-5.1	3.0	1.6	280.8	-57.7	21.1	-8.0	7.9	4.5	29.0	2.2	29.3	15.9	0.2	0.3
2011	446.5	-66.4	75.2	12.6	3.4	-0.6	260.7	-49.7	22.8	-10.1	9.4	0.1	42.3	-24.7	32.6	5.9	0.2	0.0
2012	526.5	-141.2	70.3	15.9	2.2	1.0	342.2	-111.3	23.9	-10.5	9.8	-3.6	38.3	-23.8	39.5	-8.9	0.3	-0.1
2013	512.1	-18.9	81.2	5.6	1.8	1.9	316.3	6.8	21.0	-3.5	9.9	-3.4	31.0	-7.5	50.6	-18.5	0.5	-0.3
2014	563.5	-104.4	79.9	-9.1	2.4	1.0	368.3	-70.9	16.0	2.9	9.5	-2.3	31.6	-3.4	55.2	-22.2	0.6	-0.5
2015	511.4	-75.6	81.0	-21.1	2.7	1.1	337.1	-43.6	15.9	-2.3	7.7	-0.4	30.3	-8.0	36.0	-0.7	0.7	-0.6
2016	483.1	-9.1	73.2	-9.5	2.2	3.8	327.8	7.3	17.2	-8.6	5.7	1.2	25.8	-8.6	30.6	5.8	0.5	-0.5
2017	319.0	127.0	44.2	30.9	2.8	0.3	213.3	103.0	12.2	-4.8	5.0	1.2	16.5	-2.5	24.8	-1.0	0.2	-0.1
2018	269.3	162.5	31.8	50.0	4.3	-1.9	183.7	116.1	9.7	-2.5	4.1	1.4	13.6	-0.7	21.9	0.2	0.2	-0.1
2019	261.8	36.4	32.2	35.0	2.7	-0.8	183.1	8.6	8.1	-1.9	5.0	-1.3	13.2	-1.8	17.1	-1.2	0.2	-0.1

Table 6.L.2 Activity in ABARES Land Use regions, 5 years to June 2019 (kha)

	2015			2016			2017			2018			2019		
	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth
1 Conservation and natural environments															
1.1 Nature conservation	0.7	9.1	4.6	0.5	8.2	4.6	0.4	5.6	3.9	0.5	3.9	3.6	0.5	3.3	3.0
1.2 Managed resource protection	1.2	3.3	3.4	1.0	2.8	2.9	2.5	2.2	2.5	0.9	2.5	1.6	1.5	2.7	1.4
1.3 Other minimal use	11.3	39.4	23.6	12.1	37.7	23.3	8.0	25.2	19.3	7.9	20.4	19.3	5.8	16.8	14.7
2 Production from relatively natural environments															
2.1 Grazing native vegetation	41.6	388.3	262.9	44.8	363.1	305.1	42.4	231.9	304.6	46.0	187.6	286.3	28.2	186.7	190.4
2.2 Production native forests	2.2	12.2	7.7	2.0	12.5	6.2	1.1	8.1	4.4	2.0	7.0	4.2	0.9	5.9	3.9
3 Production from dryland agriculture and plantations															
3.1 Plantation forests	0.7	5.2	5.5	0.9	4.4	7.3	0.4	3.1	6.1	1.3	3.9	6.3	0.4	2.8	5.6
3.2 Grazing modified pastures	1.8	31.7	20.5	1.1	25.1	17.3	0.8	16.9	14.5	0.7	13.7	15.3	0.5	13.4	13.2
3.3 Cropping	1.5	16.2	13.2	1.1	15.5	12.8	0.6	13.2	8.6	0.5	10.9	10.3	0.3	8.4	7.3
3.4 Perennial horticulture	0.0	0.2	0.1	0.0	0.2	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1
3.5 Seasonal horticulture	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.6 Land in transition	0.1	0.9	0.8	0.2	0.8	1.3	0.1	0.6	0.7	0.1	0.6	0.5	0.0	0.5	0.3
4 Production from irrigated agriculture and plantations															
4.0 Production from irrigated agriculture and plantations	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4.1 Irrigated plantation forests	0.0	0.2	0.5	0.0	0.3	0.2	0.0	0.3	0.1	0.0	0.4	0.1	0.0	0.3	0.2
4.2 Grazing irrigated modified pastures	0.0	0.7	0.5	0.0	0.6	0.5	0.0	0.7	0.4	0.0	0.6	0.5	0.0	0.5	0.4
4.3 Irrigated cropping	0.2	3.4	3.3	0.2	3.6	3.7	0.1	4.0	2.4	0.1	2.3	3.9	0.0	1.9	3.7
4.4 Irrigated perennial horticulture	0.0	0.3	0.1	0.0	0.2	0.2	0.0	0.2	0.2	0.0	0.2	0.1	0.0	0.1	0.2
4.5 Irrigated seasonal horticulture	0.0	0.3	0.4	0.0	0.3	0.3	0.0	0.3	0.2	0.0	0.3	0.3	0.0	0.3	0.3
4.6 Irrigated land in transition	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1

	2015			2016			2017			2018			2019		
	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth
5 Intensive uses															
5.0 Intensive uses	-	0.0	0.0	-	-	0.0	-	-	-	-	-	-	-	-	-
5.1 Intensive horticulture	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
5.2 Intensive animal production	0.0	0.5	0.3	0.0	0.4	0.3	0.0	0.3	0.2	0.0	0.3	0.2	0.0	0.3	0.2
5.3 Manufacturing and industrial	0.0	0.4	0.4	0.0	0.3	0.3	0.0	0.2	0.3	0.0	0.2	0.2	0.0	0.2	0.2
5.4 Residential and farm infrastructure	1.5	13.1	10.5	1.3	12.2	9.7	1.0	6.9	8.3	0.9	6.6	7.3	0.6	7.0	5.9
5.5 Services	0.2	2.4	1.8	0.2	2.0	1.8	0.1	1.3	1.5	0.1	1.3	1.2	0.1	1.2	1.0
5.6 Utilities	0.0	0.4	0.3	0.0	0.3	0.2	0.0	0.2	0.2	0.0	0.2	0.2	0.0	0.2	0.1
5.7 Transportand communication	0.3	5.1	3.2	0.2	4.3	2.5	0.2	2.6	2.4	0.2	2.4	2.2	0.1	2.3	1.7
5.8 Mining	0.3	3.5	2.1	0.3	4.8	1.8	0.2	3.5	1.6	0.1	5.2	1.4	0.2	4.6	1.2
5.9 Waste treatment and disposal	0.0	0.2	0.2	0.0	0.2	0.2	0.0	0.1	0.2	0.0	0.1	0.1	0.0	0.1	0.1
6 Water															
6.0 Not elsewhere defined	-	0.0	0.0	-	0.0	0.0	-	0.0	0.0	-	0.0	-	-	0.0	-
6.1 Lake	0.0	0.5	0.4	0.0	0.4	0.5	0.0	0.4	0.4	0.0	0.3	0.3	0.0	0.3	0.2
6.2 Reservoir/dam	0.1	2.7	1.9	0.1	2.5	2.1	0.1	1.9	2.1	0.0	1.8	1.8	0.0	1.5	1.5
6.3 River	0.1	1.6	0.6	0.1	1.2	0.7	0.1	0.8	0.7	0.1	0.6	0.7	0.1	0.6	0.6
6.4 Channel/aqueduct	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1
6.5 Marsh/wetland	0.3	2.1	2.6	0.2	2.5	1.6	0.2	1.9	1.7	0.2	1.4	1.7	0.1	1.2	1.3
6.6 Estuary/coastal waters	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0
Undefined	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
All lands	**64.4**	**544.1**	**371.6**	**66.4**	**506.9**	**407.7**	**58.2**	**333.1**	**387.8**	**61.6**	**275.2**	**370.2**	**39.3**	**263.4**	**259.0**

Table 6.L.3 Activity in BoM River regions, 5 years to June 2019 (kha)

	2015			2016			2017			2018			2019		
	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth
Gulf Of Carpentaria	2.2	8.0	12.0	1.9	8.4	7.1	3.4	4.9	7.5	2.0	3.5	4.8	1.7	5.0	3.1
Indian Ocean	0.3	2.3	1.8	0.2	2.4	1.5	0.2	2.1	1.2	0.2	1.4	1.3	0.1	1.1	0.8
Lake Eyre	3.2	34.4	13.4	2.5	39.3	21.2	2.5	24.2	25.6	2.0	8.0	25.6	1.2	13.9	10.7
Murray-Darling	22.9	194.3	133.7	25.5	167.7	151.8	29.5	101.3	163.9	32.6	70.3	159.6	23.2	66.0	105.1
North East Coast	20.4	200.0	143.6	20.9	196.9	161.0	13.8	139.7	132.4	17.1	136.1	124.6	6.9	125.0	95.2
North Western	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Plateau	0.5	5.4	2.4	0.3	5.4	1.8	0.1	4.4	1.1	0.1	3.3	1.4	0.2	2.3	2.9
South Australian	4.2	49.0	29.5	3.6	43.1	26.1	3.2	21.6	28.8	2.9	20.2	28.4	2.8	24.2	23.4
Gulf	7.4	30.9	20.9	8.1	25.7	21.8	3.3	20.1	15.7	2.6	18.0	14.2	1.7	13.3	10.7
South East Coast	1.2	8.5	5.2	1.2	9.2	4.3	0.8	6.5	3.6	0.9	5.7	3.4	0.7	4.7	2.4
South West Coast	1.6	7.6	5.6	1.3	5.7	5.5	1.1	5.0	4.9	1.0	4.1	4.4	0.7	5.0	2.9
South Western	0.6	3.0	3.1	0.7	2.6	5.3	0.3	2.9	2.9	0.2	4.4	2.3	0.2	2.8	1.7
Plateau	0.1	0.7	0.3	0.0	0.5	0.3	0.0	0.4	0.2	0.0	0.3	0.2	0.0	0.2	0.2
Tasmania	2.2	8.0	12.0	1.9	8.4	7.1	3.4	4.9	7.5	2.0	3.5	4.8	1.7	5.0	3.1
Timor Sea	0.3	2.3	1.8	0.2	2.4	1.5	0.2	2.1	1.2	0.2	1.4	1.3	0.1	1.1	0.8
Undefined	3.2	34.4	13.4	2.5	39.3	21.2	2.5	24.2	25.6	2.0	8.0	25.6	1.2	13.9	10.7
All lands	**64.4**	**544.1**	**371.6**	**66.4**	**506.9**	**407.7**	**58.2**	**333.1**	**387.8**	**61.6**	**275.2**	**370.2**	**39.3**	**263.4**	**259.0**

Table 6.L.4 Activity in NRM regions, 5 years to June 2019 (kha)

	2015			2016			2017			2018			2019		
	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth
ACT	0.0	0.8	0.1	0.0	0.5	0.1	0.0	0.2	0.1	0.0	0.2	0.1	0.0	0.2	0.1
Adelaide and Mount Lofty Ranges	0.1	0.3	0.3	0.0	0.3	0.3	0.0	0.3	0.2	0.0	0.3	0.2	0.0	0.3	0.1
Alinytjara Wilurara	0.0	0.0	0.2	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maranoa Balonne and Border Rivers	4.0	41.0	28.7	3.2	36.9	33.7	2.7	22.8	31.7	3.9	20.3	31.1	3.0	17.4	19.3
Burdekin	6.2	36.2	53.2	7.8	31.8	47.9	5.1	17.0	41.5	4.6	23.9	33.4	1.1	31.0	15.1
Burnett Mary	3.6	15.3	18.4	2.7	19.0	16.7	2.8	9.4	17.9	4.7	8.5	20.7	1.5	5.3	9.9
Cape York	2.5	3.9	3.2	1.2	3.3	2.1	2.9	2.2	2.6	1.5	1.6	2.3	1.6	2.6	1.6
Central Tablelands	0.3	14.0	1.8	0.3	7.9	2.5	0.3	3.9	2.9	0.3	2.4	4.2	0.2	2.4	2.6
Central West	1.0	9.6	8.9	1.1	11.1	8.7	2.1	9.0	9.0	3.1	5.6	11.4	2.3	3.4	9.7
Condamine	1.1	3.0	7.1	0.7	4.7	6.3	0.4	3.1	4.3	0.6	5.0	3.8	0.2	2.8	2.4
Co-operative Management Area	0.2	0.2	0.4	0.2	0.3	0.3	0.1	0.2	0.2	0.1	0.1	0.3	0.0	0.2	0.0
Corangamite	0.3	2.4	2.5	0.4	1.2	2.5	0.1	1.2	1.7	0.1	1.4	1.2	0.0	1.2	0.7
Desert Channels	2.9	28.3	11.0	2.2	35.2	17.7	2.2	22.4	21.8	1.6	7.3	21.1	0.8	11.4	9.1
East Gippsland	0.2	3.0	0.7	0.1	2.2	1.0	0.1	0.5	1.7	0.1	0.5	1.7	0.1	0.9	1.3
Eyre Peninsula	0.3	7.8	2.3	0.1	8.9	1.7	0.1	5.8	1.6	0.1	4.9	1.5	0.1	3.4	1.2
Fitzroy	5.8	132.6	54.5	4.7	127.2	73.6	2.9	102.2	59.2	5.1	95.0	59.3	2.8	79.7	58.0
Glenelg Hopkins	0.1	2.4	3.1	0.1	1.6	2.0	0.1	1.6	1.8	0.0	1.7	1.5	0.0	0.8	1.6
Goulburn Broken	0.2	2.1	2.0	0.2	2.1	1.7	0.1	1.7	0.8	0.1	1.4	0.7	0.0	1.3	0.7
Greater Sydney	0.2	2.5	1.5	0.2	1.5	2.0	0.2	0.8	2.2	0.2	0.9	1.4	0.1	1.5	0.9
Hunter	0.5	7.0	3.0	0.4	5.2	2.9	0.4	3.1	4.0	0.5	2.8	4.3	0.5	4.0	3.6
Kangaroo Island	0.2	0.9	0.6	0.1	0.9	0.4	0.0	0.7	0.2	0.0	0.4	0.3	0.1	0.4	1.7
Mackay Whitsunday	1.2	9.0	4.7	2.2	11.8	8.9	0.9	5.3	4.6	0.4	3.4	4.1	0.3	4.4	5.8
Mallee	0.1	5.7	0.7	0.0	6.2	0.5	0.0	4.4	0.6	0.0	2.6	0.8	0.0	2.4	0.7
Murray	0.1	3.2	1.5	0.1	3.2	1.2	0.1	3.8	1.2	0.1	2.2	1.7	0.4	1.6	2.9
North NRM Region	0.8	4.2	2.1	0.7	2.9	1.8	0.5	2.2	1.9	0.5	1.9	1.8	0.3	2.4	1.1
North Central	0.1	3.4	3.1	0.1	2.2	2.6	0.1	2.0	2.0	0.1	1.7	1.7	0.0	1.4	1.1
North Coast	1.1	4.9	3.3	1.2	7.4	3.2	0.9	5.0	2.8	0.7	4.8	3.1	0.5	4.7	3.1
North East	0.2	6.5	1.0	0.1	4.6	1.1	0.1	2.2	0.9	0.1	1.5	1.0	0.1	1.5	1.8

	2015			2016			2017			2018			2019		
	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth	Primary Conversion	Re-clearing	Identified regrowth
North West NRM Region	0.4	1.6	2.4	0.4	1.0	2.8	0.3	0.9	2.2	0.3	1.1	1.5	0.3	1.1	1.0
North West NSW	1.8	5.0	5.5	2.1	6.7	5.6	1.7	5.5	4.9	1.0	2.3	5.9	0.8	1.7	3.9
Northern and Yorke	0.2	1.6	0.9	0.1	1.6	0.7	0.0	1.3	0.3	0.0	0.8	0.4	0.0	0.5	0.3
Northern Gulf	0.9	1.7	8.4	1.1	3.0	3.8	0.6	1.9	2.4	0.4	1.2	1.7	0.1	2.0	1.3
Northern Tablelands	0.7	6.9	4.2	0.7	7.6	3.5	0.6	4.1	3.6	0.8	3.3	4.2	1.3	4.3	5.6
Northern Territory	0.7	3.1	3.1	0.9	2.5	5.2	0.3	2.9	2.8	0.2	4.4	2.1	0.2	2.7	1.7
Port Phillip and Western Port	0.2	2.6	2.9	0.1	2.1	1.9	0.1	1.0	1.8	0.1	1.0	1.5	0.0	2.0	1.1
Riverina	0.1	3.9	1.7	0.1	4.0	1.0	0.1	2.5	1.4	0.2	1.4	2.0	0.3	1.2	2.3
South NRM Region	0.4	2.2	1.2	0.3	2.0	1.0	0.3	1.9	0.9	0.3	1.2	1.2	0.2	1.5	0.9
South Australian Arid Lands	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1
South Australian Murray Darling Basin	0.5	4.2	3.8	0.1	4.1	2.6	0.3	3.1	2.9	0.3	2.1	2.9	0.1	2.2	1.4
South East	0.2	1.6	4.2	0.0	1.6	2.2	0.1	1.3	1.5	0.1	1.3	1.3	0.1	1.3	1.0
South East NSW	0.6	18.2	4.8	0.5	16.2	5.8	0.7	5.0	9.2	0.6	4.1	9.8	0.8	4.5	7.8
South East Queensland	1.7	4.1	8.3	2.1	5.4	9.4	1.5	2.6	6.8	1.6	2.5	5.3	0.8	1.7	4.2
South West Queensland	10.7	78.9	50.2	13.6	61.7	67.2	15.5	29.5	80.9	16.7	15.5	72.9	10.7	22.9	39.5
Southern Gulf	0.1	2.4	1.9	0.2	2.1	2.2	0.1	1.1	2.8	0.2	1.0	0.9	0.0	1.1	0.5
Torres Strait	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West Gippsland	0.3	3.1	1.8	0.2	3.0	1.6	0.1	1.4	1.3	0.1	0.9	1.5	0.1	1.2	1.2
Western	2.6	12.3	14.9	3.9	7.6	16.9	6.0	4.5	20.7	6.2	3.0	20.1	4.6	3.2	12.9
Wet Tropics	0.4	2.2	2.3	0.6	1.3	3.2	0.4	2.6	1.8	0.5	2.3	1.2	0.2	1.6	1.8
Wimmera	0.4	1.5	2.5	0.1	1.8	0.9	0.0	1.5	0.7	0.0	1.2	0.8	0.0	0.7	0.6
Northern Agricultural Region	1.6	10.3	6.6	1.6	9.1	6.7	0.9	6.7	4.7	0.6	5.8	3.6	0.3	4.1	2.3
Peel-Harvey Region	0.7	1.7	1.3	0.9	1.1	1.6	0.3	1.1	0.9	0.2	0.9	0.9	0.1	0.6	0.6
Swan Region	0.8	2.1	2.0	0.7	1.6	1.7	0.4	1.2	1.4	0.3	1.3	1.2	0.2	1.3	0.7
Rangelands Region	0.8	2.5	2.7	0.9	2.5	2.7	0.8	2.1	2.3	0.8	2.0	2.3	0.4	2.3	1.2
South Coast Region	2.7	9.8	6.8	3.5	8.6	7.1	0.7	6.3	5.3	0.9	5.4	5.4	0.7	4.4	4.4
South West Region	0.5	4.5	2.6	0.4	3.3	2.6	0.3	3.2	1.9	0.3	3.1	2.3	0.2	1.6	2.4
Avon River Basin	1.6	6.0	4.7	1.4	5.2	4.5	0.8	4.6	3.1	0.6	3.7	2.7	0.4	2.9	1.8
All lands	**64.4**	**544.1**	**371.6**	**66.4**	**506.9**	**407.7**	**58.2**	**333.1**	**387.8**	**61.6**	**275.2**	**370.2**	**39.3**	**263.4**	**259.0**

Table 6.L.5 Annual areas of sparse woody vegetation gains and losses over the period 1990 to 2019 (kha)

	National		NSW		NT		QLD		SA		TAS		VIC		WA		ACT	
Year	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses
1990	1,118.6	-2,163.5	117.7	-195.3	205.0	-315.4	551.2	-989.2	33.9	-71.3	3.0	-7.4	6.4	-23.7	201.2	-561.0	0.1	-0.2
1991	1,184.9	-1,954.4	125.8	-175.8	221.9	-311.3	521.8	-814.8	43.3	-72.7	2.9	-7.9	7.0	-16.0	262.1	-555.7	0.1	-0.2
1992	1,152.3	-1,927.6	107.4	-145.6	237.2	-411.3	481.0	-840.2	49.4	-53.3	1.1	-5.7	6.0	-15.5	270.0	-455.9	0.1	-0.2
1993	993.3	-989.6	77.7	-95.1	194.2	-188.8	407.9	-451.2	52.9	-29.0	1.2	-3.9	6.6	-9.3	252.6	-212.3	0.2	-0.1
1994	1,058.4	-1,004.2	81.4	-98.5	204.4	-193.0	440.0	-459.2	59.5	-27.4	1.5	-2.0	7.6	-6.4	263.8	-217.7	0.3	-0.1
1995	902.3	-733.4	62.5	-83.0	179.4	-130.8	353.8	-282.0	46.2	-28.9	1.4	-2.0	4.7	-6.5	254.0	-200.1	0.2	-0.1
1996	957.3	-756.6	56.9	-93.4	214.9	-128.8	370.8	-286.0	37.5	-33.1	1.0	-1.8	3.2	-6.9	273.0	-206.5	0.2	-0.1
1997	971.7	-768.2	57.8	-94.4	224.4	-133.9	363.8	-283.7	38.8	-34.1	1.1	-2.1	3.3	-7.2	282.4	-212.7	0.2	-0.1
1998	968.5	-807.6	81.7	-78.9	187.0	-158.6	374.0	-322.4	38.1	-35.1	1.0	-1.9	4.8	-6.1	281.6	-204.5	0.2	-0.1
1999	1,414.7	-1,121.8	121.5	-76.4	276.1	-252.9	598.1	-475.8	53.1	-56.3	1.5	-1.9	7.5	-5.7	356.6	-252.5	0.3	-0.1
2000	1,090.3	-1,051.8	106.8	-69.6	245.9	-236.1	413.5	-431.4	49.3	-47.0	1.5	-1.3	8.0	-5.0	264.9	-261.3	0.3	-0.1
2001	1,033.2	-1,154.8	111.0	-78.0	248.6	-252.3	354.6	-477.7	53.6	-44.8	1.8	-1.1	10.8	-4.7	252.4	-296.2	0.3	-0.1
2002	963.5	-1,126.5	101.1	-83.2	237.4	-247.7	346.7	-461.8	47.5	-41.4	1.6	-1.2	10.6	-4.8	218.5	-286.2	0.2	-0.2
2003	1,057.1	-1,227.8	109.5	-106.3	206.5	-307.4	443.4	-422.8	44.8	-41.1	1.6	-2.7	12.4	-6.2	238.7	-341.1	0.2	-0.3
2004	1,150.3	-1,323.1	142.3	-120.9	214.3	-322.6	443.5	-469.8	40.7	-60.6	1.5	-2.8	11.9	-10.3	295.8	-335.9	0.2	-0.3
2005	1,517.3	-1,902.8	187.2	-153.1	293.9	-492.2	506.7	-742.3	43.9	-85.4	1.7	-3.1	12.8	-17.8	470.5	-408.4	0.4	-0.4
2006	1,925.2	-1,751.9	173.6	-183.8	375.1	-393.9	677.5	-692.7	58.3	-78.1	2.3	-2.5	12.0	-20.0	625.9	-380.4	0.3	-0.5
2007	2,192.5	-1,841.1	207.9	-209.8	477.7	-386.9	707.1	-769.3	75.2	-74.0	2.8	-2.1	13.4	-14.8	708.2	-383.6	0.1	-0.6
2008	2,395.5	-1,456.3	241.6	-143.3	464.9	-308.6	891.1	-530.7	84.5	-70.4	3.3	-2.8	14.3	-14.0	695.8	-386.1	0.1	-0.4
2009	2,442.5	-1,334.4	276.5	-182.0	533.7	-232.6	822.1	-485.1	101.7	-51.5	6.2	-2.2	19.3	-14.7	682.9	-365.7	0.2	-0.6
2010	2,932.8	-1,443.7	263.2	-251.0	736.2	-252.2	1,010.6	-482.8	112.7	-54.0	7.2	-3.9	24.0	-13.0	778.4	-386.2	0.5	-0.4
2011	2,976.9	-1,578.2	271.0	-205.9	629.4	-320.4	1,048.7	-529.9	126.7	-67.1	4.6	-5.9	36.6	-10.6	859.1	-438.0	0.7	-0.3
2012	2,718.3	-1,974.5	315.8	-183.4	504.3	-512.4	890.8	-686.4	125.2	-87.9	6.0	-4.1	49.6	-10.2	825.2	-489.9	1.3	-0.2
2013	2,516.3	-2,906.2	399.0	-198.2	350.7	-727.2	738.0	-1,278.1	122.1	-120.2	7.3	-4.2	41.4	-18.8	856.0	-559.3	1.7	-0.2
2014	2,565.2	-2,581.0	367.7	-196.3	414.5	-601.8	699.9	-1,029.1	122.6	-147.2	6.9	-5.4	44.9	-22.1	907.4	-578.9	1.4	-0.2
2015	2,182.5	-2,720.7	308.6	-221.8	391.2	-884.8	584.1	-882.1	132.6	-133.2	6.7	-4.9	40.6	-26.6	717.4	-566.8	1.1	-0.3
2016	2,671.9	-2,671.0	326.4	-244.6	405.4	-802.3	975.4	-767.8	156.7	-107.2	8.5	-3.4	34.7	-28.6	763.6	-716.7	1.1	-0.3
2017	2,493.0	-2,305.7	312.2	-208.1	521.5	-485.8	714.3	-762.1	160.4	-96.3	12.0	-1.9	45.4	-23.8	725.6	-727.7	1.5	-0.1
2018	2,355.6	-2,059.0	267.2	-200.9	519.7	-510.2	647.4	-654.2	147.9	-82.2	12.2	-1.9	50.6	-22.2	708.7	-587.2	1.8	-0.1
2019	2,034.8	-1,584.0	154.9	-150.5	537.2	-496.9	603.7	-472.3	95.9	-61.2	8.4	-2.7	30.4	-16.1	603.2	-384.1	1.2	-0.3

Table 6.L.6 UNFCCC Forest conversions – National annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth(a)	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	598.5	118.4	325.5	9.8	46.4	234.5	856.1	-1.6	689.5
1991	482.4	104.8	353.3	9.8	45.3	254.5	998.2	-2.1	581.3
1992	379.7	71.7	389.7	9.2	34.0	269.6	1,138.6	-2.5	499.8
1993	269.4	57.8	312.5	8.4	34.1	232.5	1,306.8	-3.6	349.4
1994	274.7	48.7	335.5	8.6	29.0	253.9	1,428.1	-3.0	356.2
1995	218.7	44.2	256.7	8.3	25.6	191.0	1,587.6	-4.4	284.4
1996	223.9	36.3	291.1	7.1	29.0	188.9	1,658.8	-5.5	326.1
1997	222.6	39.2	282.6	8.8	24.4	182.8	1,732.5	-6.4	322.4
1998	226.4	36.9	299.6	9.3	24.4	192.1	1,785.8	-7.3	333.9
1999	263.9	42.1	375.5	11.3	28.4	245.2	1,806.5	-7.3	394.2
2000	270.6	43.3	342.1	12.9	23.5	194.7	1,894.9	-8.3	417.9
2001	313.7	44.8	394.3	13.3	35.6	206.1	1,899.1	-8.0	501.9
2002	281.8	47.2	350.8	15.2	27.9	201.9	1,938.3	-7.4	430.7
2003	227.0	38.9	368.1	13.7	29.9	244.2	1,958.6	-7.5	350.8
2004	236.6	37.7	395.6	15.2	27.4	257.3	1,999.3	-8.0	374.9
2005	294.6	47.2	565.1	19.9	29.9	331.4	1,944.7	-7.9	528.3
2006	249.1	46.9	534.9	21.3	27.8	320.9	1,958.4	-7.4	463.1
2007	208.7	43.2	497.2	21.0	30.7	347.1	1,958.7	-7.4	358.7
2008	144.9	31.4	389.7	15.0	26.2	455.4	2,036.7	-8.4	79.2
2009	108.5	24.5	349.9	12.7	22.4	526.0	2,245.4	-8.2	-67.5
2010	85.0	21.1	333.0	13.1	32.5	464.3	2,527.1	-9.1	-46.3
2011	68.7	16.4	311.4	10.9	23.8	446.5	2,756.2	-10.0	-66.4
2012	60.0	12.9	325.2	9.6	22.7	526.5	2,961.5	-11.7	-141.2
2013	64.1	12.3	429.1	11.1	26.3	512.1	3,176.4	-11.7	-18.9
2014	64.8	14.5	394.3	12.7	23.4	563.5	3,393.5	-11.7	-104.4
2015	64.3	12.0	371.5	10.7	18.9	511.4	3,675.6	-12.3	-75.6
2016	66.4	13.5	407.6	11.7	14.7	483.1	3,872.9	-15.5	-9.1
2017	58.2	11.6	387.8	11.7	16.2	319.0	4,048.3	-14.9	127.0
2018	61.6	11.4	370.2	11.8	19.2	269.3	4,072.0	-14.7	162.5
2019	39.3	10.5	258.9	10.3	10.7	261.8	4,130.0	-13.1	36.4

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.7 UNFCCC Forest conversions – QLD annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[(a)]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	426.4	64.3	214.4	5.4	26.0	150.4	526.3	-0.3	490.4
1991	343.7	58.2	220.2	5.2	26.1	154.7	623.1	-0.6	409.2
1992	284.9	40.1	250.1	5.0	17.4	153.8	710.7	-0.8	381.2
1993	203.8	33.3	212.8	4.7	19.9	139.4	799.2	-1.3	277.1
1994	209.6	29.0	230.7	4.9	14.6	153.7	866.8	-1.0	286.6
1995	165.5	25.9	168.9	4.5	14.2	113.7	960.1	-1.7	220.7
1996	174.7	23.0	193.6	4.0	16.8	117.6	995.7	-2.1	250.7
1997	172.2	24.7	186.2	4.8	12.6	111.7	1,039.2	-2.8	246.8
1998	181.5	23.5	207.7	5.2	15.0	115.6	1,062.1	-3.2	273.6
1999	218.2	30.8	262.8	7.0	17.5	135.6	1,059.7	-2.9	345.4
2000	229.2	31.7	245.8	7.9	13.5	101.4	1,086.1	-3.5	373.6
2001	269.8	33.0	287.6	8.5	24.5	103.8	1,054.9	-3.1	453.6
2002	233.0	34.5	249.8	9.6	16.8	106.3	1,047.0	-2.8	376.6
2003	161.3	24.3	237.1	7.8	20.8	125.4	1,046.5	-2.4	273.0
2004	177.4	21.7	254.6	8.2	16.8	130.0	1,050.5	-2.6	302.0
2005	237.7	30.0	371.7	10.9	17.9	176.9	986.3	-2.3	432.6
2006	192.1	28.5	311.0	10.7	16.6	174.1	986.9	-2.3	329.0
2007	156.5	24.7	299.0	9.6	21.2	195.9	973.6	-2.2	259.6
2008	106.4	18.4	242.5	7.6	15.0	281.3	1,003.0	-2.4	67.7
2009	73.1	12.6	195.5	5.8	13.1	340.2	1,149.2	-2.2	-71.6
2010	52.4	9.3	170.7	4.9	23.0	280.8	1,364.1	-2.5	-57.7
2011	42.0	7.0	169.0	4.1	13.7	260.7	1,514.1	-2.6	-49.7
2012	38.1	6.1	192.8	4.0	12.3	342.2	1,631.5	-4.1	-111.3
2013	42.3	6.1	280.8	4.9	17.4	316.3	1,770.1	-3.9	6.8
2014	41.7	6.9	255.6	5.6	14.9	368.3	1,894.2	-4.1	-70.9
2015	41.1	6.0	252.3	5.1	11.0	337.1	2,070.7	-4.0	-43.6
2016	42.3	6.4	292.8	6.1	9.2	327.8	2,180.1	-5.2	7.3
2017	38.0	6.2	278.3	6.4	10.0	213.3	2,284.2	-4.7	103.0
2018	41.8	5.9	258.0	5.8	12.2	183.7	2,287.7	-4.5	116.1
2019	23.2	6.2	168.5	5.4	5.9	183.1	2,330.6	-4.1	8.6

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.8 UNFCCC Forest conversions – NSW annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[(a)]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	67.7	26.3	63.7	2.8	8.8	45.9	171.8	-0.8	85.5
1991	52.6	19.7	74.7	2.6	7.9	54.7	195.4	-0.9	72.6
1992	40.4	15.5	82.2	2.6	7.0	64.7	221.4	-1.1	57.9
1993	26.4	11.4	55.7	2.1	4.4	51.1	265.6	-1.6	31.0
1994	27.3	10.1	57.8	2.3	5.5	53.4	295.4	-1.4	31.7
1995	20.0	8.9	48.1	2.3	4.5	39.8	330.1	-1.7	28.4
1996	18.2	5.7	56.5	1.8	4.8	38.1	345.7	-2.2	36.7
1997	18.5	6.1	55.2	2.3	4.3	37.6	360.4	-2.2	36.0
1998	17.4	5.8	54.5	2.4	3.4	38.3	373.3	-2.5	33.6
1999	19.9	5.7	71.9	2.8	4.3	51.8	376.2	-2.6	40.0
2000	17.7	6.1	58.6	3.4	4.2	43.6	397.9	-2.8	32.7
2001	18.4	5.6	61.9	2.9	4.8	48.5	406.8	-2.8	31.8
2002	16.5	6.0	53.4	3.4	4.1	48.7	424.8	-2.6	21.2
2003	15.7	4.6	60.3	2.8	3.4	68.9	437.0	-2.8	7.1
2004	17.7	4.6	66.9	3.1	3.6	73.3	464.8	-3.1	11.2
2005	20.9	7.3	91.7	4.6	4.5	87.5	479.3	-3.2	25.1
2006	18.0	7.0	104.0	4.8	4.2	79.3	497.3	-2.9	42.7
2007	17.1	7.1	100.2	5.7	2.8	77.6	506.3	-2.8	39.7
2008	11.9	4.6	66.4	3.5	4.4	91.0	536.5	-3.5	-12.8
2009	10.2	3.7	72.7	3.0	3.2	100.6	573.8	-3.6	-17.7
2010	9.3	3.3	78.7	3.2	2.6	93.1	615.8	-4.3	-5.1
2011	9.4	3.2	78.4	3.5	4.0	75.2	651.8	-4.7	12.6
2012	9.7	3.2	76.5	3.4	4.0	70.3	670.5	-4.5	15.9
2013	9.3	3.2	77.6	4.0	3.8	81.2	684.0	-4.5	5.6
2014	9.1	3.4	61.7	4.0	2.9	79.9	719.2	-4.4	-9.1
2015	9.0	2.7	51.0	2.9	3.1	81.0	761.8	-4.7	-21.1
2016	10.6	2.7	53.2	2.5	2.2	73.2	804.3	-5.9	-9.5
2017	13.1	3.1	62.0	2.9	2.8	44.2	831.6	-5.5	30.9
2018	13.6	3.7	68.1	3.8	3.4	31.8	826.1	-5.6	50.0
2019	11.8	2.9	55.4	3.2	1.6	32.2	816.5	-4.9	35.0

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.9 UNFCCC Forest conversions – VIC annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[(a)]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	17.1	7.6	14.2	0.7	2.2	8.6	37.6	-0.2	22.6
1991	13.4	5.7	17.7	0.7	2.1	10.1	42.7	-0.2	21.0
1992	10.7	3.9	19.5	0.6	1.8	13.4	48.3	-0.3	16.8
1993	7.1	3.5	15.9	0.6	2.2	12.4	57.6	-0.3	10.5
1994	6.1	2.1	18.9	0.5	1.9	13.1	64.4	-0.3	11.9
1995	5.4	2.1	14.7	0.6	1.3	8.8	73.1	-0.4	11.2
1996	5.5	1.6	13.9	0.5	1.5	7.5	77.2	-0.5	11.9
1997	5.8	1.8	13.8	0.6	1.5	7.4	80.1	-0.5	12.1
1998	5.5	1.6	12.7	0.6	1.0	9.1	83.2	-0.5	9.2
1999	5.8	0.9	14.3	0.4	1.1	14.8	87.3	-0.6	5.3
2000	4.6	0.8	11.3	0.5	0.9	12.5	98.0	-0.7	3.4
2001	4.2	1.4	9.4	0.6	1.4	13.3	106.7	-0.7	0.4
2002	11.4	1.7	13.2	0.7	1.4	11.5	114.1	-0.8	13.1
2003	26.5	4.4	27.3	1.3	1.5	12.5	112.5	-0.8	41.3
2004	16.9	5.2	26.6	1.6	1.7	14.2	111.7	-0.8	29.3
2005	7.5	2.7	34.7	1.7	1.8	18.3	107.5	-0.8	24.0
2006	9.9	4.4	43.0	2.7	2.1	18.2	101.6	-0.7	34.6
2007	6.8	3.8	30.2	2.4	1.7	24.0	102.1	-0.6	13.0
2008	5.4	2.3	23.8	1.4	1.8	28.8	111.0	-0.7	0.3
2009	7.0	3.3	27.5	1.6	1.6	25.9	121.4	-0.7	8.6
2010	5.0	3.8	26.3	2.4	1.7	29.0	129.2	-0.6	2.2
2011	1.8	1.1	15.7	0.9	2.4	42.3	147.8	-0.7	-24.7
2012	1.3	0.6	13.2	0.6	1.8	38.3	181.7	-0.9	-23.8
2013	1.6	0.6	21.9	0.7	1.2	31.0	206.4	-1.1	-7.5
2014	2.1	0.8	26.1	1.0	1.4	31.6	220.4	-0.9	-3.4
2015	1.9	0.8	20.3	0.9	0.9	30.3	237.7	-1.3	-8.0
2016	1.3	0.7	15.9	0.8	0.6	25.8	256.7	-1.7	-8.6
2017	0.9	0.5	13.1	0.7	0.9	16.5	272.6	-1.7	-2.5
2018	0.7	0.3	12.3	0.6	0.8	13.6	279.8	-1.8	-0.7
2019	0.5	0.2	10.9	0.5	0.5	13.2	284.8	-1.6	-1.8

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.10 UNFCCC Forest conversions – WA annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[(a)]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	59.2	13.2	19.7	0.5	6.4	19.6	81.2	-0.3	59.3
1991	46.8	12.6	23.6	0.8	6.2	21.8	91.8	-0.3	48.5
1992	27.2	6.4	18.9	0.5	5.2	24.2	105.6	-0.4	21.9
1993	21.3	4.4	15.6	0.4	5.4	15.5	122.2	-0.4	21.4
1994	22.2	4.8	16.4	0.5	4.7	15.4	129.7	-0.4	23.2
1995	19.0	4.5	14.7	0.5	3.9	13.5	137.8	-0.5	20.2
1996	17.6	3.5	15.9	0.5	3.9	14.1	143.2	-0.6	19.4
1997	17.6	3.9	15.5	0.6	4.0	13.8	149.5	-0.7	19.3
1998	14.7	3.6	13.4	0.6	3.6	18.2	156.5	-0.8	9.9
1999	12.9	2.6	12.9	0.5	3.5	28.5	167.6	-0.8	-2.7
2000	12.6	2.7	14.2	0.6	3.5	24.7	188.1	-1.0	2.2
2001	13.8	2.7	20.9	0.8	2.9	24.6	200.0	-1.0	10.1
2002	13.9	2.9	20.3	0.9	3.6	21.1	212.1	-0.9	13.1
2003	16.1	3.5	24.8	1.2	2.7	20.8	217.8	-1.0	20.1
2004	16.4	3.7	26.6	1.4	3.6	21.3	221.8	-1.0	21.7
2005	18.0	4.2	36.1	1.6	3.6	24.3	219.8	-1.0	29.8
2006	19.2	4.2	43.8	1.9	3.3	24.7	215.4	-1.1	38.3
2007	18.3	4.9	39.8	2.2	3.4	28.7	212.7	-1.1	29.4
2008	13.1	3.8	33.0	1.6	3.5	30.1	217.2	-1.1	16.0
2009	11.2	3.0	32.0	1.5	3.1	30.3	223.1	-1.0	12.9
2010	11.8	3.0	33.4	1.7	3.6	29.3	227.9	-0.8	15.9
2011	10.7	3.5	27.7	1.6	2.4	32.6	235.1	-1.1	5.9
2012	7.4	2.0	23.2	1.0	3.0	39.5	248.7	-1.2	-8.9
2013	7.0	1.5	25.0	0.9	2.5	50.6	267.5	-1.2	-18.5
2014	7.2	2.2	25.8	1.2	2.7	55.2	296.4	-1.2	-22.2
2015	8.7	1.5	26.6	0.9	2.5	36.0	329.5	-1.3	-0.7
2016	9.4	3.0	26.9	1.4	1.8	30.6	343.1	-1.4	5.8
2017	4.2	1.2	19.6	0.8	1.5	24.8	356.8	-1.8	-1.0
2018	3.7	0.9	18.4	0.9	1.7	21.9	365.7	-1.6	0.2
2019	2.5	0.7	13.5	0.7	1.8	17.1	375.8	-1.4	-1.2

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.11 UNFCCC Forest conversions – TAS annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth(a)	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	12.1	3.5	3.9	0.1	1.4	3.8	6.4	0.0	12.3
1991	14.3	6.7	7.5	0.4	1.8	5.6	8.8	0.0	16.2
1992	6.6	4.3	7.0	0.3	1.7	4.6	12.3	0.0	9.1
1993	5.5	3.8	5.0	0.3	0.9	3.8	15.4	0.0	6.7
1994	4.8	2.0	4.2	0.2	1.2	4.2	17.9	0.0	4.8
1995	4.8	2.0	4.1	0.2	1.1	4.0	20.8	0.0	4.9
1996	3.8	1.8	3.5	0.2	1.1	2.8	23.2	0.0	4.5
1997	4.3	1.8	4.2	0.2	1.0	3.2	23.8	-0.1	5.2
1998	3.8	1.8	3.7	0.2	0.9	3.0	25.2	-0.1	4.4
1999	3.3	1.5	4.1	0.2	1.1	6.2	26.5	-0.0	1.2
2000	3.1	1.5	3.1	0.2	1.0	5.0	31.3	-0.1	1.2
2001	3.3	1.3	3.1	0.2	1.1	5.2	34.9	-0.1	1.1
2002	3.1	1.4	3.1	0.2	1.1	4.7	38.7	-0.1	1.5
2003	3.8	1.6	6.4	0.3	1.0	5.6	39.6	-0.1	4.6
2004	4.3	1.8	6.3	0.4	0.8	6.2	41.4	-0.2	4.3
2005	5.2	2.1	7.7	0.5	1.0	9.2	42.6	-0.2	3.7
2006	4.5	2.0	7.6	0.5	1.1	10.4	46.6	-0.2	1.7
2007	4.4	1.7	7.6	0.4	0.8	6.8	51.6	-0.3	5.3
2008	4.5	1.9	10.4	0.5	0.9	6.8	50.3	-0.3	8.1
2009	3.9	1.5	8.1	0.4	0.8	6.9	50.9	-0.3	5.1
2010	3.8	1.3	8.7	0.5	1.1	7.9	51.1	-0.3	4.5
2011	2.7	1.2	6.8	0.5	1.2	9.4	53.7	-0.3	0.1
2012	1.5	0.6	4.7	0.3	0.9	9.8	59.3	-0.4	-3.6
2013	1.6	0.4	4.9	0.2	0.6	9.9	65.2	-0.5	-3.4
2014	1.9	0.7	5.3	0.3	0.8	9.5	70.9	-0.4	-2.3
2015	1.6	0.6	5.7	0.4	0.6	7.7	75.6	-0.5	-0.4
2016	1.3	0.6	5.6	0.6	0.5	5.7	78.5	-0.6	1.2
2017	1.1	0.5	5.0	0.6	0.7	5.0	79.8	-0.5	1.2
2018	1.0	0.4	4.5	0.4	0.4	4.1	80.9	-0.5	1.4
2019	0.7	0.4	3.0	0.3	0.5	5.0	82.4	-0.5	-1.3

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.12 UNFCCC Forest conversions – SA annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth(a)	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	13.4	2.8	7.0	0.2	1.5	4.7	28.0	-0.0	15.8
1991	9.6	1.8	7.2	0.2	1.1	5.9	30.6	-0.0	10.9
1992	6.8	1.1	8.3	0.1	0.6	6.3	33.7	-0.1	8.9
1993	4.3	1.1	5.8	0.2	1.1	8.3	37.9	-0.1	1.8
1994	3.6	0.6	5.8	0.1	1.0	12.1	43.8	-0.1	-2.7
1995	3.1	0.6	4.7	0.1	0.4	9.3	53.9	-0.1	-1.5
1996	2.7	0.4	5.1	0.1	0.8	7.0	61.2	-0.1	0.8
1997	2.7	0.5	5.1	0.1	0.8	7.2	66.1	-0.1	0.7
1998	2.6	0.4	5.5	0.1	0.3	5.8	71.0	-0.2	2.2
1999	2.8	0.4	7.3	0.2	0.7	5.5	73.6	-0.2	4.6
2000	2.5	0.4	6.8	0.2	0.2	5.3	75.9	-0.3	4.0
2001	3.2	0.5	8.5	0.2	0.8	8.5	77.3	-0.3	3.2
2002	2.9	0.6	8.2	0.3	0.7	7.6	82.0	-0.3	3.5
2003	2.6	0.4	8.9	0.3	0.4	7.8	85.4	-0.3	3.7
2004	3.0	0.4	11.3	0.3	0.6	9.0	87.8	-0.3	5.3
2005	3.7	0.6	16.8	0.5	1.0	11.9	88.2	-0.3	8.6
2006	4.0	0.5	17.8	0.5	0.4	11.0	90.0	-0.3	10.9
2007	3.7	0.7	14.1	0.5	0.6	10.9	92.5	-0.3	6.9
2008	2.1	0.4	9.3	0.3	0.6	14.0	97.8	-0.3	-2.6
2009	2.2	0.3	9.7	0.3	0.4	19.2	105.5	-0.3	-7.3
2010	2.0	0.3	11.1	0.3	0.3	21.1	117.3	-0.4	-8.0
2011	1.5	0.2	11.2	0.3	0.1	22.8	130.8	-0.6	-10.1
2012	1.5	0.3	11.8	0.3	0.6	23.9	145.3	-0.5	-10.5
2013	1.8	0.3	15.7	0.3	0.7	21.0	158.2	-0.4	-3.5
2014	2.1	0.4	16.9	0.5	0.6	16.0	167.2	-0.4	2.9
2015	1.3	0.3	12.3	0.3	0.6	15.9	174.4	-0.5	-2.3
2016	0.6	0.1	8.0	0.2	0.2	17.2	184.6	-0.6	-8.6
2017	0.6	0.1	6.8	0.2	0.2	12.2	196.6	-0.7	-4.8
2018	0.6	0.1	6.7	0.2	0.5	9.7	203.7	-0.6	-2.5
2019	0.3	0.1	5.9	0.1	0.3	8.1	208.7	-0.4	-1.9

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.13 UNFCCC Forest conversions – NT annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[(a)]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	2.3	0.6	2.2	0.1	0.1	1.3	4.5	-0.0	3.3
1991	2.0	0.3	2.0	0.0	0.1	1.5	5.4	0.0	2.5
1992	3.0	0.4	3.0	0.1	0.2	2.4	6.1	0.0	3.7
1993	1.0	0.3	1.5	0.0	0.1	1.7	8.0	0.0	0.8
1994	1.0	0.1	1.6	0.0	0.2	1.9	9.3	0.0	0.7
1995	0.9	0.1	1.4	0.0	0.1	1.8	10.7	0.0	0.5
1996	1.3	0.2	2.2	0.0	0.1	1.7	11.5	0.0	1.8
1997	1.4	0.3	2.3	0.1	0.2	1.8	12.2	-0.0	2.0
1998	1.0	0.2	1.7	0.1	0.1	2.0	13.2	-0.0	0.7
1999	0.9	0.1	1.9	0.0	0.1	2.5	14.4	-0.0	0.3
2000	0.8	0.1	2.0	0.0	0.1	1.9	16.0	-0.0	0.8
2001	0.8	0.1	2.6	0.0	0.2	2.0	16.8	-0.0	1.4
2002	0.8	0.1	2.4	0.1	0.2	1.9	17.8	-0.0	1.3
2003	0.8	0.1	2.4	0.1	0.2	3.0	18.4	-0.0	0.2
2004	0.9	0.1	2.5	0.1	0.1	3.1	20.1	-0.0	0.3
2005	1.5	0.2	5.5	0.1	0.1	3.2	20.0	-0.0	3.8
2006	1.3	0.2	6.8	0.1	0.1	3.0	19.6	-0.0	5.2
2007	1.7	0.2	5.6	0.1	0.2	2.9	19.3	-0.0	4.4
2008	1.5	0.2	4.1	0.1	0.1	2.8	20.1	-0.0	2.7
2009	0.9	0.1	3.7	0.1	0.2	2.7	20.7	-0.0	2.0
2010	0.7	0.1	3.8	0.1	0.1	3.0	21.0	-0.0	1.6
2011	0.5	0.1	2.3	0.1	0.1	3.4	22.3	-0.0	-0.6
2012	0.4	0.1	2.8	0.1	0.2	2.2	23.8	-0.0	1.0
2013	0.5	0.1	3.1	0.1	0.1	1.8	24.0	-0.0	1.9
2014	0.6	0.1	2.9	0.1	0.1	2.4	23.8	-0.0	1.0
2015	0.7	0.1	3.1	0.1	0.2	2.7	24.1	-0.0	1.1
2016	0.8	0.1	5.2	0.1	0.1	2.2	23.1	-0.0	3.8
2017	0.3	0.1	2.8	0.1	0.0	2.8	23.7	-0.0	0.3
2018	0.2	0.0	2.1	0.1	0.1	4.3	25.0	-0.0	-1.9
2019	0.2	0.0	1.7	0.0	0.1	2.7	28.0	-0.0	-0.8

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.14 UNFCCC Forest conversions – ACT annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[(a)]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	0.21	0.068	0.25	0.002	0.015	0.18	0.36	-0.002	0.28
1991	0.15	0.048	0.43	0.005	0.014	0.21	0.48	-0.002	0.36
1992	0.11	0.031	0.48	0.005	0.009	0.16	0.61	-0.004	0.43
1993	0.05	0.025	0.15	0.004	0.011	0.18	0.73	-0.005	0.02
1994	0.05	0.021	0.15	0.003	0.010	0.20	0.87	-0.005	0.00
1995	0.05	0.020	0.16	0.004	0.009	0.16	1.03	-0.007	0.05
1996	0.05	0.018	0.28	0.006	0.007	0.11	1.13	-0.010	0.22
1997	0.06	0.022	0.27	0.009	0.011	0.11	1.18	-0.009	0.22
1998	0.05	0.020	0.26	0.010	0.009	0.14	1.23	-0.007	0.18
1999	0.10	0.030	0.31	0.011	0.013	0.35	1.29	-0.010	0.06
2000	0.07	0.038	0.30	0.015	0.015	0.27	1.56	-0.012	0.10
2001	0.04	0.011	0.41	0.015	0.012	0.22	1.70	-0.013	0.22
2002	0.07	0.009	0.47	0.017	0.012	0.17	1.73	-0.010	0.38
2003	0.19	0.051	0.86	0.044	0.021	0.15	1.45	-0.010	0.90
2004	0.16	0.060	0.88	0.057	0.027	0.16	1.22	-0.007	0.88
2005	0.14	0.049	0.90	0.062	0.022	0.21	1.06	-0.006	0.83
2006	0.10	0.033	0.85	0.032	0.029	0.17	0.87	-0.003	0.77
2007	0.06	0.027	0.73	0.039	0.017	0.32	0.64	-0.003	0.47
2008	0.01	0.004	0.28	0.007	0.010	0.57	0.75	-0.004	-0.27
2009	0.03	0.003	0.72	0.008	0.011	0.21	0.76	-0.003	0.53
2010	0.03	0.010	0.43	0.019	0.025	0.21	0.63	-0.002	0.25
2011	0.01	0.005	0.21	0.007	0.027	0.21	0.66	-0.003	0.01
2012	0.01	0.002	0.17	0.004	0.023	0.30	0.73	-0.003	-0.12
2013	0.02	0.006	0.15	0.006	0.008	0.47	0.91	-0.005	-0.30
2014	0.03	0.011	0.12	0.005	0.016	0.62	1.28	-0.005	-0.46
2015	0.02	0.012	0.09	0.005	0.012	0.74	1.82	-0.009	-0.64
2016	0.01	0.001	0.08	0.001	0.005	0.54	2.50	-0.015	-0.45
2017	0.01	0.005	0.14	0.004	0.006	0.22	2.92	-0.017	-0.07
2018	0.00	0.001	0.09	0.002	0.005	0.17	3.06	-0.019	-0.08
2019	0.00	0.000	0.07	0.003	0.000	0.22	3.17	-0.018	-0.14

(a) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Table 6.L.15 UNFCCC Forest conversions – Great Barrier Reef Catchment[a] annual areas and related GHG emissions

Year	Annual Area of primary forest converted	Direct emissions from primary forest clearing	Annual area of secondary forest converted	Direct emissions from secondary forest clearing	Emissions from decay on previously cleared lands	Annual area of identified regrowth	Total area of sustained regrowth[b]	Net emissions from the regrowing forest (negative values denote removals)	Net clearing of forests (conversions less identified regrowth)
	kha	Mt CO_2-e	kha	Mt CO_2-e	Mt CO_2-e	kha	kha	Mt CO_2-e	kha
1990	237.3	32.6	116.8	2.8	14.6	84.5	266.1	-0.0	269.6
1991	198.5	35.2	122.7	3.0	15.2	72.1	318.3	-0.0	249.1
1992	163.9	23.3	142.0	2.9	9.5	63.2	349.9	-0.2	242.7
1993	107.3	19.4	120.9	2.8	11.6	62.3	373.2	-0.6	165.9
1994	107.4	15.6	132.4	2.8	8.3	72.3	390.6	-0.3	167.6
1995	76.4	13.6	85.4	2.6	7.1	52.7	430.0	-0.7	109.0
1996	76.6	9.9	87.9	1.8	9.4	58.4	445.1	-0.7	106.1
1997	74.4	10.5	83.3	2.1	5.8	54.3	468.2	-1.1	103.4
1998	68.9	10.0	92.2	2.3	8.3	57.0	479.7	-1.3	104.1
1999	72.5	10.6	108.2	2.9	9.3	66.9	483.7	-1.0	113.8
2000	104.2	11.3	107.8	3.2	6.0	48.5	499.8	-1.5	163.6
2001	138.5	16.6	131.5	3.9	12.6	48.0	484.5	-1.4	222.0
2002	125.7	17.6	116.7	4.5	8.5	48.0	477.3	-1.3	194.4
2003	67.5	12.4	96.7	3.7	11.5	50.8	478.5	-1.2	113.4
2004	75.7	9.6	113.4	3.7	9.4	46.4	471.3	-1.2	142.8
2005	118.9	14.6	194.6	6.0	7.6	72.7	412.6	-1.1	240.8
2006	80.7	14.4	130.8	5.6	7.5	96.7	406.4	-1.1	114.8
2007	61.9	11.4	120.1	4.4	10.5	108.1	424.4	-1.0	74.0
2008	43.4	8.5	114.3	3.5	10.2	165.2	451.7	-1.0	-7.6
2009	27.9	5.6	81.6	2.7	7.0	192.4	559.0	-0.9	-82.9
2010	18.4	3.6	75.1	2.1	12.0	130.5	695.0	-0.9	-37.0
2011	15.2	3.1	78.8	2.0	8.8	110.2	764.3	-0.7	-16.2
2012	12.2	2.5	89.8	1.9	6.1	157.0	807.2	-1.9	-55.0
2013	15.5	2.5	137.9	2.4	9.2	138.7	861.6	-1.9	14.6
2014	16.6	3.0	122.8	2.8	8.1	209.6	904.5	-2.3	-70.2
2015	18.7	2.9	135.2	2.6	6.2	182.9	1,006.3	-2.1	-28.9
2016	18.8	3.2	151.6	3.1	4.1	182.7	1,067.6	-2.7	-12.3
2017	12.3	2.6	125.6	2.9	4.1	131.4	1,149.9	-2.4	6.6
2018	15.5	2.4	119.3	2.5	6.1	130.9	1,185.2	-2.4	3.9
2019	6.1	2.4	90.9	2.5	1.5	122.4	1,238.6	-2.4	-25.3

(a) The Great Barrier Reef Catchment is defined as the Australian Drainage Division of the North East Coast excluding where it overlaps with the Natural Resource Management region of South East Queensland Catchments.

(b) The area of sustained regrowth only includes those area which had identified regrowth in an earlier year and continue to show forest cover. This means that where identified regrowth is subjected to re-clearing in the following year then it will not be counted in the area of sustained forest. This area correlates with the emissions reported under *Land converted to Forest* for regrowth on previously cleared lands.

Appendix 6.M Carbon Stock Accounting

Carbon stock accounting is conducted under the principles of the System of Environmental-Economic Accounting (UNSD, 2014a) and Experimental Ecosystem Accounting (UNSD, 2014b). By compiling estimates from sources consistent with the National Inventory, this establishes an alternative accounting perspective of the underlying data, the results of which which are shown in Annex 6.3 of Volume 3. Some scope differences exist, and so comparisons between the accounting structures should be made with this in mind.

The accounts were inspired by the work of Ajani and Comisari (2014), and in collaboration with the ABS in development of experimental ecosystem accounts for the Great Barrier Reef catchment areas (ABS, 2017b). The accounts remain subject to ongoing improvements as methods are consolidated and feedback from stakeholders is incorporated.

Emissions estimation is based off of modelling in FullCAM, and carbon stock levels are readily obtainable from the simulation results. Due to the simulation projects being designed for only emissions reporting, special treatments were made to account for the limitations of these simulation projects, such as rebasing soil carbon levels (Table 6.M.1). Project results are summed and adjusted for sources of carbon stocks and their changes calculated outside of the FullCAM modelling systems.

Changes in carbon stocks are attributed to one of four types of change:

- *Reclassifications* are the movement of carbon from one type of land use to another, such as through land clearing and re-clearing, plantation establishment, or other forms of regeneration.
- *Transfers to wood products* includes the carbon in logs removed from a forest during a harvesting event.
- *Fire and regrowth from fire* includes the immediate losses of carbon in deadwood and litter due to a fire event, and the subsequent recoveries within the forest. Contributions of recovery are counted in the years where the regrowth occurs rather than in the year where the fire occurred. The impacts of non-anthropogenic Natural Disturbances are included in this account.
- *Net growth and decay* includes all other changes in carbon stocks, including the growth of trees and the loss of woody material left or burned on a harvesting site following a harvesting event. This also includes the gains or losses of carbon associated with a reclassification of land use after the movement between land uses has been assessed under reclassifications.

Table 6.M.1 Sources of carbon stock data, compilation matrix

Data Source	Special treatments and adjustments
Tier 3 Fu llCAM simulations – Deforestation	• Expanded to include coverage for growth transitions occurring before the first clearing event.
Tier 3 FullCAM simulations – Afforestation / Reforestation	• Expanded to include all transitions occurring before the first post-1989 planting event.
Tier 3 FullCAM simulations – Additional Land converted to Forest	• Expanded to include coverage for forest cover loss transitions occurring before the first forest growth event. • Expanded to include all transitions occurring before the first post-1989 growth event in locations subject to emissions reduction fund project areas. • Added 2016 stock levels for unprotected and fire-affected areas not in scope of the emissions inventory. • Added 2006 stock levels for areas of central Australia otherwise not simulated.
Tier 2 models – Forest Management	• Added stocks from the series used to calculate emissions for multiple use forests, harvested private native forests and pre-1990 plantations, as per the Forest Management scope.
Tier 3 FullCAM simulations – Forests remaining Forests (project in development, not yet in use for NIR)	• Added 2016 stock levels for all areas associated with forest not experiencing anthropogenic transitions. Results by state and major vegetation group are scaled to the 2016 forest extent, less areas already accounted for by other sources.
Tier 2 models – Fire and Fuelwood	• Adjustments applied to stocks for the emissions series on fuelwood, wildfire and prescribed burning. The full impact of natural disturbances are included. Levels are set in 1999 and are cast forward and back using the source's emissions series.
Tier 3 FullCAM simulations – Grasslands	• Assessment of stocks in 2016 for above-ground biomass, and in 1972 for below-ground biomass, applied to the full series. Results are scaled to the 2016 extent of grasslands, settlements wetlands and other lands, less areas already accounted for from other sources. The NIR emissions series is used to cast back stock changes relating to changes in soil management practices.
Tier 2 models – Sparse Transitions	• Added stocks for sparse woody vegetation on grasslands, wetlands and settlements, drawn directly from the associated revegetation models of sparse extent and transitions.
Tier 1 models – Wetlands converted to Croplands and Grasslands	• Adjustments to stock series applied for the emissions series of Wetlands converted to Croplands and Grasslands, casting forward and back from the 2015 level estimate.
Tier 3 FullCAM simulations – Croplands	• Assessment of stocks in 2016 for above-ground biomass, and in 1972 for below-ground biomass, applied to the full series. The NIR emissions series is used to cast back stock changes relating to changes in soil management practices. • Total stocks scaled to include areas excluded from the simulation due to being classified as areas of Woody Horticulture.
Tier 2 models – Woody Horticulture	• Added stocks of living biomass for areas of woody horticulture, discerned from the parameters of the stock-change based emissions model.
Tier 2 models – Mangroves and Tidal Marshes	• Added stocks based on a 2016 assessment of mangrove and tidal marsh extent using the same parameters as applied in the tier 2 model. Levels are set in 2010 and are cast forward and back using the source's emissions series.
Tier 2 models – Harvested Wood Products	• Source data used as-is.
Tier 2 models – Solid Waste	• Only the modelled results for paper and wood products' carbon accumulated are incorporated. See note (e) below.

Further notes

a) Where 1972 values rather than 2016 values are used, this is due to uncertainty around FullCAM's estimates of soil carbon stocks in the absence of transition events on grasslands and croplands. Stock initialisation is taken as the most reliable estimate of levels in such circumstances pending further improvements to FullCAM.

b) Where 2006 levels are used on central Australian tiles, it is because this was the latest set of Landsat images processed for these locations at the time of compilation.

c) Where 1999 levels are used for forests, it is because this was identified as the median year for maximum above-ground biomass calculations in native forests.

d) Seagrasses have not been incorporated into the accounts.

e) Only solid waste disposal data on paper and wood products are included from the waste sector on the basis that other sources of carbon in landfill and waste streams do not have their creation accounted for in the accounts. For example, the growing and harvesting of food is excluded from the accounts and so it would be in error to include the carbon of food waste in landfill.

f) Harvested wood products and solid waste models are operated on the basis of carbon stock changes, facilitating the direct utilization of their models without needing to transform emissions series. The direct loss of carbon in landfill from paper and wood products in the form of methane is also accounted for in the tier 2 waste models as a direct loss rather than as a flux on CO_2 emissions and so no further adjustment to model results is required.

g) Due to carbon stock accounts having not been recompiled based on the 2019 Inventory updates as at the time of publication, the results of accounting are not shown in this NIR. Images of carbon stock densities are shown for the purpose of demonstrating capability, and will be subject to revision as accounts are recompiled.

7. Waste

7.1 Overview

Total estimated *waste* emissions for 2019 were 12.4 Mt CO_2-e, or 2.3 per cent of total net national emissions (excluding *LULUCF)* (Table 7.1). The majority of these emissions were from solid waste disposal, contributing 9.2 Mt CO_2-e or 73.6 per cent of waste emissions. *Wastewater treatment and discharge* contributed a further 3.0 Mt CO_2-e (23.9 per cent) of waste emissions while *waste incineration* and *biological treatment of solid waste* contributed 0.03 Mt CO_2-e (0.2 per cent) and 0.3 Mt CO_2-e (2.3 per cent) 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.

Waste

Table 7.1 Waste sector, Australia 2019, 2020

Greenhouse gas source and sink categories	CO_2-e emissions (Gg)				
	CO_2	CH_4	N_2O	Total	Preliminary 2020 (CO_2-e)
5 WASTE	**30.7**	**11,754.1**	**653.9**	**12,438.6**	**11,998.8**
A. Solid waste disposal	NA	9,153.8	NA	9,153.8	8,237.4
B. Biological treatment of solid waste	NA	112.2	171.3	283.5	283.5
C. Incineration and open burning of waste	30.7	A	NE	30.7	30.7
D. Wastewater treatment and discharge	NA	2,488.1	482.6	2,970.7	3,447.3

7.1.1 Trends

Total estimated *waste* emissions for 2019 were 12.4 Mt CO_2-e, emissions decreased by 37.9 per cent (7.6 Mt CO_2-e) over the period from 1990 to 2019 and also decreased by 1.2 per cent (0.1 Mt CO_2-e) from 2018 to 2019.

Preliminary estimates of *waste* sector emissions for 2020 are 12.0 Mt CO_2-e. These estimates will be subject to revision in the official inventory submission in 2022.

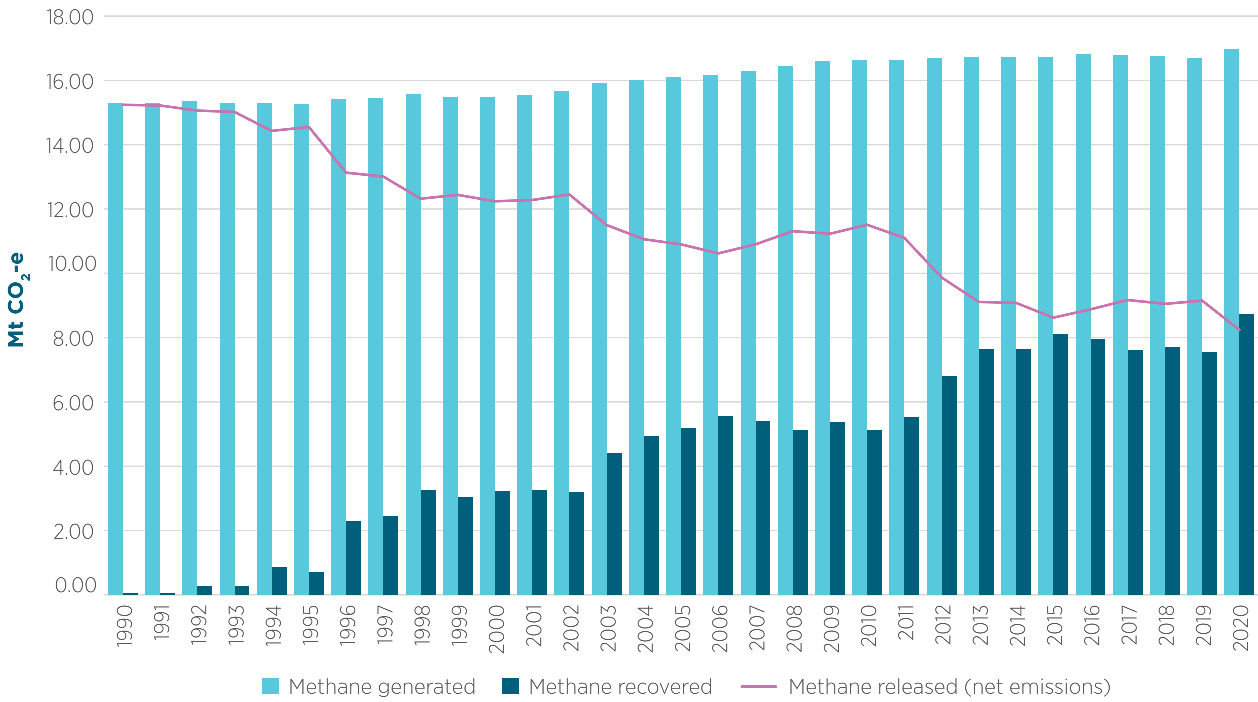
Emissions from *solid waste disposal* decreased by 39.9 per cent (6.1 Mt CO_2-e) over the period 1990 to 2019 (Figure 7.1) and increased by 1.2 per cent (0.1 Mt CO_2-e) from 2018 to 2019. This decline since 1990 is mainly due to increases in methane recovery. As waste degradation is a slow process, estimates 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, increasing from a negligible amount in 1990 to 7.5 Mt CO_2-e of methane in 2019.

Emissions from the *Biological treatment of solid waste* have increased by 0.7 per cent (0.002 Mt CO_2-e) since 2018. Emissions of CO_2 from the incineration of solvents and clinical waste decreased by 58.2 per cent (0.04 Mt) between 1990 and 2019.

Wastewater treatment and discharge emissions decreased by 36.5 per cent (1.7 Mt CO_2-e) over the period 1990 to 2019 and also decreased 8.0 per cent (0.3 Mt CO_2-e) from 2018 to 2019. 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 Trends in methane generation, recovery and emissions from solid waste disposal, 1990–2019 (preliminary estimates 2020)



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

And Sink Categories	CO_2 Method applied	CO_2 Emission factor	CH_4 Method applied	CH_4 Emission factor	N_2O Method applied	N_2O Emission factor
5. Waste	**T2**	**CS**	**T1/T2/T3**	**CS,D**	**T1/T2/CS**	**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:

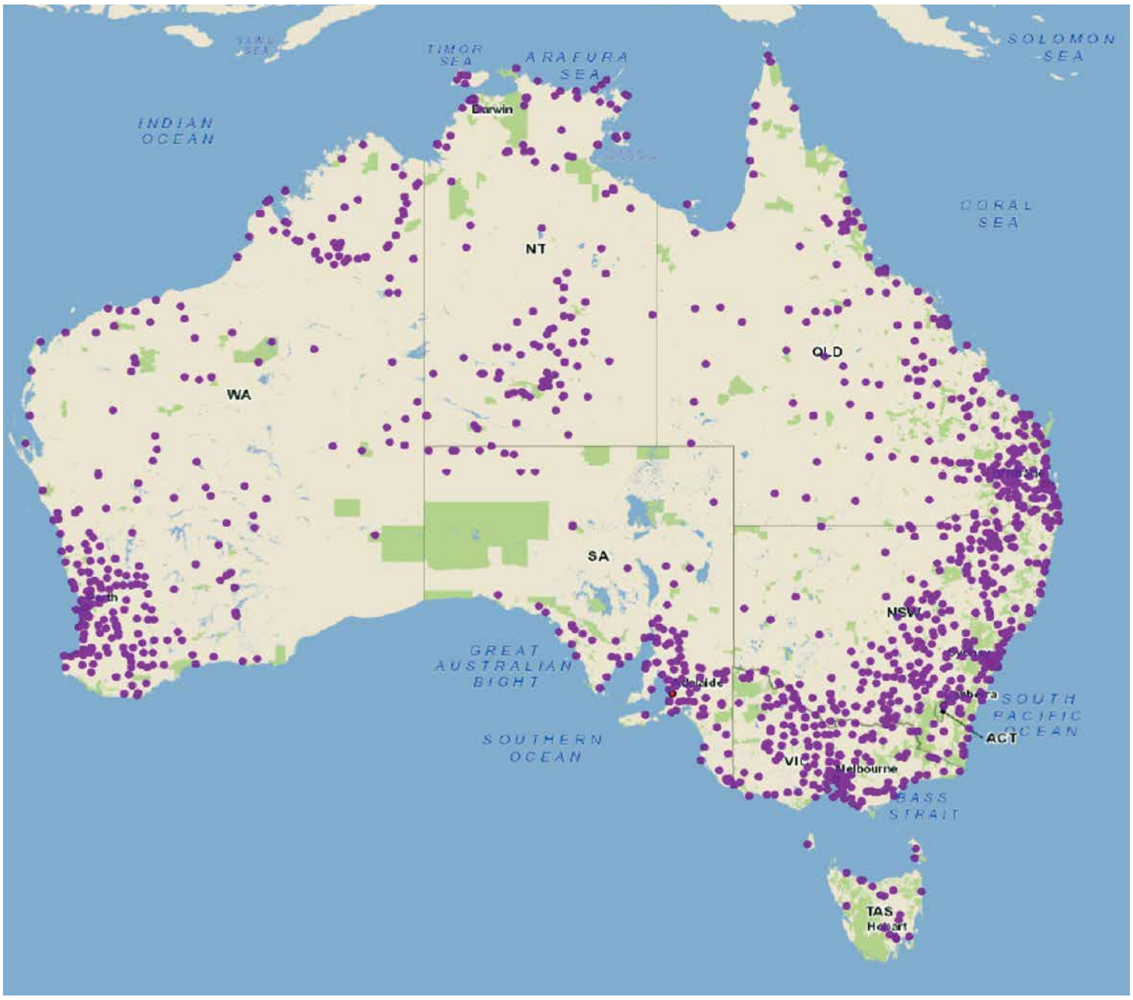
- landfill;
- biological treatment/composting;
- incineration; and
- recycling/reuse.

There are approximately 1274 operating landfills in Australia (disposal facilities). It is reported in the National Waste Report 2020 (DAWE and Blue Environment Pty Ltd, 2020) that these landfills receive around 27 Mt of waste. This amount equates to approximately 36 per cent of the estimated total waste generated (74 Mt). The balance of waste, 61 per cent 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.

Australia's solid waste management task has become more concentrated in the last decade with many smaller landfills closing and larger centralised landfills taking the bulk of disposed waste. On the basis of NGER data for 2019, a relatively small number of sites are responsible for the bulk of the waste received in Australia. 50 per cent of Australia's waste disposal occurs in the 21 largest landfills. Of the landfills reporting under NGERS, 18 process more than 200 kt of waste per year, 12 process between 100 kt and 200 kt per year, 18 process between 50 kt and 100 kt per year, 12 process between 25 kt and 50 kt per year, 4 process between 10 kt and 25 kt per year and the remainder (25 landfills, or around 28 per cent of the total number of landfills) process less than 10 kt each per year.

In terms of waste management practices in place at Australian landfills, 11 per cent of landfills have a landfill gas collection system in place. However, in the larger scale landfills, this practice is more common meaning that around 43 per cent of the methane generated is collected for either flaring or energy generation.

Figure 7.2 Australian landfill locations



Source: DAWE

According to a landfill survey conducted by the Waste Management Association of Australia in 2007, common management practices amongst larger landfills include the use of leachate collection systems (38 per cent of landfills). Landfill designs include 38 per cent of landfills with clay cell liners in place, 9 per cent use HDPE cell liners while 7 per cent use GCL liners. In terms of capping practices, 59 per cent of landfills use clay capping, whilst 12 per cent 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 65 per cent 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 1990–2019

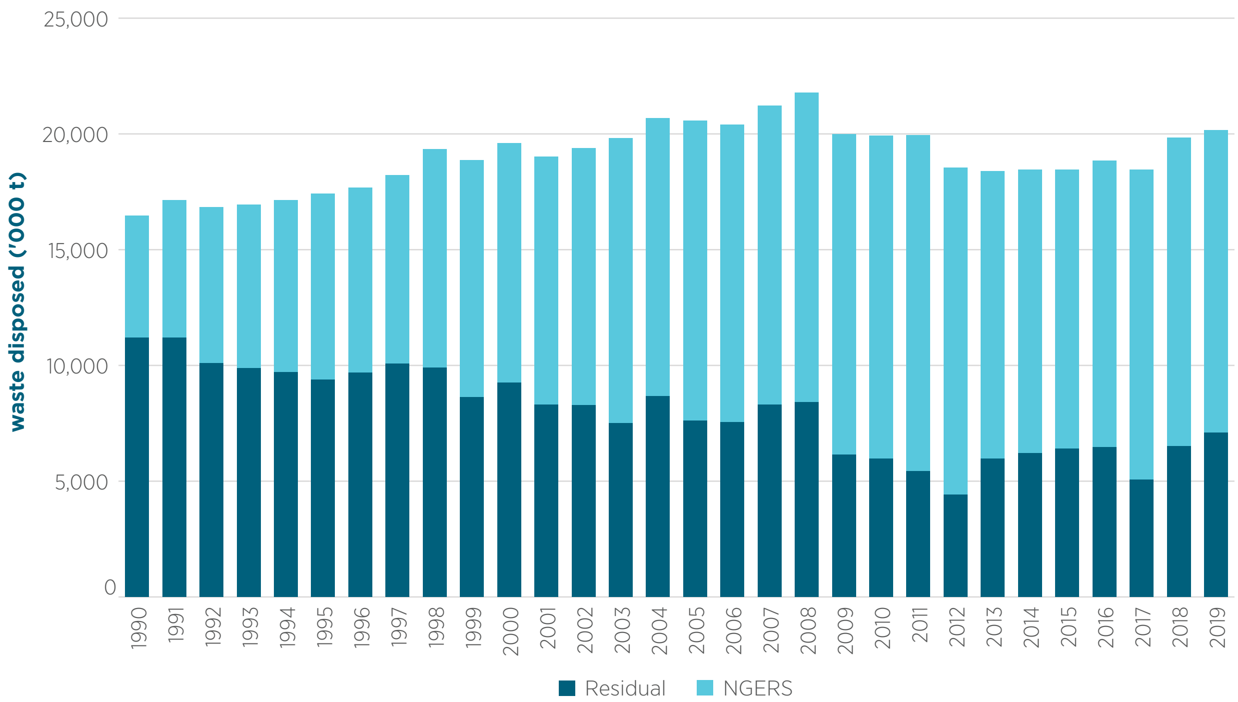
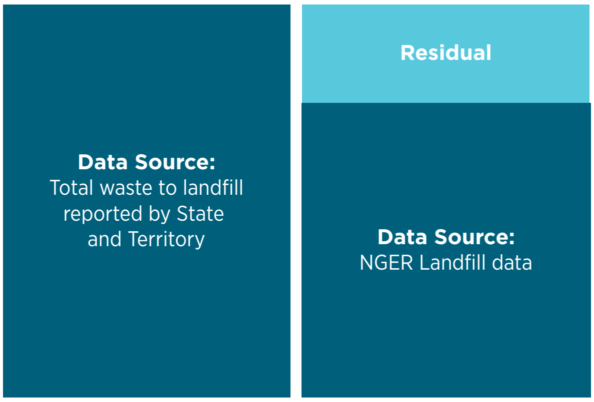
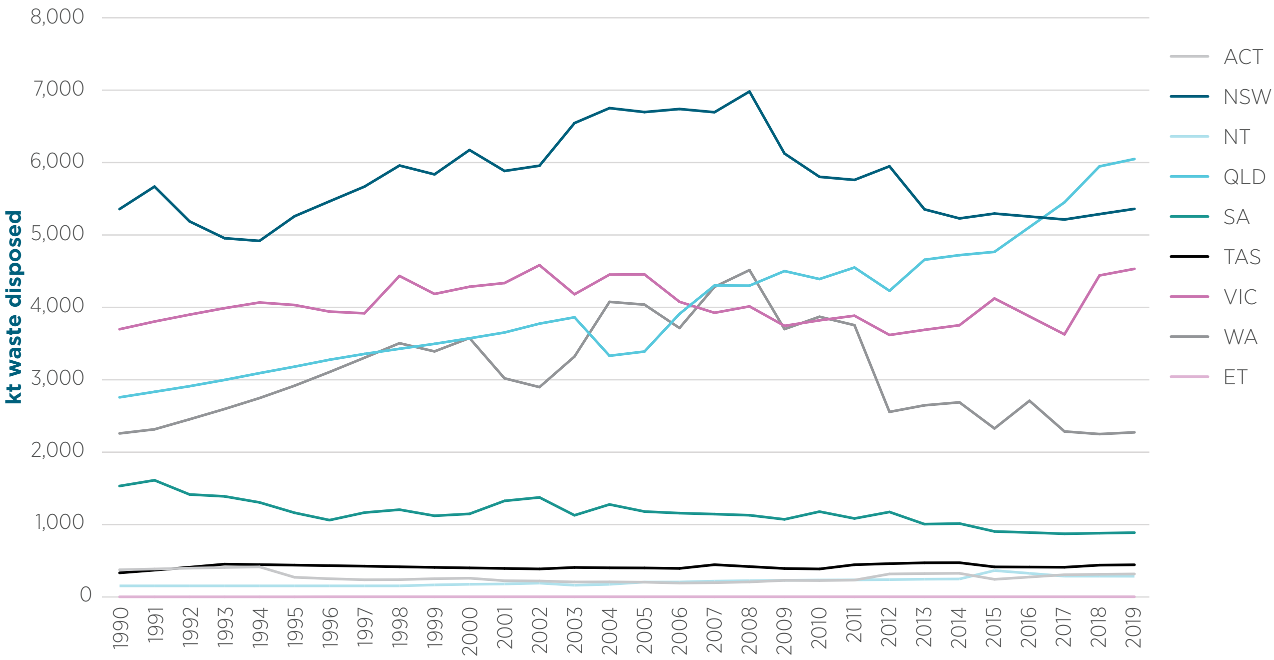


Figure 7.4 Relationship between State and Territory reported disposal and NGERS reported disposal.



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 1990–2019



Source: DISER and NGER 2019

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).

Waste

Table 7.3 Waste streams: municipal, commercial and industrial, construction and demolition: percentages by State: 2019

	NSW	VIC	QLD	NT	SA	WA	TAS	ACT
Municipal Solid Waste	36.9	47.8	32.3	43.0	36.9	33.2	42.4	31.3
Commercial and Industrial	33.9	26.3	33.3	14.0	27.7	34.4	51.6	61.9
Construction and Demolition	29.1	25.9	34.5	43.0	35.4	32.4	6.1	6.8

Source: DISER and NGER 2019

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. 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:

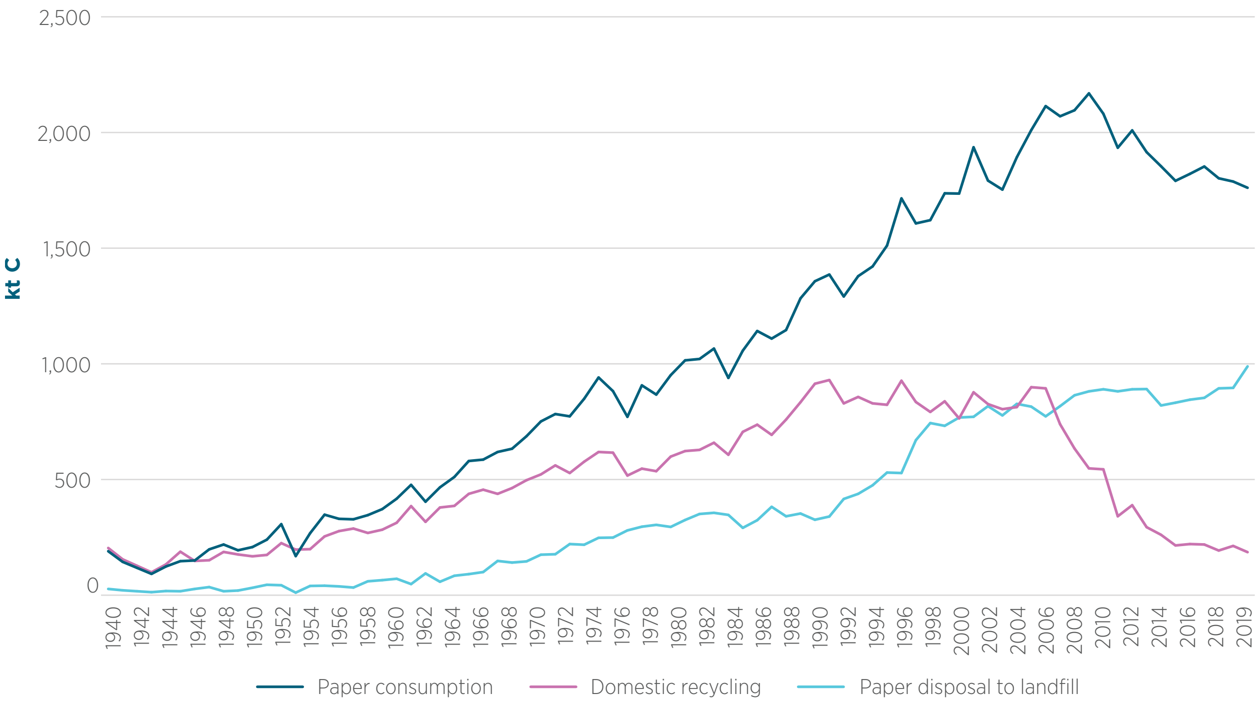
- Food;
- Paper;
- Garden and green;
- Wood;
- Wastes from the production of harvested wood products;
- Textiles;
- Sludge (including biosolids);
- Nappies;
- Rubber and leather; and,
- Inert (concrete, metal, plastics, glass, soil etc).

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: 1940–2019



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 3,473.2 kt in 2019 (ABARES 2020) reflecting both increasing population and increasing per capita consumption levels. In terms of carbon, these consumption estimates translate into an estimated 190.0 kt C in 1940 and 1,760.7 kt C in 2019 (Table 7.4). Per capita consumption of paper has increased from an estimated 26.4 kg C per person in the 1940s to 69.4 kg C per person in 2019. Reflecting the growth in paper consumption, waste paper generation is estimated to have increased from 244.6 kt C in 1940 to 1,774.2 kt C in 2019.

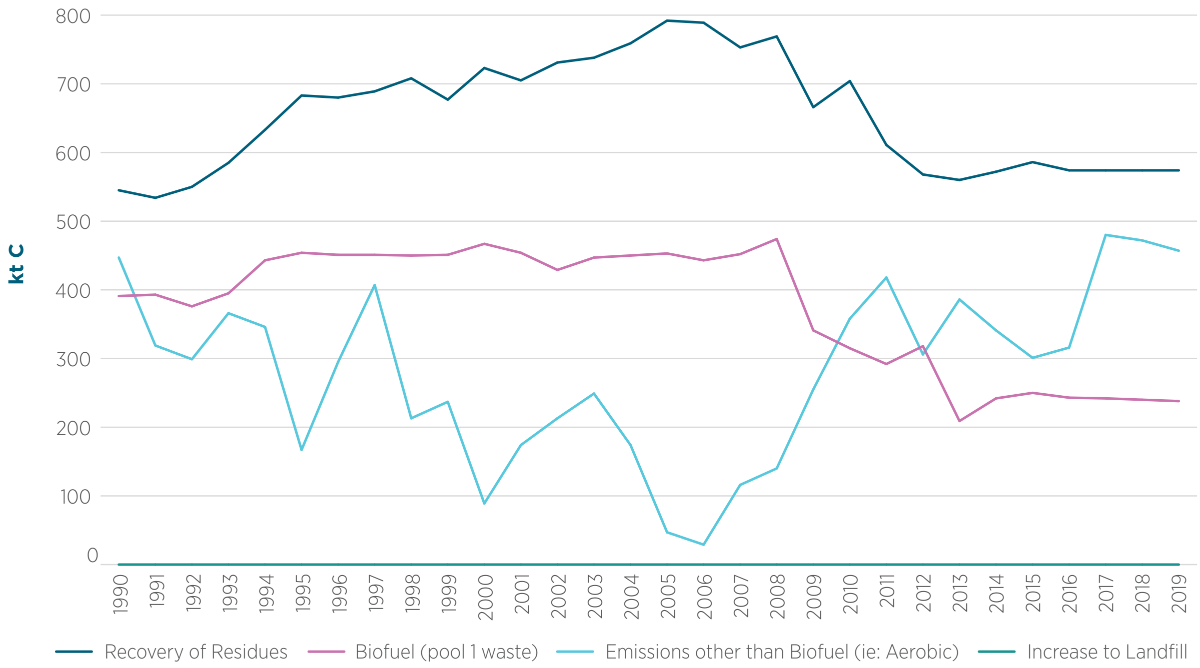
The proportion of paper waste generated that reaches landfill depends critically on the amount of paper diverted to other disposal paths. In Australia, an increasing trend to paper recycling has led to a decrease in the proportion of paper disposed to landfill. The amount of waste paper disposed to domestic recycling as a share of product reaching the end of its useful life has increased from an estimated 25 per cent in 1990 to 65 per cent in 2019. A sharp jump in recycling was 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; this has offset declines in the production of sawnwood from hardwood species. In contrast, the ratio of waste generated to harvested wood product produced has fallen over time. This trend reflects 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 83.2 per cent. By 2019, this ratio had fallen to 10.5 per cent.

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[17], 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).

17 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: 1990–2019



Source: Refer to Table 7.6

Table 7.4 Paper consumption, waste generation and disposal: Australia, 1940 to 2019

	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	190.0	26.4	200.0	244.6	27.0	203.5	0.1	0.8
1990	1,385.9	80.7	764.0	1,362.0	340.0	930.1	0.2	0.7
2000	1,935.6	101.1	1,044.1	1,854.3	771.0	876.6	0.4	0.5
2005	2,114.1	104.1	1,156.3	2,054.2	773.2	894.3	0.4	0.4
2008	2,168.5	101.0	1,193.1	2,136.4	881.2	548.1	0.4	0.3
2009	2,081.0	95.2	1,168.6	2,105.5	890.4	544.0	0.4	0.3
2010	1,933.9	87.2	1,098.5	2,003.9	881.0	340.6	0.4	0.2
2011	2,008.9	89.2	1,106.8	2,000.6	890.1	389.1	0.4	0.2
2012	1,915.2	83.5	1,077.6	1,944.3	890.8	293.9	0.5	0.2
2013	1,853.7	79.5	1,040.7	1,890.6	820.0	261.0	0.4	0.1
2014	1,791.3	75.7	1,006.0	1,826.1	832.0	214.8	0.5	0.1
2015	1,821.1	75.8	1,008.2	1,818.9	844.5	221.5	0.5	0.1
2016	1,852.8	76.0	1,024.0	1,836.9	853.0	219.0	0.5	0.1
2017	1,802.0	72.7	1,008.5	1,817.6	893.5	192.6	0.5	0.1
2018	1,787.7	71.0	996.1	1,800.0	896.0	213.2	0.5	0.1
2019	1,760.7	69.4	982.7	1,774.2	988.6	186.2	0.6	0.1

Source: DISER estimates: derived from ABARES 2020, 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, 1940 to 2019

	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	1,467.0	831.0	0.6	0.3	0.0	0.0	0.0
1990	4,287.5	1,383.0	0.3	0.3	0.0	0.3	0.4
2000	5,679.9	1,278.8	0.2	0.4	0.0	0.1	0.6
2005	1,027.2	1,291.0	0.2	0.4	0.0	0.0	0.6
2008	1,015.0	1,383.7	0.2	0.3	0.0	0.1	0.6
2009	884.6	1,262.0	0.2	0.3	0.0	0.2	0.5
2010	942.1	1,377.2	0.2	0.2	0.0	0.3	0.5
2011	854.8	1,321.8	0.2	0.2	0.0	0.3	0.5
2012	810.9	1,191.9	0.2	0.3	0.0	0.3	0.5
2013	794.6	1,155.5	0.2	0.2	0.0	0.3	0.5
2014	808.4	1,155.4	0.2	0.2	0.0	0.3	0.5
2015	830.5	1,137.0	0.2	0.2	0.0	0.3	0.5
2016	810.8	1,133.6	0.2	0.2	0.0	0.3	0.5
2017	879.8	1,296.0	0.2	0.2	0.0	0.4	0.4
2018	830.1	1,285.7	0.2	0.2	0.0	0.4	0.4
2019	811.2	1,269.5	0.2	0.2	0.0	0.4	0.5

Source: DISER derived from ABARES 2020, 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 2020; Jaakko Pöyry 2000, Department of National Development 1969.	Not applicable.	ABARES 2020; 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 2020, 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 2020) 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. 0% 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 2020 and the Department of National Development 1969) and paper recycling (ABARES 2020). 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 2020 and the Department of National Development 1969) and on the combustion of wood and wood waste (DISER 2020). 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: 2019

	kt C
Additions to the HWP carbon stock	
Apparent consumption of HWP	3,473.2
Generation of HWP wastes	1,269.5
Total additions	4,742.8
Deductions from the HWP carbon stock	
Disposal to landfill	186.2
Disposal through combustion for energy/ waste incineration	238.1
Disposal through aerobic decay	1,056.6
Recycling/use in other products	1,562.8
Total deductions	3,043.7
Net increment in HWP stock	1,699.1

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 2019, the reduction in carbon stock from combustion for energy of HWP and wastes generated from HWP production is estimated at 238.1 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 2019, the reduction in carbon stock from disposal to landfill is estimated at 186.2 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

Carbon dioxide emissions from landfill are estimated using the assumption that landfill gas is 50 per cent carbon dioxide 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). These mixes were confirmed in 2014 by a desktop audit of waste composition data conducted by Anne Prince Consulting. Data on paper, wood and and wastes from the production of harvested wood products disposed to landfill are based on data and assumptions set out in Table 7.8. Actual waste mix percentages change over time as the amount of wood and paper entering landfills vary – percentages for 2019 are reported in Table 7.8.

Waste

Table 7.8 Individual waste type mix: percentage share of individual waste streams disposed to landfill 2019

	Municipal Solid Waste	Commercial & Industrial	Construction & Demolition
Food	38.5%	23.2%	0.0%
Paper [(a)]	3.0%	4.4%	0.5%
Garden and Green	18.5%	4.9%	2.1%
Wood [(a)]	0.8%	7.4%	4.8%
Waste from HWP production [(a)]	0.0%	0.0%	0.0%
Textiles	1.7%	4.9%	0.0%
Sludge	0.0%	1.8%	0.0%
Nappies	4.4%	0.0%	0.0%
Rubber and Leather	1.3%	4.3%	0.0%
Inert (concrete, metal, plastics and glass, soil etc)	31.9%	49.1%	92.6%

Source: Derived from GHD 2008, Hyder Consulting 2008 and Anne Prince Consulting (2014);
(a) DISER estimates based on data and assumptions in Table 7.6 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	10,444.0	1,978.0	933.0	1,878.0	1,925.0	421.0	4,726.0
1990	16,366.0	3,238.0	2,307.0	1,358.0	716.0	832.0	7,916.0
2005	20,472.0	3,691.0	2,219.0	1,582.0	925.0	1,081.0	10,974.0
2008	21,692.0	4,197.0	1,361.0	1,758.0	1,026.0	1,235.0	12,115.0
2009	19,998.9	4,121.2	1,359.3	1,681.7	921.5	1,240.2	10,675.0
2010	19,915.7	4,292.3	851.2	1,767.0	915.5	1,280.6	10,809.0
2011	19,951.1	4,319.5	968.4	1,741.3	870.1	1,341.4	10,710.4
2012	18,547.5	4,072.7	722.5	1,638.3	856.7	1,252.6	10,004.7
2013	18,398.2	4,033.1	622.1	1,605.9	843.1	1,243.5	10,050.5
2014	18,458.2	4,180.1	505.3	1,681.0	842.5	1,306.5	9,942.9
2015	18,445.2	4,273.0	528.0	1,693.8	842.7	1,290.0	9,817.7
2016	18,856.1	4,137.0	527.9	1,721.3	845.9	1,248.9	10,375.2
2017	18,459.1	4,123.7	399.4	1,688.6	845.1	1,209.8	10,192.6
2018	19,731.2	4,373.8	533.9	1,777.6	842.6	1,341.0	10,862.3
2019	20,250.3	4,701.7	471.4	1,864.2	847.9	1,356.1	11,008.9

(a) State Government Agencies; (b) Department of Industry, Science, Energy and Resources estimates.

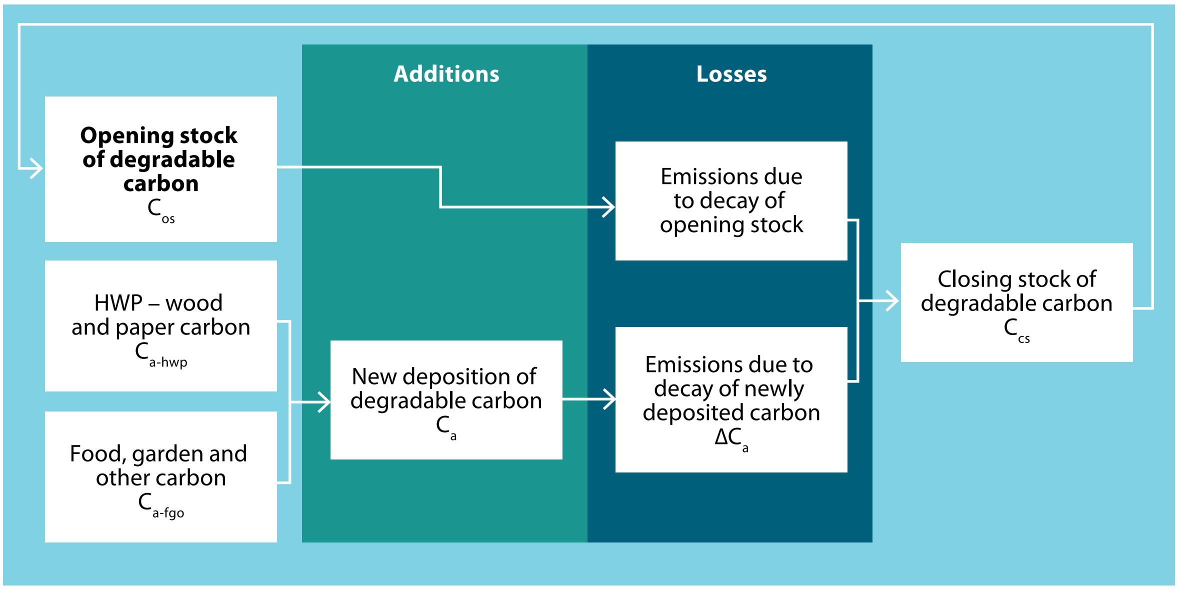
(b) The percentages derived from table 7.9 will not align with those provided in table 7.8 as these are based on the entire waste load entering landfill while table 7.8 presents information by individual waste stream.

7.3.4 Methodology

The Australian methodology for the estimation of emissions from solid waste disposal utilises the IPCC tier 2 first order decay (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 for solid waste to landfill



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.

$$C_{cs} = C_{os} - \Delta C_{os} \text{ (emissions lost from opening stock)} + C_a - \Delta C_a \text{ (emissions lost from new deposition)}$$

In Australia, 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 values of degradable organic carbon of individual waste types that is dissimilable (DOC_f); 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

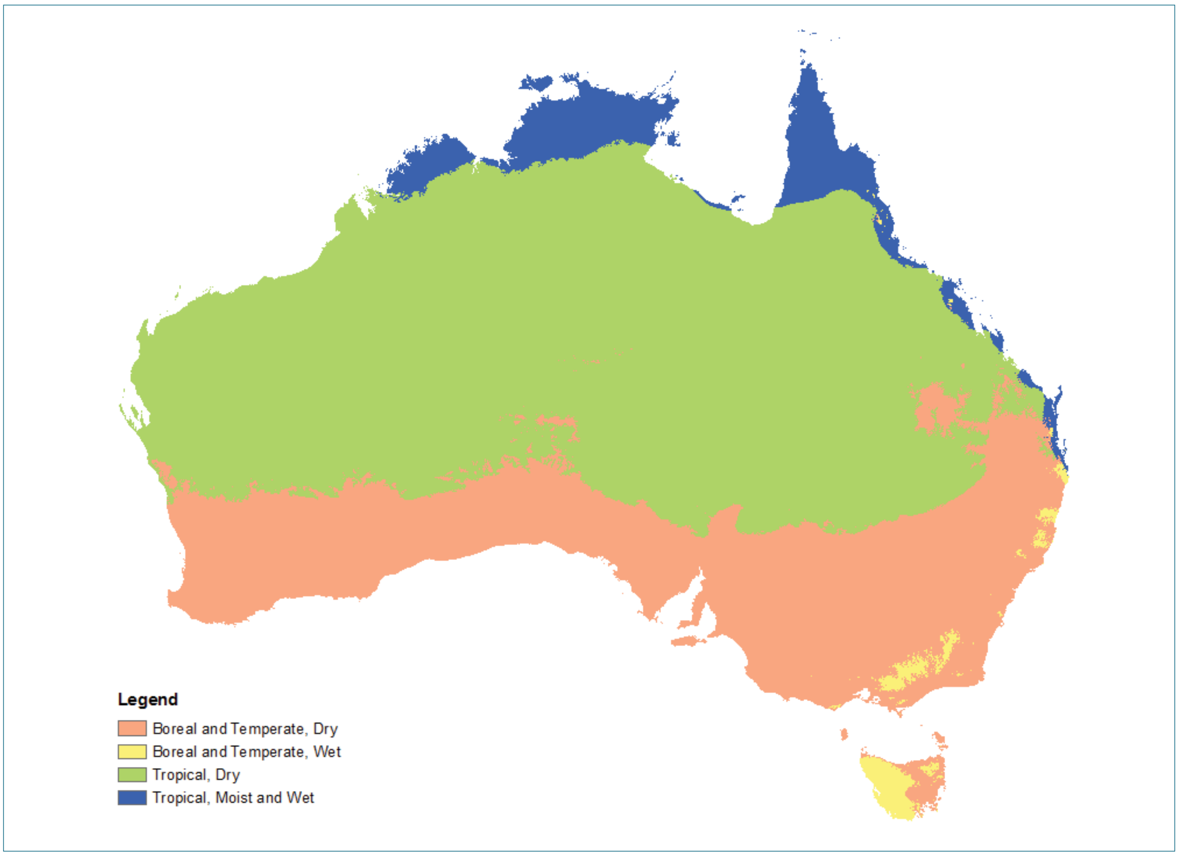
Waste Type (wet)	DOC
Food	0.2
Paper	0.4
Garden and Green	0.2
Wood and waste from HWP production	0.4
Textiles	0.2
Sludge	0.1
Nappies	0.2
Rubber and Leather	0.4
Other	-

Source: IPCC 2006.

7.3.4.2 Decay function values 'k'

The half-lives and associated decay rate constants '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	0.2
		Paper and Textiles	0.1
		Garden and Green	0.1
		Wood	0.0
		Textiles	0.1
		Sludge	0.2
		Nappies	0.0
		Rubber and leather	0.1
VIC, WA, SA, TAS, ACT	Dry Temperate	Food	0.1
		Paper and Textiles	0.0
		Garden and Green	0.1
		Wood	0.0
		Textiles	0.0
		Sludge	0.1
		Nappies	0.0
		Rubber and leather	0.0
QLD, NT	Moist and Wet Tropical	Food	0.4
		Paper and Textiles	0.1
		Garden and Green	0.2
		Wood	0.0
		Textiles	0.1
		Sludge	0.4
		Nappies	0.1
		Rubber and leather	0.1

Source: IPCC 2006.

7.3.4.3 Fraction of degradable organic carbon dissimilated (DOCf)

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 DOCf 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	0.5	0.4	0.2
Office paper	0.4	0.1	0.9
Old corrugated containers	0.5	0.3	0.5
Coated paper	0.3	0.3	0.2
Branches	0.5	0.4	0.2
Grass	0.5	0.2	0.5
Leaves	0.4	0.3	0.3
Food	0.5	0.1	0.8

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 (Bariaz 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 DOCf 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 0.05 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 0.1 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 per cent 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 0.8 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 0.5 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 53 for 2019.

Table 7.14 Key model parameters: DOC_f values by individual waste types

Waste type	DOC_f value
Food	0.8
Paper and paper board	0.5
Garden and park	0.5
Wood	0.1
Wood waste	0.1
Textiles	0.5
Sludge	0.5
Nappies	0.5
Rubber and Leather	0.5
Inert waste (including concrete, metal, plastic and glass)	0

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 per cent of landfills, receiving an estimated 95 per cent 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 2019

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	2,224.6	1,017.4	679.6	2.3	609.6
2000	2,386.0	1,007.8	673.2	129.2	489.5
2005	2,457.6	1,035.9	692.0	207.5	436.1
2008	2,307.8	1,059.4	707.7	205.1	452.4
2009	2,224.9	1,068.4	713.7	214.5	449.3
2010	2,072.4	1,071.6	715.8	204.2	460.4
2011	2,116.1	1,069.6	714.5	221.1	444.1
2012	1,933.3	1,064.7	711.2	272.4	395.0
2013	1,872.6	1,062.5	709.8	305.1	364.2
2014	1,882.4	1,062.1	709.5	306.1	363.0
2015	1,857.2	1,058.7	707.2	323.9	344.9
2016	1,817.4	1,066.4	712.4	317.9	355.0
2017	1,808.1	1,065.8	711.9	304.5	366.7
2018	1,937.8	1,063.7	710.5	308.5	361.8
2019	1,981.7	1,060.3	708.3	301.5	366.2

Note: (a) methane generated prior to oxidation.

Source: Department of Industry, Science, Energy and Resources 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/m3) 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/m3 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 per cent 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 0.3 Mt CO_2-e in 2019.

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.

Anaerobic digestion at biogas facilities

To date, no facilities have reported emissions associated with the anaerobic digestion of solid waste at biogas facilities under NGERS.

According to the Australian Clean Energy Finance Corporation bioenergy projects are not widely deployed in Australia (CEFC 2015). The majority of bioenergy capacity in Australia is associated with the consumption of bagasse in the sugar industry.

There are three known facilities in operation in Australia that could be classed as anaerobic digestion facilities. The Richgro facility in Jandakot Western Australia became operational in 2015 and has the capacity to process up to 140 tonnes of food waste per day.

Another facility known as Earthpower has been operating in Sydney since 2003 and can process up to 130 tonnes of organic waste per day. As with the Richgro facility, emissions of less than 1,000 tonnes of CO_2-e are estimated.

A third facility has been commissioned in the Yarra valley in Victoria as of May 2017. The facility has the capacity to process around 90 tonnes of food waste per day.

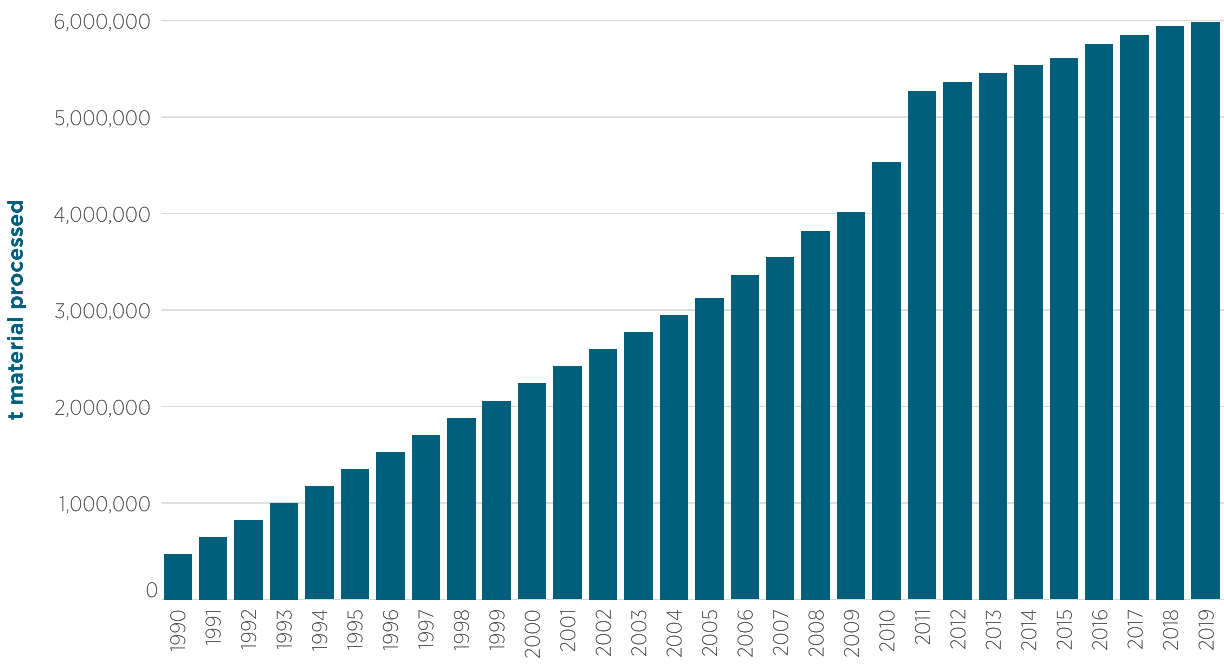
When the IPCC default CH_4 EF of 0.8 g CH_4/kg wet waste treated is applied to the total quantity of waste processed at these three facilities, annual emissions of around 2.6 Gg of CO_2-e result. This is well below the significance threshold for reporting. Accordingly this source is reported as 'Not Estimated'.

There are also a number of biogas facilities associated with agricultural activities in operation in Australia. Emissions associated with these operations are reported under 3.B manure management or 5.D.2 Industrial wastewater treatment where appropriate.

7.4.1 Methodology

Australia has applied the tier 1 method from the *2006 IPCC Guidelines* and country-specific emission factors 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 1990–2019



7.4.2 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 [(a)]

	CH_4 emission factor 4 (t CO_2-e/t material processed)	N_2O emission factor (t CO_2-e/t material processed)
Composting	0.019	0.03

(a) In raw-gas terms, these emission factors are 0.00075 t CH_4/ tonne of material processed and 0.000096 t N_2O/ tonne of material processed.

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 from the incineration and open burning of solid waste were 0.03 Mt CO_2-e in 2019.

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-1990s.

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 per cent is based upon empirical data presented in NGGIC (1995) for incineration activities occurring in 1990. Of this 7 per cent of fossil carbon in municipal waste, it is estimated that 80 per cent 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 per cent (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).

COD has been used as the data input as this is preferred parameter measured by companies reporting under NGERS. This aligns best with domestic licensing provisions and is consistent with the 2006 IPCC Guidelines, which also provide a default factor in terms of COD

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 (NO3). 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 per cent 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.

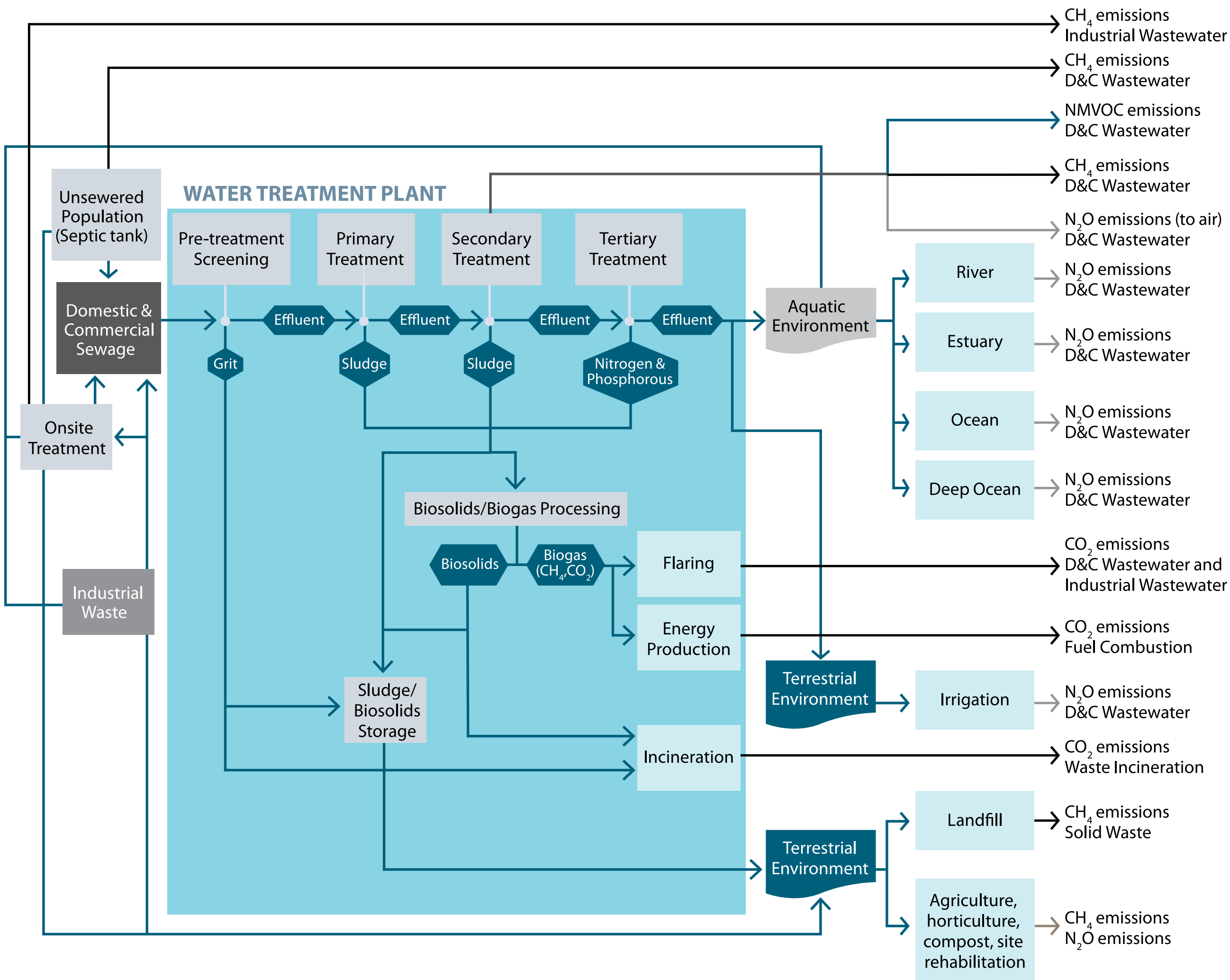
Consistent with IPCC *good practice,* methane emissions from effluent discharge to receiving waters is not reported in the inventory. Similarly, N_2O emissions from any form of industrial wastewater discharge and from discharge of municipal wastewater to ocean and deep ocean waters or used in irrigation 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

In 2019 the total Australian population was approximately 25 million people and approximately 95 per cent of this population is connected to one of the many centralised wastewater treatment networks.

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.

Effluent discharged by wastewater treatment plants in Australia 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):
  - that are ordinarily subject to tidal influence, and

- 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.

Table 7.18 indicates 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 per cent). However, when the non-coastal population is taken into consideration, this proportion becomes 29 per cent, 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 per cent 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 7.18 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 7.18 Effluent discharged from wastewater treatment plants by type of aquatic environment for 2019

Type of aquatic environment	Nitrogen discharged (t N)	
River	6,858	24%
Estuary	4,885	17%
Ocean or deep ocean	16,699	59%
Total	**28,442**	**100%**

Source: NGERS 2020.

Sludge treatment and disposal practices include transfer to landfill or agricultural land. NGER data for 2019 indicate that approximately 83 per cent of the nitrogen in sludge transferred out of treatment plants was reported as being used in a land application and 17 per cent was reported as being sent to landfills. 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 agriculture.

Table 7.19 Sludge reuse and disposal in 2019

	Nitrogen (t)	% Contribution
Sludge to Landfill	2,424	17%
Sludge Reused in Land Application	11,491	83%
Total	**13,916**	**100%**

Source: NGER 2020

Sectoral snapshot: Sydney Water's effluent discharge Sydney Water Corporation is Australia's largest wastewater utility, with 16 wastewater treatment plants and 14 water recycling plants servicing approximately 1.8 million homes and businesses in Sydney, the Illawarra and the Blue Mountains. In addition to providing annual reports on each facility to the New South Wales state government, Sydney Water also publishes information about their operations on their website at www.sydneywater.com.au. A map of Sydney Water's operations is shown in Figure 7.12 and information made available on their website has been summarised in Table 7.20 below.

Figure 7.12 Sydney Water Wastewater Systems

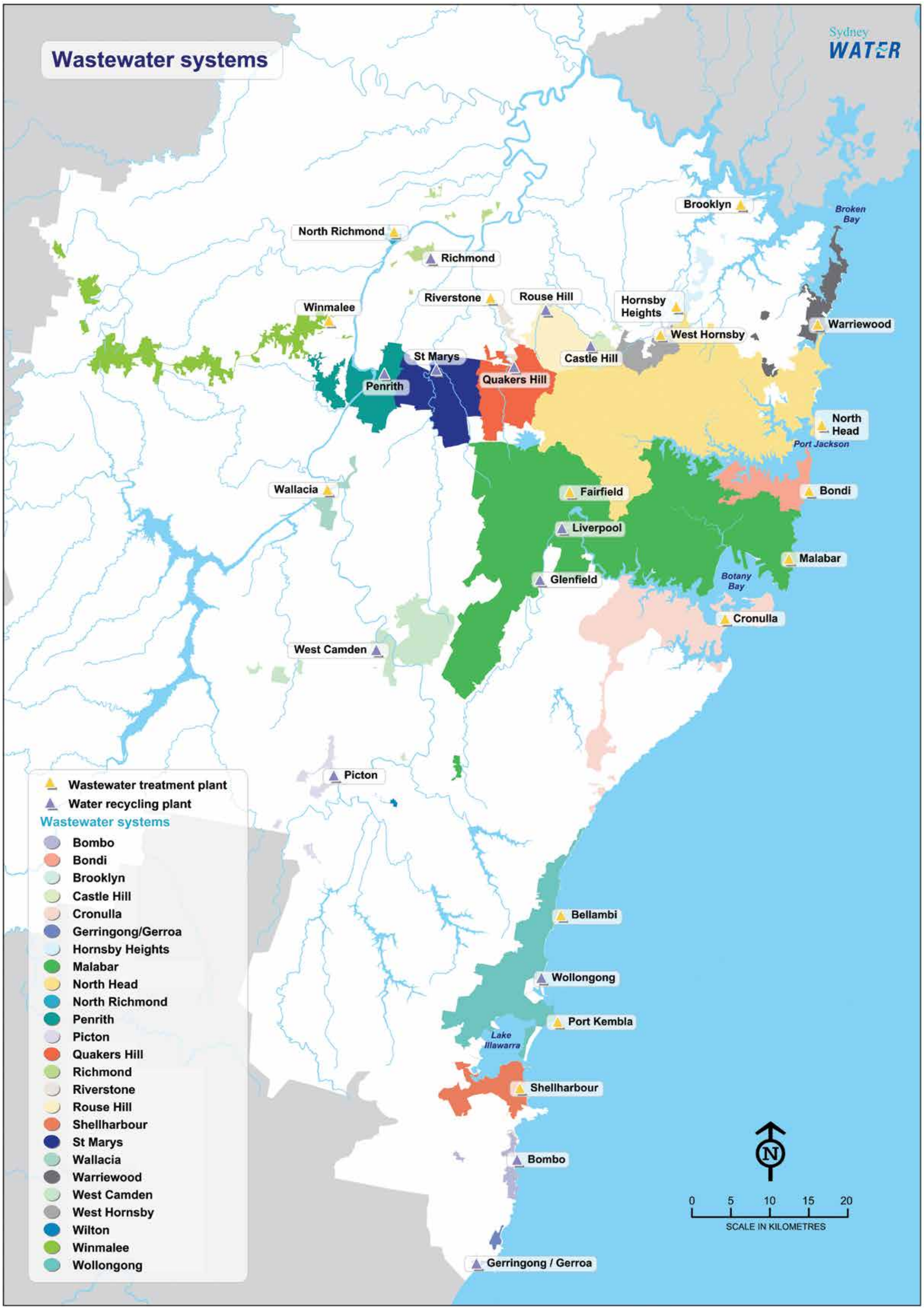


Table 7.20 Source: Sydney Water Wastewater Treatment Plants (including wastewater recycling plants)

Treatment Plant	Treatment level	Discharge (ML/day)	Discharge location
Bellambi	Primary	0	Bellambi Point during wet weather
Bondi	Primary	126.5	Deepwater ocean outfall 2.2 km from shoreline, 63 m maximum water depth, 512 m diffuser zone
Brooklyn	Tertiary (includes disinfection using ultra-violet light and membrane bioreactor technology)	0.2	Hawkesbury River, Brooklyn
Cronulla	Tertiary (disinfection)	53	Potter Point, Kurnell
Fairfield*	Primary (includes chemically assisted sedimentation)	0	Orphan School Creek (to Georges River) during wet weather
Hornsby Heights	Tertiary (includes additional phosphorus and nitrogen removal and disinfection)	5.2	Calna Creek to Berowra Creek
Malabar	Primary	488	Deepwater ocean outfall 3.6 km from shoreline, 82 m maximum water depth, 720 m diffuser zone
North Head	Primary	336	Deepwater ocean outfall 3.7 km from shoreline, 65 m maximum water depth, 762 m diffuser zone
North Richmond	Tertiary (includes additional phosphorus removal and disinfection)	0.9	Redbank Creek to the Hawkesbury River
Port Kembla*	Primary (includes screening, de-gritting, primary sedimentation and disinfection)	0	Red Point during wet weather
Riverstone	Tertiary (includes additional phosphorus removal and disinfection)	1.8	Eastern Creek to South Creek
Shellharbour	Secondary (includes disinfection)	16.9	Offshore outfall 130 m from Barrack Point, with diffuser zone
Wallacia	Tertiary (includes additional phosphorus and nitrogen removal and disinfection)	0.6	Warragamba River
Warriewood	Secondary (includes disinfection)	17.6	Turimetta Head
West Hornsby	Tertiary (includes additional phosphorus and nitrogen removal and disinfection)	11.9	Waitara Creek to Berowra Creek
Winmalee	Tertiary (includes additional phosphorus and nitrogen removal and disinfection)	16.5	Unnamed creek to the Nepean River
Bombo	Secondary and de-nitrification and disinfection	3.7	Headland north of Bombo Beach Supplies to Minnamurra Golf Club
Castle Hill	Tertiary (includes additional phosphorus removal and disinfection)	6.5	Cattai Creek Supplies to Castle Hill Country Club

Treatment Plant	Treatment level	Discharge (ML/day)	Discharge location
Gerringong-Gerroa	Partial tertiary (includes screening, storm tank or primary sedimentation, ponding and chlorination)	1.3	Re-used for on-site agricultural irrigation Excess discharged to sand dune systems. Once sand dunes reach capacity, excess is discharged to Crooked River
Glenfield	Partial tertiary (includes screening, storm tank or primary sedimentation, ponding and chlorination)	0	Treated wastewater transported to Malabar Occasionally discharged to Georges River in wet weather
Liverpool	Secondary (includes screening, de-gritting, primary sedimentation, ponding and chlorination)	0	Treated wastewater transported to Malabar Re-used at Liverpool Golf Course and Warwick Farm Race Course. Also supplies to Fairfield Water Recycling Plant (operated by Aquanet and Veolia Water) under Rosehill Recycled Water Scheme Occasionally discharged to Georges River in wet weather
Picton	Tertiary (includes additional phosphorus removal and disinfection)	1.5	Re-used on-site for agricultural irrigation precautionary discharge to Stone Quarry Creek
Penrith	Tertiary (includes additional phosphorus and nitrogen removal and disinfection)	23.1	Re-used locally Remainder transferred to St Marys Advanced Water Treatment Plant Some excess discharged to Boundary Creek
Quakers Hill	Tertiary (includes additional phosphorus and nitrogen removal and disinfection)	35.4	Re-used locally Remainder transferred to St Marys Advanced Water Treatment Plant Some excess discharged to Breakfast Creek
Richmond	Tertiary (includes additional phosphorus removal and disinfection)	2.2	Re-used for irrigation at University of Western Sydney – Richmond Campus. Also Re-used for irrigation at Richmond Golf Course Excess overflows to Rickabys Creek
Rouse Hill	Tertiary (includes additional phosphorus and nitrogen removal and disinfection) also includes ultra-violet irradiation and super-chlorination for reuse water	15.3	Recycled back to households for non drinking use Excess discharged to Second Ponds Creek via wetlands to Cattai Creek
St Marys	Tertiary (includes ultrafiltration, reverse osmosis, de-carbonation, additional phosphorous and nitrogen removal and disinfection)	39.2	Re-used locally and at Dunheved Remainder transferred to St Marys Advanced Water Treatment Plant Some excess discharged to South Creek
West Camden	Tertiary (includes additional phosphorus removal and disinfection)	13.1	Re-used at Agricultural Institute Remainder discharged via Matahill Creek to the Nepean River
Wollongong	Tertiary and disinfection	49.8	Re-used at BlueScope Steel Remainder discharged via offshore outfall with diffuser zone
St Marys Advanced Water Treatment Plant	Reverse osmosis and ultra filtration	42	Receives flow from St Marys, Quakers Hill and Penrith WRP to produce highly treated water discharged to Boundary Creek under Western Sydney Replacement Flows Recycled Water Scheme

Source: Sydney Water

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 IPCC 2006, 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 80 per cent of facilities reporting under the NGER system (numbering 30 in total and servicing around 50 per cent of Australia's population) measured the quantity of COD entering their facility directly. The weighted average per-capita COD entering these facilities is 0.049 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:

$$CH_{4(t)} = (COD_{in} - COD_{sl} - COD_{out}) \times EF_t$$

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:

$$CH_{4(t)} = (COD_{sl} - COD_{trl} - COD_{tro}) \times EF_{sl}$$

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 sent 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 7.21. Facilities reporting under the NGER system select the most appropriate MCF value for their operational circumstances.

Table 7.21 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 • Imhofftanks
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

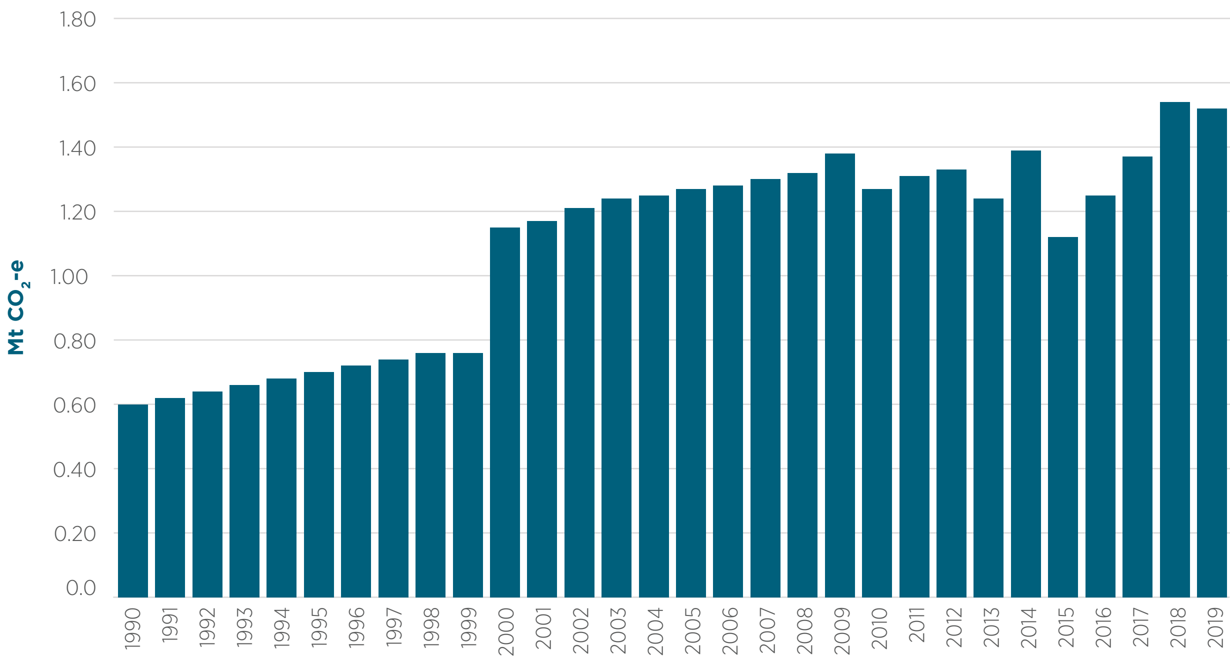
Waste

Emission factors for each facility for wastewater and sludge are derived using equation 6.2 in IPCC 2006. The IPCC default maximum methane producing capacity (B_0) 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 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 2016 is due declines in capture levels reported under the NGER System at that time.

Figure 7.13 Methane capture from domestic and commercial wastewater treatment 1990–2019



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

EFs by facility are derived according to equation 6.2 in IPCC 2006 where MCFs by facility are applied to the maximum CH_4 producing capacity (B_0) of 0.25 kg CH_4/kg COD.

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

IPCC 2006 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 2020) 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 50 per cent, which is the IPCC default fraction for total urban wastewater (IPCC 2006). IPCC 2006 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 2006 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:

$$N_2O_{(t)}N = (N_{in} - N_{out} - N_{trl} - N_{tro}) \times EF_6$$

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 is obtained from facility specific measurements under NGER. In total, facility level data obtained under NGER covers 146 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 and the average nitrogen input received by the wastewater plants per person serviced by the plants derived from the NGER system (2009 onwards). 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 97.04 kg per person per day in 2019.

Estimates of nitrogen leaving the system as effluent or as sludge disposed to landfill or to a land application, N, Ntrl and Ntro have also been obtained by facility under the NGER system.

The emission factor for the estimation of N_2O emissions from wastewater treatment, EF_6, is the IPCC 2006 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.

The emissions of N_2O from the discharge of effluent are estimated using the following equation:

$$N_2O_{(d)}N = N_{out}r \times (EF_5r + EF_5e) + N_{out}e \times (EF_5e)$$

Where $N_2O_{(d)}$-N is the emissions from discharge of effluent

$N_{out}r$ is the amount of nitrogen discharged into rivers which then flows into an estuary

$N_{out}e$ is the amount of nitrogen discharged into estuaries

EF_5-r is the emission factor for rivers

EF_5-e is the emission factor for estuaries

The amount of nitrogen discharged by aquatic environment is obtained by facility under the NGER system.

The IPCC 2006 default initial emission factors are 0.0025 kg N_2O-N/kg N for wastewater discharged into rivers ($EF_{5\,r}$) and 0.0025 kg N_2O-N/kg N for wastewater discharged into estuaries ($EF_{5\,e}$) (IPCC 2006 11.24). For wastewater discharged into rivers, the final emission factor is cumulative, ($EF_{5\,r}$ + $EF_{5\,e}$), 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 ($EF_{5\,e}$) 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 7.22 IPCC emission factors for disposal of effluent by type of aquatic environment

Type of Aquatic Environment	Emission factor for initial disposal
River ($EF_{5\text{-}r}$).	0.0025 kg N_2O-N/kg N
Estuary ($EF_{5\text{-}e}$).	0.0025 kg N_2O-N/kg N

Source: IPCC 2006 page 11.24.

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:

$$N_2O_{(l)}N = N_{tro} \times EF_7$$

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). 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 (3.D) consistent with good practice.

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.

Completeness

An analysis has been undertaken of the proportions of current production and facility numbers covered by NGERS. Where company/ facility coverage is complete or there is robust information about the composition and operational circumstances of the industry, it is possible to conclude that any residual production is not subject to onsite anaerobic wastewater treatment. This is the case for Pulp & paper, sugar and beer production. For the paper industry, NGERS covers all paper producing entities. Three of these four companies report emissions some form of anaerobic wastewater treatment. In the sugar industry, there are 8 producers operating 24 facilities. Five of these facilities do not undertake onsite anaerobic wastewater treatment. In the beer industry, there are three major producers operating 10 breweries. Nine of these breweries are covered by NGER reporting. The tenth brewery does not operate onsite anaerobic wastewater treatment.

For the remaining commodities considered under industrial, wastewater treatment, NGER coverage is not complete and emissions from residual wastewater are estimated using national statistics on production levels and commodity-specific parameters. Table 7.23 provides further details of the consideration of residual commodity production and associated onsite wastewater treatment.

Table 7.23 Commodity production, coverage and residual wastewater treatment 2019

	Total commodity production (litres)	NGERS commodity production (tonnes)	% NGER coverage	Residual treatment
Dairy Production	8,793,371,712	1,286,230	14%	Residual based on total national production and commodity – specific parameters
Pulp and Paper Production	3,227,375	1,554,350	48%	All facilities covered by NGERS. Residual production not subject to onsite WW treatment or aerobic processes
Meat and Poultry Production	4,324,330	3,287,509	76%	Residual based on total national production and commodity – specific parameters
Organic Chemicals Production	1,837,591	46,807	3%	Residual based on total national production and commodity – specific parameters
Sugar Production	4,725,000	4,122,006	87%	All facilities covered by NGERS. Residual production not subject to onsite WW treatment or aerobic processes
Beer Production	1,774,232,876	932,788	53%	2 of 3 major producers covered by NGERS. The remaining producer does not have on-site wastewater treatment.
Wine Production	833,735,714	474,173	57%	Residual based on total national production and commodity – specific parameters
Fuit Processing	2,793,432	210,753	8%	Residual based on total national production and commodity – specific parameters
Vegetable Processing	3,722,378	32,310	1%	Residual based on total national production and commodity – specific parameters

Table 7.24 Country-specific COD generation rates for industrial wastewater, 2019

Commodity	Wastewater generation rate (m^3 wastewater/ t commodity produced)	COD generation rate (kg COD/m^3 wastewater generated)
Dairy	5.7	1.2
Pulp and Paper	26.7	0.2
Meat and Poultry	13.7	4.6
Organic Chemicals (a)	67.0	C
Sugar	0.4	3.7
Beer	5.3	4.7
Wine	23.0	1.3
Fruit	20.0	0.2
Vegetables (a)	20.0	C

Source: NGER 2020 (a) facility-level parameters obtained for organic chemical and vegetable production under the NGER system are confidential (C).

Waste

Choice of methane conversion factor

Emission factors for each facility for wastewater and sludge are derived using equation 6.2 in the IPCC 2006. The IPCC default maximum methane producing capacity (B_0) 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 all listed commodities. Country-specific MCF values outlined in Table 7.25 are the weighted average MCF values based on data reported under NGERS.

Table 7.25 Methane conversion factors for industrial wastewater emissions, 2019

Commodity	MCF wastewater	MCF Sludge
Dairy	0.6	0.6
Pulp and Paper	0.8	0.7
Meat and Poultry	0.8	0.4
Organic Chemicals (a)	C	C
Sugar	0.3	0.07
Beer	0.8	0.8
Wine	0.8	0.7
Fruit	0.01	0.01
Vegetables (a)	C	C

Note: These values represent weighted averages where facility-level MCF values are reported.

Source: NGER 2020 (a) facility-level parameters obtained for organic chemical and vegetable production under the NGER system are confidential (C).

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 2019

Commodity	Fraction of methane recovered/flared (%)
Dairy	43.3%
Pulp and Paper	93.3%
Meat and Poultry	29.1%
Organic Chemicals	1.7%
Sugar	0.0%
Beer	100.0%
Wine	41.4%
Fruit	0.5%
Vegetables	3.9%

Source: NGER 2020.

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: 1990–2019

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
2016	109.0
2017	104.9
2018	98.7
2019	97.0

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 per cent 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 former DoEE 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 dot point 2;
- Check sectoral totals match AGEIS output – if there is a mismatch then go to dot point 3;
- Check sub-sectoral emissions by gas match AGEIS output by gas; and
- 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; and
- 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 consumption for the 2019 Inventory, derived from NGER facility data, is 97.04 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 per cent 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 per cent and the dry content matter of wet sludge is 15 per cent. 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 per cent.

Using these assumptions an estimate of the minimum and maximum possible quantities of wet sludge sent to landfill has been calculated for 1990 to 2019. 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 2018 Inventory

7.9.1 Solid waste disposal

Recalculations to *5.A Solid Waste Disposal* are detailed in Table 7.28.

Revisions to the National Greenhouse and Energy Reporting system data contributed to revisions of 0.5 per cent in 2017.

Table 7.28 5.A Solid Waste: recalculation of methane emissions (Gg CO_2-e)

	2019 Submission Gg CO_2-e	2020 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.A Solid Waste Disposal				
1990	15,239.9	15,239.9	0.0	0.0%
2000	12,238.6	12,238.6	0.0	0.0%
2005	10,901.6	10,901.6	0.0	0.0%
2008	11,308.8	11,308.8	0.0	0.0%
2009	11,231.4	11,231.4	0.0	0.0%
2010	11,510.6	11,510.6	0.0	0.0%
2011	11,101.8	11,101.8	0.0	0.0%
2012	9,874.5	9,874.5	0.0	0.0%
2013	9,105.7	9,105.7	0.0	0.0%
2014	9,075.6	9,075.6	0.0	0.0%
2015	8,623.3	8,623.3	0.0	0.0%
2016	8,875.2	8,875.2	0.0	0.0%
2017	9,122.7	9,166.7	44.1	0.5%
2018	9,045.1	9,045.2	0.1	0.0%

7.9.2 Wastewater treatment and discharge

No recalculations were required for emissions associated with *wastewater treatment and discharge.*

Table 7.29 5.D Domestic wastewater: recalculation of emissions (Gg CO_2-e)

	2020 Submission Gg CO_2-e	2021 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.D.1 Domestic Wastewater				
1990	2,320.6	2,320.6	0.0	0.0%
2000	1,843.8	1,843.8	0.0	0.0%
2005	1,905.9	1,905.9	0.0	0.0%
2008	2,055.9	2,055.9	0.0	0.0%
2009	2,038.2	2,038.2	0.0	0.0%
2010	2,149.3	2,149.3	0.0	0.0%
2011	1,943.0	1,943.0	0.0	0.0%
2012	1,731.1	1,731.1	0.0	0.0%
2013	1,687.1	1,687.1	0.0	0.0%
2014	1,858.1	1,858.1	0.0	0.0%
2015	2,057.7	2,057.7	0.0	0.0%
2016	2,028.4	2,028.4	0.0	0.0%
2017	2,041.2	2,041.2	0.0	0.0%
2018	2,002.9	2,002.9	0.0	0.0%

Recalculations to *5.D Industrial wastewater* are detailed in Table 7.30.

Revisions to the National Greenhouse and Energy Reporting system data contributed to revisions of between -7.8 and 0.02 per cent between the period 2014 to 2018.

Table 7.30 5.D Industrial wastewater: recalculation of emissions (Gg CO_2-e)

	2020 Submission Gg CO_2-e	2021 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.D.2 Industrial Wastewater				
1990	2,356.4	2,356.4	0.0	0.0%
2000	1,445.8	1,445.8	0.0	0.0%
2005	1,405.1	1,405.1	0.0	0.0%
2008	1,416.6	1,416.6	0.0	0.0%
2009	1,413.3	1,413.3	0.0	0.0%
2010	1,317.1	1,317.1	0.0	0.0%
2011	1,257.4	1,257.4	0.0	0.0%
2012	1,193.8	1,193.8	0.0	0.0%
2013	1,388.2	1,388.2	0.0	0.0%
2014	1,327.6	1,326.6	-0.9	-0.1%
2015	1,084.8	1,077.5	-7.4	-0.7%
2016	1,381.9	1,390.2	8.3	0.6%
2017	1,182.9	1,183.0	0.2	0.02%
2018	1,331.1	1,227.3	-103.8	-7.8%

7.9.3 Incineration and open burning of waste

No recalculations have been made to *incineration and open burning of waste.*

Table 7.31 5.C Incineration: recalculation of emissions (Gg CO_2-e)

	2020 Submission Gg CO_2-e	2021 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.C Incineration and Open Burning of Waste				
1990	87.0	87.0	0.0	0.0%
2000	27.7	27.7	0.0	0.0%
2005	28.4	28.4	0.0	0.0%
2008	29.5	29.5	0.0	0.0%
2009	29.9	29.9	0.0	0.0%
2010	29.7	29.7	0.0	0.0%
2011	29.8	29.8	0.0	0.0%
2012	30.0	30.0	0.0	0.0%
2013	30.4	30.4	0.0	0.0%
2014	30.8	30.8	0.0	0.0%
2015	30.5	30.5	0.0	0.0%
2016	30.6	30.6	0.0	0.0%
2017	30.7	30.7	0.0	0.0%
2018	30.7	30.7	0.0	0.0%

7.9.4 Biological treatment of solid waste

No recalculations have been made to *biological treatment of solid waste.*

Table 7.32 5.B Biological Treatment of Solid Waste: recalculation of emissions (Gg CO_2-e)

	2019 Submission Gg CO_2-e	2020 Submission Gg CO_2-e	Change Gg CO_2-e	Change %
5.B Biological Treatment of Solid Waste				
1990	22.1	22.1	0.0	0.0%
2000	106.0	106.0	0.0	0.0%
2005	147.9	147.9	0.0	0.0%
2008	181.1	181.1	0.0	0.0%
2009	189.9	189.9	0.0	0.0%
2010	214.8	214.8	0.0	0.0%
2011	249.6	249.6	0.0	0.0%
2012	253.9	253.9	0.0	0.0%
2013	258.3	258.3	0.0	0.0%
2014	262.1	262.1	0.0	0.0%
2015	265.8	265.8	0.0	0.0%
2016	272.6	272.6	0.0	0.0%
2017	276.9	276.9	0.0	0.0%
2018	281.4	281.4	0.0	0.0%

7.10 Source specific planned improvements

7.10.1 Solid waste disposal

The former DoEE 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 DISER 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 DISER 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.

A desktop audit of waste mix percentages was conducted in 2014 to confirm the representativeness of the CS waste mix percentages used in the inventory. The DISER will explore the possibility of conducting a new desktop audit of available waste composition data to either confirm or update the CS waste mix percentages applied to landfills not reporting their own composition under NGERS.

As part of the in-country review of Australia's 2008 national inventory, the Expert Review Team encouraged Australia 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 DISER 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 DISER 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

The ERT reviewing Australia's 2017 Inventory submission recommended that Australia provide more information in the NIR on the choice of proxy for extrapolating composting AD. Accordingly, Australia is reviewing the use of population data as a proxy and investigating whether a more appropriate driver is available. It is anticipated that this work will be complete in the next inventory submission.

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 and 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 submission, and are in addition to recalculations made in the 2019 submission on the 2018 submission which was the subject of the most recent UNFCCC review.

Table 10.1 Recalculations in the 2019 inventory (compared with the 2018 inventory) key reasons and quantitative impact

Sector		Category	Reason for Recalculation	Further Explanation and quantitative impact
1.A – Fuel combustion	Energy Industries	1.A.1	A revision has been made to the calculations for electricity generation to include specific LNG plants using data sourced from NGERS. This change was made in response to the increasing production of LNG in Australia in recent years and to better capture the self-use generation at these plants. A time series recalculation has been made to 1.A.1.c.ii Oil and gas extraction as part of the natural gas gathering and boosting methodology improvements made within 1.B.2 Oil and gas. The combustion methane emission factors for combustion at gas plants were revised from 1.98 t CH_4/PJ, based on gas turbine equipment, to 404.61 t CH_4/PJ, based on four-stroke rich burn/lean burn engines taken from EPA AP-42 and weighted in the proportions observed by Zimmerle et al 2020 in the US industry to derive a single methane emission factor for reciprocating engines for use in the Australian inventory. This new value is considerably higher than the previous value applied and reflects, essentially, a reallocation of methane emissions previously allocated as a source of fugitive leakages (which has been recalculated down in response in this inventory).	Section 3.3.5
	Manufacturing Industries and Construction	1.A.2	Recalculations were made in response to revisions in fuel consumption for natural gas and various liquid fuels reported in the Australian Energy Statistics. These are reflected in minor adjustments within the time series of 1.A.2.g Other and in 2018 for 1.A.2.c Chemicals.	Section 3.4.5
	Transport	1.A.3	Recalculations were made in response to revisions to AES fuel consumption data. Minor adjustment to 2016 and 2017 in road transport resulted from revisions to the allocated fuels between vehicle types within road transport.	Section 3.5.5
	Other Sectors	1.A.4	Recalculations were made in response to revisions to AES. These revisions were made to 1.A.4.a and 1.A.4.b.	Section 3.6.5
	Other	1.A.5	There were no recalculations affecting this subsector in the 2021 submission.	Section 3.7.5
1.B – Fugitive emissions		1.B.1	Recalculations of coal mining fugitive emissions estimates have occurred due to: A. Revised NGER activity data for 2017 and 2018. B. Reclassification of emissions from partially closed underground coal mines.	Section 3.8.5
		1.B.2	Improved emission factor methodology for onshore gathering and boosting stations to reflect latest published research. Correct activity data is now used - applying to onshore gathering and boosting only. Amended the calculation of the CO_2 fraction in condensate venting to better reflect the appropriate gas composition of the respective geological basins. The gas distribution leakage method was improved by adjusting the unaccounted gas factor to reflect improvements in the distribution pipeline network over time. The allocation of upstream oil and gas facilities to geological basins was improved to better reflect respective basin gas characteristics. Activity data for post-meter leakages of natural gas (1.B.2.b.6.ii) were revised to ensure coverage of all relevant fuel types.	Sections 3.9.2, 3.9.5 and Table 3.52

Sector	Category	Reason for Recalculation	Further Explanation and quantitative impact
2 – IPPU	2.A	Recalculations we undertaken in the mineral products sector due to updates to construction industry indexes from 2011 – 2017 published by the Australian Bureau of Statistics which is used to estimate emissions from brick manufacturing.	Section 4.3.10
	2.B	A revision to natural gas consumption in the production of ammonia occurred in the 2014 inventory year, resulting in the recalculations presented in Table 4.16. Minor revisions to N_2O use due to revised population statistics from 2016–2017. Corrected production data one facility in Australia for Ammonia Production was made for 2014. Revisions to Petrochemicals and Carbon Black were made due to the inclusion of new CO_2 estimates for Methanol Production.	Section 4.4.11
	2.C	Recalculations for 1990 – 2008 were made by deriving historical reductant use in Ferroalloys and other metals from production data.	Section 4.5.8
	2.D	There were no recalculations affecting this subsector in the 2021 submission.	
	2.E	There were no recalculations affecting this subsector in the 2021 submission.	
	2.F	Recalculations were made to the entire time series arising from revised atmospheric calibration of annual leakage rates, revised HFC destruction activity data, and revised retirement parameters for split system air conditioning equipment.	Section 4.8.4
	2G	Recalculations were made from 2010 to 2018 arising from revised atmospheric calibration of annual leakage rates.	Section 4.9.3
	2.H	There were no recalculations affecting this subsector in the 2021 submission.	
3-Agriculture	3.A	There were no recalculations affecting this subsector in the 2021 submission.	
	3.B	Recalculations of Manure Management have occurred due to a revised N_2O EF for beef cattle feedlots.	Section 5.4.11
	3.C	There were no recalculations affecting this subsector in the 2021 submission.	
	3.D	Recalculations of agricultural soils estimates have occurred due to: A. Revised N_2O EF for the cultivation of histosols. B. Revised cropland remaining cropland activity data throughout the timeseries, impacting emissions from mineralisation due to loss of soil C. C. Revised N_2O EF for beef cattle feedlots.	Section 5.6.13
	3.E	There are no emissions in this category.	
	3.F	There were no recalculations affecting this subsector in the 2021 submission.	
	3.G	There were no recalculations affecting this subsector in the 2021 submission.	
	3.H	There were no recalculations affecting this subsector in the 2021 submission.	
4 -LULUCF	4.A.1	Recalculations of *Forest land remaining Forest land* estimates have occurred due to: A. *Other native forests:* Spatial simulation of prescribed fires using FullCAM in selected states and territories: Carbon stock changes from the combustion and subsequent recovery of live biomass from prescribed fires has been added to reporting in this submission. A periodic update was also made to the fire spatial data for northern Australia. B. *Pre- 1990 plantations:* Updated spatial observations of forest cover change and revised weather and climate data using improved methodology. C. *Harvested native forests:* New spatially-explicit methodology introduced for the states of Victoria and New South Wales.	Section 6.4.5

Sector	Category	Reason for Recalculation	Further Explanation and quantitative impact
	4.A.2	Recalculations of *Land converted to Forest Land* have occurred due to: A. Updated spatial observations of forest cover change. B. Soil cover factor improvements in timing and scope of events determining agricultural plant cover. C. Agricultural parameters were updated for consistency with *grasslands* and *croplands*. D. Non-temperate fire updates. A periodic update was made to the fire spatial data	Section 6.5.5
	4.B.1	Recalculations of *Cropland Remaining Cropland* have occurred due to: A. A revision of land areas and land-use allocations across LULUCF sectors. B. Soil cover factor improvements in timing and scope of events determining agricultural plant cover. C. Resistant fractions were updated for cotton to account for it behaving like a woody plant rather than a crop.	Section 6.6.5
	4.B.2	Recalculations of *Land converted to Cropland* due to: A. Updated spatial observations of forest cover change. B. Soil cover factor improvements in timing and scope of events determining agricultural plant cover. C. Agricultural parameters were updated for consistency with *croplands remaining croplands*. D. Application of stratified emission factor values that are based on both soil type and climate zone for *wetlands converted to croplands*.	Section 6.7.5
	4.C.1	Recalculations of *Grassland Remaining Grassland* have occurred due to: A. A revision of land areas and land-use allocations across the LULUCF sectors. B. Non-temperate fire updates. A periodic update was made to the fire spatial data. C. A Pasture Lands of Northern Australia spatial map was implemented to provide the location of grass species. D. Soil cover factor improvements in timing and scope of events determining agricultural plant cover. E. Resistant fractions (DPM/RPM ratio) were updated for unimproved grasses to a more accurate value of 0.67.	Section 6.8.5
	4.C.2	Recalculations of *Land converted to Grassland* have occurred in the sub-category *forest land converted to grassland*. This is due to: A. Updated spatial observations of forest cover change. B. Soil cover factor improvements in timing and scope of events determining agricultural plant cover. C. Agricultural parameters were updated for consistency with *grasslands remaining grasslands*. D. Non-temperate fire updates. A periodic update was made to the fire spatial data E. Application of stratified emission factor values that are based on both soil type and climate zone.	Section 6.9.5

Sector	Category	Reason for Recalculation	Further Explanation and quantitative impact
	4.D.1	Recalculations of *Wetlands Remaining Wetlands* have occurred due to: A. Revised activity data for grass and shrub transitions due to improvements in image analysis and expanded national coverage. B. Non-temperate fire updates. A periodic update was made to the fire spatial data . C. ERT recommended correction applied to the Aquaculture Use calculation D. Update to Australia's aquaculture production statistics for 2016/17 and 2017/18 applied to Aquaculture Use E. Revised activity data due to improved analysis of Flooded Land (reservoir) spatial data F. Revised Flooded Land (reservoir) emission estimates due to improved application of age-based stratified EF values with additional reservoir age data.	Section 6.10.5
	4.D.2	Recalculations of *Land converted to Wetlands* have occurred due to improvements in remote sensing of forest cover change and in FullCAM agricultural modelling parameters.	Section 6.11.5
	4.E.1	Recalculations of *Settlements remaining Settlements* have occurred due to revisions to activity data for grass and shrub transitions due to improvements in image analysis.	Section 6.12.5
	4.E.2	Recalculations of *Land converted to Settlements* have occurred due to: A. Updated spatial observations of terrestrial forest cover change. B. Updated spatial observations of mangrove forest and Wetland (tidal marsh) converted to settlements areas. C. Soil cover factor improvements in timing and scope of events determining agricultural plant cover. D. FullCAM software improvements: improvements in calibration parameters for FullCAM tree growth / biomass turnover and decay simulation were made based on latest scientific information and advice.	Section 6.13.5
	4.G	Recalculations of *Harvested Wood Products* have occurred due to.	Section 6.15.5
5 – Waste	5.A	Recalculations were made in response to revisions in solid waste disposal reported in the NGERS. Recalculations were made in response to revisions in national solid waste disposal totals reported in the National Waste Database.	Section 7.9.1
	5.B	There were no recalculations affecting this subsector in the 2021 submission.	
	5.C	There were no recalculations affecting this subsector in the 2021 submission.	
	5.D	A recalculation was performed on *Domestic and commercial wastewater treatment and discharge* in response to revisions in data reported in the NGERS	Section 7.9.2

10.2 Implications for emission levels

Table 10.2 gives the estimated recalculations for this submission for each category for 1990 and the past ten years.

Table 10.2 Estimated recalculations for this submission (compared with last year's submissions 1990, 2009–2018)

Sector	Mt CO_2-e											
	1990	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
1.A Fuel Combustion	0.1	0.1	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.0	- 0.0
1.A.1, 2, 4, 5 Stationary Energy	0.1	0.1	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.0	0.7
1.A.3 Transport	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	-	0.0	0.0	- 0.7
1.B Fugitives	- 1.4	- 1.8	- 2.3	- 2.7	- 3.1	- 2.7	- 2.4	- 3.0	- 2.9	- 3.7	- 4.4	- 5.0
2 Industrial Processes	- 0.1	- 0.1	- 1.5	- 2.2	- 2.0	- 2.3	- 2.4	- 2.7	- 2.7	- 2.8	- 2.5	- 2.8
4 Agriculture	0.1	- 0.3	- 0.3	- 0.4	- 0.4	- 0.4	- 0.4	- 0.4	- 0.5	- 0.5	- 0.5	- 0.4
5 LULUCF	- 0.8	- 3.2	6.5	11.8	5.1	10.3	11.5	1.8	0.3	- 0.7	- 6.7	- 1.9
6 Waste	-	-	-	- 0.0	-	-	0.0	- 0.0	- 0.0	0.0	0.0	- 0.1
Total Recalculation	- 2.2	- 5.2	2.6	6.8	- 0.3	5.1	6.8	- 3.9	- 5.2	- 7.2	- 14.0	- 10.2

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 a decrease of emission estimates between 0.3 and 1.5 per cent. The net effect of the recalculations on aggregate emission trends for the sectors including *LULUCF* is between a decrease of 2.6 per cent and an increase of 1.3 per cent of emission estimates.

Table 10.3 Estimated recalculations for this submission (compared with last year's submission 1990–2018)

	Including LULUCF				Excluding LULUCF			
	Previous estimate	Current Estimate	Difference		Previous estimate	Current Estimate	Difference	
	Mt CO_2-e	Mt CO_2-e	Mt CO_2-e	%	Mt CO_2-e	Mt CO_2-e	Mt CO_2-e	%
1990	617.7	615.5	- 2.2	- 0.4	425.0	423.7	- 1.3	- 0.3
1991	600.2	600.7	0.5	0.1	426.0	423.7	- 2.3	- 0.5
1992	541.7	537.4	- 4.2	- 0.8	430.2	427.4	- 2.8	- 0.6
1993	523.8	516.5	- 7.3	- 1.4	430.6	428.3	- 2.3	- 0.5
1994	513.4	515.4	2.0	0.4	430.7	428.8	- 1.8	- 0.4
1995	497.9	495.0	- 3.0	- 0.6	439.0	437.3	- 1.7	- 0.4
1996	506.9	496.3	- 10.6	- 2.1	446.7	443.9	- 2.8	- 0.6
1997	512.2	504.5	- 7.6	- 1.5	458.8	456.0	- 2.8	- 0.6
1998	506.3	504.6	- 1.7	- 0.3	472.6	469.8	- 2.9	- 0.6
1999	523.4	520.6	- 2.8	- 0.5	478.2	476.4	- 1.8	- 0.4
2000	545.4	542.3	- 3.1	- 0.6	489.4	487.8	- 1.6	- 0.3
2001	575.9	573.1	- 2.8	- 0.5	497.0	495.6	- 1.4	- 0.3
2002	567.4	567.0	- 0.4	- 0.1	500.8	499.2	- 1.6	- 0.3
2003	582.7	580.4	- 2.4	- 0.4	502.3	500.6	- 1.7	- 0.3
2004	586.7	582.4	- 4.3	- 0.7	520.3	517.7	- 2.6	- 0.5
2005	617.2	612.0	- 5.2	- 0.8	526.2	524.2	- 2.0	- 0.4
2006	614.9	612.6	- 2.3	- 0.4	530.8	528.0	- 2.7	- 0.5
2007	634.6	632.3	- 2.3	- 0.4	536.9	534.4	- 2.5	- 0.5
2008	623.4	618.3	- 5.0	- 0.8	540.7	537.3	- 3.4	- 0.6
2009	616.2	618.8	2.6	0.4	544.3	540.4	- 3.9	- 0.7
2010	593.5	600.3	6.8	1.1	540.6	535.5	- 5.0	- 0.9
2011	573.0	572.8	- 0.3	- 0.0	542.5	537.2	- 5.3	- 1.0
2012	555.3	560.4	5.1	0.9	544.7	539.5	- 5.2	- 1.0
2013	540.6	547.5	6.8	1.3	535.0	530.3	- 4.7	- 0.9
2014	539.7	535.8	- 3.9	- 0.7	530.4	524.7	- 5.7	- 1.1
2015	538.8	533.6	- 5.2	- 1.0	538.6	533.1	- 5.6	- 1.0
2016	526.1	518.9	- 7.2	- 1.4	548.9	542.3	- 6.6	- 1.2
2017	529.5	515.5	- 14.0	- 2.6	556.6	549.3	- 7.3	- 1.3
2018	537.4	527.2	- 10.2	- 1.9	558.0	549.7	- 8.3	- 1.5

10.3.1 Recalculation trends by sector

Including LULUCF, the sectors with the largest average recalculation across the time series, and the primary drivers of the recalculations, are identified in Table 8.4 below.

Table 10.4 Drivers of sectoral recalculations (including LULUCF)

Sector	Driver of recalculation	Further Explanation and quantitative impact
LULUCF	Changes to carbon stocks in harvested native forest reflecting the new Tier 3, spatial explicit modelling approach in the states of Victoria and NSW.	Section 6.4.5
IPPU	Method improvements to hydrofluorocarbons, arising from revised atmospheric calibration of annual leakage rates.	Section 4.9.3
Energy	Method improvements for fugitive gas gathering and boosting leakage.	Sections 3.9.2 and 3.9.5

Excluding LULUCF, the sectors with the largest average recalculation across the time series, and the primary drivers of the recalculations, are identified in Table 8.5 below.

Table 10.5 Drivers of sectoral recalculations (excluding LULUCF)

Sector	Driver of recalculation	Further Explanation and quantitative impact
IPPU	Method improvements to hydrofluorocarbons, arising from revised atmospheric calibration of annual leakage rates.	Section 4.9.3
Energy	Method improvements for fugitive gas gathering and boosting leakage, see sections 3.9.2 and 3.9.5 for further information.	Sections 3.9.2 and 3.9.5
Energy	Activity data revisions from 2016 to 2018 to stationary energy, transport and fugitive categories.	Sections 3.4.5, 3.5.5, 3.6.5 and 3.8.5

As indicated from the nature of the above recalculations, the impact of the recalculations to LULUCF driven by updates to carbon stocks in harvested native forest mostly concerns carbon dioxide on a gas by gas basis, recalculations to IPPU due to revised atmospheric calibration of annual leakage rates exclusively impacts hydrofluorocarbons and recalculations to energy driven by method improvements for fugitive gas gathering and boosting leakage almost exclusively concerns methane.

10.4 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 guidance

The Department is progressively implementing IPCC methods for sources identified in IPCC 2019 and IPCC 2013 on a voluntary basis, as appropriate.

Changing international practice

The Department actively monitors the implementation of inventory guidelines by other Parties to the UNFCCC / Kyoto Protocol / Paris Agreement 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 review by the Australian National Audit Office 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 processes and product use,* 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 Emissions 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.

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 *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. Current investment priorities includes: AGEIS upgrades to support Australia's inventory reporting obligations under the Paris Agreement, exploring options for automated data ingestion and additional automated QC measures to improve efficiency and emission estimation accuracy; modernising and investing in reliability of FullCAM architecture including moving to cloud-based platform, investing in new technologies for data collection, adopting advances in remote sensing data sources and machine learning, and increasing the scope land use change monitored by *FullCAM* and adopting new technologies to streamline maintenance of systems.

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

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 harvested native forests and controlled burning

The Department has implemented fully spatially-explicit tier 3 methodologies for native forest harvesting in multiple use forests in Victoria and New South Wales, and for prescribed fire in Victoria, New South Wales, the Australian Capital Territory and South Australia. These methodologies, which utilise datasets published by state governments, will continue to be implemented from the remaining states until national coverage is achieved.

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 non-temperate fire management.

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 recovery following fire events based on available scientific research.

Enteric fermentation

An accounting framework is being developed to enable emission reductions in the livestock industry associated with feed supplements and alternative feeds to be incorporated into the inventory.

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 and freshwater ponds and reservoirs. Empirical research into carbon processes and related emissions and removals arising from activities affecting these 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. Data from the NAMMP may 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 DOC_f, 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

Empirical research and field data collection for fugitive emissions from the coal seam gas industry is being undertaken by CSIRO. Current method parameters will be tested against the new data and research results as it emerges.

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, including the IPCC *2019 Refinement to the 2006 IPCC Guidelines for national greenhouse gas inventories*;
- 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 Emissions 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 described in the IPCC *2019 Refinement to the 2006 IPCC Guidelines for national greenhouse gas inventories* (Volume 4, chapter 2.5) and IPCC expert meetings.[18]

Model development will be progressed across all land sectors. In particular, it is intended that *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;
- extension of methods for forest lands remaining forests which provide for a tier 3 spatially explicit method with additional estimation of forest carbon stocks as well as fluxes to all states and territories;
- methods for spatial modelling of sparse woody vegetation across Australia's grasslands;
- fire mapping will be extended 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
- modelling of wetlands emissions and removals resulting from management activities and changes in management practices will be developed and enhanced over time.

Over the coming years, the department will focus on further developing the *FullCAM* fire model to reflect the latest scientific data relating to fire intensity, frequency and climate impacts on post-fire recovery.

18 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.

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