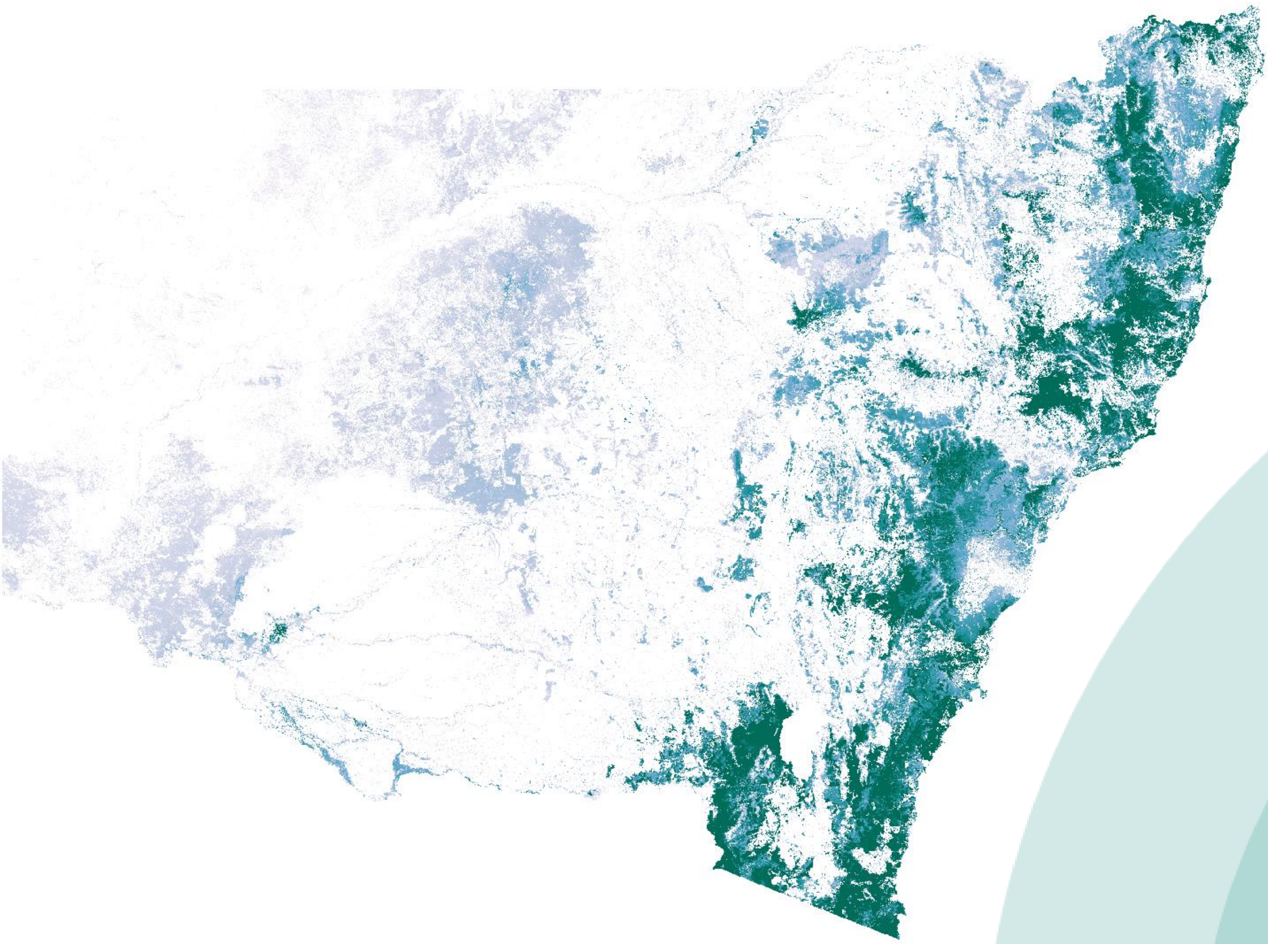
Carbon Balance of NSW Forests – Update Report

Prepared by the Mullion Group

June 2023



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Acknowledgement

The development of the carbon balance for NSW required the collation of large datasets from multiple agencies. The Authors are grateful for all contributions to the report, in particular Michael Parsons (NSW NRC) and Mike Sutton (FCNSW), as well as Jonathon Gray, Belinda Medlyn, Tom Fairman, and Rachael Nolan for their input in the original assessment.

Citation:

Roberts, G., Hislop, S., Johnson, T., Fitzgerald, E. (2023) *Carbon Balance of NSW Forests – Update Report*, NSW Natural Resources Commission

Contents

List of Acronyms

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
AGB	Aboveground Biomass
AGS	Australian Group Selection
BGB	Belowground Biomass
C	Carbon
CAMFor	Carbon Accounting Model for Forests
CO_2	Carbon Dioxide
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DB	Database
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DOM	Dead Organic Matter
ERF	Emissions Reduction Fund
FCNSW	Forestry Corporation of NSW
FESM	Fire Extent and Severity Mapping (FESM)
FLINT	Full Lands Integration Tool
FLINTpro	Full Lands Integration Tool Professional
FPI	Forest Productivity Index
FullCAM	Full Carbon Accounting Model
GHG	Greenhouse Gas
H_2O	Water
HUM	Humic Layer
HWP	Harvested Wood Products
IBRA	Interim Biogeographic Regionalisation for Australia
IFOA	Integrated Forestry Operations Approvals
NIR	National Inventory Report
MVG	Major Vegetation Groups
NCAS	National Carbon Accounting System
NDVI	Normalized Difference Vegetation Index
NGGI	National Greenhouse Gas Inventory
NPI	National Plantation Inventory
NSW	New South Wales
NVIS	National vegetation information system

RFA	Regional Forest Agreement
RFS	NSW Rural Fire Service
STGGI	State and Territory Greenhouse Gas Inventories
TYF	Tree Yield Formula
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

In 2020, the NSW Natural Resources Commission engaged the Mullion Group to undertake a historical carbon assessment of NSW forests under the Forest Monitoring and Improvement Program (FMIP) (Roberts et al. 2022). This report presents updated results from a new FLINTpro simulation, which is based on updated data and method improvements. The original report contains detailed descriptions of the methods, while this report focuses specifically on the differences in the updated approach and presents updated results, which supersede those of the original report.

The updated simulation indicates that the difference in carbon stocks in NSW forests between 1990 and 2021 is a loss of 165 million tonnes, with most of this loss due to the 2019-2020 wildfires (Figure 1 & Figure 2). The results indicate that there was a general decline in forest carbon stocks from 1990 through to the mid-2000s, after which stocks increased through to 2019, prior to the fires. In 2021 there is a slight increase in stocks due to the forest entering a post-fire regrowth phase.

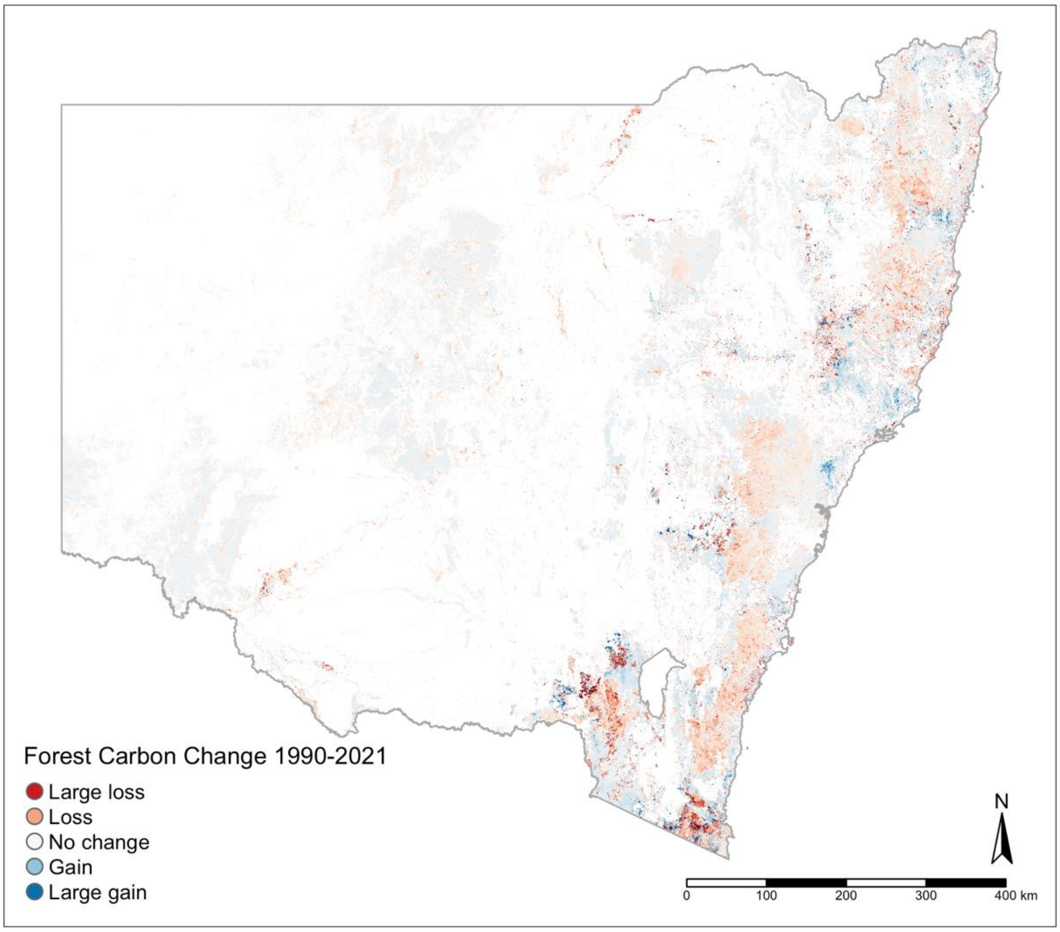


Figure 1 – Spatial Output of change in forest carbon within NSW between 1990 and 2021, including Aboveground Biomass, Belowground Biomass, and Dead Organic Matter. Harvested Wood Products in use is not included in the spatial aggregation. Soil carbon was excluded from the results. Red indicates there was less forest carbon in 2021 than there was in 1990, and blue indicates there was more carbon in 2021 than there was in 1990.

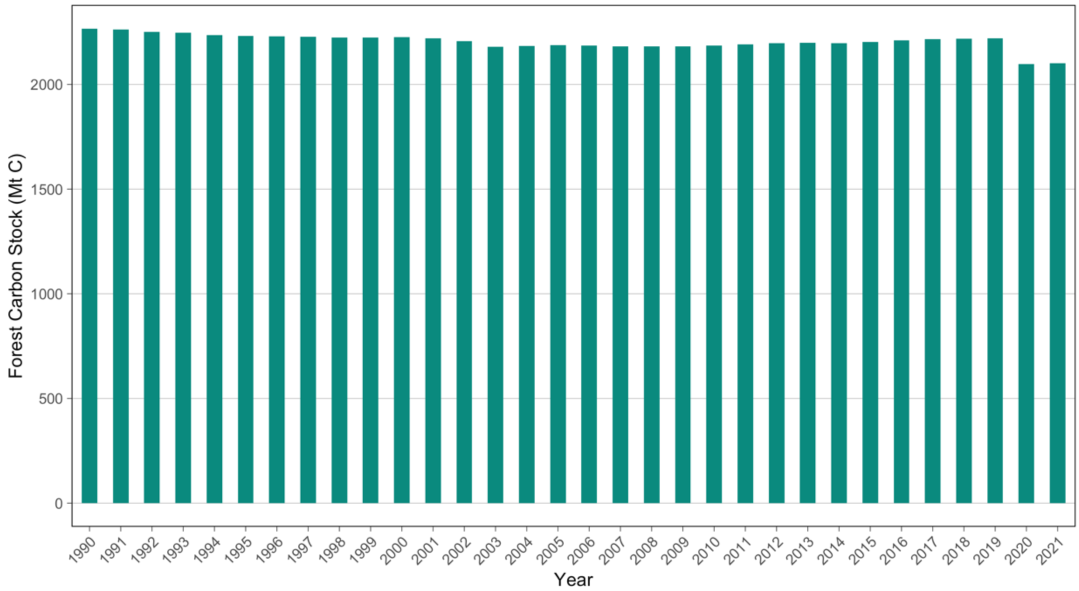


Figure 2 – NSW Forest and Harvested Wood Products (HWP) Carbon Stock 1990-2021, including Aboveground Biomass, Belowground Biomass, Dead Organic Matter and HWP in use. Soil Organic Carbon is not included in the output.

1. Introduction

This report presents updated analysis and results based on the latest data from the 2022 Carbon Balance of NSW Forests Project, commissioned by the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program (FMIP). The NSW FMIP Framework 2019-2024 outlines a plan to improve the management of NSW forests by providing relevant and timely information on forests to decision makers and the general community. The Program established nine State-wide Evaluation Questions that address the extent to which the NSW Forest Management Framework is delivering ecologically sustainable management outcomes for current and future generations.

One of the State-wide Evaluation Questions is: *What is the carbon balance of NSW forests currently and under different scenarios?* The question focuses on the contribution of NSW forests to regional and global carbon cycles and identifying opportunities to enhance carbon storage in NSW forests.

As part of this, in 2020 the Natural Resources Commission engaged the Mullion Group and its partners, CSIRO and the NSW Department of Primary Industries, to develop an operational system for monitoring carbon stock and stock change across NSW forests. The original assessment was delivered in 2022 (Roberts et al. 2022). Since the submission of that report, additional data has become available to improve the accuracy of the outputs, and there have also been changes in Australia's National Greenhouse Gas Inventory (NGGI), which required adjustments to the forest growth rates. As with the original assessment, this update aims to have general consistency with the methods, assumptions, and data used for the NGGI. The assessment was completed using the FLINTpro system.

Consistent with the original assessment, the updated project modelled, as far as practical, 'what the atmosphere sees', using comparable methods and data to the NGGI. No policy or reporting overlays were taken into consideration when collating the outputs, meaning the project did not apply national or international policy or reporting rules to the output. This is an important difference between the objectives of Australia's NGGI and this project. For example, the NGGI does not aim to report forest carbon stock, rather GHG emissions. Furthermore, not all activities are included in the NGGI, such as forest cover loss events within some national parks, and conversely, not all emission sources included within the NGGI are represented in the outputs of this project (e.g., non-CO_2 emissions from fire). Given the differences between the NGGI and this assessment, it is inappropriate to make a direct comparison of carbon stock change estimates from this project with any values reported within the State and Territory Greenhouse Gas Inventories for NSW.

This report outlines the key method differences, data updates, and core assumptions that underpin the NSW Forest Carbon Assessment Update. A summary of results is provided within this report and output data will be made available through NSW government data portals.

1.1. Modelling the Carbon Cycle

This assessment used the same methodological concept as the original assessment, modelling a series of processes and events that impact the carbon stock within forest systems (Roberts, et al 2022). This includes:

- Sequestration
- Decomposition and Respiration
- Fire
- Forest cover losses (drought or human induced)
- Timber harvesting.

The underpinning models reflect those of the NGGI, in particular the Tree Yield Formula that underpins forest growth within FullCAM (Richards, 2001; Richards and Brack, 2004; Richards and Evans, 2004; Brack et al., 2006; Waterworth et al. 2007).

1.1.1. Background into the Carbon Cycle

Carbon occurs within the earth systems in various compositions, including solid and gaseous states. Carbon moves between these states as well as between different reservoirs (or pools) in the oceans, terrestrial biosphere, and atmosphere via a range of exchanges sometimes referred to as 'pathways'. The movement of carbon through these pathways to different carbon pools collectively comprises the carbon cycle. A simplified representation of the forest components of the carbon cycle is provided in Figure 3.

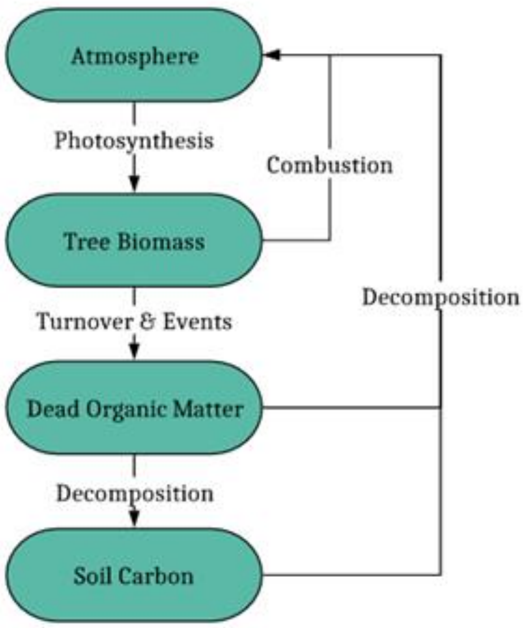


Figure 3 – Simplified example of the natural carbon cycle, with the cyclical movement of carbon from the atmosphere into three terrestrial carbon pools, and back to the atmosphere.

There are two distinct causes for the movement of carbon along the pathways: processes and events. Processes include sequestration (growth), turnover and decomposition. Events can be natural events such as fire (combustion) and human interventions, such as cutting down trees within a forest for timber (harvesting) or removing forests from areas of land (clearing). Processes tend to occur continuously over time, whereas events are often episodic, and thus occur relatively discretely over limited timeframes.

Sequestration (plant growth)

Sequestration by plant growth is the process by which plants remove gaseous CO_2 from the atmosphere and store it in solid form as plant biomass. Approximately 50% of plant biomass (dry weight) is composed of carbon (C). In simple terms, plants, both aquatic and terrestrial, will absorb water (H_2O) and CO_2, and through photosynthesis, transform these elements into carbohydrates and oxygen. These carbohydrates form the basis of all plant material, including stem and branch wood, bark, leaves, and roots.

Decomposition and Respiration

As plants and forests grow, various tissues die, such as branches, leaves, roots and even whole trees. This process transfers these forest components from the living pool to the dead organic matter pools. Where individual tree components die and are then regrown, such as branches, leaves, and roots, this is referred to as 'turnover'. Once in the dead organic matter pool, decomposition normally commences. Decomposition is the breakdown of plant material into simpler elements, including carbon dioxide, which is released back to the atmosphere.

Decomposition is rarely complete, and the process generally results in carbon moving from being classified as dead organic matter into soil organic carbon (SOC). SOC will continue to breakdown, although where the inputs are greater than the decomposition rates, there can be an accumulation of carbon in soil. Soil carbon is therefore a balance between inputs from dead organic matter and dead root material and outputs due to decomposition, respiration from decomposers and oxidation.

Fire (Combustion)

Fire is a critical component of Australia's forests, and in many systems required for the health of the forest system. Fire can be either a natural or a human induced event, with two implications for the carbon cycle. One is that fire kills trees and tree components, moving carbon from living biomass to dead organic matter where it will decompose. The second is the combustion of carbon during the fire event, releasing CO_2 and other greenhouse gases (GHG) such as methane and nitrous oxide back to the atmosphere. Unlike decomposition, where dead organic matter is slowly lost over many years, combustion typically results in the rapid loss of dead organic matter and some of the living biomass pool.

Other Events

Other events that impact on forest carbon are human management activities such as harvesting and clearing as well as natural events, such as die-back, insect outbreaks and windstorms. Harvesting refers to management of the area of forest for timber production and includes the removal of some or all trees from an area followed by activities to promote trees to regrow. Harvesting results in the movement of carbon from living pools to harvested wood products and dead organic matter pools. Harvesting is distinct from clearing (deforestation). Clearing involves the permanent removal of living trees from an area of land. Harvested forest areas are regenerated after a harvest event (Ximenes et al 2012). Natural events, including die-back, are where natural processes result in widespread death of trees, such as through pests and diseases. Harvesting, clearing, and natural events result in the movement of carbon stored from living biomass to the dead organic matter pools, where they will decompose, moving carbon into the soil carbon pools or return it to the atmosphere.

The objective of this project is to, as far as practical, represent all processes and events that occur within forested land, and to quantify the associated implications for forest carbon stock. To achieve this, a selection of different methods and approaches were used within a spatial and temporal modelling system to fully capture the spatial and temporal dynamics of the NSW forest carbon balance.

2. Input Data

In this project, FLINTpro was used to model the changes in forest carbon across all forests in NSW on all tenures: National Parks, State forests, other crown land and private land. A conceptual framework for the modelling system is shown in Figure 4.

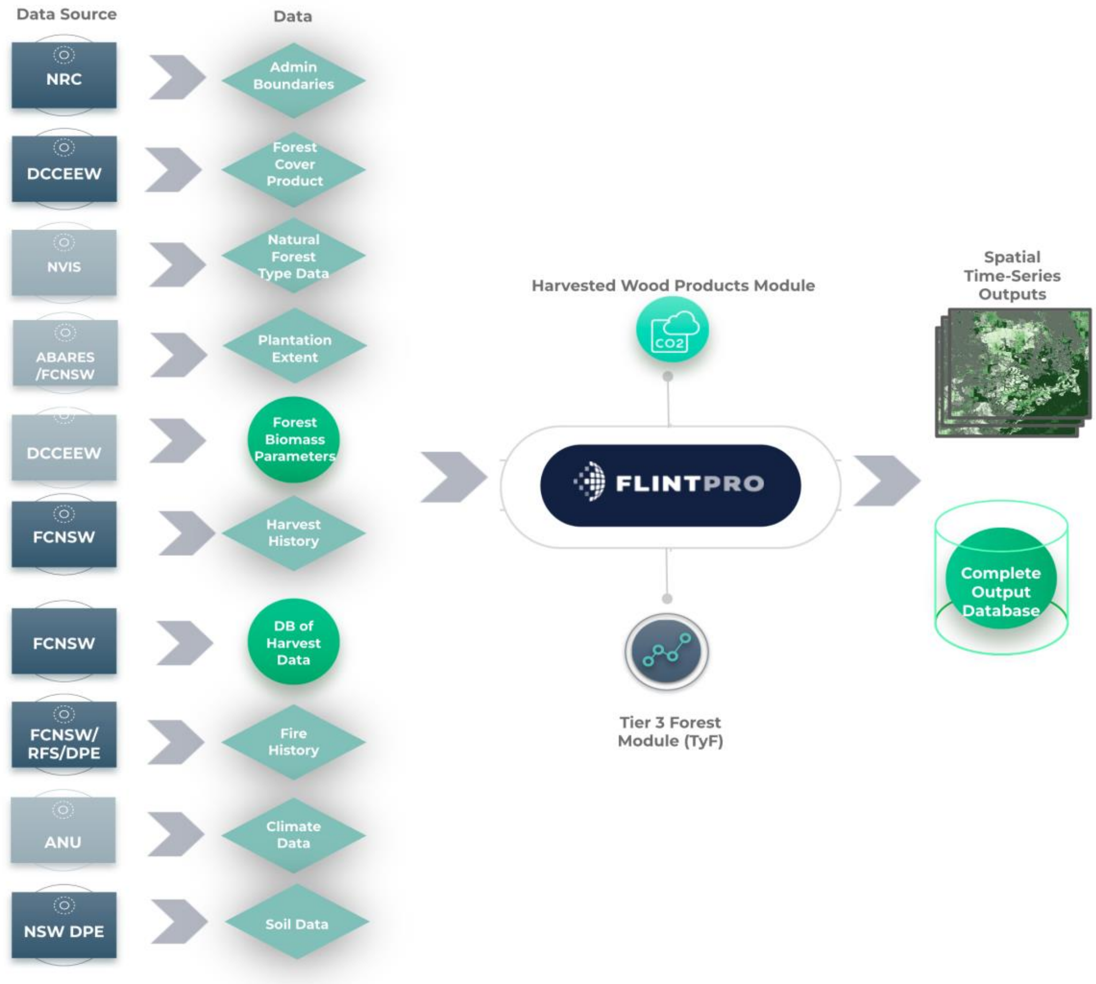


Figure 4 – Conceptual framework for the Carbon balance of NSW forests project. The simulation used data from the NSW Natural Resources Commission (NRC), The Commonwealth Department of Climate Change, Energy, the Environment and Water (DCCEW), Forestry Corporation of NSW (FCNSW), NSW Department of Planning & Environment (DPE), the Australian Bureau of Agricultural and Resource Economics (ABARES), the Australian National University (ANU), and the Rural Fire Service (RFS).

As described above, two main drivers of change were modelled: Processes, such as forest growth; and Events, such as fire, timber harvesting and clearing. In this update, additional data sources were used for reviewing and differentiating the drivers of change in NSW forest carbon stocks. These included:

- NSW Statewide Landcover and Trees Study (SLATS)
- Extended harvest history data

- Improved plantation species and age class data
- Extended forest cover data

FLINTpro was also configured such that the following carbon fluxes or carbon stock could be distinguished:

- Controlled fire and wildfires
- Clearing and timber harvesting
- Land which transitions between forest and sparse woody vegetation from land which changes between forest and non-woody vegetation.

The assessment also updated the forest growth parameters for native forests and plantations to reflect changes published in the 2020 National Inventory Report (NIR) (DCCEEW 2022, Paul et al. 2022). These changes are described in more detail in the subsequent sections.

2.1. Updated Configuration

2.1.1. Forest Types & Growth Parameters

Native Forests

The forest types used in the updated simulation reflect the same Major Vegetation Groups as used previously (Table 1). While the spatial modelling is comparable with the original assessment, there were updates to the growth rates, in particular the plant allocations, turnover and decomposition rates. The forest biomass partitioning was modified from the original assessment, with the values adjusted to reflect those more recently published in the NIR 2020 (DCCEWW, 2022). Noting that there is a published error in Table 6.4.9 of the NIR 2020 report, where incorrect plant allocations are referenced (e.g., 64% of biomass partitioned to fine roots for Callitris forests). Corrected values were obtained from DCCEEW. The *allocation rate* was adjusted to reflect the native forests within the NIR (Table 6.4.9 in NIR 2020), however, the *turnover* and *decomposition* rates for planted forests were used (Table 6.5.5 and 6.5.6 in NIR 2020 (DCCEWW, 2022)). This position was taken over concern that the turnover rates were resulting in excess carbon movements through the fine root matter of forests, as noted in the original assessment. By using the alternative turnover and decomposition rates, there was a modest variation in the dead organic matter component, however, the carbon sequestration rates across the plant components better reflected the biomass partitioning (i.e., fine roots are no longer the largest carbon sequestering pool). While soil carbon was not modelled within this assessment, it is expected that this modification will correct the extraordinary increases in soil carbon under natural forests modelled using the NIR values in the original assessment.

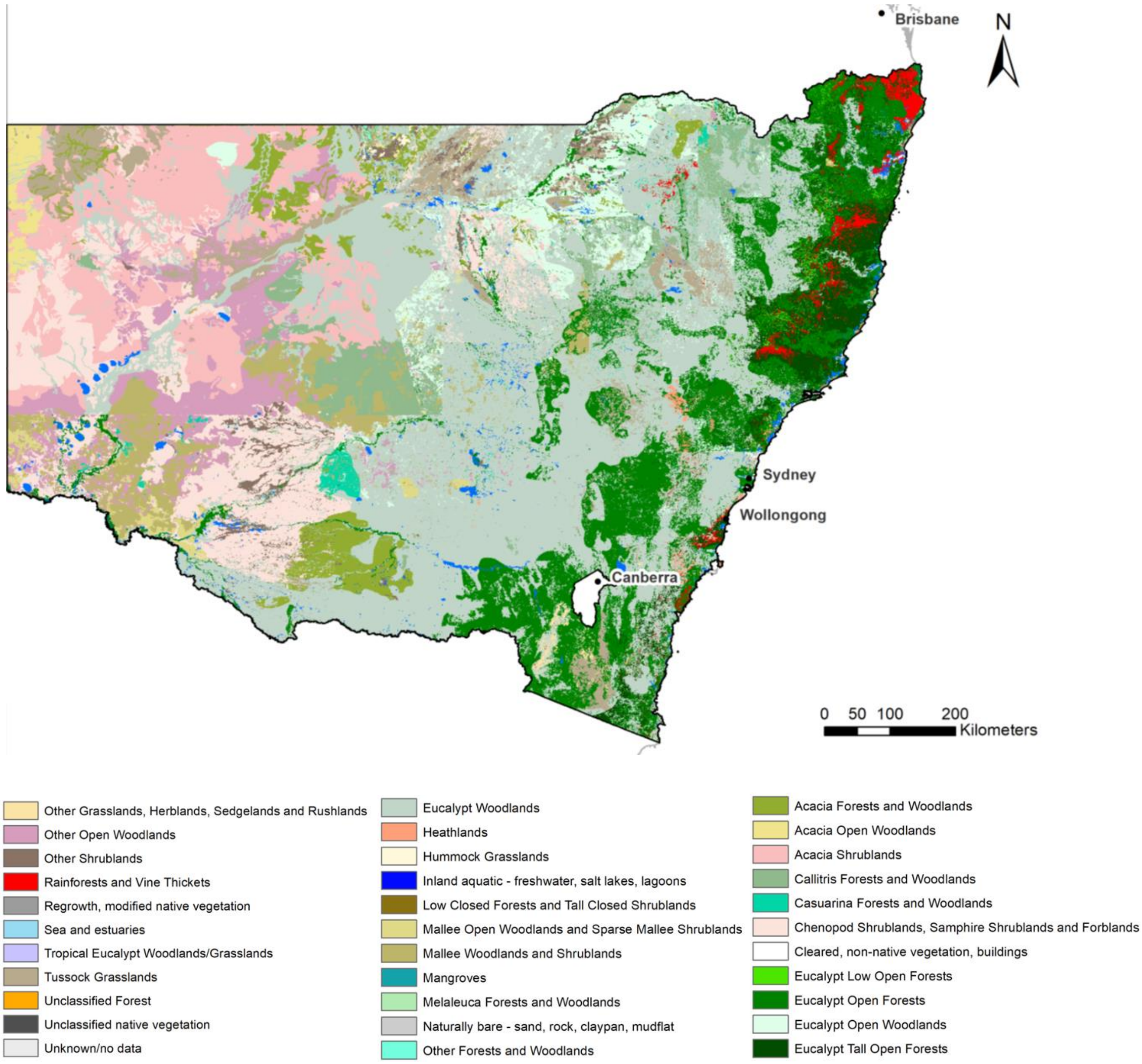


Figure 5 – Pre-1750 NVIS Major Vegetation Groups (MVG 5.1). Natural forests were modelled based on the MVG classifications. Data from NVIS: https://www.environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products

Table 1 – Major vegetation groups and plantation types, along with biomass allocations, replicated from the 2020 National Greenhouse Gas Inventory Report for native species (DCCEEW, 2022).

Name	Stem allocation	Branch allocation	Bark allocation	Leaf allocation	Coarse root allocation	Fine root allocation
Rainforests and Vine Thickets	0.42	0.2	0.11	0.06	0.18	0.03
Eucalypt Tall Open Forests	0.42	0.2	0.11	0.06	0.18	0.03
Eucalypt Open Forests	0.4	0.19	0.11	0.07	0.2	0.04
Eucalypt Low Open Forests	0.49	0.11	0.09	0.04	0.24	0.03
Eucalypt Woodlands	0.31	0.2	0.08	0.11	0.23	0.07
Acacia Forests and Woodlands	0.28	0.19	0.07	0.12	0.25	0.09
Callitris Forests and Woodlands	0.28	0.22	0.08	0.07	0.27	0.08
Casuarina Forests and Woodlands	0.3	0.2	0.07	0.12	0.24	0.08
Melaleuca Forests and Woodlands	0.31	0.2	0.08	0.11	0.23	0.07
Other Forests and Woodlands	0.31	0.2	0.08	0.11	0.24	0.07

Eucalypt Open Woodlands	0.29	0.19	0.07	0.12	0.25	0.09
Tropical Eucalypt Woodlands/Grasslands	0.31	0.16	0.08	0.08	0.28	0.09
Acacia Open Woodlands	0.27	0.19	0.07	0.12	0.25	0.1
Mallee Woodlands and Shrublands	0.31	0.2	0.08	0.11	0.24	0.07
Low Closed Forests and Tall Closed Shrublands	0.31	0.2	0.08	0.11	0.24	0.07
Acacia Shrublands	0.28	0.19	0.07	0.12	0.25	0.1
Other Shrublands	0.29	0.19	0.07	0.12	0.25	0.09
Heathlands	0.35	0.21	0.09	0.1	0.21	0.04
Tussock Grasslands	0.31	0.2	0.08	0.11	0.24	0.07
Hummock Grasslands	0.31	0.2	0.08	0.11	0.24	0.07
Other Grasslands, Herblands, Sedgelands and Rushlands	0.31	0.2	0.08	0.11	0.24	0.07
Chenopod Shrublands, Samphire Shrublands and Forblands	0.33	0.2	0.08	0.11	0.22	0.06
Mangroves	0.33	0.2	0.08	0.11	0.22	0.06
Inland aquatic - freshwater, salt lakes, lagoons	0.33	0.2	0.08	0.11	0.22	0.06
Unclassified native vegetation	0.26	0.2	0.07	0.12	0.28	0.08
Naturally bare - sand, rock, claypan, mudflat	0.33	0.2	0.08	0.11	0.22	0.06
Sea and estuaries	0.31	0.2	0.08	0.11	0.24	0.07
Unclassified Forest	0.31	0.2	0.08	0.11	0.24	0.07
Other Open Woodlands	0.31	0.2	0.08	0.11	0.24	0.07
Mallee Open Woodlands and Sparse Mallee Shrublands	0.31	0.2	0.08	0.11	0.24	0.07
Unknown/no data	0.31	0.2	0.08	0.11	0.24	0.07
All	0.31	0.2	0.08	0.11	0.24	0.07
Native Forest	0.31	0.2	0.08	0.11	0.24	0.07
Southern Pine	0.473	0.136	0.064	0.086	0.209	0.032
P. radiata	0.473	0.136	0.064	0.086	0.209	0.032
E. globulous	0.408	0.19	0.072	0.106	0.193	0.031
E. grandis	0.408	0.19	0.072	0.106	0.193	0.031
E. nitens	0.408	0.19	0.072	0.106	0.193	0.031
Other Eucalypt	0.408	0.19	0.072	0.106	0.193	0.031
Softwood	0.473	0.136	0.064	0.086	0.209	0.032
Hardwood	0.408	0.19	0.072	0.106	0.193	0.031
P. Pinaster	0.378	0.108	0.051	0.069	0.325	0.068
Pellita Hybrid	0.408	0.19	0.072	0.106	0.193	0.031
Mangium	0.408	0.19	0.072	0.106	0.193	0.031
Other Acacia	0.408	0.19	0.072	0.106	0.193	0.031
Mallee Block	0.238	0.164	0.041	0.114	0.363	0.08
Mallee Belt L	0.238	0.164	0.041	0.114	0.363	0.08
Mallee Belt HW	0.238	0.164	0.041	0.114	0.363	0.08
Mallee Belt HN	0.238	0.164	0.041	0.114	0.363	0.08
Other Belt	0.238	0.164	0.041	0.114	0.363	0.08

Table 2 – Percentage change in the plant allocations from the Original Assessment. The values represent the percentage change between the previous values and the new values for native forests. Note, that changes in the allocations between living aboveground biomass pools does not influence the total living aboveground biomass estimated on the site, however changes in the allocations to belowground biomass pools may impact the total living belowground biomass estimate. This change is indicated in the Change in Root:Shoot ratio column.

Name	Stem allocation	Branch allocation	Bark allocation	Leaf allocation	Coarse root allocation	Fine root allocation	**Change In Root:Shoot Ratio**
Rainforests and Vine Thickets	-14%	82%	22%	50%	-25%	0%	-28%
Eucalypt Tall Open Forests	-14%	82%	22%	50%	-25%	0%	-28%
Eucalypt Open Forests	-18%	73%	22%	75%	-17%	33%	-16%
Eucalypt Low Open Forests	0%	0%	0%	0%	0%	0%	0%
Eucalypt Woodlands	11%	-9%	0%	57%	-15%	-13%	-20%
Acacia Forests and Woodlands	0%	-14%	-13%	71%	-7%	13%	-4%
Callitris Forests and Woodlands	0%	0%	0%	0%	0%	0%	0%
Casuarina Forests and Woodlands	7%	-9%	-13%	71%	-11%	0%	-14%
Melaleuca Forests and Woodlands	11%	-9%	0%	57%	-15%	-13%	-20%
Other Forests and Woodlands	11%	-9%	0%	57%	-11%	-13%	-18%
Eucalypt Open Woodlands	4%	-14%	-13%	71%	-7%	13%	-6%
Tropical Eucalypt Woodlands/Grasslands	-37%	45%	-11%	100%	17%	200%	59%
Acacia Open Woodlands	-4%	-14%	-13%	71%	-7%	25%	0%
Mallee Woodlands and Shrublands	11%	-9%	0%	57%	-11%	-13%	-18%
Low Closed Forests and Tall Closed Shrublands	11%	-9%	0%	57%	-11%	-13%	-18%
Acacia Shrublands	0%	-14%	-13%	71%	-7%	25%	-2%
Other Shrublands	4%	-14%	-13%	71%	-7%	13%	-6%
Heathlands	25%	-5%	13%	43%	-22%	-50%	-38%
Tussock Grasslands	11%	-9%	0%	57%	-11%	-13%	-18%
Hummock Grasslands	11%	-9%	0%	57%	-11%	-13%	-18%
Other Grasslands, Herblands, Sedgelands and Rushlands	11%	-9%	0%	57%	-11%	-13%	-18%
Chenopod Shrublands, Samphire Shrublands and Forblands	18%	-9%	0%	57%	-19%	-25%	-28%
Mangroves	18%	-9%	0%	57%	-19%	-25%	-28%
Inland aquatic - freshwater, salt lakes, lagoons	18%	-9%	0%	57%	-19%	-25%	-28%
Unclassified native vegetation	-47%	82%	-22%	200%	17%	167%	50%
Naturally bare - sand, rock, claypan, mudflat	18%	-9%	0%	57%	-19%	-25%	-28%
Sea and estuaries	11%	-9%	0%	57%	-11%	-13%	-18%
Unclassified Forest	11%	-9%	0%	57%	-11%	-13%	-18%
Other Open Woodlands	11%	-9%	0%	57%	-11%	-13%	-18%
Mallee Open Woodlands and Sparse Mallee Shrublands	11%	-9%	0%	57%	-11%	-13%	-18%
Unknown/no data	-14%	82%	22%	50%	-25%	0%	-18%

Plantation Forests

In the original assessment, the distribution of plantation types was implemented based on the results of the 2020 Plantation Forest Inventory data for the National Plantation Regions (Downham & Gavran 2020). In the updated assessment, data from Forestry Corporation of NSW was used as the primary input for publicly owned plantations, with the ABARES data used for areas outside of the public forest estate (Figure 6). Within the public plantation estate, this identified 45 individual plantation species, rather than the generic hardwood/softwood classes in the ABARES data. Of note, while the spatial data identified 45 species, there are only 11 plantation calibrations available (Paul et al 2022) (Table 1). Where a species-specific plantation calibration was not available, a generic hardwood/softwood calibration was used. Similarly, where the ABARES data identified a hardwood or softwood plantation, generic calibrations were used, with Eucalyptus regimes for hardwoods and *Pinus radiata* regimes for softwoods.

In addition to the changes in the method used to identify the plantation type, there have been recent changes within the NGGI for the calculation of the r parameter for plantations. The concepts are published in Paul et al. (2022), and the 2021 NIR (DCCEEW, 2023)[1]. These changes were reflected in the calculations for the plantations.

Tree Yield Formula (TYF):

$$\Delta AGB = M \times r \times [exp(-k/A_2) - exp(-k/A_1)] \times (FPI_t/FPI_{avg})$$

Where:

ΔAGB = Current annual increment in above-ground biomass (AGB, Megagram Dry Matter per Hectare Per Year (Mg DM per ha^{-1} $year^{-1}$))

M = Maximum AGB in undisturbed native vegetation (Mg DM ha^{-1})

r = value of the Type 2 multiplier to account for factors that increase growth potential at a given site (e.g. planting configuration, Snowdon 2002)

A_1, A_2 = age (years) in year 1 and 2, respectively, etc.

k = 2 x G - 1.25, where G = tree age of maximum growth rate (years),

FPI_t = Annual Forest Productivity Index over the period A1 to A2, and is the sum of site factors (soil type, fertility and climate) driving growth, regardless of the type of planting or its age (Kesteven and Landsberg 2004); and

FPI_{avg} = mean long-term average annual forest productivity index based on data, which is independent of age (Kesteven and Landsberg 2004).

The TYF is used to simulate growth in both natural forests and plantations. For plantations, r is also influenced by M (DCCEEW, 2023) where:

$r = \exp(ar) \times M^{br}$, if $\mathrm{MIN}_{r\times M} \leq r \times M \leq \mathrm{MAX}_{r\times M}$, else

$r = \mathrm{MIN}_{r\times M}$ / *M*, if $r \times M < \mathrm{MIN}_{r\times M}$, or

$r = \mathrm{MAX}_{r\times M}$ / *M* , if $r \times M > \mathrm{MAX}_{r\times M}$.

And where:

ar and *br* are constants (see Table 3)

First, r $(\exp(ar) \times M^{br})$ is calculated for a location, and is multiplied by M for that location, to give $r \times M$. If $r \times M$ is within the bounds ($\mathrm{MIN}_{r\times M}$, $\mathrm{MAX}_{r\times M}$) then $r \times M$ (as calculated above) is used in the TYF. If $r \times M$ is less than $\mathrm{MIN}_{r\times M}$ $\mathrm{MIN}_{r\times M}$ / *M* is used for r . If $r \times M$ is greater than $\mathrm{MAX}_{r\times M}$ then $\mathrm{MAX}_{r\times M}$ / *M* is used for r.

[1] Note: The published equations (Equation A5.6.6.1) within the NIR 2022 and Paul et al 2022 contain typographical errors, the equation presented is the correct equation, as confirmed by DCCEEW (per comms. 2023)

See Table 3 for Min_{rxM}, Max_{rxM}, ar, br and G parameters used for plantation species. For all native forests, a G parameter of 10 was used, which corresponds to the default user defined value in FullCAM. This deviates from the NIR, which applies 6.35 for State forests, and 12.53 for all other forests. Rather than model forest growth rates based on administrative boundaries, a 'mid' value of 10 was applied. See the original assessment (Roberts et al. 2022) for a discussion on this approach.

Table 3 – Tree yield formula parameters for various plantation forest types

forest type id	Min_{rxM}	Max_{rxM}	G	ar	br
Southern Pine	202	578	6.505	3.204	-0.447
P. radiata	146	654	6.311	3.828	-0.617
E. globulus	92	484	5.554	4.358	-0.767
E. grandis	89	464	4.229	2.695	-0.514
E. nitens	98	596	6.913	3.317	-0.576
Other Eucalypt	45	891	8.002	2.355	-0.368
Other SW	176	886	10.917	3.204	-0.447
Other HW	104	448	6.745	3.23	-0.584
P. Pinaster	154	637	11.318	2.769	-0.386
Pellita Hybrid	92	449	4.051	2.861	-0.446
Mangium	98	273	3.936	3.63	-0.681
Other Acacia	130	436	6.547	2.251	-0.384
Mallee Block	15	220	6.317	0	0
Mallee Belt L	18	264	4.533	0.182	0
Mallee Belt HW	18	264	3.492	0.182	0
Mallee Belt HN	24	354	2.288	0.475	0
Other Belt	1	1	2	1.212	0

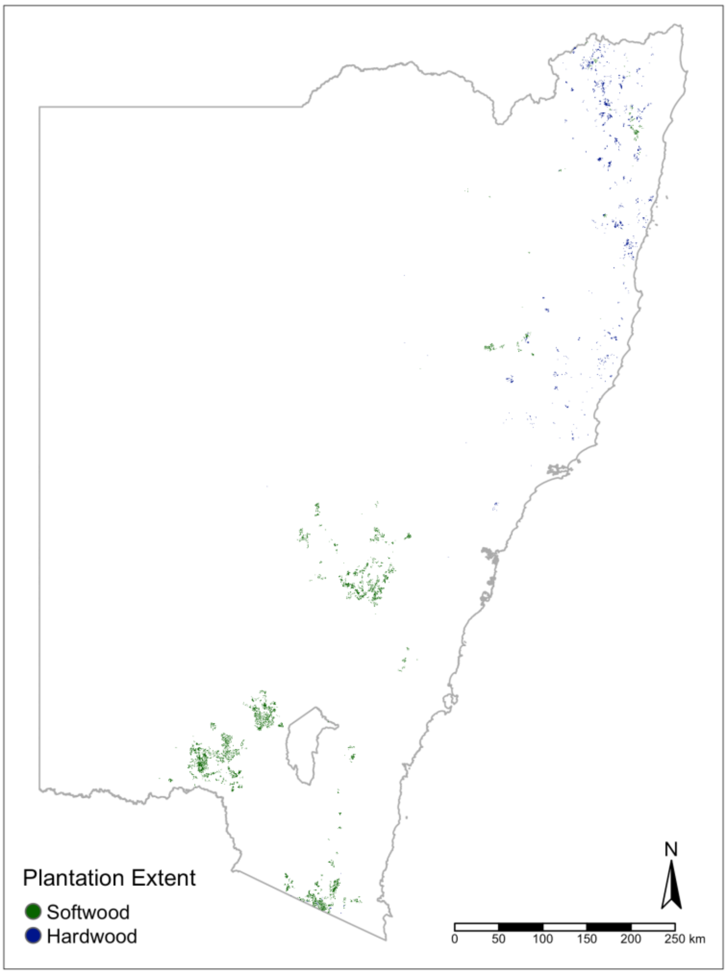


Figure 6 – Plantation extent of NSW, made from a combination of FCNSW data and national data from 2016. Areas identified as plantation in 2016 were modelled as a plantation for the entire simulation. FCNSW plantation data is not publicly available. Data from ABARES is available at https://www.agriculture.gov.au/abares/research-topics/forests/forest-data#australian-plantation-stat

Other Forests

Other forests, including urban forests, farm forestry and horticultural crops (e.g., orchards) were not separately identified and hence were modelled as if they were native forest types based on their MVG class. These areas may be excluded post-analysis where the spatial data exists to identify them, such as by using a land use mask developed through the forest extent, condition and health monitoring component of the NSW FMIP.

In developing the FLINTpro simulation, there are a number of considerations in addition to the forest growth elements – notably, the initial condition assumptions and the events. These elements are described in the following sections.

Forest Type Assumptions & Improvements

Consistent with the Original Approach

- Natural forest types are static, meaning distribution of forest types will not change through time.
- There was no conversion of native forest to plantations.
- Simplified plantation species were implemented, with a static temporal distribution.

Improvements Implemented

- Updated forest growth parameters to match the NIR 2020 and Paul & Roxburgh (2022).
- Improved spatial distribution of plantation species on public forests.
- Updated harvest regimes for *Pinus radiata* and wood product destinations.

Potential Future Improvements

- Full time series of plantation extent by species, including more specific information on management regimes of NSW forest types to better inform the simulation of thinning events and the treatment of thinning and harvest residues.
- Incorporating changes in forest type distributions following frequent disturbances or climate induced changes.
- Exclude or modify the database to model horticultural crops using NSW-specific land use data.
- Modify how urban forests are modelled to better reflect the different growth capacity.

2.1.2. Initial Condition

The period of interest for the carbon balance of NSW forests project is 1990 onwards. The same 'spin up' period was used as in the original assessment to account for pre-1990 events, with a modelling start date of 1935. This allowed the use of NSW-specific harvest and fire records, as well as providing sufficient time for the accumulation of carbon in the debris pools to stabilise (Figure 7).

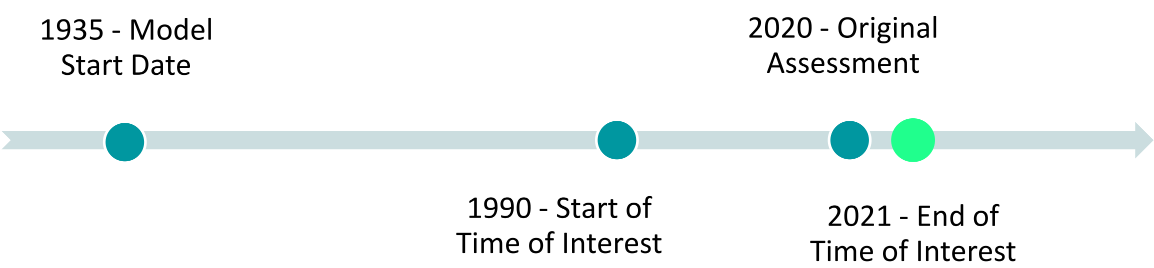


Figure 7 – Timeline of the carbon balance of NSW forests simulation

The forest cover data used in the simulation was the National Forest and Sparse Woody Vegetation Data (Version 6.0) for the period from 1989 to 2021, which has periodic gaps in temporal coverage (Figure 8). The initial year of the forest cover data, 1988, was removed from the timeseries as there are concerns with the reliability of this year (there are consistent, state-wide loss and gain events between 1988 and 1989). To support a spin up of the biomass pools, it was assumed that any area that was forest in 1989, the first year of the forest cover data, was forest in 1935 (modelling start date). Reflecting the assumptions of the NGGI (age 0 in 1920), these areas of native forest were 15 years old at the modelling start date (1935), meaning that they would be below the maximum potential aboveground biomass in 1989. This assumption provides an age class comparable to the modelling undertaken by DCCEEW (Collett pers comm. April 2021). The dead organic matter at the modelling start date is zero (no biomass).

Areas that were identified as private plantation and were forest in 1989 were assumed to have been planted in 1935 and managed on a standard management regime up to 1989 such that for the private plantation estate, the forests were assumed to be 7 years old in 1990 for hardwoods and 15 years old for softwoods. For the public plantation estate where there was a known age class, harvest and replant events were used to align the plantation age with the known age. For the private plantation estate, this assumption will result in over- and under-estimates in biomass in specific plantation forests. However, as true harvest and replanting events are identified in the forest cover data post-1989, the influence of this assumption should decline.

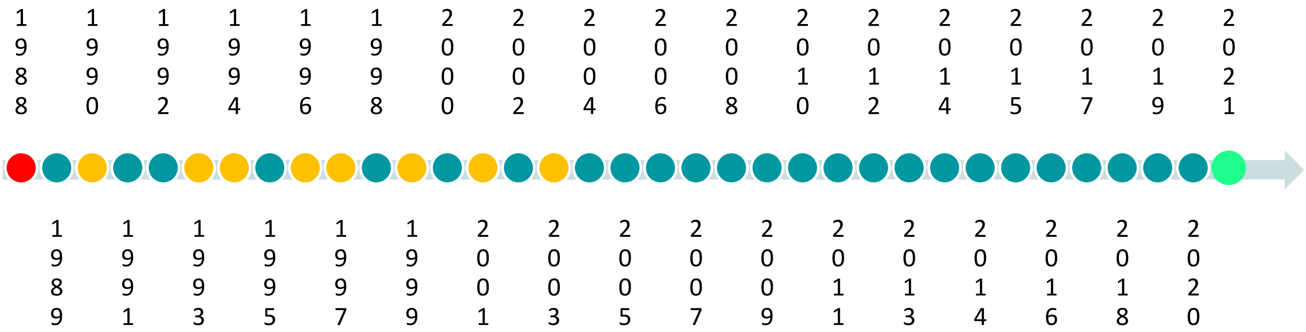


Figure 8 – Green circles represent the years represented in the timeseries of remote sensing data, bright green represents the new year added since the original assessment, and yellow circles represent gaps in the remote sensing product within the timeseries. In the 1990s, several years are missing. In the circumstance that a change is detected where there are gaps between the years, a random date between the years is applied. The 1988 forest layer (in red) was not used in this simulation due to it being less reliable.

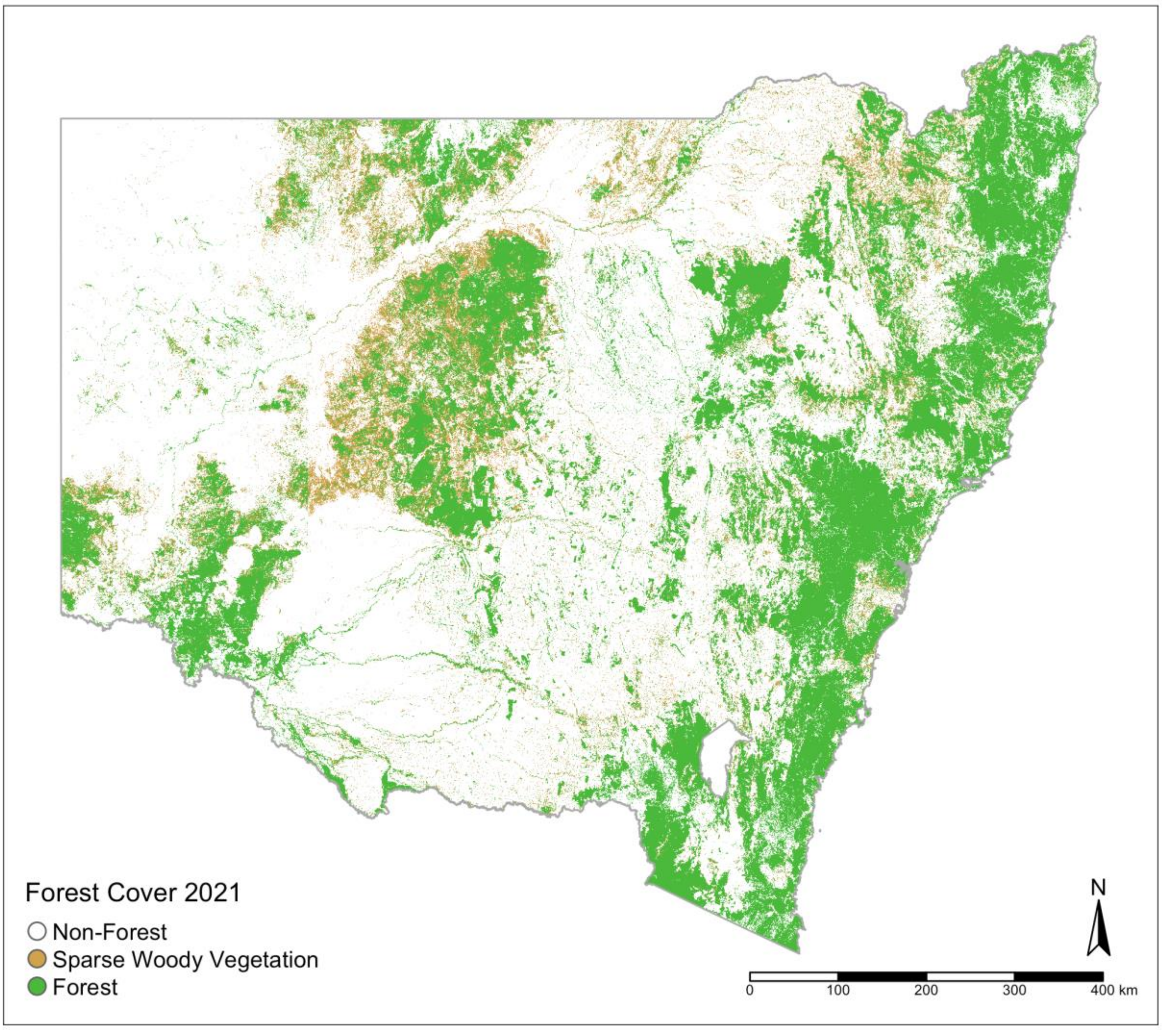


Figure 9 – NSW Land Cover for 2021, from the National Forest and Sparse Woody Vegetation Data (Version 6, 2021 Release), https://data.gov.au/dataset/ds-dga-b0d6b762-fe24-4873-91bd-ae0a8bbb452e/

Initial Condition Assumptions & Improvements

Consistent with the Original Approach

- Any area of native forest present at the start of the simulation (i.e., 1935) was 15 years old in 1935 and growing toward maximum biomass.
  - Modelling known disturbances pre-1990 reduces the impact of this assumption.
- There is no biomass in the dead organic matter pools at the start of the simulation.
  - A 'spin up' period of 55 years was used to overcome this assumption.

Improvements Implemented

- Plantation extent in 2016 was used to estimate the plantation extent in 1989 for the private estate, and the current plantation extent from Forestry Corporation of NSW was used for the public estate.
- Areas that were forest in 1989 and mapped as private plantation in 2016 were assumed to have been managed such that they were 7 years old for hardwoods and 15 years old

for softwoods in 1990. After 1989, clearfell harvest events and forest cover gain events detected through the forest cover data were used for plantations.

- Ages for public plantations present in 1989 were back calculated using FCNSW Age Class data.

Potential Future Improvements

- Complete a sensitivity assessment of the initial forest type assumption.
- Use an Initial Forest Biomass input layer (which in turn is based on disturbance and harvest cycle assumptions) to provide a more accurate representation of the age class and biomass distribution across the State's private plantation forests. This may assist with introducing more spatial variation within the pre-1990 results and overcome the limitation of the assumption that all native forests were 15 years old in 1935.
- Develop a complete timeseries of forest cover from the earliest year possible. The current forest cover data is missing several years, as shown in Figure 8.
- Include a complete timeseries of plantation extent from 1989 onwards, to capture plantation ages and transitions from native forest to plantation. The current ABARES plantation data is a static extent from 2016.

2.2. Event Types

The same events were used in the updated assessment as in the original assessment. This included natural and anthropogenic events including fire, timber harvesting, forest establishment (planting), and forest clearing. There were some improvements to the configuration to provide deeper insights into the drivers of change associated with these events, as described below.

2.2.1. Fire

The treatment of fire events was consistent with the original assessment, where timing and extent of both fire types was provided by the NSW RFS and FCNSW, covering the period of 1935 through to 2016, and data from the NSW Fire Extent and Severity Mapping (FESM) project was used post 2017. The proportions of carbon emitted to the atmosphere and transferred to the DOM pool are detailed in the original assessment and provided here in Annex 1 – Fire parameters.

In the updated assessment, the treatment of forest cover loss events coupled with fire events was modified. Previously, where there was a fire event in native forest and also a forest cover loss event (according to the forest cover data), the forest was burnt and subsequently cleared. This assumed that the forest cover data was a 'point of truth'. While this assumption would, under normal circumstances, have a comparatively minor impact on the forest carbon, with the extreme 2019-20 fire season, we were concerned it would overestimate the losses. Accordingly, this assumption was changed in the system, such that where there was a fire within a native forest and a forest cover loss, only the fire event was triggered (with varying severity classes).

In the original assessment, the carbon fluxes (movements) associated with controlled fire or wildfire events were aggregated for the output reports. In this updated simulation, the fire types were separated, with fluxes from wildfire mapped separately to fluxes from controlled fire.

Fire Assumptions & Improvements

Consistent with the Original Approach

- There are only two forest fire types prior to 2017, wildfire and hazard reduction burns.
- Post 2017, severity classes (Low, Moderate, High, Extreme) were applied based on FESM.
- The entire area within the fire boundary is affected by the fire in a uniform manner.

Improvements Implemented

- Where fire and forest cover loss occurred in the same year for native forests, only the fire event was simulated.
- Fire fluxes were distinguished as either controlled fire or wildfire, rather than a single fire type.
- Belowground biomass reduced by the same proportion as stem wood as a result of the fire events.

Potential Future Improvements

- Expanding the spatial-temporal data on fire severity class to incorporate vegetation type responses to improve the estimates of the impacts of fire on carbon pools. Note that further research would be required to calibrate each of the NSW forest types.
- Further expand the residue management to land clearing events.
- Retrospective application of fire severity classes for the entire modelling period once data is available.

2.2.2. Forest clearing

Forest clearing is the loss or removal of tree cover to a level below the forest threshold (20% canopy cover). This may or may not result in deforestation, which is the conversion of forest land to non-forest land. However, a forest clearing event can also be triggered by natural disturbances such as drought and fire, after which it is expected that the forest will recover. Forest clearing events result in the movement of biomass from living pools to dead organic matter, and subsequent loss to the atmosphere.

Consistent with the original assessment, forest clearing was identified from a forest cover time-series dataset produced for the NGGI. However, as noted above, where a fire event and forest cover loss event coincided in the same year, only the fire event was applied. This causes the forest cover and spatial outputs to be out of step.

All fluxes that occurred as a result of forest cover loss, and not associated with timber harvesting, were aggregated as 'clearing'. This is an improvement from the original assessment which aggregated the fluxes from harvesting and clearing into a single category.

Forest Clearing Assumptions & Improvements

Consistent with the Original Approach

- Forest cover loss converts all living biomass to dead organic matter, where it is left on-site to decay.

Improvements Implemented

- The forest cover product is the point of truth where there is not a fire event within the same year. That is, where a pixel transitions from forest to non-forest in the absence of a fire, a forest clearing event is modelled. Where there is a forest cover loss in the cover product, and a fire event in the same period, only the fire is modelled.

- Flux events from clearing are reported separately from fluxes associated with timber harvesting.
- An attribution data layer based on SLATS data was incorporated.
- Delineation of forest to sparse woody transitions from forest to non-woody transitions.

Potential Future Improvements

- Only apply a forest clearing event where there is a transition of forest cover to non-woody biomass, as opposed to when there is only a forest cover loss.
- Add capacity to model regrowth from epicormic resprouting in addition to modelling complete forest clearing. This would require consideration of vegetation types and land management regimes across NSW so that a forest cover loss observation can trigger either replanting or regrowth.
- Attribute the drivers of forest cover change and incorporate more detailed regimes for these. For example, modelling debris management post-clearing where deforestation is carried out.

2.2.3. Growth/Replanting/Reforestation

In a similar way that forest clearing is detected, the system also detects replanting (re-establishment of forest cover on land that has a forest 'land use') and reforestation/afforestation (conversion of non-forest land to forest). The remote sensing based forest cover data is used to determine where there is a change from non-forest to forest, triggering a 'planting event'. Where this event is triggered for a pixel, the forest type data is used to identify the appropriate growth parameters and the pixel will start to accumulate carbon consistent with the growth rates described in Section 2.1. As noted in Section 2.1, the plant allocations have been updated from the original assessment.

Reforestation Assumptions & Improvements

Consistent with the Original Approach

- Forests start to grow in the year 'forest' cover (20%) is attained.
- Growth rates match FullCAM growth rates.

Improvements Implemented

- Biomass partitioning was updated to reflect the National Inventory Report 2020.
- Updated modelling of plantations.

Potential Future Improvements

- Use the sparse woody component of the national dataset to detect when 'forest' starts to regenerate. This is likely to improve the accuracy of the 'plant date', however as not all sparse woody vegetation becomes forest, further research into this concept is needed.
- Use known plant dates for plantation areas.
- Differentiate FullCAM growth rates based on management, for example human induced regeneration of native woody vegetation in land managed for grazing. Similarly, where

belt-plantings can be identified in NSW, implement the FullCAM growth rate assumptions for plantings established in belt configurations.

2.2.4. Harvesting

The extent of harvesting of native forests was identified from spatial records provided by the Forestry Corporation of NSW. This includes data of native forest harvesting in State forests only and does not include areas of native forest harvested on private land. The data is from 1950 through to early 2020, allowing for a comprehensive modelling of the changes in forest carbon as a result of harvest activities on native State forests (Figure 10). The expanded data represents the amalgamation of two data sets, whereas the original assessment only incorporated one of these data sets.

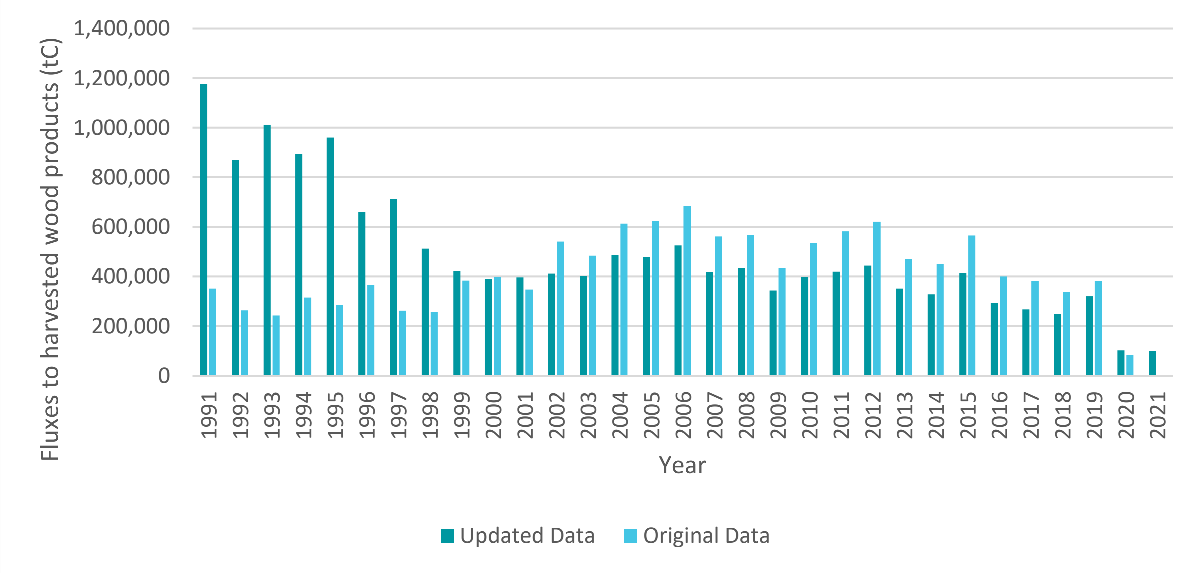


Figure 10 – Comparison between the original harvest data and the updated harvest data of carbon fluxes to harvested wood products associated with native harvesting in State forests. There were significant gaps in the pre-2000 harvest data in the original assessment. Note that the comparison is of fluxes, not area harvested, meaning that reduced estimates in forest carbon stock will also have influenced the total flux estimates (See Section 2.1.1)

As with the original assessment, a simplifying assumption was made that the percentage of basal area affected translated to the proportion of biomass affected by the harvest (Table 4). It is recognised that this assumption may over- or under-estimate the effect of timber harvesting on biomass, and further research is needed to reach an improved estimate. An improvement would be to introduce a dynamic relationship of wood volume with the Forest Productivity layer (Brack et al. 2011). A Biomass Age Adjustment was applied after each harvest event.

Harvesting of plantations was completed using a standard management regime for intra-rotational events (i.e., commercial thin events), or identified from remote sensing.

Where there was a harvesting event, carbon was moved from the living carbon pools to harvested wood products in use or dead organic matter. Once within these pools, it slowly decays to the atmosphere. Allocations to various destinations and decay rates are specified in the FLINTpro database using parameters supplied for this simulation or sourced from the national inventory. Harvested wood products in landfill were not included in this analysis.

Table 4 – Harvest types represented in the modelling, and an indication of the basal area removed. Depending on the harvest type, different proportions of carbon was moved into harvested wood products.

Harvest Type	%BA removed
Australian Group Selection (AGS)	25%
Alternate Coupe	80%
Miscellaneous	10%
Non-Harvest	0%
Fire, wind, road lines etc	50%
Single Tree Selection – heavy	40%
Single Tree Selection – light	20%
Single Tree Selection – unknown	30%
Single Tree Selection – moderate intensity	30%
Single Tree Selection – regeneration	60%
Cypress release to promote regeneration	30%
Thinning	40%
Hardwood plantation clear-fell	0%*

*plantation harvesting is set to 0% as the forest cover product was used to identify final harvests, rather than the spatial harvest data.

Harvesting Assumptions and Improvements

Consistent with the Original Approach

- There are a limited number of harvest events (13) that were applied for the whole timeseries.
- The entire area that could have been harvested was uniformly affected by the harvest event. This assumption will overestimate the impact of the harvesting.
- Basal area removed is equivalent to proportion of biomass affected.

Improvements Applied

- Harvest history data was expanded through compilation of different data sources.
- Updated plantation harvest events were used to improve the temporal resolution of the data.

Potential Future Improvements

- Improve the temporal changes in harvesting (i.e., changes in silviculture – historically and in future (e.g., post-2018 Coastal Integrated Forestry Operations Approvals (IFOA conditions) for public forests and Private Native Forestry Codes of Practice for private forests)). The FLINTpro structure supports this, however the data was not available to use this functionality.
- Expand the silvicultural treatments that can be applied and ensure that the impacts of these treatments on growth responses are well calibrated.
- Review the treatment of roots following harvesting. It currently assumed they are killed at the time of harvesting.

3. FLINTpro Simulation & Outputs

To support different reporting requirements, different spatial filters were applied to the data, including:

- Regional Forest Agreement Region boundaries
- Land tenure (National Parks, State Forests, other)
- Integrated Forestry Operations Approval Regions (IFOA)
- Plantation Extent by type
- Statewide Landcover and Tree Study (SLATS)
    - The annual timeseries of the SLATS data was flattened into single layers based on four classes (Agriculture, Forestry, Natural and Infrastructure) and applied as a filter. This was done to account for any misalignment in the temporal elements of the data.
- Always woody between 1989 and 2021 (to facilitate analysis of forest to sparse transitions).
- Major vegetation groups (MVGs).

This allows the results to be reported separately for each of these sub-categories, or combinations thereof. The completed simulation[2] spanned 1935 to 2021 and required analysis of 1.3 billion land units (pixels). The run required more than 35,000 hours of computer time but was completed in under 1 day using FLINTpro's distributed cloud processing.

3.1. Spatial Outputs

FLINTpro models monthly timesteps for every pixel (0.00025 decimal degrees or ~25m) within the Simulation Area and aggregates results to annual values. At the end of each calendar year, FLINTpro writes out a spatial file of the carbon stock or flux rate of every pool included within the simulation. This can include aggregates of carbon pools, such as Aboveground Biomass (stem + leaves + branches + bark) or total Forest Biomass (Aboveground Biomass + Belowground Biomass + Dead Organic Matter). The outputs are geoTiff files with either the carbon stock per pixel (tonnes carbon), or the carbon stock (tonnes carbon per hectare) (Figure 11). The spatial outputs help to identify spatial patterns in data, and greatly assist in developing an understanding of the underlying data.

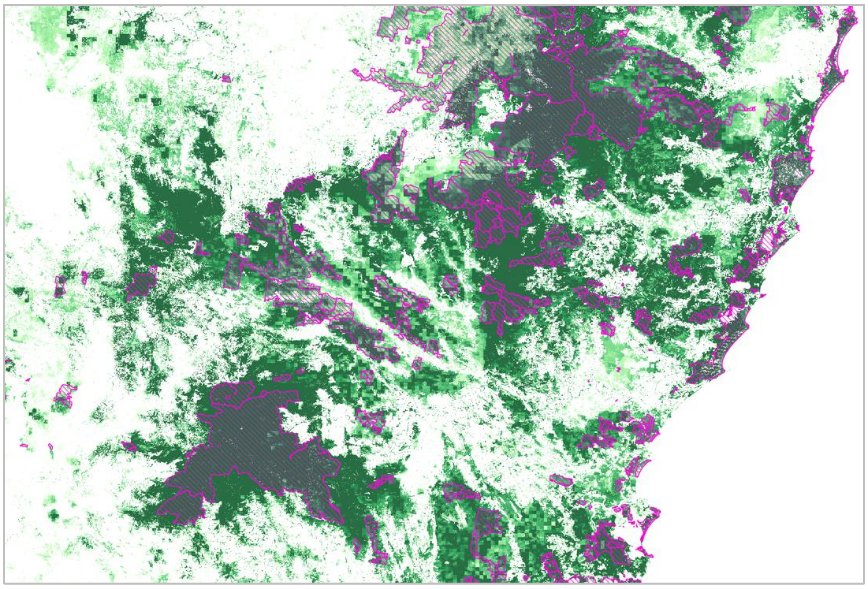


Figure 11 - FLINTpro outputs for Forest Carbon Stock (green) with the boundaries of national parks (Pink). Spatial outputs allow users to quickly identify patterns in the data.

[2] Run name NSW Forest Carbon Assessment Update - 1989-2021 V1.2

3.2. Databases

In addition to spatial outputs, FLINTpro creates a database record of the aggregated results. This includes the carbon stock of each pool and the fluxes (from and to). As a minimum, the carbon stock and fluxes are aggregated by spatial filters. As noted above, spatial filters are inputs in the simulation for reporting purposes (they don't impact the calculations, which are applied at the pixel level). One or more spatial files can be added to a simulation, allowing the results to be reported by the categories within the spatial files. Notably, the database size will increase with the more spatial filters that are applied.

4. NSW Forest Carbon 1990-2021

4.1. Forest Carbon Balance

As described above, changes in forest carbon stock within NSW are driven by processes and events triggered through forest cover gain and loss events, fire and harvesting. The balance between these event types culminates in the forest carbon stock. Reflecting trends in forest cover loss and gain, the results indicate that there was a general decline in forest carbon stock from 1990 through to the mid-2000s, after which there has been a marked increase in forest carbon until 2019, prior to the impacts of the 2019-20 fire season. This trend suggests that the state of NSW transitioned from being a net source of carbon from forests from 1990 to 2003, to being a net sink up to 2019. Following the 2019-20 fire season, NSW forests were a net source of emissions. The results indicate that the carbon in NSW forests is 165 million tonnes less in 2021 than in 1990 (Figure 12, Figure 13 & Figure 14).

While the overall trend is largely consistent with the original assessment, the quantum of carbon modelled to be within the forest is lower in the current assessment. This is largely due to the revised biomass partitioning values (Table 1), and the subsequent reduction in belowground biomass (lower Root:Shoot ratios for major forest groups; Figure 13). These parameter changes resulted in a ~20% reduction in carbon in the belowground pool, while the aboveground pool remained largely consistent. The updated results supersede the results from the previous assessment.

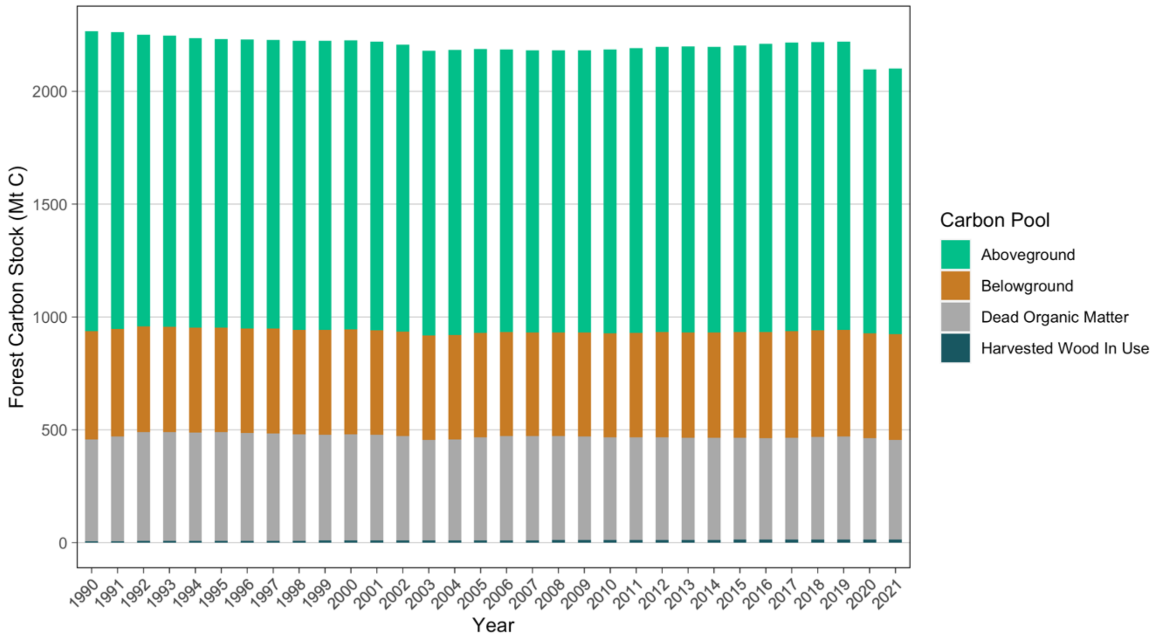


Figure 12 – Estimates of total Forest Carbon Stock for NSW 1990-2021, incorporating aboveground biomass, belowground biomass, dead organic matter, and harvested wood products in use. Soil carbon and harvested wood products in land fill were not included in this result. Developed with the 'Mid' forest growth rate where G=10.

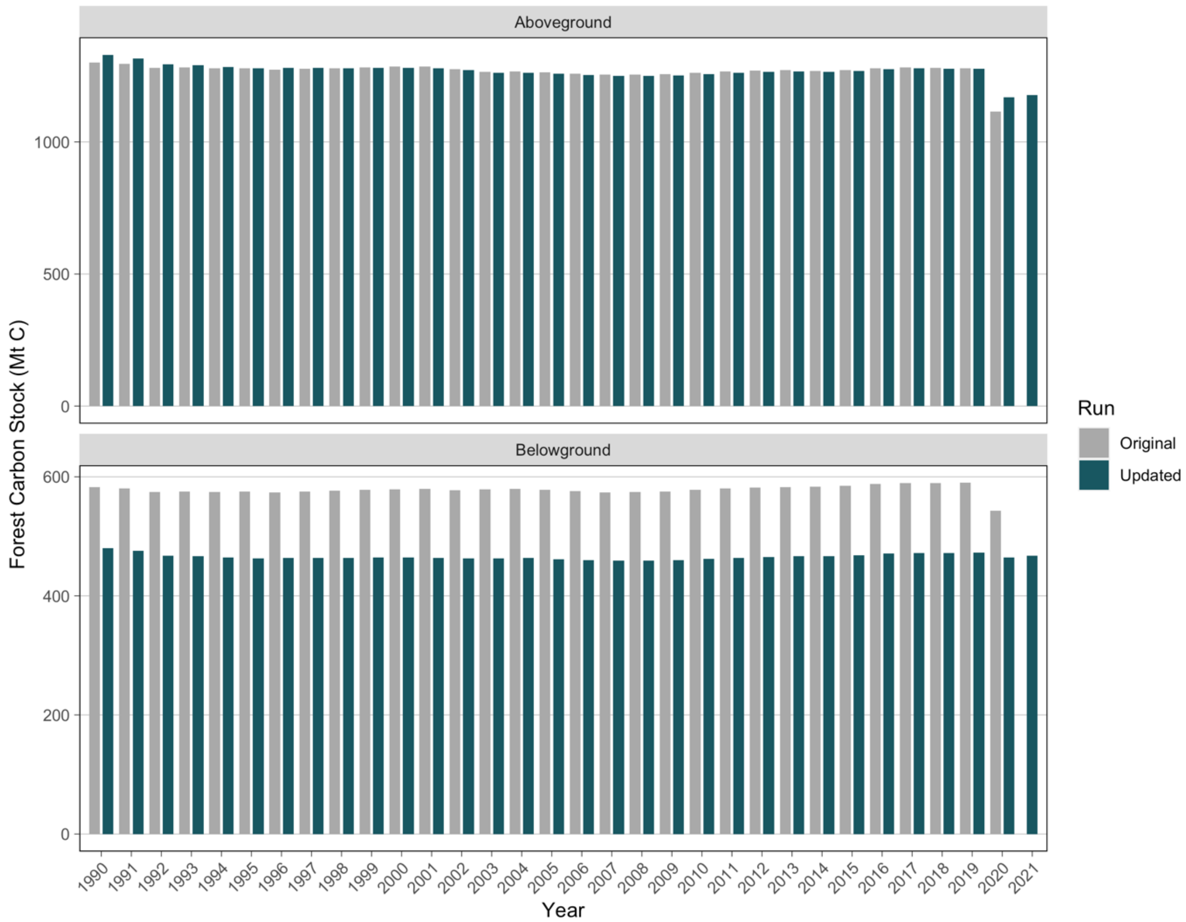


Figure 13 – Comparison of aboveground and belowground carbon stock between the original and updated assessments.

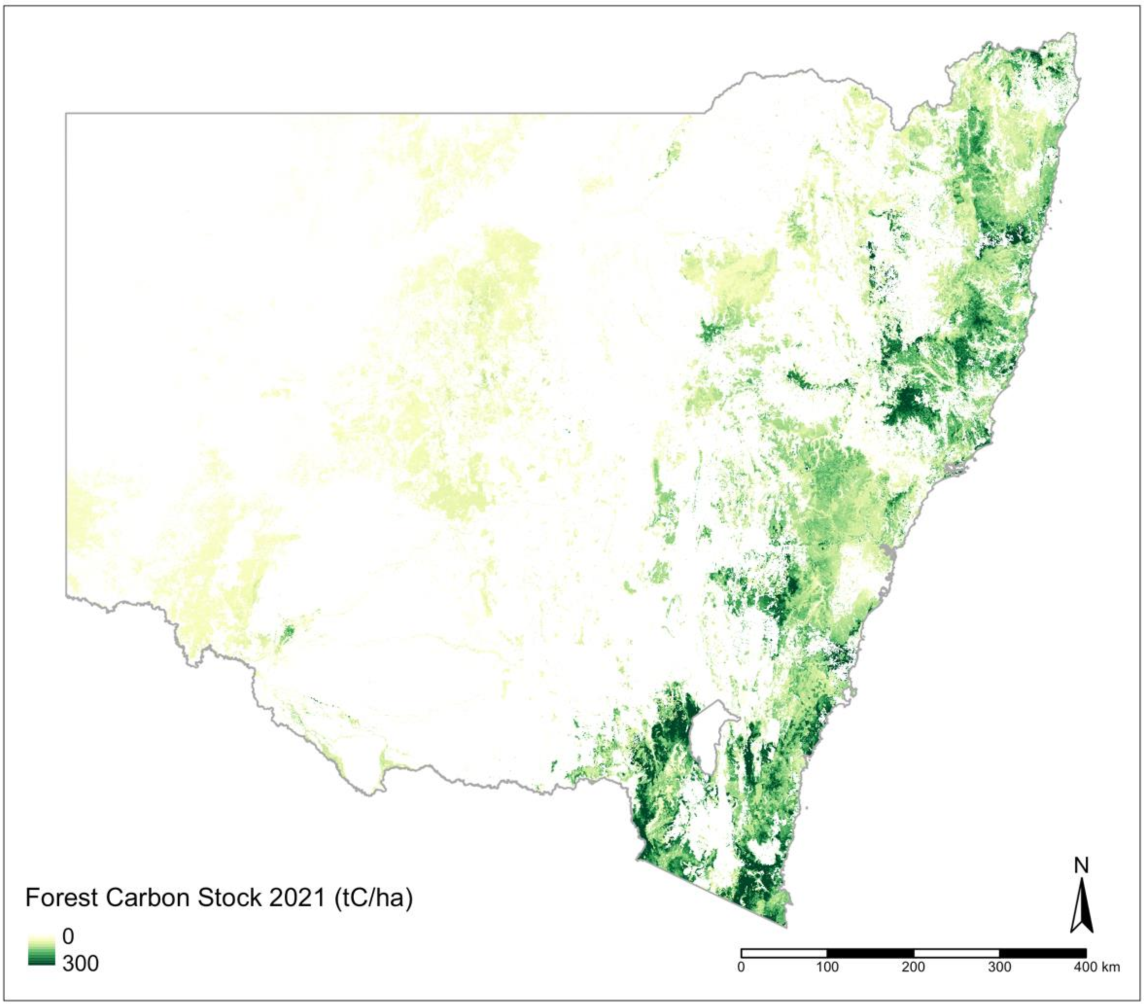


Figure 14 – Spatial Output of Forest Carbon for NSW in 2021, including aboveground biomass, belowground biomass and dead organic matter. Harvested wood products in use were not included in the spatial aggregation. Soil carbon and harvested wood products in landfill are not included. Developed with the 'Mid' forest growth rate where G=10.

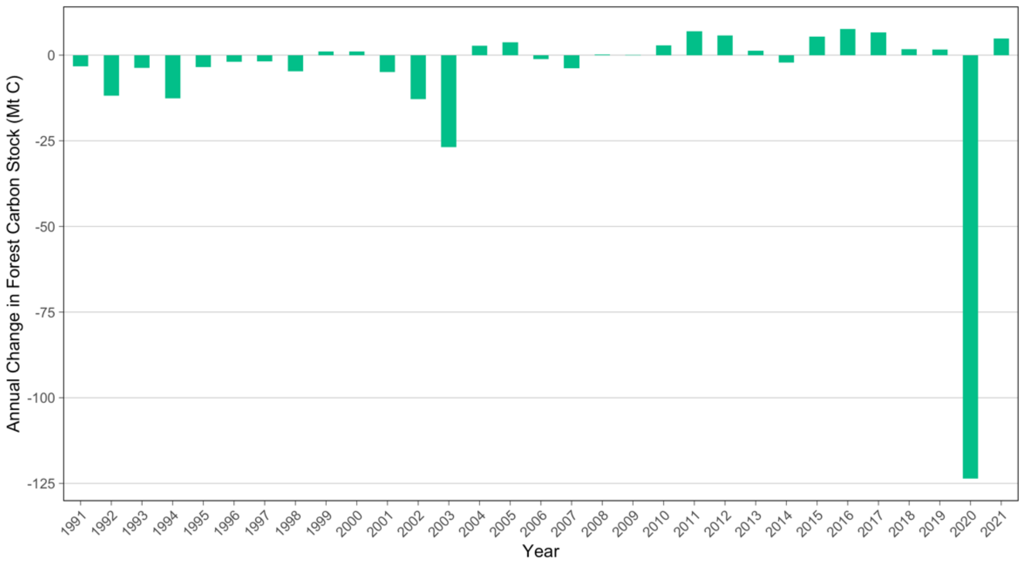


Figure 15 – Net Annual Change in Forest Carbon Stock 1990-2021, including aboveground biomass, belowground biomass, dead organic matter and harvested wood products in use. Negative numbers indicate a net loss in forest carbon, while positive numbers represent a net gain in forest carbon. Developed with the 'Mid' forest growth rate where G=10.

Between 1990 and 2019, there was an average decline of close to 1.5 MtC per annum (Figure 15). There was a general decline in forest carbon stock from 1990 to 2003 of close to 6 MtC per annum (noting a large drop in 2003 due to wildfires), and an average gain in forest carbon stock between 2004 and 2019 of 2.3 MtC per annum.

Changes in forest carbon were not spatially consistent, with regions of gain and loss spread across NSW (Figure 16). The forest carbon stock and carbon stock change also differ between land tenure. The trends in forest carbon stock change was similar between State Forests and National Parks, but trended differently for forests outside of these management systems (Figure 18). Most of the loss of carbon appears to be outside of State Forests and National Parks, though it has stabilised since 2010 (up until the 2019-20 wildfires). The results also indicate the contribution of plantation forests to the NSW forest carbon balance, in particular the softwood estate (Figure 20). Note that although there is a reduction in area of both softwood and hardwood plantations following the 2019-20 fires, the carbon stock in hardwood plantations remained stable due to gains in the remaining estate (i.e., growth) balancing out losses (Figure 21).

Figure 17 shows examples of forest carbon change between 1990 and 2021 at a local level, with panel A showing natural and harvesting operations (including plantations), while panel B indicates an area of agricultural clearing. Panel C shows examples of edge effects, possibly due to true change (e.g., woody thickening along forest edges) and false change (i.e., mixed pixels flip-flopping from forest to non-forest). Locations for these areas are indicated on Figure 16.

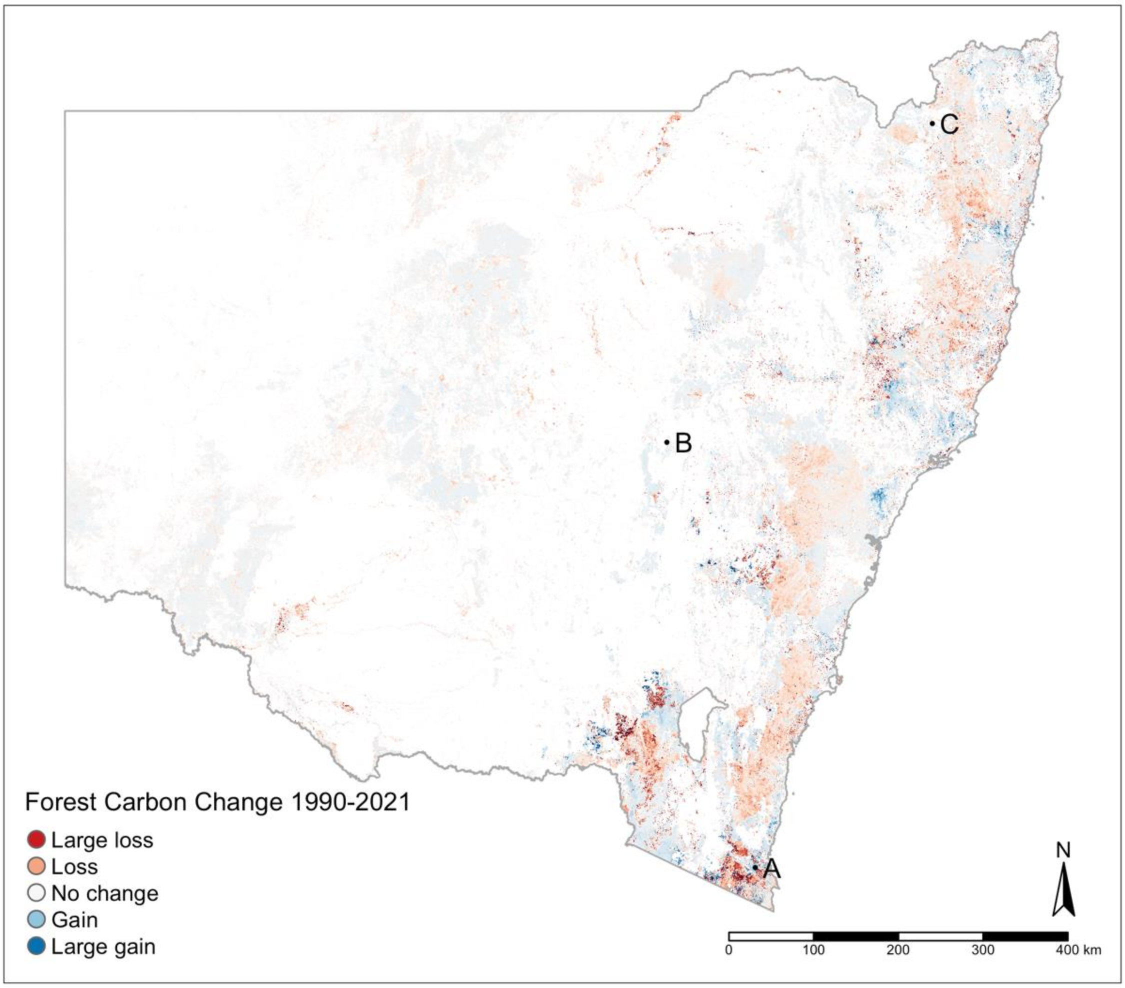


Figure 16 – Spatial output indicating the areas where forest carbon has increased (blue) and decreased (red) across NSW between 1990 and 2021. Developed with the 'Mid' forest growth rate where G=10. A, B and C indicate locations of maps shown in Figure 17.

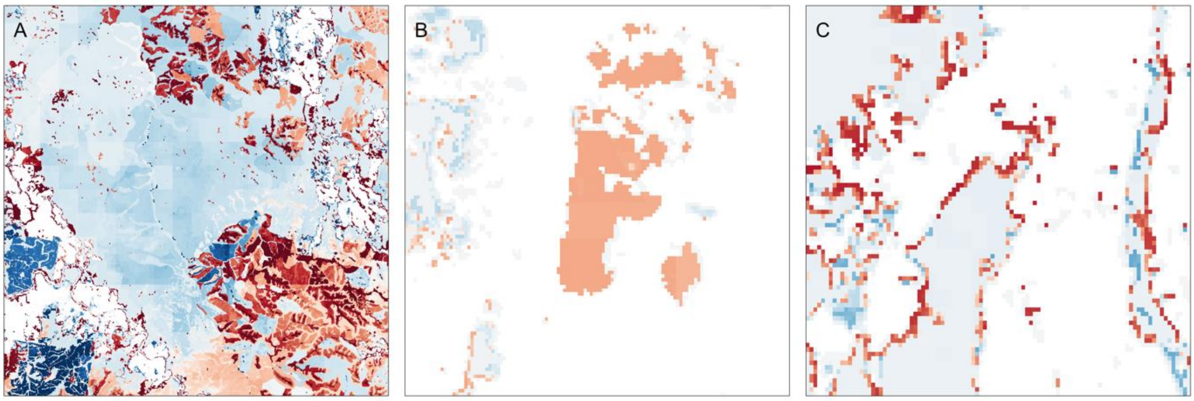


Figure 17 – Zoomed in areas of forest carbon change, showing A. natural change and forestry operations (excluding the harvested wood products pool), B. agricultural clearing and C. edge effects (gains and losses). Locations indicated on Figure 16.

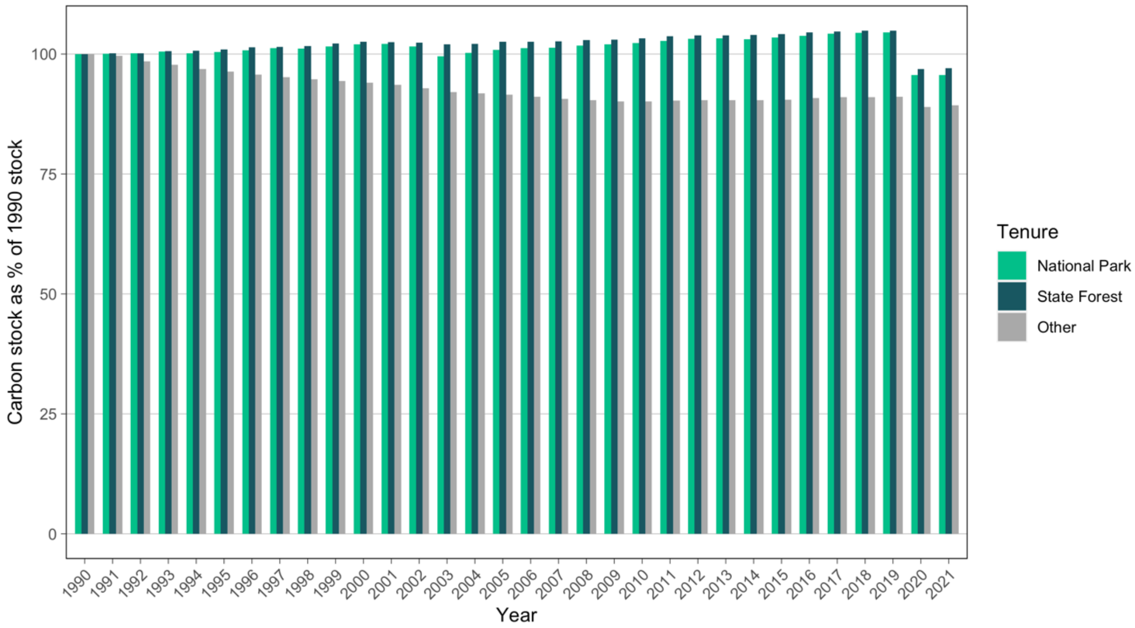


Figure 18 - Annual Carbon Stock of native forests relative to the 1990 carbon stock for the different Land Tenures. The graph indicates the temporal variation in carbon stock between land tenures. The cause of this variation was not analysed as part of this assessment. Estimates are based on current land tenure extent. Other forests refer to forests not within State Forests or National Parks. Developed with the 'Mid' forest growth rate where G=10.

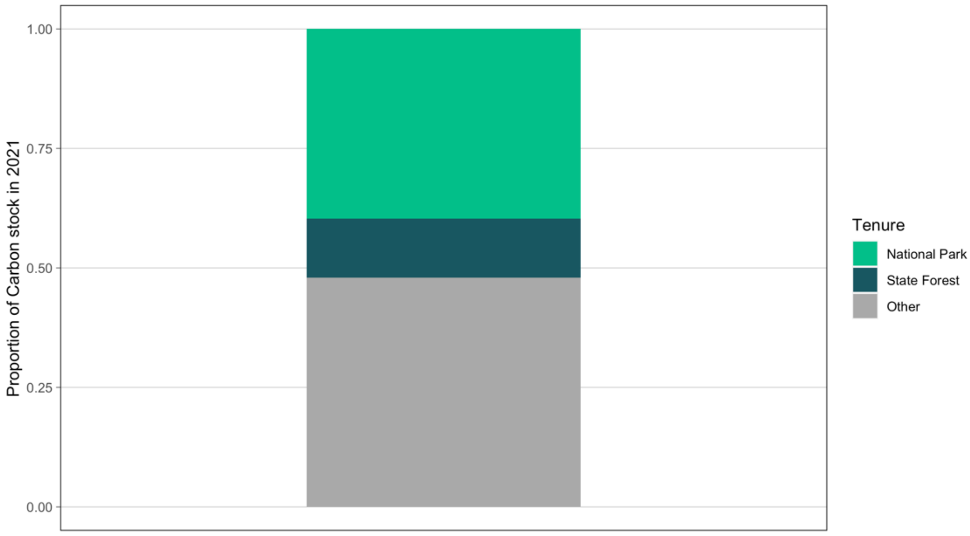


Figure 19 – Proportion of Forest Carbon Stock in 2021 in non-plantation forests by land tenure. Developed with the 'Mid' forest growth rate where G=10.

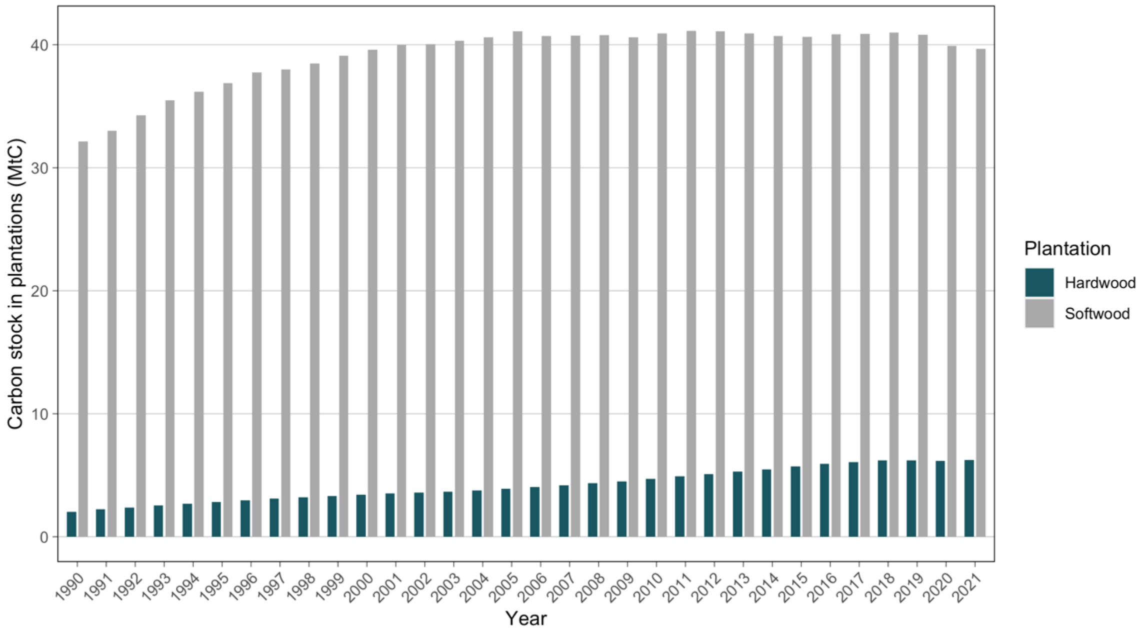


Figure 20 – Carbon stock estimates within the plantation estate. Note that Forestry Corporation (FCNSW) data was used for plantations under FCNSW management, and the national 2016 plantation extent was used for private plantations. Also note that any forest area within plantation extent is modelled as a plantation from the start of the simulation.

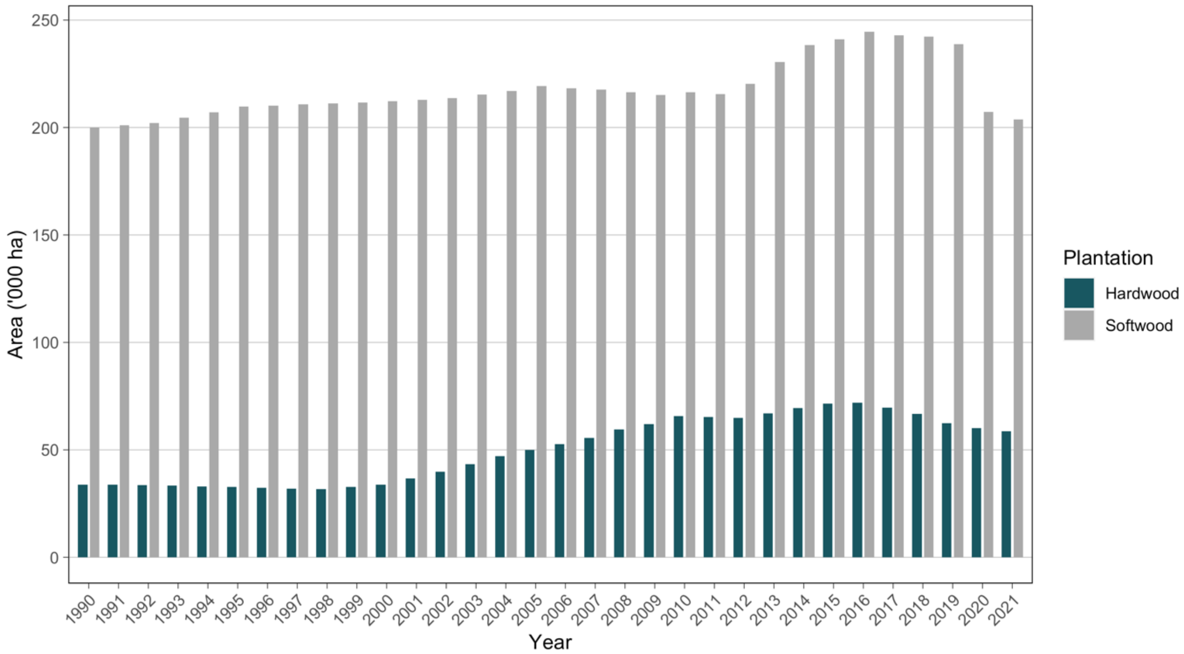


Figure 21 – Area of plantation forest ('000 ha) over time. Note that this assumes a static plantation extent and represents gains in forest cover within that extent.

5. Drivers of Change

With the exception of the 2003 and 2019-20 fire seasons, the majority of changes in forest carbon stock across NSW were driven by forest cover losses and gains. Outside of known fire and harvest areas, losses are assigned as 'clearing' events (Figure 22). A 'clearing' event is defined as a forest cover loss event that was detected in the remote sensing product that was not associated with timber harvesting activities or fire. This will include natural (e.g., drought) and human induced changes, as well as any remote sensing omission and commission errors. The majority of these clearing events are not mapped in the Statewide Landcover and Trees Study (SLATS) data (Figure 23 – areas not in SLATS are in the 'Other' category). A proportion of these areas are likely driven by pixels moving back and forth between classes in the national forest cover data from one year to the next due to changes in rainfall or edge effects. Therefore, many are likely not complete clearing events, but may represent a contraction of the canopy cover (but not necessarily tree loss). This is demonstrated in Figure 24. While Figure 23 shows clearing events categorised by SLATS data, Figure 24 shows clearing categorised by whether or not the area in question contains woody vegetation across the entire time series. Almost half of the carbon fluxes marked as 'clearing' occur in areas that are mapped as having woody vegetation for the entire time series – that is, the pixels have moved from 'forest' to 'sparse woody' in the national forest cover data, not from 'forest' to 'non-forest' (Figure 24). Note also that fluxes do not equal emissions, rather they are movements from one pool to another – e.g., aboveground biomass to dead organic matter.

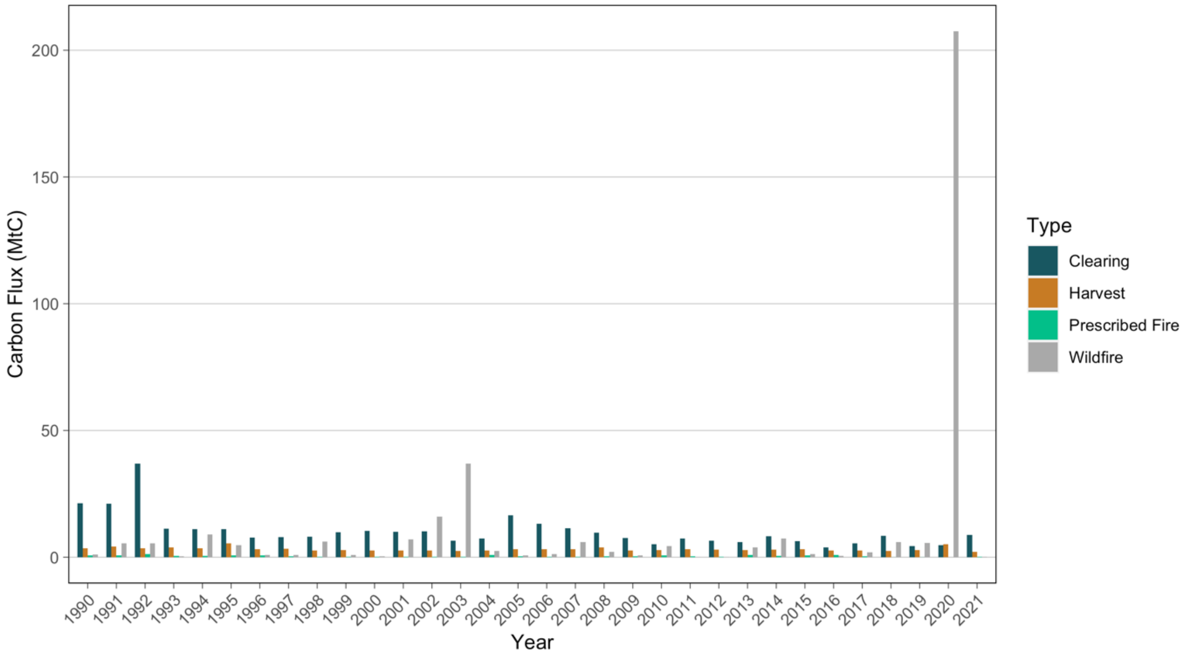


Figure 22 – Carbon Fluxes (movements) split into categories of clearing, harvesting, wildfire and prescribed fire. Forest clearing or harvesting result in movements of carbon from Forest Aboveground Biomass and Forest Belowground Biomass to the Dead Organic Matter Pool or Harvested Wood Products Pools. Fire results in movements from Aboveground Biomass and Dead Organic Matter to the Atmosphere and Dead Organic Matter pools. The presented fluxes do not represent net emissions to the atmosphere.

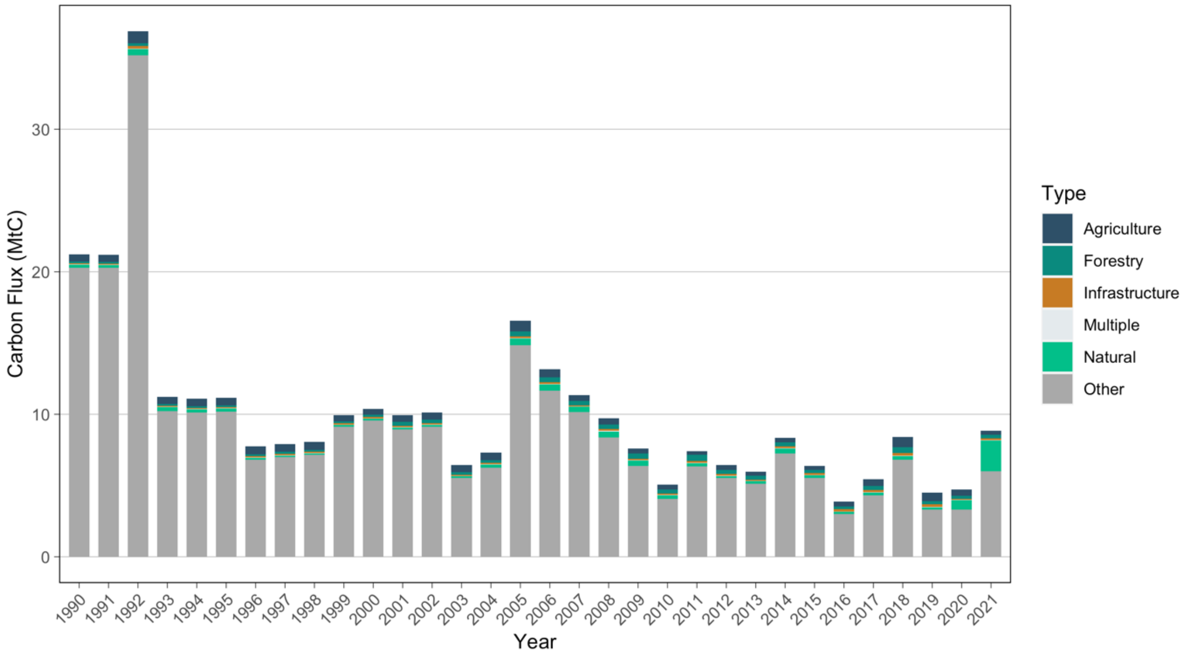


Figure 23 – Carbon fluxes due to clearing only, broken into classes based on NSW SLATS data. The 'Other' category includes clearing events from the national forest data that do not appear in the SLATS data. Forest clearing results in movements of carbon from Forest Aboveground Biomass and Forest Belowground Biomass to the Dead Organic Matter Pool.

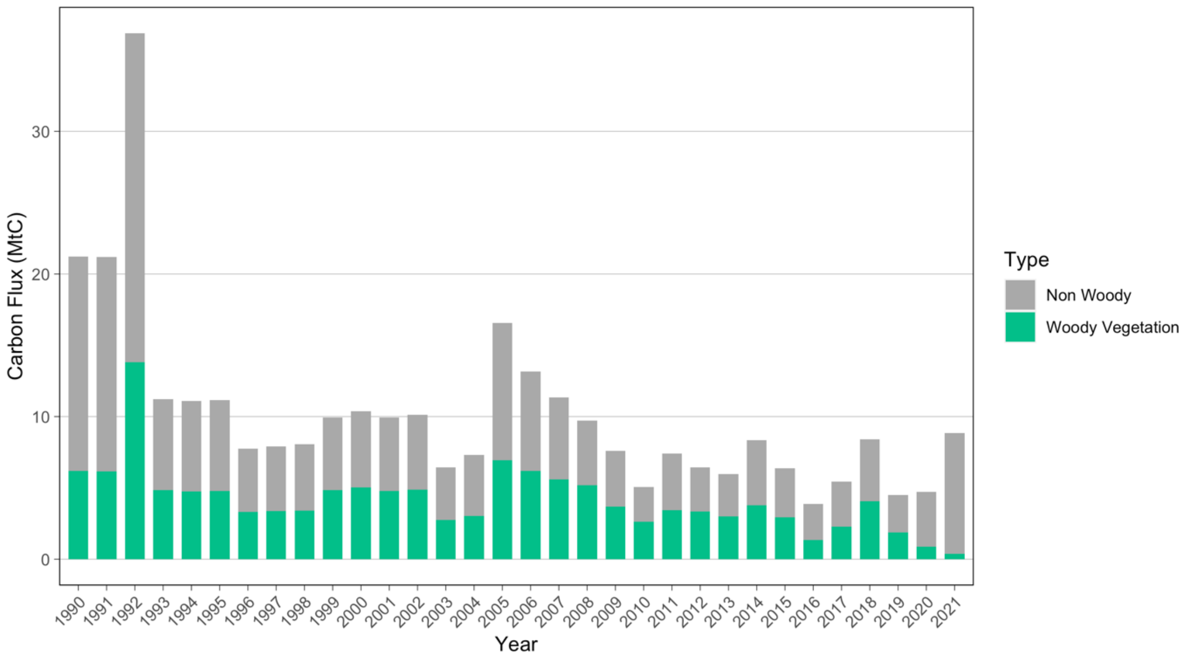
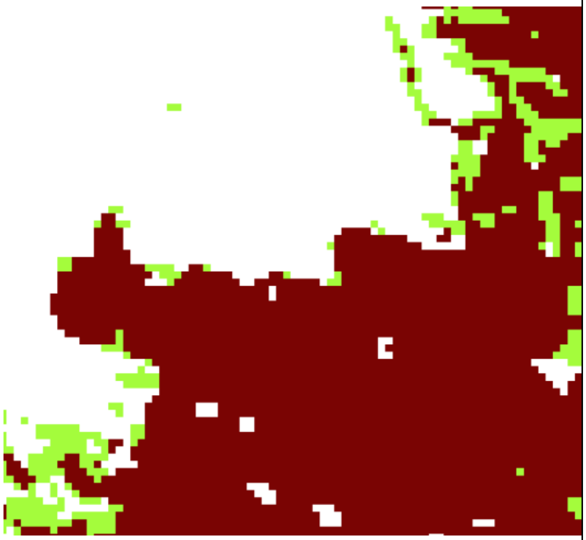


Figure 24 – Carbon fluxes due to clearing, broken into classes based on whether the national forest data indicates woody vegetation through the entire time series or not. Where a pixel was always woody for the entire time series ('Woody Vegetation'), it indicates the change was between 'forest' and 'sparse woody' categories, and not a complete loss event. In comparison, where the pixel was non woody at some point in the simulation ('Non Woody'), it is more likely there was full forest cover loss. Sparse woody vegetation was excluded from the simulation (other than as this filter), in that is assumed to have no carbon content. Forest clearing results in movements of carbon from Forest Aboveground Biomass and Forest Belowground Biomass to the Dead Organic Matter Pool.

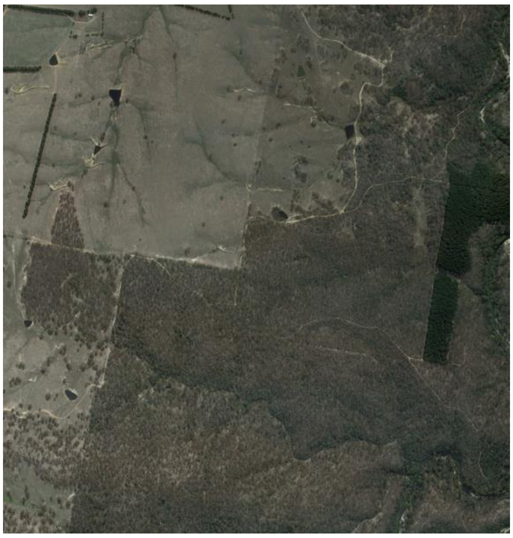
6. Identified Forest Cover Issues

From 2010 onwards there has been a marked increase in forest cover within NSW. This may be an anomaly in the national forest cover data more so than a landscape level change for some areas of NSW. The images below (Figure 25) compare a more temperate rainfall zone with an area which has been identified as a carbon project in an arid zone of NSW. The images show strong alignment in the changes in forest cover for the temperate zone, but less so for the arid areas. Within the arid area, while there does not appear to be a discernible change in woody vegetation between 2004 and 2020 (outside of the river corridor) in the Google Earth imagery, the national forest cover product has nearly all of the scene as 'forest' in 2020. It is hypothesised that the green flush following heavy rainfall in 2012 resulted in misclassification of vegetation, which has then persisted through the land cover product. It is not believed to be a state-wide issue, but rather a more localised occurrence in some of the arid areas of NSW. It is recommended that a further review of the land cover product within arid areas of Australia be undertaken. The issues are expected to lead to an over-estimation of carbon fluxes from forests, however at a whole-of-state scale these extra fluxes are likely negligible; a broader assessment would be required to confirm this.

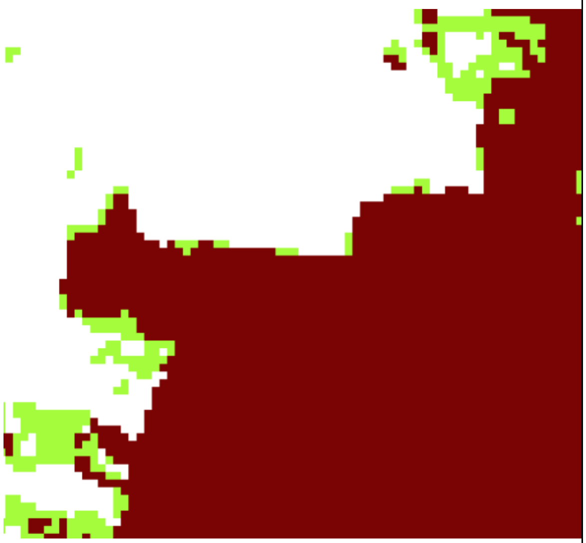
Temperate Year: 2002 Source: Google Earth



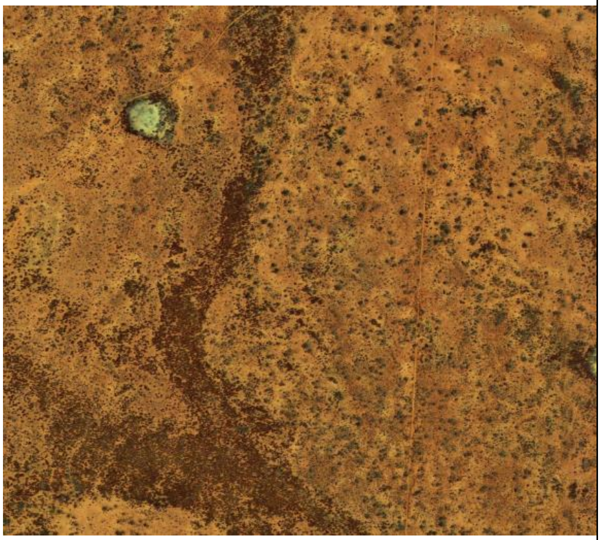
Temperate Year: 2002 Source: National Sparse Woody and Forest Cover



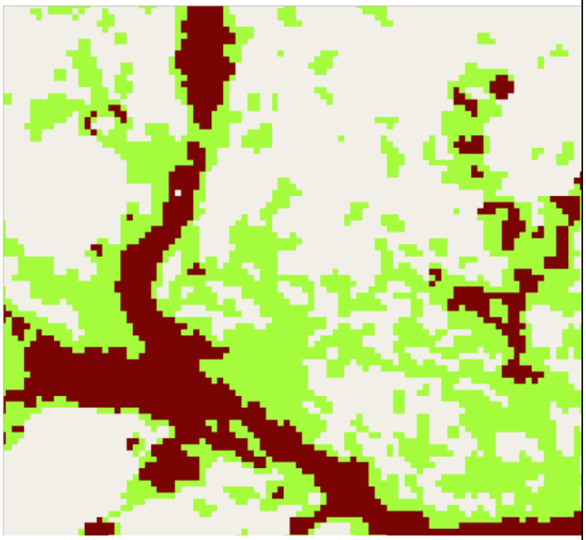
Temperate Year: 2019 Source: Google Earth



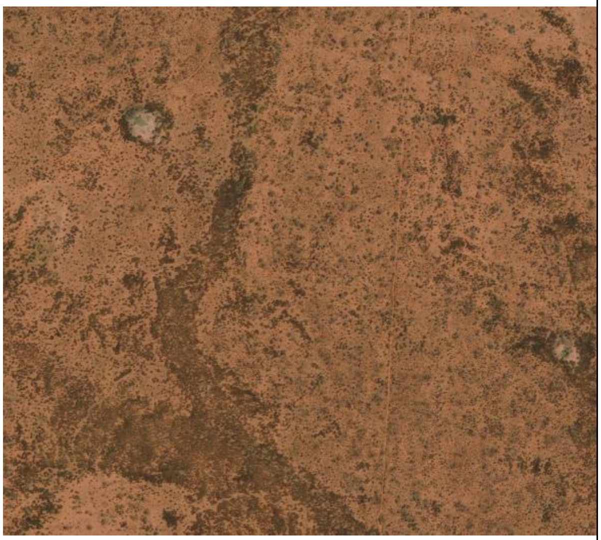
Temperate Year: 2019 Source: National Sparse Woody and Forest Cover



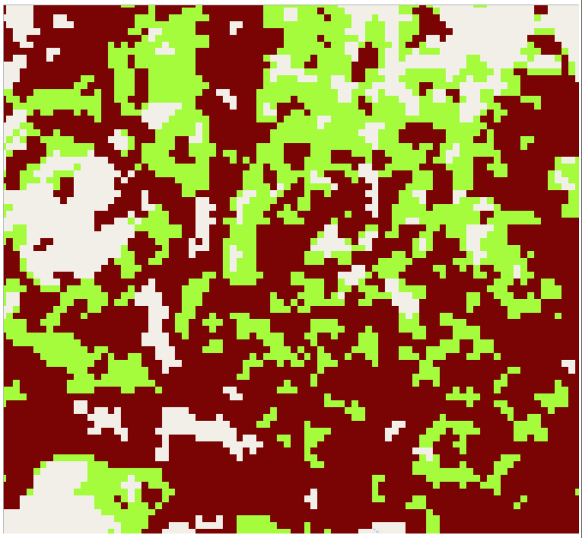
Arid Year: 2004 Source: Google Earth



Arid Year: 2004 Source: National Sparse Woody and Forest Cover



Arid Year: 2020 Source: Google Earth



Arid Year: 2020 Source: National Sparse Woody and Forest Cover

Figure 25 - High resolution imagery from Google Earth (left image) and the National Forest (brown) and Sparse Woody Vegetation (green) (right image) for temperate zones (top) and arid zones (bottom) at various time steps between 2002 and 2020.

Forest Cover Assumptions and Improvements

Consistent with the Original Approach

- Clearing and regrowth events are trigged by forest loss and gain events in the National Forest and Sparse Woody Vegetation data.

Improvements Applied

- 1988 was not used as this layer is considered unreliable. An extra year in the series (2021) was added.

Potential Future Improvements

- Conduct a comprehensive accuracy assessment of the forest/non-forest product for NSW forests.
- Develop alternative ways to manage the data

7. Uncertainty

The majority of the methods and data used in the project are reliant on data used in the NGGI, with the associated uncertainties within that account carried through into the output of this study. The NGGI reports uncertainty by reporting categories, with the most relevant for this study being forest land remaining forest land, land converted to forest land, and forest land converted to cropland, or grassland. Consistent with the original assessment, the NGGI reports that the uncertainty of activity data (forest cover product) is not published, but the uncertainty associated with forest land remaining forest land is assumed to be +/- 15 per cent, while the uncertainty associated with the emission factors values were assumed to be +/- 30 per cent (DCCEEW 2020). This relates largely to the modelling of State forests. For forest land converted to grassland or cropland, or land converted into forest land, the uncertainty is reported to be +/- 3.5 per cent, with uncertainty on standing biomass of +/- 11.5 per cent (DCCEEW 2020). While National Parks are not generally included within the NGGI (unless they were formerly harvested lands), it is assumed that the uncertainties within this assessment will be comparable with those of the NGGI. The uncertainties associated with the FESM fire data, harvest data, plantation extent, and plantation types were not available for inclusion in this discussion.

While these uncertainties reflect the uncertainties with specific input parameters, testing the results against empirical measurements is beyond the scope of this project. In this context, it is recommended that a sensitivity assessment be completed to determine the implications of the modelling assumptions, in particular the initial condition assumptions. It is also recommended to compare the modelled outputs with measured data to assess accuracy of the output.

8. Conclusion

Through this project we updated the estimate of the forest carbon balance for NSW Forests from 1990 to 2021. The results are largely consistent with the original assessment, finding that the carbon stock within the NSW forests is far from static, and subject to change due to natural and anthropogenic activities. The results also indicate that the temporal trends and spatial patterns in forest carbon change differ across the State. The assessment also provides new insights into the drivers of change within forests in NSW and highlights areas for future focus.

The main differences from the original assessment include:

- An additional year (2021) in the time series
- The inclusion of more accurate datasets for plantations
- Updated parameters from the latest National Inventory Report
- Additional filters to query the data, including separating harvest, clearing, wildfires and prescribed fires and using SLATS data for more in-depth exploration of clearing types.

Consistent with the original assessment, the largest changes in the forest carbon stock occur in forested areas outside of State Forests and the NSW Reserve system. This reinforces the recommendation that forested areas on other crown land, private land and indigenous management areas be prioritised for data improvements, in particular in the more arid areas of NSW (<400mm rainfall).

Through the expanded use of data, this assessment highlights the difficulties that are created by having a binary forest/non forest classification, rather than modelling transitions between sparse woody vegetation and forest. In this sense, the project demonstrates not only the importance of having a comprehensive forest monitoring system to provide insights into the system, but the need for this to be expanded to a full lands monitoring program.

Finally, the assessment, which was delivered at ¼ of the cost and time of the original assessment, highlights the value in having an operational system that allows for continuous improvement of input data for more refined results.

9. References

ABARES (2016) Australia's plantations 2016 dataset, Australian Bureau of Agricultural and Resource Economics and Sciences – (ABARES), Accessed from https://www.agriculture.gov.au/

Brack C., Richards G., and Waterworth R., (2006) Integrated and comprehensive emissions estimation for Greenhouse Gases. Sustainability Science, 1, 91 - 106.

Brack C., McElhinny, C., Waterworth, R., Roberts, S., (2011) Multi-scale Forest Inventory and Modelling for Multi-purpose Management, Journal of Forest Planning, 16, 133-139

Cleary P. W., Thomas D., Hetherton L., Bolger M., Hilton J. E. & Watkins D. (2020) Workspace: A workflow platform for supporting development and deployment of modelling and simulation. Mathematics and Computers in Simulation 175, 25-61.

De Kauwe, MG, Medlyn, BE, Ukkola, AM, et al. (2020) Identifying areas at risk of drought-induced tree mortality across South-Eastern Australia. Global Change Biology, 26: 5716– 5733

DCCEEW (2022) National Inventory Report 2020, Australian Government Department of Climate Change, Energy, the Environment and Water.

DCCEEW (2021) FullCAM Guidelines, http://www.fullcam.com/. Accessed December 2021

DCCEEW (2020) National Inventory Report 2018, Australian Government Department of Climate Change, Energy, the Environment and Water.

DCCEEW (2020b), The Department of Climate Change, Energy, the Environment and Water, FullCAM Guidelines: Requirements for using the Full Carbon Accounting Model (FullCAM) in the Emissions Reduction Fund (ERF) methodology determination Carbon Credits Carbon Credits (Carbon Farming Initiative— Plantation Forestry) Determination 2017".

Downham, R, Gavran, M., (2020) Australian plantation statistics 2020 update, Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)

Fairman, T., (2021) Personal Communication, email, 8 November 2021

Farrell, S., (2021) Forest Extent Condition and Health – Monitoring Program, Spatial Vision Innovations, developed for the NSW Natural Resource Commission.

Furby, S., (2021) Personal Communication, email, 15 December 2021

Kesteven, J.L., Landsberg, J. and URS Australia 2004. Developing a National Forest Productivity Model: National Carbon Accounting System, Technical Report No.23. Department of Climate Change, Australian Government, Canberra.

Landsberg, J.J. and Waring, R.H. (1997) A Generalised Model of Forest Productivity Using Simplified Concepts of Radiation-Use Efficiency, Carbon Balance and Partitioning. Forest Ecology and Management, 95, 209-228.

Paul, K.I., Roxburgh, S.H., England, J.R., de Ligt, R., Larmour, J.S., Brooksbank, K., Murphy, S., Ritson, P., Hobbs, T., Lewis, T., Preece, N.D., Cunningham, S.C., Read, Z., Clifford, D., Raison, R.J. (2015a). Improved models for estimating temporal changes in carbon sequestration in above-ground biomass of mixed-species environmental plantings. Forest Ecology and Management, 338, 208-218.

Paul, K.I., Roxburgh, S.H., de Ligt, R., Ritson, P. Brooksbank, K., Peck, A., Wildy, D.T., Mendham, D., Bennett, R., Bartle, J., Larmour, J.S., Raison, R.J., England, J.R., Clifford, D. (2015b). Estimating temporal changes in carbon sequestration in plantings of mallee eucalypts: Modelling improvements. Forest Ecology and Management, 335, 166-175.

Paul, K., Roxburgh, P., (2020), Predicting carbon sequestration of woody biomass following land restoration, Forest Ecology and Management, 460, 117838

Paul, K., Roxburgh, S.H., England, J.R (2022) Sequestration of carbon in commercial plantations and farm forestry, Trees, Forests and People Volume 9, September 2022

Richards, G. (2001) The FullCAM Carbon Accounting Model: Development, Calibration and Implementation for the National Carbon Accounting System, Technical Report 28 of National Carbon Accounting System, Australian Greenhouse Office

Richards, G., Brack, C. (2004). A continental biomass stock and stock change estimation approach for Australia. Australian Forestry, 67, 284-288.

Richards G., Evans D., (2004) Development of a carbon accounting model (FullCAM Vers. 1.0) for the Australian continent. Australian Forestry, 67 (4), 277-283.

Roxburgh S., Davies I., (2006) COINS: an integrative modelling shell for carbon accounting and general ecological analysis. Environmental Modelling & Software 21, 359-74.

Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology Report*, NSW Natural Resources Commission

Richards, G., Borough, C., Evans, D., Reddin, A., Ximenes, X., Gardner, D. (2007) Developing a carbon stocks and flows model for Australia wood products. Australian Forestry 70:2, 108-117

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K. and Venevsky, S. (2003), Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology, 9: 161-185.

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., and Zaehle, S., (2014) Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences Discuss, 11, 2027-2054.

Snowdon, P., (2002) Modeling Type 1 and Type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. Forest Ecology and Management 163, 229-244.

Wardlaw, T., (2021) The effect of climate change on the health and productivity of Australia's temperate eucalypt forests. Australian Forestry, 84:4, 167-170.

Waterworth R., Richards G., Brack C., and Evans D,. (2007) A generalised hybrid process empirical model for predicting plantation forest growth. Forest Ecology and Management, 238, 231-243.

Ximenes, F. D. A., George, B. H., Cowie, A., Williams, J., & Kelly, G. (2012). Greenhouse gas balance of native forests in New South Wales, Australia. Forests, 3(3), 653-683.

10. Annex 1 – Fire parameters

Table 5 - Fraction of carbon in living tree pools that was moved to the atmosphere or dead organic matter in response to prescribed fire or wildfire events, as applied between 1950 and 2017.

Fire Type		**Fraction of Named Pool to Atmosphere**				**Fraction of Named Pool to Dead Organic Matter**			
	Patchiness	Stem	Branch	Bark	Leaf	Stem	Branch	Bark	Leaf
Prescribed Fire	0.65	4.5%	4.5%	4.5%	2.5%	0.5%	0.5%	0.5%	0.5%
Wildfire	0.8	9.0%	9.0%	9.0%	5.0%	1.0%	1.0%	1.0%	5.0%

Table 6 - Fraction of carbon in living tree pools that was moved to the atmosphere or dead organic matter in response to prescribed fire or wildfire events, as applied between 2017 and 2021, based on FESM fire severity classes.

Fire Severity Class		**Fraction of Named Pool to Atmosphere**				**Fraction of Named Pool to Dead Organic Matter**			
	Patchiness	Stem	Branch	Bark	Leaf	Stem	Branch	Bark	Leaf
Low	0.65	5%	9%	9%	5%	1%	1%	1%	5%
Moderate	0.8	5%	9%	15%	30%	1%	30%	1%	50%
High	1	5%	9%	15%	50%	15%	65%	1%	50%
Extreme	1	5%	9%	20%	90%	15%	65%	1%	10%

11. Annex 2 – Data Requirements

The following data was used for the development of the carbon balance of NSW forests.

Dataset Name	Type	Description
NRC 2023 Update V1.5_FullCAM_NF2020_P2022.sqlite	SQLite Database (.sqlite)	Classification: Database Dataset Name: NRC 2023 Update V1.5_FullCAM_NF2020_P2022.sqlite ID: b6114c1bb3c547e49aeb1b672e90a04f Data Type: SQLite Database (.sqlite) The sqlite database was created by the Mullion Group.
NSW State Boundary	Vector - Geojson (.geojson)	Classification: Administrative Boundary (Level 3) Dataset Name: NSW State Boundary ID: 11829773ca784b06955afe427c78de4a Data Type: Vector - Geojson (.geojson) Incorporates or developed using Administrative Boundaries © Geoscape Australia licensed by the Commonwealth of Australia under Creative Commons Attribution 4.0 International licence (CC BY 4.0). Accessed at: https://www.data.gov.au/dataset/ds-dga-a1b278b1-59ef-4dea-8468-50eb09967f18/details?q=NSW%20State%20Boundary
MVG 5.1 (incl. ACT) non-forest types filled with nearest pixel	Raster - GeoTiff (.tif)	Classification: Ecological Zone Dataset Name: MVG 5.1 (incl. ACT) non-forest types filled with nearest pixel ID: 65cc7f9dd4c7423a8c7bfeb5dcc5d999 Data Type: Raster - GeoTiff (.tif) National Vegetation Information System V 5.1 © Australian Government Department of Agriculture, Water and the Environment. CC - Attribution (CC BY). Accessed at: https://www.data.gov.au/dataset/ds-environment-7c6ba95a-4554-4fed-aa53-4d6c040c0810/details?q=MVG

NSW Fire History - 1902-2021 (Combined Wildfire and FESM)	Raster Time-Series - GeoTiff (.tif)	Classification: Annual Fire Dataset Name: NSW Fire History - 1902-2021 (Combined Wildfire and FESM) ID: c744b89a0b0e4274b2da056d4db80fb0 Data Type: Raster Time-Series - GeoTiff (.tif) Combined datasets of fire extent from RFS and Forestry Corporation converted to tif raster format integrated with the Fire Severity and Extent Study (FESM) data. Creative Commons Attribution 4.0. Department of Planning, Industry and Environment asserts the right to be attributed as author of the original material in the following manner: "© State Government of NSW and Department of Planning, Industry and Environment 2010". Accessed at: Acquired
Combined_NSW_Plantation_Extent_1935	Raster Time-Series - GeoTiff (.tif)	Classification: Plantation Extent Dataset Name: Combined_NSW_Plantation_Extent_1935 ID: d6e66869c4b0404d86ca4640689217eb Data Type: Raster Time-Series - GeoTiff (.tif) This dataset is a rasterised adaptation of the product created by ABARES under the auspices of the National Plantation Inventory (NPI). The NPI has surveyed public and private plantation growers and managers to collect data on plantations established primarily for wood production in Australia since 1993. Creative Commons Attribution 4.0. The ABARES data was integrated with Forestry Corporation of NSW plantation data. ABARES data accessed at: https://www.data.gov.au/dataset/ds-dga-61351472-9ab5-45e4-a90b-3bf18ce51caf/details?q=2016%20plantation
Australian Forest Cover Data 1989-2021 (Version 6.0 – 2021 Release)	Raster Time-Series - GeoTiff (.tif)	Classification: Forest/Non-Forest Cover Dataset Name: Australian Forest Cover Data 1989-2021 (Version 6.0 – 2021 Release) ID: 94fb38051d834c3290abe068626c3525 Data Type: Raster Time-Series - GeoTiff (.tif) Transformed from the National Forest and Sparse Woody Vegetation Data (Version 6.0 - 2021 Release) - Landsat satellite imagery is used to derive woody vegetation extent products that discriminate between forest, sparse woody and non-woody land cover across a time series from 1988 to 2021. A forest is defined as woody vegetation with a minimum 20 per cent canopy cover, at least

		2 metres high and a minimum area of 0.2 hectares. Sparse woody is defined as woody vegetation with a canopy cover between 5-19 per cent. Collapsed to Forest/Non-Forest and converted to WGS84. Accessed at: https://data.gov.au/dataset/ds-dga-b0d6b762-fe24-4873-91bd-ae0a8bbb452e
Average Forest Productivity Index (V2.0 - 2019)	Raster - GeoTiff (.tif)	Classification: Forest Productivity Index (Long Term Average) Dataset Name: Average Forest Productivity Index (V2.0 - 2019) ID:82484315eb1346818f25c8d7178750b0 Data Type: Raster - GeoTiff (.tif) Creative Commons Attribution Share Alike 4.0 International Accessed at: https://www.data.gov.au/dataset/ds-dga-b46c29a4-cc80-4bde-b538-51013dea4dcb/distribution/dist-dga-1e3af98e-967a-4908-882f-2d217b0d0e5a/details?q=FPI
ERF Potential Forest Aboveground Biomass (V2.0 - 2019)	Raster - GeoTiff (.tif)	Classification: Potential Forest Aboveground Biomass Dataset Name: ERF Potential Forest Aboveground Biomass (V2.0 - 2019) ID:c60d8123282b48958950bd5dda64ee81 Data Type: Raster - GeoTiff (.tif) Creative Commons Attribution Share Alike 4.0 International Accessed at: https://www.data.gov.au/dataset/ds-dga-b46c29a4-cc80-4bde-b538-51013dea4dcb/distribution/dist-dga-1e3af98e-967a-4908-882f-2d217b0d0e5a/details?q=FPI
NSW Data - FPI Time-Series	Raster Time-Series - GeoTiff (.tif)	Classification: Forest Productivity Index (Time Series) Dataset Name: NSW Data - FPI Time-Series ID: 0fe591b7a7e743d2b632260ad486f11c Data Type: Raster Time-Series - GeoTiff (.tif) Product acquired from Australian Government Department of Climate Change, Energy, the Environment and Water. Adaptation of dataset included merging tiles. Accessed at: Acquired from DCCEEW

Monthly Rainfall	Raster Time-Series - GeoTiff (.tif)	Classification: Monthly Rainfall Dataset Name: ANUClimate 2.0 rainfall ID: a347dd4e4bb6485b875d40ba4f638f56 Data Type: Raster Time-Series - GeoTiff (.tif) Monthly total rainfall for the Australian continent from 1900 to present, on the ANUClimate 0.01 x 0.01 degree grid. Generated using the ANUClimate 2.0 model developed by the Australian National University (Hutchinson, Kesteven and Xu) and automated in collaboration with the University of Sydney (Marang and Evans). Monthly total rainfall is the total rainfall for each month, as recorded at each of around 3000 stations from 1900 to 1915, and 5000-7000 stations after 1915, as operated by the Australian Bureau of Meteorology. ANUClimate interpolates these monthly values across the Australian terrestrial landmass. The derived grids are useful in understanding the spatial and temporal distribution of evaporation and for modelling monthly soil water balance, plant growth and crop yield. The monthly rainfall is modelled by expressing each value as a normalised anomaly with respect to the 1976-2005 monthly mean rainfall and monthly mean rainfall occurrence, as interpolated by thin plate smoothing spline functions of longitude, latitude and vertically exaggerated elevation. All high quality daily station observations were obtained from the Bureau of Meteorology after a minimum quality control period of six months. The monthly anomalies were interpolated by fitting tri-variate thin plate smoothing spline functions of longitude, latitude and vertically exaggerated elevation using ANUSPLIN Version 4.6, with the degree of data smoothing optimised by minimising the generalised cross validation. Station elevations were obtained from 0.05 degree local averages of grid values from the GEODATA 9 second DEM version 3. ANUSPLIN is the software package that contains the thin plate spline fitting and grid interrogation programs. ANUClimate uses these algorithms to derive the monthly rainfall grids. Automated quality assessment for the period 1970-2020 rejected on average 22 data values with extreme studentised residuals for each monthly analysis (0.4% of the average number of data points). Point-wise cross validated values of the fitted spline surfaces for the period 1970-2020 gave a mean bias of -0.5 mm (1% of the mean), a mean absolute

		predictive error of 10.7 mm (18% of the mean) and a root mean square predictive error of 20.8 mm (36% of the mean). Accessed at: Acquired from DCCEEW
Monthly Air Temperature	Raster Time-Series - GeoTiff (.tif)	Classification: Monthly Air Temperature Dataset Name: ANUClimate 2.0 average temperature ID:3f4157b9204f43cc817c7d4ac6b2c58f Data Type: Raster Time-Series - GeoTiff (.tif) Monthly average temperature for the Australian continent from 1960 to present, on the ANUClimate 0.01 x 0.01 degree grid. Generated using the ANUClimate 2.0 model developed by the Australian National University (Hutchinson, Kesteven and Xu) and automated in collaboration with the University of Sydney (Marang and Evans). Daily average temperature is the average of the minimum air temperature in the 24-hour period preceding 9 am and the maximum air temperature in the 24 hour period following 9 am, as recorded at each of around 300 to 700 stations operated by the Australian Bureau of Meteorology. Monthly average temperature is the mean of these daily average values for each month. ANUClimate interpolates these monthly values across the Australian terrestrial landmass. The derived grids are useful in understanding the spatial and temporal distribution of temperature and for modelling plant growth and crop yield. The monthly average temperature is modelled by expressing each value as a difference anomaly with respect to the average of the 1976-2005 monthly mean minium temperature and the 1976-2005 monthly mean maximum temperature, as interpolated by thin plate smoothing spline functions of longitude, latitude, vertically exaggerated elevation and proximity to the coast. All high quality daily station observations were obtained from the Bureau of Meteorology after a minimum quality control period of six months. The monthly anomalies were interpolated by fitting tri-variate thin plate smoothing spline functions of longitude, latitude and vertically exaggerated elevation using ANUSPLIN Version 4.6, with the degree of data smoothing optimised by minimising the generalised cross validation. Actual station elevations were used for the spline analyses and 0.01 degree local

		averages of grid values from the GEODATA 9 second DEM version 3 were used to support the calculation of the final temperature grids. ANUSPLIN is the software package that contains the thin plate spline fitting and grid interrogation programs. ANUClimate uses these algorithms to derive the monthly average temperature grids. Automated quality assessment for the period 1970-2020 rejected on average 0.7 data values with extreme studentised residuals for each monthly analysis (0.1% of the average number of data points). Point-wise cross validated values of the fitted spline surfaces for the period 1970-2020 gave a mean bias of 0.00 degrees Celsius, a mean absolute predictive error of 0.36 degrees Celsius and a root mean square predictive error of 0.47 degrees Celsius