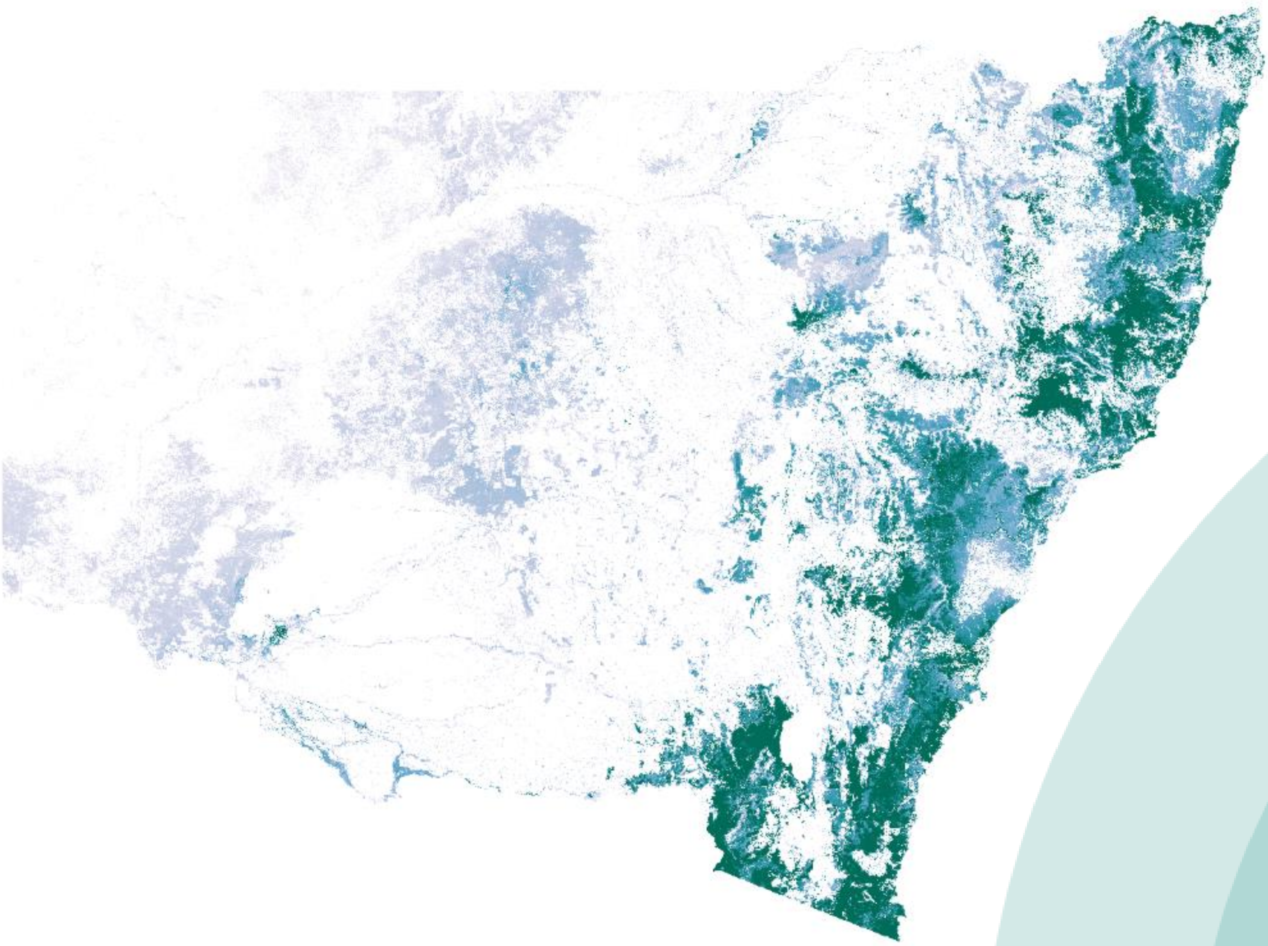
Carbon Balance of NSW Forests – Methodology and Baseline Report

Prepared by the Mullion Group, CSIRO, and NSW Department of Primary Industries



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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
DISER	Department of Industry, Science, Energy and Resources
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
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

RothC	Rothamsted Carbon Model
SOC	Soil Organic Carbon
STGGI	State and Territory Greenhouse Gas Inventories
TYF	Tree Yield Formula
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

The NSW Forest Monitoring and Improvement Program Framework 2019-2024 outlines an ambitious plan to improve the management of NSW forests by providing relevant and timely information for decision makers and the general community. The Program has 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. The Natural Resources Commission commissioned a project to answer one of these State-wide Evaluation Questions: *What is the carbon balance of NSW forests currently and under different scenarios*?

The project team led by the Mullion Group, collaborating with CSIRO and the NSW Department of Primary Industries, developed a comprehensive spatial and temporal analysis of NSW forests from 1990 to 2020. Existing data on forest type and extent, management history, and disturbance history, were analysed using FLINTpro, a spatially explicit integration system. The outcomes of this assessment represent a significant advancement in understanding the trends in forest carbon across NSW. It also highlights deficiencies in data that limit the accuracy of the outputs. Notwithstanding, the results indicate that between 1990 and the end of 2020, there has been a net loss of forest carbon within NSW. Using a 'mid' growth scenario, this loss was estimated as 164 Mt of carbon (excluding soil) (Figure 2). Much of this loss is driven by the 2019/2020 fire season, where the magnitude of change that year is not representative of years in the preceding two decades. The results indicate a general decline in forest carbon in the 1990s, net gains in forest carbon from the mid-2000s to 2019 (Figure 1 & Figure 2), followed by a large loss of forest carbon in 2020 associated with fire events. These trends differ spatially (Figure 1), and are driven by natural disturbances (fire, drought, natural regeneration) and anthropogenic activities (land clearing, reforestation, prescribed fire and timber harvesting).

The results indicate that 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, and that catastrophic events may not be representative of the broader trends. The project demonstrates not only the importance of having a comprehensive forest monitoring system to provide insights into the system, it also highlights the importance of having an operational system for conducting the analysis.

While the output of this project represents a significant advancement in the understanding of the dynamics of forest carbon across NSW, the process also highlights the need to improve data and expanded model coverage. For example, new data sets currently being developed under the NSW Forest Monitoring and Improvement Program, as well as by research organisations independent of the monitoring program, could be utilised. Four priority areas for improvement were identified:

- Attributing change in forest cover to delineate between anthropogenic and natural disturbances;
- Improved initial carbon stock estimates for native and plantation forests;
- Working with the NSW STGGI to implement any new model developments and calibrations arising from collation of datasets on the disturbances (wildfires, prescribed fires, management burns, harvesting regimes, drought-induced die-back) on different categories of NSW's native forests, and
- Sensitivity assessments on model parameters.

As the largest changes in the forest carbon stock occur in forested areas outside of the NSW Reserve system and State Forests, we recommend that forested areas on other crown land, private land and indigenous management areas be prioritised for data improvements.

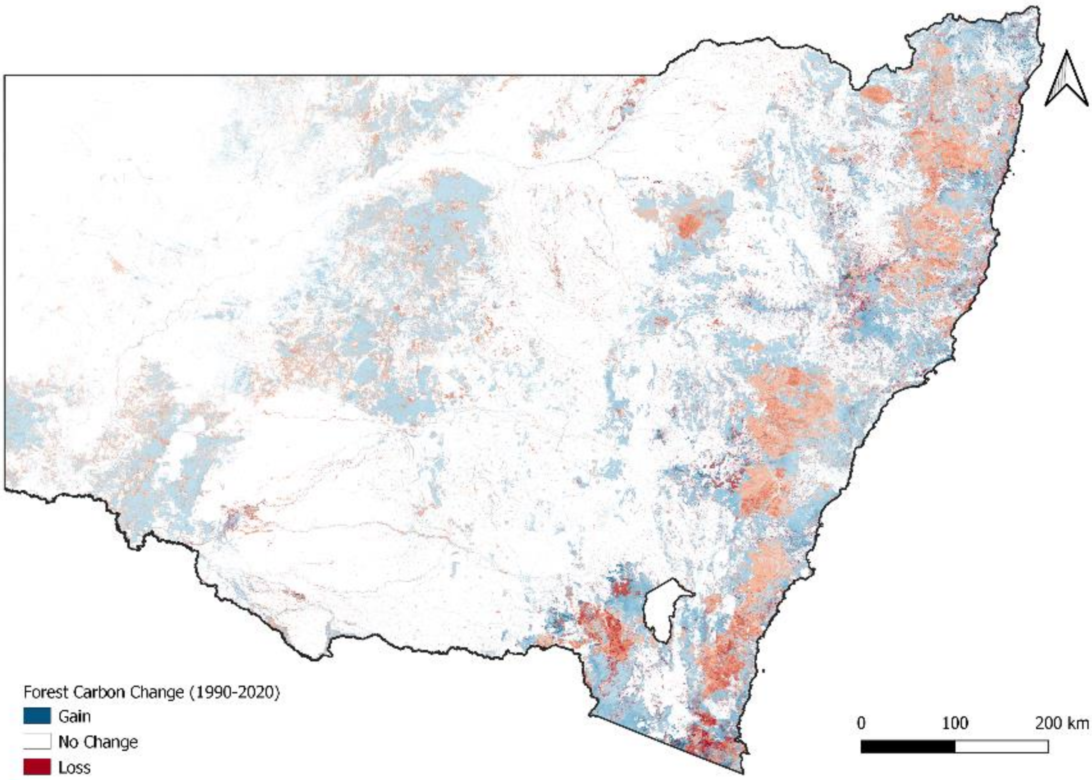

Figure 1 – Spatial Output of change in forest carbon within NSW between 1990 and 2020, including Aboveground Biomass, Belowground Biomass, and Dead Organic Matter. Harvested Wood Products in use is not included in the spatial aggregation. Soil carbon was excluded from the results. Red indicates there was less forest carbon in 2020 than there was in 1990, and blue indicates there was more carbon in 2020 than there was in 1990.

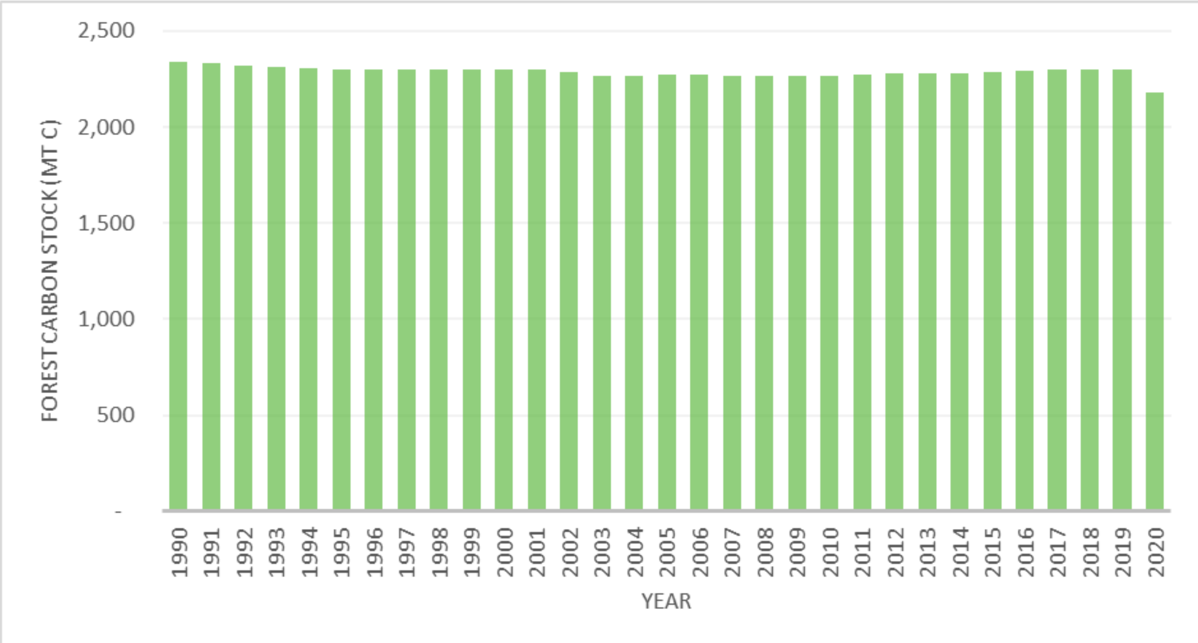

Figure 2- NSW Forest and Harvested Wood Products (HWP) Carbon Stock 1990-2020, including Aboveground Biomass, Belowground Biomass, Dead Organic Matter and Harvested Wood Products in use. Soil Organic Carbon is not included in the outputs.

1. Introduction

This report details the core design and initial results of the Carbon Balance of NSW Forests Project, commissioned by the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program. The NSW Forest Monitoring and Improvement Program Framework 2019-2024 outlines the 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 these State-wide Evaluation Questions was: *What is the carbon balance of NSW forests currently and under different scenarios?* The question focuses on simulating the contribution of NSW forests to regional and global carbon cycles and identifying opportunities to enhance carbon storage in NSW forests.

The Natural Resources Commission engaged the Mullion Group and its partners, CSIRO and NSW Department of Primary Industries to develop an operational system for monitoring carbon stock and stock change across all of NSW forests. An important principle of the carbon assessment was, where possible, to maintain consistency with Australia's National Greenhouse Gas Inventory (NGGI). In this context, the assessment aimed to have general consistency with the methods, assumptions, and data used for the NGGI. To complete the assessment, FLINTpro was used to replicate the fundamental forest growth models within the NGGI. Where possible, the same data and assumptions were also used except where more detailed NSW-specific data were available.

The approach we took for this project was, as far as practical, to model 'what the atmosphere sees', using comparable methods and data as 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. Further, 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 this, there are different land areas and categories between the NGGI and this assessment, making it inappropriate for 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 methods, data sources, and core assumptions that underpin the NSW Forest Carbon Assessment. 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

Carbon is a fundamental element within Earth's systems, and in its various compositions can be found in 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.

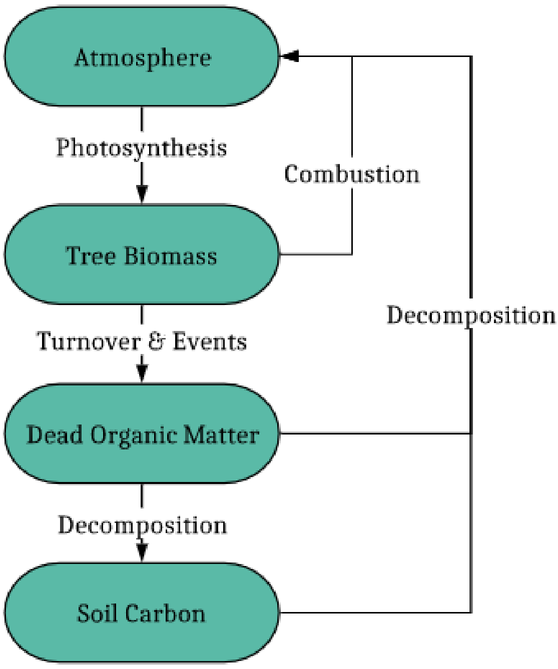

Figure 3– Simplified example of the natural carbon cycle, with the cyclical movement of carbon from the atmosphere into three terrestrial carbon pools, and back to the atmosphere.

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) being 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 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). Soil organic carbon 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 both a natural and 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.

1.2. Spatial Modelling Systems

A spatial modelling approach is where individual units of land (pixels in this case) are tracked through time for change and modelled on a continuous basis. Where change is identified, the carbon implications are quantified. A spatial modelling system is required for carbon accounting in Australia given the vast and climatically diverse areas across the country where pools of carbon (live and dead biomass, debris, soil, and products produced), and GHG emissions from fires, are influenced by the changing activities of land managers.

Australia has been well positioned to develop such spatial systems given its capabilities in data management, including utilisation of national coverage of remotely-sensed vegetation cover data that has been collected since 1972. FullCAM is a spatial modelling system developed by the Australian Government for the purpose of informing international reporting emissions associated with the Land Sector (e.g. Richards and Brack 2004). FullCAM is therefore a key contributor to Australia's NGGI (DISER 2020).

FullCAM was designed specifically for the modelling and reporting to support the NGGI. It is a freely available software system for modelling GHG emissions and changes in carbon stocks associated with land use and management in Australian agricultural and forest systems (Richards, 2001; Richards and Brack, 2004; Richards and Evans, 2004; Brack et al., 2006; Waterworth et al. 2007).

However, FullCAM is not publicly available as a spatial modelling system, with only the stand-alone application for simulation of single locations currently being publicly available.

There are a limited number of alternative spatial modelling systems suitable for representing the carbon balance of Australian ecosystems. They include the Continental Integration Shell (COINS; Roxburgh and Davies 2006), Workspace (Cleary et al. 2020), and FLINTpro (see next section).

The COINS framework is no longer actively supported. Although it would be possible to implement the analyses required for this project within the Workspace environment, Workspace is a generic modelling platform and not optimised for developing dynamic carbon balance models, as it would require significant additional coding to implement both the base model equations, and the graphical interface for visualising and summarising results.

Given the desire in this project for outputs to be consistent with the NGGI, the selected spatial modelling system was FLINTpro - a description of FLINTpro and its application in this project is provided in the next section. Due to its modular construction the core FullCAM equations can be readily incorporated into the FLINTpro model library, with the complexities of spatially-explicit input data and the management of spatial results also handled by FLINTpro functionality. FLINTpro also has the capability, and flexibility, to provide a system on which ongoing reporting of changes in the carbon balance of NSW forests over time can be based.

1.3. FLINTpro

FLINTpro is a cloud hosted software as a service that provides an enterprise solution for monitoring greenhouse gas emissions and removals from the land sector. FLINTpro is built around the Full Lands Integration Tool, or FLINT[1]. The FLINT is an open-source C++ platform that provides tools to integrate multiple data types (including remote sensing) with FLINT-compatible modules to produce spatially-explicit calculations of GHG emissions and other variables.

The FLINT provides a framework for coordinating the interaction of data (e.g. spatial and aspatial data, carbon pools data, variables, fluxes) and modules, and managing the outputs of any computations. This is applied through set generic rules, such as maintaining mass-balance, and specific calculation rules. The calculations are completed by FLINT-compatible modules, which are discrete software packages attached to FLINT that makes calculations (e.g. emissions) or enhances functionality (e.g. data aggregation and reporting). Modules connect with FLINT resources (Pools, Variables, Timing). The combination of specific modules and data types attached to the FLINT is called an 'Implementation'. FLINTpro is one such Implementation, with a range of modules attached and suitable for using the data from the NGGI.

In essence, FLINTpro allows the integration of remote sensing products, such as forest cover, with a variety of models, such as forest growth models, to identify various events within the landscape, such as clearing or reforestation, and subsequent processes, such as growth and decomposition (Figure 4).

[1] https://moja.global/tools-of-moja-global/

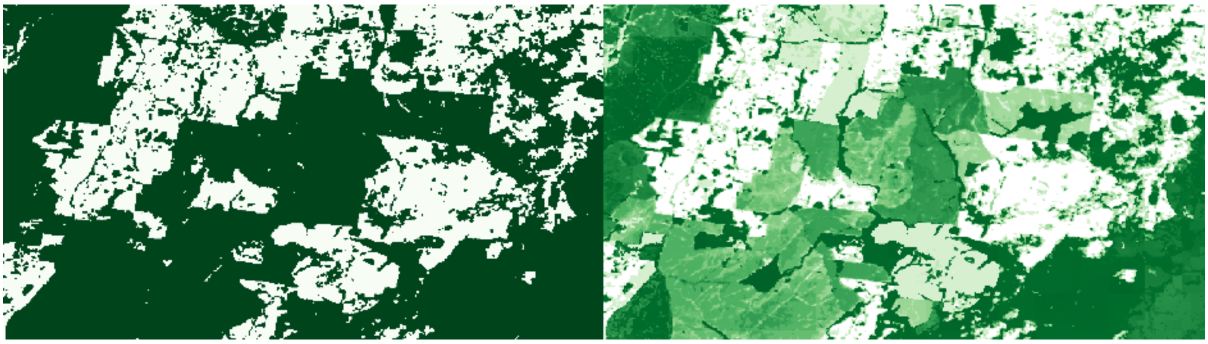

Figure 4 - Through FLINTpro, the land cover products delineating forest extent (left image) are integrated with forest growth models to produce estimates of carbon stock (right image) and stock change

2. Modelling Change

For the Carbon Balance of NSW Forests Project, FLINTpro was used to model the changes in forest carbon for all forests in NSW on all tenures: national parks, state forests, other crown land and private land (Figure 5).

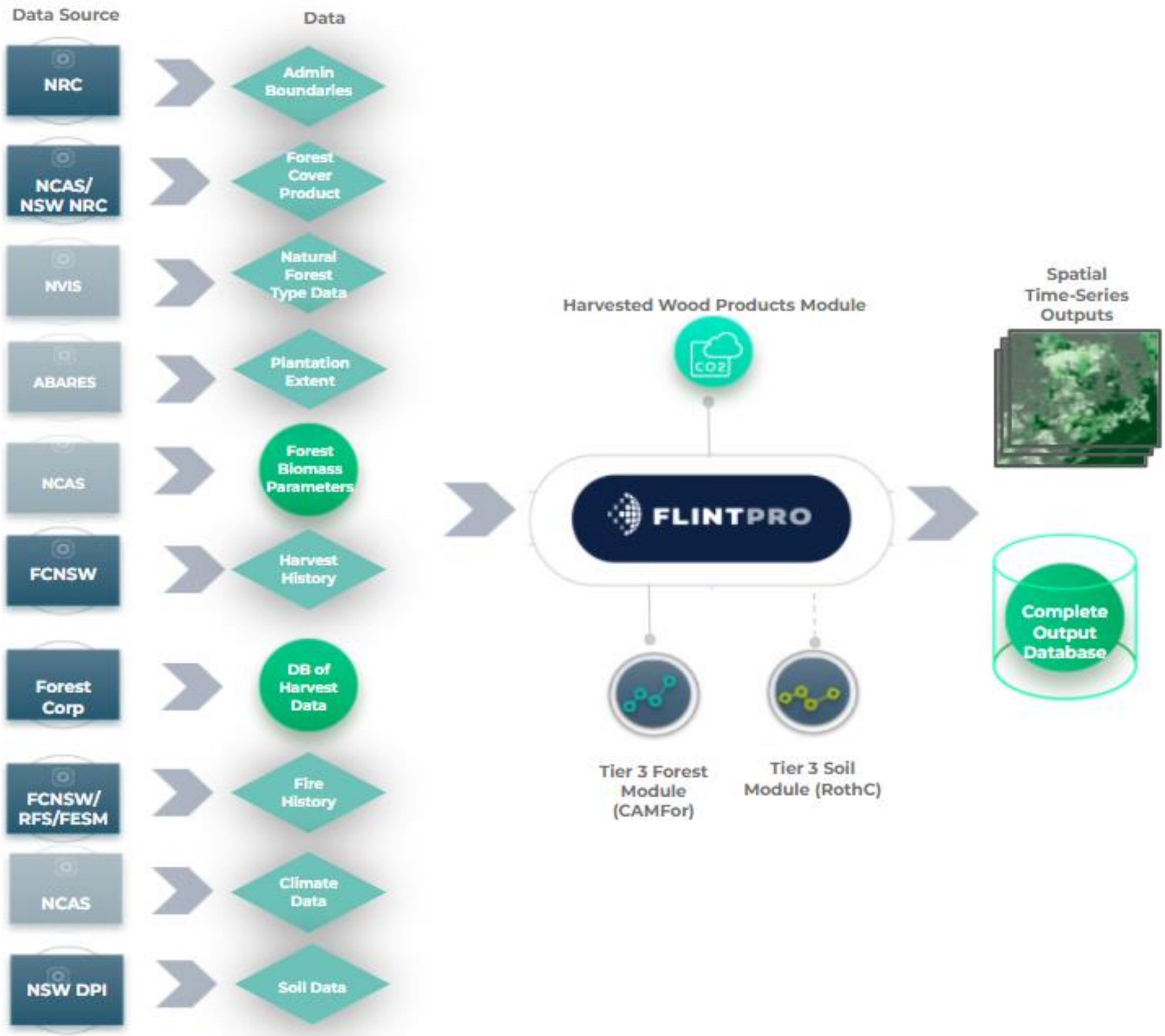

Figure 5 - Conceptual framework for the Carbon balance of NSW forests project

As described above, two main drivers of change were modelled: Processes, such as forest growth; and Events, such as fire and clearing. Each of these are described below.

2.1. Processes

Processes continuously occur on every time-step (month) of a simulation once a condition is met. This includes processes that increase carbon stock in biomass, such as plant growth, as well as processes that decrease carbon stock in biomass, such as decomposition and turnover. When the variable of tree status is set to 'True', for example, tree growth will occur. FLINTpro was configured to model growth, turnover and decomposition as processes.

2.1.1. Forest Growth

Native Forests

Many types of native forests occur in NSW, from dry woodlands in western NSW to tall coastal eucalypt forests and rainforests along the coast and ranges. Growth of each type of forest reflects local climate and soil conditions and historical disturbances such as fire and human intervention. Modelling how these forests grow and respond to changing conditions is complex and requires assumptions based on the best available research and other information sources.

Given the requirement of this project to use methods consistent with the NGGI, FLINTpro was configured to model forests in a manner consistent with FullCAM. FullCAM is applied at the national scale for land sector GHG emissions accounting (DISER 2020), and at the local scale for monitoring and reporting carbon sequestration projects under the Emissions Reduction Fund (ERF), such as revegetation and the management of regrowth (Paul et al. 2015a;b).

In modelling forest biomass, aboveground biomass in trees is initially estimated, after which belowground biomass, dead organic matter, harvested wood products, and soil carbon can be calculated. To estimate the aboveground biomass, FullCAM uses a hybrid of empirical and process-based modelling represented by a Tree Yield Formula (TYF; Equation 1; Waterworth et al. 2007). The process-based modelling component uses the forest growth model 3-PG (Landsberg and Waring 1997) to derive a dimensionless index (the Forest Productivity Index, or FPI) that indicates potential site productivity for any given location and year based on the Normalised Difference Vegetation Index (NDVI), soil fertility, vapour pressure deficit, soil water content, and temperature (Kesteven and Landsberg 2004).

Equation 1 $AGB = M \times r \times [exp(-1/A_2) - exp(-k/A_1)] \times (FPI_t/FPI_{avg})$

Where:

AGB = 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 values of M are provided by a CSIRO developed spatial file, representing the maximum potential biomass of an undisturbed native forest (Figure 6). Whereas the value of k, as calculated from G, is set based on forest type and defined within a database. The G parameter represents the age of maximum growth and is generally constant between native forest types and varies by species and location for plantations. The lower the value of G, the faster the forest grows.

Within FullCAM, there are three key G parameters for native forests, 6.37, 10, and 12.53. These represent the calibrations for Environmental Plantings Block (6.37), Default User Defined Value (10), and Human Induced Regeneration (12.53). Within the NGGI, a G value of 12.53 is applied to all natural forests that are outside of state forests, while a G value of 6.37 is applied to natural forests in state forests (Collett pers comm. April 2021). The effect being that within the NGGI, natural forests in state forests will grow at a faster rate than the adjacent national park.

Through this project, to test the sensitivity of modifying the G parameters, we used each of the mentioned values, where 6.37 is the high growth scenario ('High'), 10 is the mid-growth scenario ('Mid') and 12.53 is the low-growth scenario ('low').

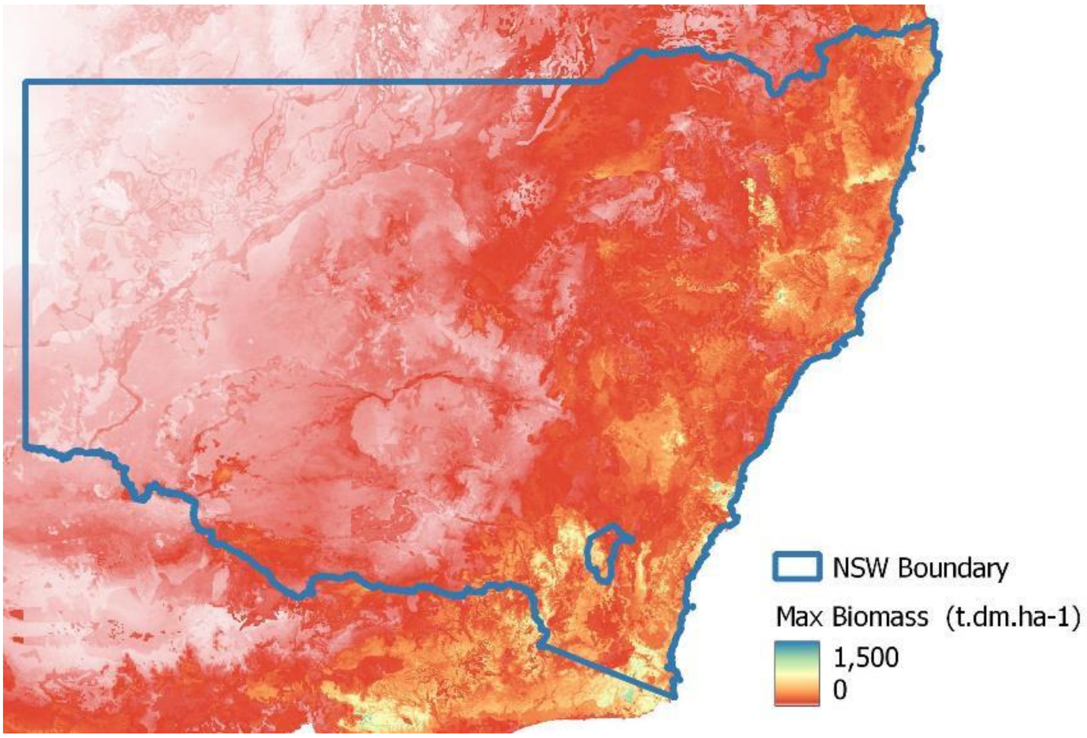

Figure 6 – Maximum Biomass Layer for Australia. The M layer underpins FullCAM growth curves

In addition to M and k, the TYF includes FPI. The FPI incorporates a range of climate variables, and is also provided as a spatial layer, with variables including (Kesteven et al 2004):

- Long-term average climate data
  - Average temperature
  - Number of frost days
  - Radiation
  - Vapour Pressure Deficit
- Monthly climate data
  - Average temperature
  - Maximum temperature
  - Minimum temperature
  - Rainfall

  - Frost days
  - Radiation

Where the annual FPI is lower than the average FPI (for which the model was originally calibrated), the growth increment for that year will be lower. This may offer the opportunity to incorporate future climate scenarios, however it is limited. Moving to a more dynamic or process-based models within FLINTpro would support improved incorporation of the future climate scenarios.

Plantation Forests

Within FullCAM, plantation forests are modelled using the same growth function (Equation 1) as with the native forests, but with specific plantation calibrations (Roxburgh et al. 2019). The G and r parameters vary for the plantation species based on National Plantation Inventory (NPI) reporting area, and species. The plantation calibrations also vary by plantation type (hardwood or softwood) and management regime (long rotation or short rotation). The implementation under this project used growth parameters from the 2020 FullCAM release. Where a plantation species falls within an NPI region but does not have a specific calibration, natural forest calibrations were applied. It is noted, that FullCAM will have major updates in 2022, which should be reflected in any future iterations of the forest carbon assessment for plantation forests. These updates will be incorporated into FLINTpro when available.

From the initial Aboveground biomass calculations, a total of 39 carbon pools are modelled, with carbon movements resulting from processes (growth, turnover, and decomposition) and events (harvesting, clearing and fire).

Alternative models

No alternative forest growth models were considered for incorporation into this assessment given the requirement to align with the NGGI. This approach has the benefit of alignment with the NGGI, but it does limit the ability to incorporate different data types or to fully reflect the impacts of future climate scenarios. Alternative process-based models may be suitable for modelling the implications of future climate scenarios, noting that care will be needed on the extrapolation of these models to landscape level carbon implications. Examples of these models include, but are not limited to:

- 3-PG
- CSIRO Atmosphere Biosphere Land Exchange (CABLE) model
- LPJ-GUESS
- CABALA

Some of these are stand-scale models developed for forestry, such as 3-PG and CABALA (Wardlaw 2021). These are well parameterised for Australian species but may not run at landscape scale and do not simulate potential changes in vegetation type. CABLE is the Australian community land surface model. It forms part of the ACCESS earth system model used for modelling climate but is also used in modelling the carbon budget at continental scale (e.g. Haverd et al. 2018). There is also work currently being developed to simulate tree mortality related to drought (e.g. De Kauwe et al. 2020).

CABLE has the advantage of simulating carbon dynamics at landscape scale and is well-parameterised for Australian vegetation. However, it does not simulate dynamics of vegetation composition over time, which is likely to become important in the next couple of decades. Dynamic vegetation models such as LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) are more suitable for this purpose (Sitch et al. 2001, Smith et al. 2014). However, LPJ-GUESS has not yet been parameterised for Australian vegetation. Work is currently underway at Western Sydney University to develop a dynamic vegetation model that can capture dynamics of Australian vegetation types under global change.

2.1.2. Biomass-based Age Adjustments

The modelling system uses the age of the forest to calculate the annual growth rate, and the nature of the growth curve results in a decline in growth rates after the age of maximum growth until the maximum potential biomass for a site is achieved. When there is a thinning event, where biomass is removed from the site, it is therefore necessary to adjust the growth rates such that a 'functional age' based on biomass rather than the actual age is applied. To achieve this, a biomass-based age adjustment was configured into FLINTpro. This function back-calculates a functional age of the forest given the amount of biomass that is present. The effect being if biomass is lost from the forest through harvesting or fire, the forest will recover at a rate equivalent to a younger forest than the 'true' age of the forest (i.e. sequester carbon at a faster rate). In the absence of this functionality, modelling of mature forests that have very slow (or no growth) would not recover following the disturbance (Figure 7), which is not realistic. This age-related growth adjustment is a characteristic of FullCAM's TYF, and its use is consistent with the FullCAM guidelines for modelling plantations (e.g. DISER 2020b). FLINTpro differs from FullCAM in that when a biomass age adjustment is applied the age advancements from treatments are removed. This is an error in FullCAM and results in a minor change in growth rates post disturbance for forests with a growth advancement between FullCAM and FLINTpro.

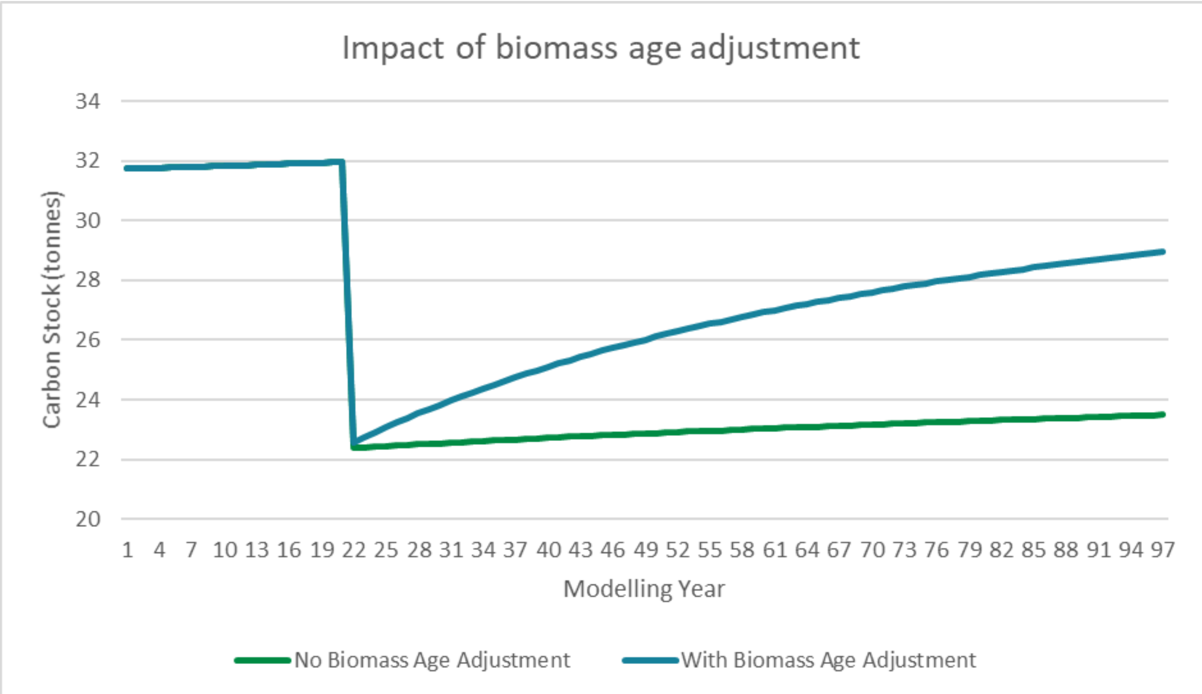

Figure 7 – Demonstration of the impact of biomass age adjustment as modelled in FullCAM and replicated in FLINTpro. Without biomass age adjustment, following a disturbance the forest continues to accumulate carbon at the same rate as prior to the disturbance. With biomass age adjustment turned on, the forest will grow at the rate of a functionally younger forest.

2.1.3. Carbon Pools

While the TYF produces an estimate of total aboveground biomass (AGB), to model the changes of carbon within the NSW forests, FLINTpro has incorporated 39 carbon pools (Table 1 & Figure 8). Non-CO_2 gases, including methane and nitrous oxide, were not included in this analysis. In broad terms, these pools represent the tree biomass, debris biomass, soil biomass and harvested wood products.

Tree biomass

Tree components are modelled as a function of the AGB pool. The tree components include Stem, Bark, Leaf, and Branch, and each are calculated as a fraction of total AGB. Belowground biomass (BGB) calculated as a ratio of AGB and is further disaggregated into Coarse roots and Fine roots. The values within FLINTpro are relative to the sum of the fractions for these pools (Example for branches shown in Equation 2).

Equation 2 $Branch_{Biomass} = (Branch_{Frac} /(Branch_{Frac} + Stem_{Frac} + Leaf_{Frac} + Bark_{Frac})) \times AGB$

where:

$Branch_{Biomass}$= The biomass allocated to Branches as part of a growth increment

$Branch_{Frac}$ = Relative fraction of aboveground biomass allocated to Branches, dimensionless

$Stem_{Frac}$ = Relative fraction of aboveground biomass allocated to Stem, dimensionless

$Leaf_{Frac}$= Relative fraction of aboveground biomass allocated to Leaf, dimensionless

$Bark_{Frac}$ = Relative fraction of aboveground biomass allocated to Bark, dimensionless

AGB = Increment in total Aboveground Biomass, Tonnes dry matter per hectare, as provided by Equation 1.

For each biomass pool, the carbon fraction can be adjusted, allowing the biomass pools to accurately reflect the carbon values. The biomass allocation fractions were sourced from FullCAM.

Tree Biomass

Assumptions

- Forest growth rates reflect those in FullCAM
- Biomass Age Adjustment is applied post disturbances

Improvements

- Update the TYF parameters for plantations and native forests when made, or if resources are available, use forest type specific calibrations reflecting NSW forest types, including calibration of parameters to datasets collated from NSW forest types (e.g. allocation of biomass, litterfall, decomposition of debris, and impacts of thinning and fire on carbon pools).

Debris Biomass

Debris Biomass is also disaggregated into specific biomass pools. This includes decomposable and resistant branch downed deadwood, chopped wood, bark litter, leaf litter, coarse dead root, and fine dead root. Biomass enters these pools from their source pools via turnover (natural process) and events (natural and anthropogenic). These pools then decompose at a set rate (exponential decay). The breakdown fractions for each of the pools were sourced from FullCAM (Figure 8). For reporting purposes, primary carbon pools are aggregated into secondary or tertiary carbon pools.

Table 1 – Relationship between Primary, Secondary and Tertiary carbon pools.

Tertiary Pool	Secondary Pool	Primary Pool
Atmosphere	Atmosphere	Atmosphere
Forest Carbon	Aboveground Biomass	Stem
		Branch
		Bark
		Leaf
	Belowground Biomass	Coarse Roots
		Fine Roots
	Dead Organic Matter	Decomposable Deadwood
		Decomposable Chopped Wood
		Decomposable Bark Litter
		Decomposable Leaf Litter
		Decomposable Coarse Roots
		Decomposable Fine Roots
		Resistant Deadwood
		Resistant Chopped Wood
		Resistant Bark Litter
		Resistant Leaf Litter
		Resistant Coarse Roots
		Resistant Fine Roots
Harvested Wood Products	Harvested Wood Products - In Use	Biofuel - In Use
		Pulp and Paper - In Use
		Packing wood - In Use
		Furniture and Poles - In Use
		Fibreboard - In Use
		Construction Wood - In Use
		Mill Residue - In Use
	Harvested Wood Products - In Landfill	Biofuel - In Landfill
		Pulp and Paper - In Landfill
		Packing wood - In Landfill
		Furniture and Poles - In Landfill
		Fibreboard - In Landfill
		Construction Wood - In Landfill
		Mill Residue - In Landfill
Soil Carbon	Soil Organic Carbon	Inert Soil
		Soil Decomposable Plant Material
		Soil Resistant Plant Material
		Soil Humic
		Biomass

Harvested Wood Products

Harvested Wood Products represent a carbon store that is subject to decay. Harvested Wood Products in-use[2] and in landfill can be modelled through FLINTpro. They were included using methods comparable with the public release of FullCAM, where a proportion of the product pool decays through time (percent per annum) or is burnt as biofuel.

While FLINTpro supports modelling of harvested wood products in landfill, as FullCAM does not include relevant values for the transfer of carbon from products in use to products in landfill, this functionality was not used.

This approach differs from that used in the NGGI which better accounts for long-term carbon storage of products. Modelling of carbon in harvested wood products in service under the NGGI is not completed with FullCAM, rather a separate database model is used. This model assigns products to pools of varying ages, with simulated periodic losses from each product pool (Richards et al 2007). This approach more faithfully represents the likely behaviour of products in service, compared to the use of generic, simple decay curves. Carbon in harvested wood products moves between respective pools via a range of end-of-life options: recycling, bioenergy, natural decay or landfill. This approach requires the tracking of the age of products in the harvested wood product pools, and the gains and losses from these cohorts.

Harvested Wood Products Assumptions and Improvements

Assumptions

- No carbon moves from harvested wood products into Landfill

Improvements

- Model temporal cohorts to better represent the life cycle of harvested wood products in use
- Model the movement of harvested wood products into landfill and long-term carbon dynamics

Soil Carbon

Soil Carbon was included in the system and modelled using the Rothamsted Carbon Model (RothC). RothC models carbon transfers between 6 different pools. The rate of turnover of organic carbon within soils is modelled with the rates varying according to temperature, soil moisture and plant cover (Coleman, 2014). Rates of decomposition vary with temperature, rainfall and soil properties (e.g. clay fraction).

RothC is the same model that underpins FullCAM, with the same input parameters that are used within FullCAM applied for the simulation, with one exception. The RothC was varied for FullCAM, with modifications to how the topsoil moisture deficit was calculated (DISER 2021). This modification is not publicly documented and was therefore not included in RothC calibrations used for this project. This may create a small difference between results from FullCAM and FLINTpro (See Section 3).

Initial soil carbon values used in this project were based on the NSW soil carbon fraction data-layer developed for 2010 by Gray et al. (2019). While the data represents 2010, the values were applied at the start of the modelling period in 1935.

[2] HWP in-use refers to harvested wood products that are being used and represent a store of carbon, such as in furniture, or construction material.

All pixels that had forest cover at any point in the modelling period were modelled. Any pixel that never had forest cover was not simulated. However, for areas of forest that were permanently cleared, no ongoing changes to soil organic carbon were modelled – such modelling would require detailed information about subsequent non-forest land management on these areas, which is beyond the scope of this project. This means there is likely to be an over-estimation of soil carbon loss from deforestation because the decay of carbon in former forest soils is assumed to be emitted to the atmosphere at the time of deforestation. In reality this would continue to change depending on the subsequent land management applied to the cleared land.

Soil Carbon Assumptions and Improvements

Assumptions

- Areas that are never forest are excluded from modelling
- Areas that are forest at any stage during the Simulation are modelled
- Soil Carbon Stock estimated in 2010 was the initial Soil Carbon Stock in 1935.
- Areas that are non-forest have no biomass input (no grass or crop model), so changes in SOC post permanent clearing of forest was not modelled.

Improvements

- Improved calibrations of inputs of carbon into the soil under forests, including using updated parameters of FullCAM when available to improve confidence in soil carbon values under forests (particularly plantation forests).
- Expand to include non-forest carbon sources (grassland and croplands)
- Set soil carbon stock in 2010 to values estimated by Gray et al (2019) and adjust initial soil carbon stock to be consistent with these values, and also assess whether a longer model 'run-in' is required to attain near equilibrium initial soil carbon values.
- Incorporate modifications to RothC for how topsoil moisture deficit is calculated

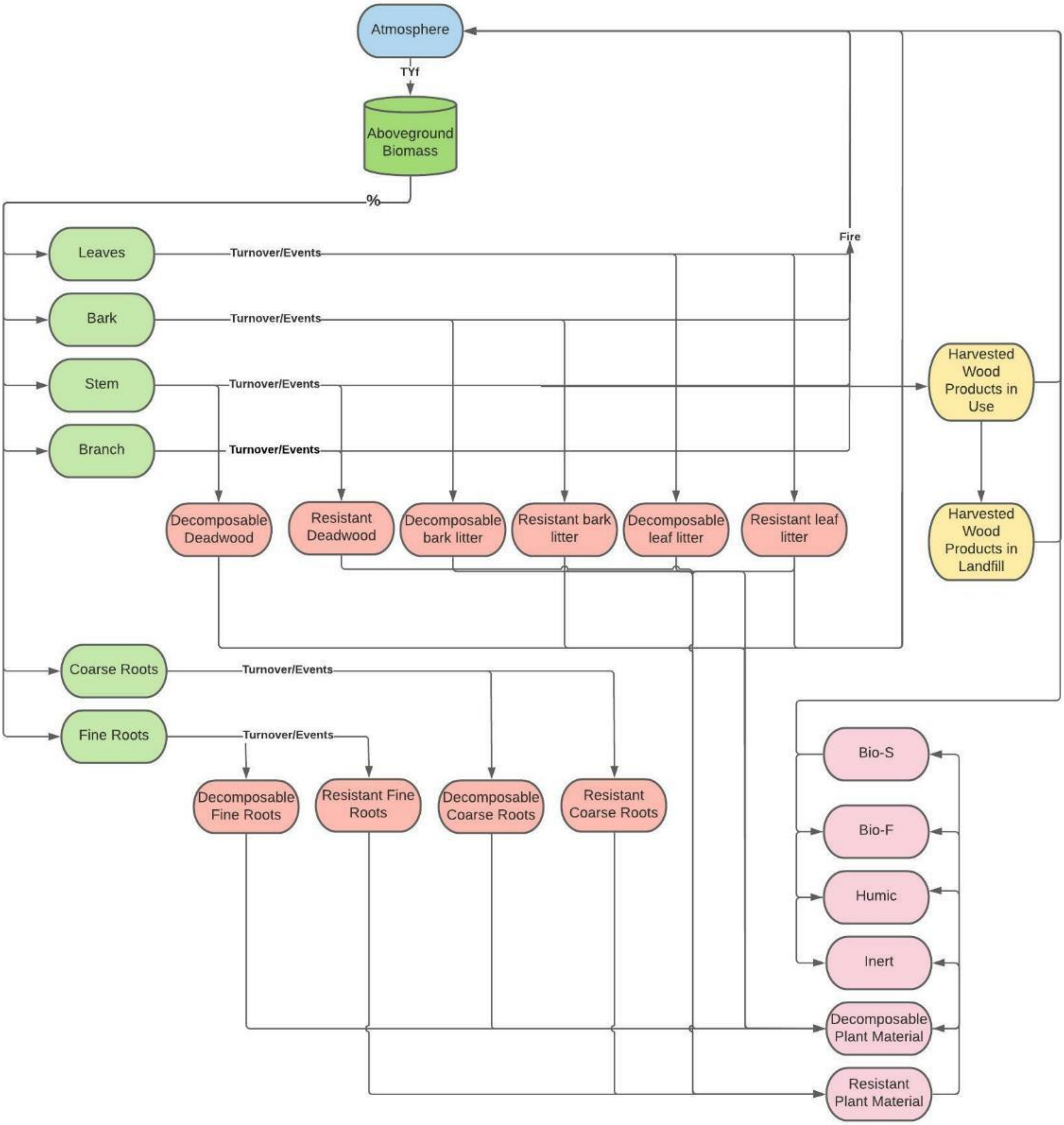

Figure 8- Schematic of the flow of carbon from Atmosphere through to the tree components through turnover to dead organic matter pools and through decomposition to the soil.

2.2. Spatial Configurations

The Public Release version of FullCAM is a single-location (or plot-level) analysis tool, which makes undertaking analyses over large spatial domains problematic. The full version of FullCAM used by the Australian NGGI is capable of spatially explicit analyses, however this version was not available for the analysis of the carbon balance of NSW forests.

FLINTpro overcomes the constraints of the FullCAM Public Release version by fully replicating the forest growth curves and turnover that underpin FullCAM. This allows spatially explicit representation of the Public Release of FullCAM. Rather than having a user manually determine the forest type and sequence the events for every location containing forest, this process is driven from spatial data.

In general terms, FLINTpro drills through all spatial files for every individual pixel (0.00025 decimal degrees, approximately 25m by 25m). To replicate FullCAM, this requires drilling through spatial files to identify the forest type, growth parameters and event queues. Through the spatial files, FLINTpro determines if a pixel is forest or not, what type of forest it is, and what events affect that forest. Pixels were only modelled if they were forest at any point in time during the analysis period as determined from remotely sensed forest extent information.

2.2.1. Forest Types

Native Forests

The forest types used reflect the Major Vegetation Groups, noting that these groups differ from what is reported from the NGGI (Table 2 & Figure 9). Plantations were identified by the ABARES (2016) Plantation Inventory data and divided into two classes – hardwood and softwood (Figure 10). A relative frequency for specific plantation types was applied based on the National Plantation Inventory Regions.

Table 2 - Mapping of the major vegetation classes to the National Greenhouse Gas Inventory Classes

Inventory Forest Class	NVIS Major Vegetation Groups
Rainforest	Rainforest and vine thickets
Tall dense eucalypt forest	Eucalyptus tall open forests
Medium density forest	Eucalypt open forest
Low dense eucalypt forest	Low Closed Forests and Tall Closed Shrubland
Tall sparse eucalypt forest	Eucalypt Open Forests
Low Sparse eucalypt forest	Eucalyptus woodland
	Eucalyptus open woodland
	Other open woodlands
	Tropical woodlands and grasslands
	Eucalypt Low Open Forests

Eucalypt Mallee	Mallee Woodlands and Shrublands
	Mallee Open Woodlands and Sparse Mallee Shrublands
Callitris forests	Callitris Forest and Woodlands
Acacia Forests	Acacia forest and woodlands
Other Forests	Casuarina Forests and Woodlands
	Melaleuca Forests and Woodlands
	Mangroves
Acacia Open Woodlands	Acacia Open Woodlands
Eucalypt Woodlands	Eucalypt Woodlands

Each forest type has calibrations included within the system to match those within FullCAM. This includes 79 individual variables for each forest type including carbon fractions of tree components, turnover rates, and decomposition rates.

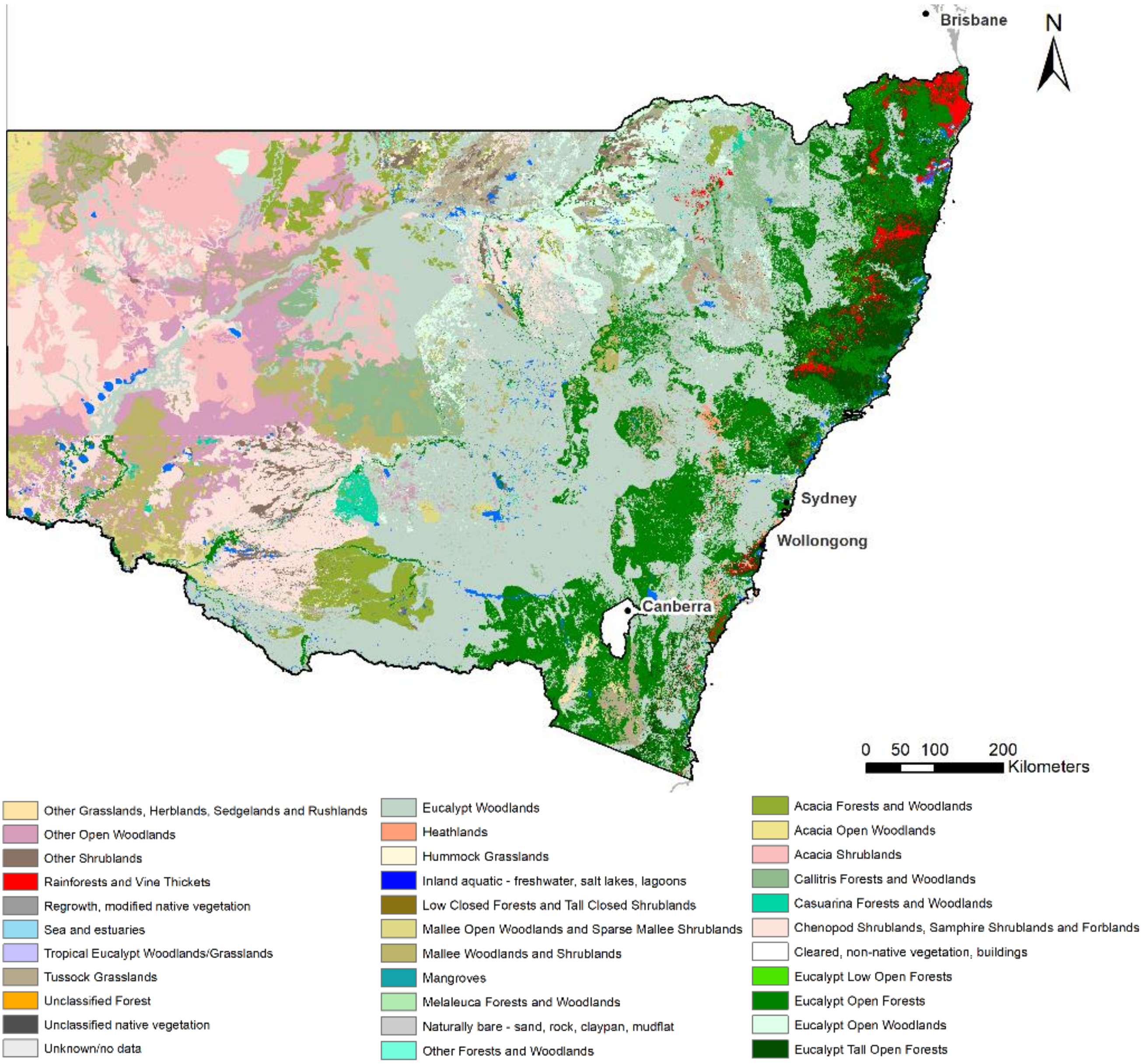

Figure 9 - Pre-1750 NVIS Major Vegetation Groups (MVG 5.1), natural forests were modelled based on the MVG classifications. Data from NVIS: https://www.environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products

Plantation Forests

The distribution of plantation types has been implemented based on the results of the 2020 Plantation Forest Inventory data for the National Plantation Regions (Downham & Gavran 2020). It is recognised that there is temporal variation in the distribution of plantation species, however as spatially explicit data is not available, a simplified approach was taken (Table 3). While there are numerous species represented within the data, many of these species have the same growing parameters (Paul et. al. 2019). It is noted that this approach will result in over and under estimates of forest carbon on the stand by stand level, as short-rotation plantations may be modelled as long-rotations and vice-versa.

Table 3 – The breakdown of the National Plantation Regions represented in NSW, the associated relative frequency of that species within the NPI region, and the corresponding FLINTpro implementation. Various simplifying assumptions were made give the absence of data.

National Plantation Region	Species	Relative Frequency of Species	FLINTpro Regime Implemented
Central Tablelands (New South Wales)	Radiata pine	96.8%	*P. radiata*: Long Rotation: NSW
	Other species	3.2%	*P. radiata:* Long Rotation: NSW
East Gippsland–Bombala (Victoria/New South Wales)	Radiata pine	100.0%	*P. radiata*: Long Rotation: NSW
Murray Valley (New South Wales/Victoria)	Radiata pine	98.7%	*P. radiata:* Long Rotation: NSW
	Maritime pine	0.1%	*P. radiata*: Long Rotation: NSW
	Other pines	0.9%	*P. radiata*: Long Rotation: NSW
	Other species	0.3%	*P. radiata*: Long Rotation: NSW
North Coast (New South Wales)	Radiata pine	2.0%	*P. radiata*: Long Rotation: NSW
	Southern pines	74.3%	Southern Pine: Long Rotation: NSW
	Hoop pine	4.1%	Southern Pine: Long Rotation: NSW
	Other pines	16.9%	*P. radiata*: Long Rotation: NSW
	Other species	2.7%	*P. radiata*: Long Rotation: NSW
Northern Tablelands (New South Wales)	Radiata pine	89.4%	*P. radiata*: Long Rotation: NSW
	Southern pines	0.7%	Southern Pine: Long Rotation: NSW
	Other pines	8.6%	*P. radiata*: Long Rotation: NSW
	Other species	1.3%	*P. radiata*: Long Rotation: NSW
Southern Tablelands (New South Wales)	Radiata pine	100.0%	*P. radiata*: Long Rotation: NSW
East Gippsland–Bombala (Victoria/New South Wales)	Tasmanian blue gum	7.0%	*E. globulus*: Short Rotation: NSW
	Shining gum	72.1%	*E. nitens*: Short Rotation: NSW
	Other eucalypts	7.0%	short rotation Hardwood: NSW
	Other species	14.0%	short rotation Hardwood: NSW
Murray Valley (New South Wales/Victoria)	Tasmanian blue gum	82.9%	*E. globulus*: Short Rotation: NSW
	Shining gum	7.1%	*E. nitens*: Short Rotation: NSW
	Other eucalypts	8.6%	short rotation Hardwood: NSW
	Other species	1.4%	short rotation Hardwood: NSW
North Coast (New South Wales)	Tasmanian blue gum	0.1%	*E. globulus*: Short Rotation: NSW
	Shining gum	3.9%	*E. nitens*: Short Rotation: NSW
	Dunn's white gum	21.9%	*E. dunnii*: Long Rotation: NSW
	Blackbutt	29.4%	*E. pilularis*: Long Rotation: NSW
	Spotted gum	12.5%	*Corymbia* Sp.: Long Rotation: NSW
	Other eucalypts	31.4%	short rotation Hardwood: NSW
	Other species	0.8%	short rotation Hardwood: NSW
Northern Tablelands (New South Wales)	Tasmanian blue gum	0.0%	*E. globulus*: Short Rotation: NSW
	Shining gum	56.5%	*E. nitens*: Short Rotation: NSW
	Dunn's white gum	4.3%	*E. dunnii*: Long Rotation: NSW
	Other eucalypts	39.1%	short rotation Hardwood: NSW
Southern Tablelands (New South Wales)	Other eucalypts	50.0%	short rotation Hardwood: NSW
	Acacia species	50.0%	short rotation Hardwood: NSW

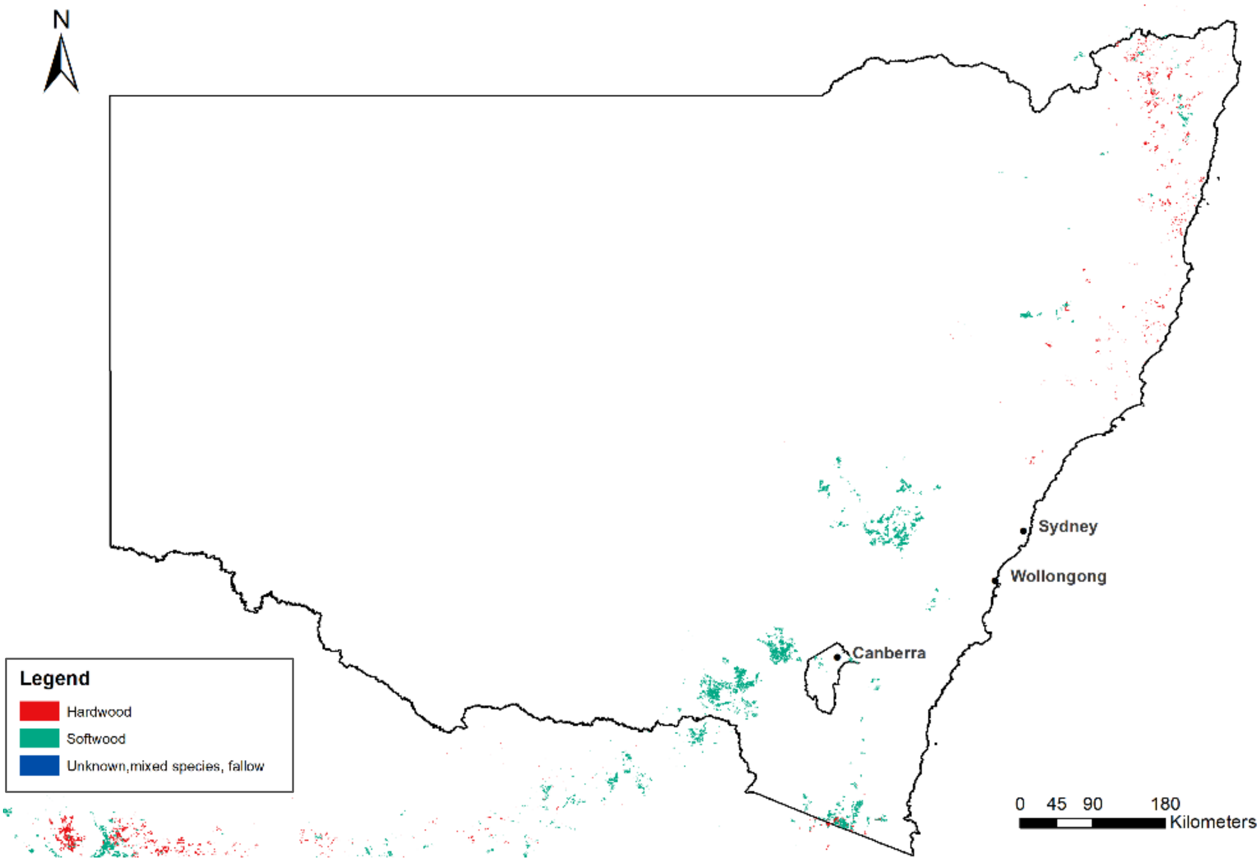

Figure 10 – Plantation Extent of NSW as of 2016. Areas identified as plantation in 2016 were modelled as a plantation for the entire simulation. Data from ABARES: https://www.agriculture.gov.au/abares/research-topics/forests/forest-data#australian-plantation-statistics

Other Forests

Non-plantation forests, including urban Forests, farm forestry and horticultural crops, such as orchards, were not separately identified and hence were modelled as if they were native forest types based on the MVG class. These areas may be excluded post-analysis where the spatial data exists to identify them, such as using the land use masking method developed through the forest extent, condition and health monitoring component of the NSW Forest Monitoring and Improvement Program.

In developing the FLINTpro Run, there are a number of considerations in addition to the forest growth elements, notably, the initial condition assumptions, and secondly, the events. These elements are described below.

Forest Type Assumptions & Improvements

Summary of core assumptions

- Natural forest types are static, meaning forest distribution will not change through time.
- There was no conversion of native forest to plantations post 1990.
- Simplified plantation species were implemented, with a static temporal distribution.

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.
- When available, use updated FullCAM events for harvested native forests, including a re-classification of forest types and data-informed revision of model parameters (allocation, turnover, standing dead, debris, and soil carbon) and the impacts of different types of disturbances of differing severities on carbon dynamics.
- Exclude or modify database for modelling horticultural crops using NSW-specific land use masking data.
- Modify how Urban forests are modelled to better reflect the different growth capacity.

2.2.2. Initial Condition

The time period of interest for the carbon balance of NSW forests project is 1990 onwards; however, it is necessary to start the model before this date to allow a 'spin up' of different carbon pools. A modelling start date of 1935 was chosen, as 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 11).

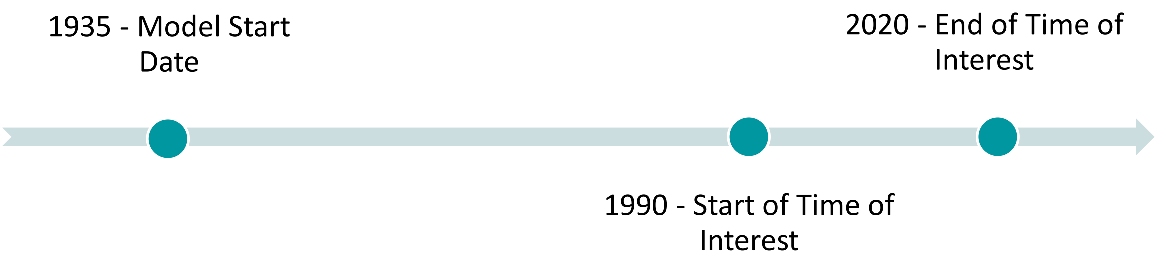

Figure 11 – Timeline of the carbon balance of NSW forests simulation

The forest cover data used in the NGGI covers the period from 1988 to 2020, with periodic gaps in temporal coverage (Figure 12 & Figure 13). To support a spin up of the biomass pools, it was assumed that any area that was forest in 1988, the first year of the forest cover data, was forest in 1935 (modelling start date). Reflecting the assumptions of the NIGGI, 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 1988. This assumption provides an age class comparable to modelling being undertaken by the DISER (Collett pers comm. April 2021). The dead organic matter at the modelling start date is zero (no biomass). If alternative data is made available, this assumption could be changed.

Areas that were identified as plantation and was forest in 1988 were assumed to have been planted in 1935 and managed on a standard management regime up to 1988. For *Pinus radiata*, for example, it was assumed that the plantation was planted in 1935, then harvested at age 35 (1970) and replanted 2 years later (1972). This will result in over and underestimates in biomass in specific plantation forests. However as true harvest and replanting events are identified in the remote sensing post-1988, the influence of this assumption will decline.

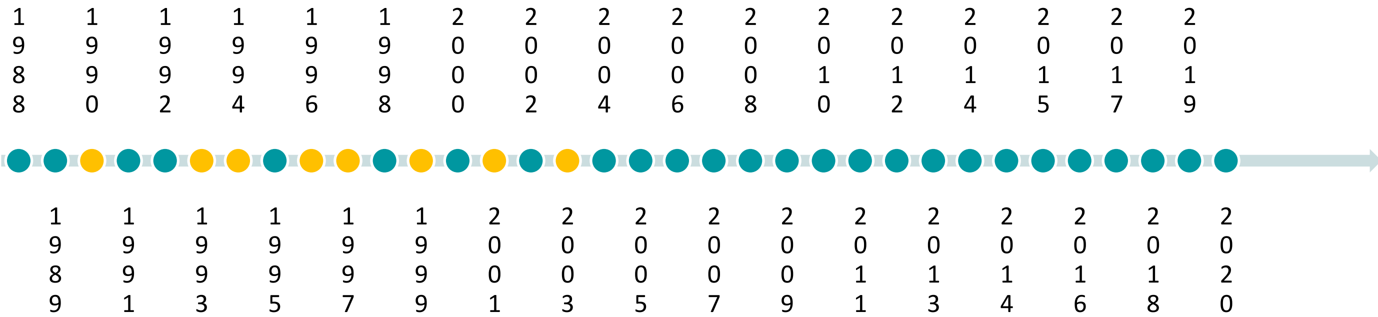

Figure 12- Green circles represent the years represented in the timeseries of remote sensing data, yellow circles represent gaps in the remote sensing product within the timeseries. In the 1990s a number of years have no remote sensing products available. In the circumstance that a change is detected where there are gaps between the years, a random date between the years is applied.

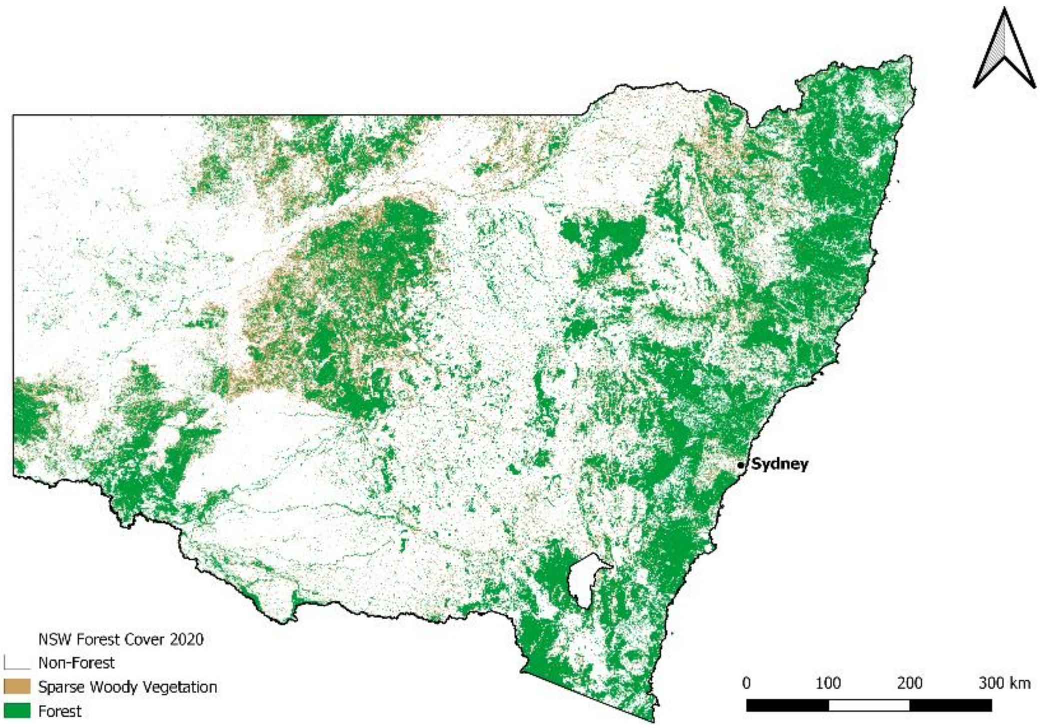

Figure 13 – NSW Land Cover for 2020, data from National Forest and Sparse Woody Vegetation Data (Version 3, 2020 Release), https://data.gov.au/data/dataset/d734c65e-0e7b-4190-9aa5-ddbb5844e86d

Integration with NSW Forest Extent Assessment

As a comparison with the National Forest Cover data, forest cover data from the NSW Forest Extent, Condition and Health project was also simulated. The Forest Extent data was developed from the National product, in conjunction with alternative data sources (Farrell 2021). The NSW Forest Extent data is limited to the Regional Forest Agreement (RFA) Areas of NSW and does not have the same temporal range as the national product, with products only available from 1995 as opposed to 1988 (Figure 14). To compare the differences in the national forest product with the state-based product, a simulation was completed for the RFA regions using the NSW Forest Extent Assessment. A comparison of the results is presented in Section 6.

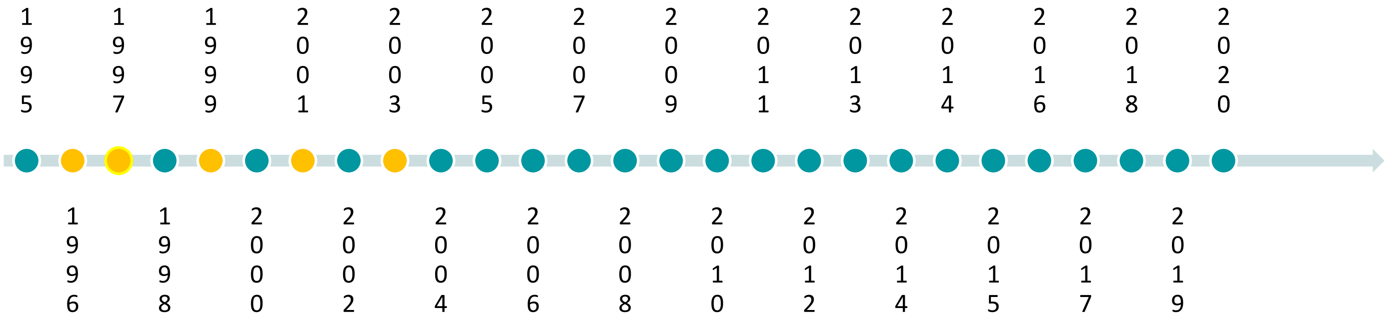

Figure 14- Green circles represent the years represented in the timeseries of remote sensing data, yellow circles represent gaps in the remote sensing product within the timeseries. In the 1990s a number of years have no remote sensing products available. In the circumstance that a change is detected with gaps between the years, a random date between the years is applied.

Initial Condition Assumptions & Improvements

Assumptions

- 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 prior to 1990 will reduce the impact of this assumption
- Plantation extent from 2016 was used to estimate plantation extent in 1988.
- Areas that were forest in 1988 and mapped as plantation in 2016 were assumed to have been planted in 1935 and managed for two rotations and replanted. After 1988, clearfell harvest events and forest cover gain events detected through the forest cover data were used.
- 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.

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. 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.
- Back calculating the plantation ages for plantations present in 1988 based on observed harvest times.
- Developing a complete timeseries of forest cover from the earliest year possible
- Include a true timeseries of plantation extent from 1988 onwards.

2.3. Event Types

Events are operations that occur intermittently (rather than every time step in a simulation) resulting in the movement of carbon from one pool to another. Events include natural and anthropogenic events including fire, timber harvesting, forest establishment (planting), and forest clearing. Within the NSW Run, fire, timber harvesting, forest clearing, and reforestation were all included. Within FLINTpro, events are defined within the input database. The event record details the event type and the associated pool movements (Table 4).

Table 4- Example of the information recorded for each event type within the FLINTpro database

Event Information	Database Record	Example
Event ID	id	1
Event name	name	Thin: product recovery
Event Type (thin, Fire, Plant)	event_type	mulliongroup.thin
Fraction affected	frac_affected	0.3
Fraction of stem moved to downed dead wood	frac_stem_to_downed_dead_wood	0.05
Fraction of stem moved to biofuel	frac_stem_to_bio_fuel	0.1

Fraction of stem moved to paper and pulp	frac_stem_to_paper_and_pulp	0.3
Fraction of stem moved to packing wood	frac_stem_to_packing_wood	0
Fraction of stem moved to furniture	frac_stem_to_furniture	0
Fraction of stem moved to fiberboard	frac_stem_to_fiberboard	0
Fraction of stem moved to construction	frac_stem_to_construction	0.5
Fraction of stem moved to mill residue	frac_stem_to_mill_residue	0.05
Fraction of branch moved to downed dead wood	frac_branch_to_downed_dead_wood	1
Fraction of branch moved to biofuel	frac_branch_to_bio_fuel	0
Fraction of branch moved to paper and pulp	frac_branch_to_paper_and_pulp	0
Fraction of branch moved to packing wood	frac_branch_to_packing_wood	0
Fraction of branch moved to furniture	frac_branch_to_furniture	0
Fraction of branch moved to fiberboard	frac_branch_to_fiberboard	0
Fraction of branch moved to construction	frac_branch_to_construction	0
Fraction of branch moved to mill residue	frac_branch_to_mill_residue	0
Fraction of bark moved to bark litter	frac_bark_to_bark_litter	0.2
Fraction of bark moved to biofuel	frac_bark_to_bio_fuel	0
Fraction of bark moved to paper and pulp	frac_bark_to_paper_and_pulp	0
Fraction of bark moved to mill residue	frac_bark_to_mill_residue	0.8
Fraction of leaf moved to leaf litter	frac_leaf_to_leaf_litter	1
Fraction of leaf moved to biofuel	frac_leaf_to_bio_fuel	0
Fraction of coarse root moved to dead coarse root	frac_coarse_root_to_dead_coarse_root	1
Fraction of coarse root biofuel	frac_coarse_root_bio_fuel	0
Fraction of fine root moved to dead fine root	frac_fine_root_to_dead_fine_root	1
Fraction of downed dead wood moved to biofuel	frac_downed_dead_wood_to_bio_fuel	0
Fraction of chopped wood moved to biofuel	frac_chopped_wood_to_bio_fuel	0
Fraction of bark litter moved to biofuel	frac_bark_litter_to_bio_fuel	0
Fraction of leaf litter moved to biofuel	frac_leaf_litter_to_bio_fuel	0

2.3.1. Fire

Fire is an important event type in the Australian context and is integral to much of Australia's forest ecology. Fire results in the combustion of aboveground biomass and dead organic matter pools, as well as the conversion of living biomass to dead biomass. For this project fire was modelled as being either natural wildfire or hazard reduction burning. Data on timing and extent of both fire types was provided by the NSW Rural Fire Service and Forestry Corporation of NSW, covering the period of 1902 through to 2017, although only applied to the Simulation from 1935 onwards (Figure 15 & Figure 17). From 2017 to 2020, data from the NSW Fire Extent and Severity Mapping (FESM) project was used. The resulting moves in forest carbon were differentiated by fire type (Figure 16 & Figure 18). Any limitations in the fire extent data will be carried through to the results. It is expected that the older data will be of lower spatial accuracy than modern data. An assessment of the completeness and accuracy of these data was not completed as part of this project.

Where fire extent data was supplied by fire season across two years (Australian summer), these events were converted to calendar year data by applying the fire event to the latter of the two years in the fire season. For example, a fire occurring in 2013/14 fire season was applied in FLINTpro to the 2014 calendar year to be consistent with other time series data and reporting.

Beyond timing and extent, the modelling system incorporates patchiness and proportion of biomass consumed. Within the boundaries of a fire affected area, not all the area is burnt, rather there are often patches of unburnt areas. This is referred to as 'patchiness'. Similarly, when an area is physically burnt, not all the available biomass is consumed. To account for both concepts, an estimate of patchiness and proportion of biomass consumed was included in the fire model.

For fire data prior to 2018, Fire type Patchiness (P) in Southern Australian forests & woodlands was 0.650 for prescribed fires and 0.800 for wildfires, as used in the NGGI (DISER 2020). Where a fire is applied, all pixels within the fire boundary are affected by the fire event. The patchiness factor is then applied to the resulting carbon changes to represent incomplete coverage of the burning. Depending on the fire type, different fractions of biomass were moved from the carbon pools to either atmosphere or dead organic matter (Table 5).

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%

For fires occurring in 2018, 2019 and 2020, the FESM fire severity classes were used. The FESM data includes 4 fire types, Low, Moderate, High and Extreme. For these fire types the patchiness was adjusted for High and Extreme severity classes to 1, indicating that 100 percent of the pixel was affected by high or extreme fire. Expert judgement was elicited to translate the FESM fire classes to impacts (Fairman, T., 2021). While it is recognised that the impact of fire varies with forest type, the forest types represented within the MVG classes are insufficient to delineate obligate seeder from resprouting forest types. Further research is required to verify and appropriately quantify the impact for NSW forest types.

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 2017 and 2020, based on FESM fire severity class

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%

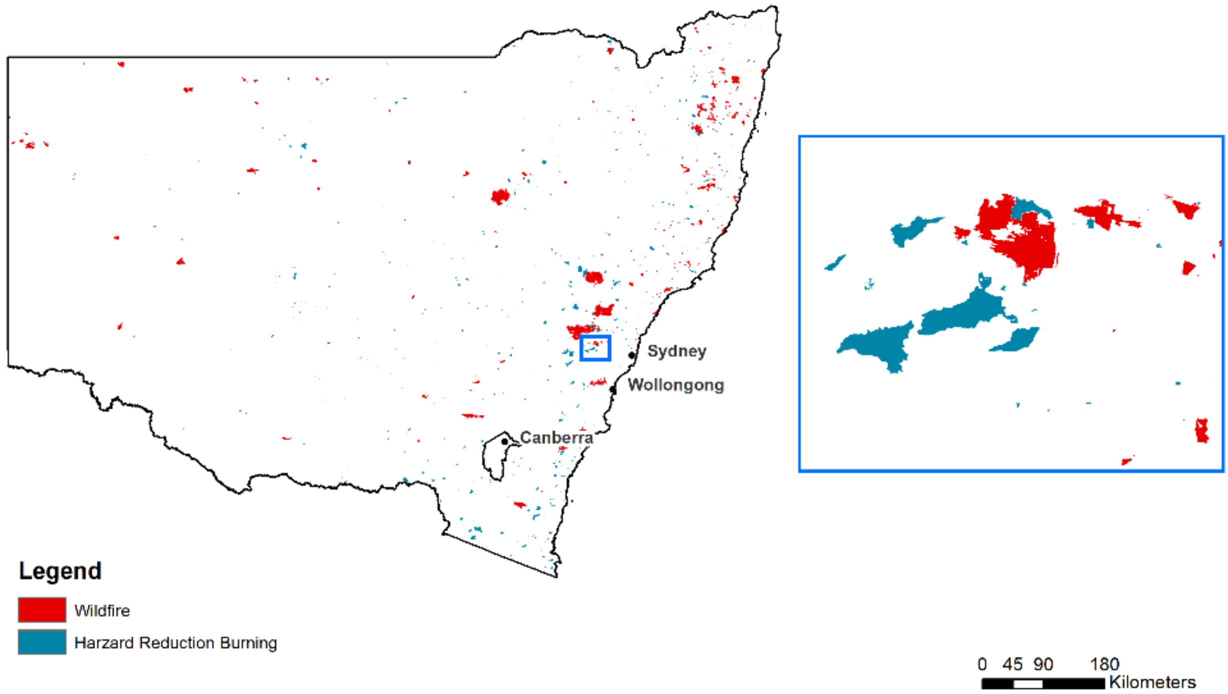

Figure 15 - Fire type example from 2013 fire data with inset, image developed by data sourced by NSW RFS and NSWFC

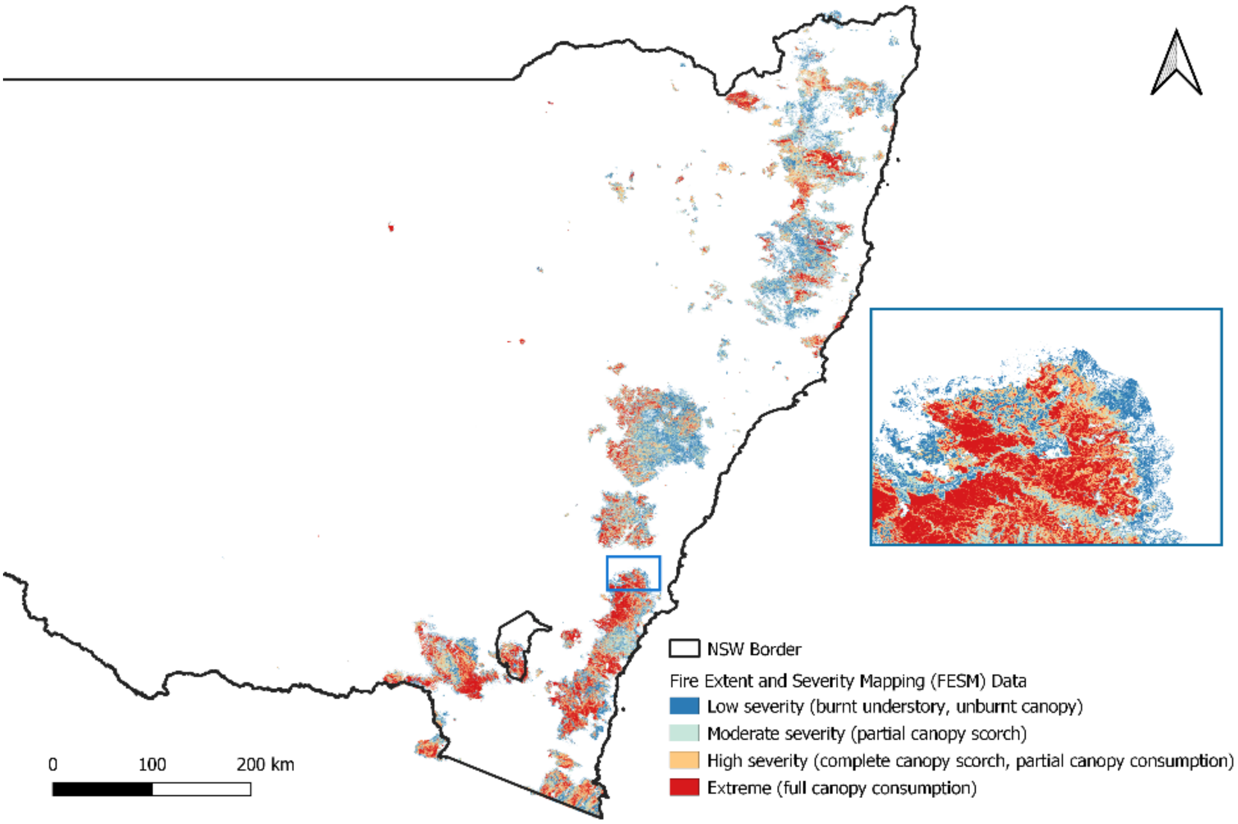

Figure 16 – Fire Severity type example from 2020 with insert, image developed by data developed by FESM

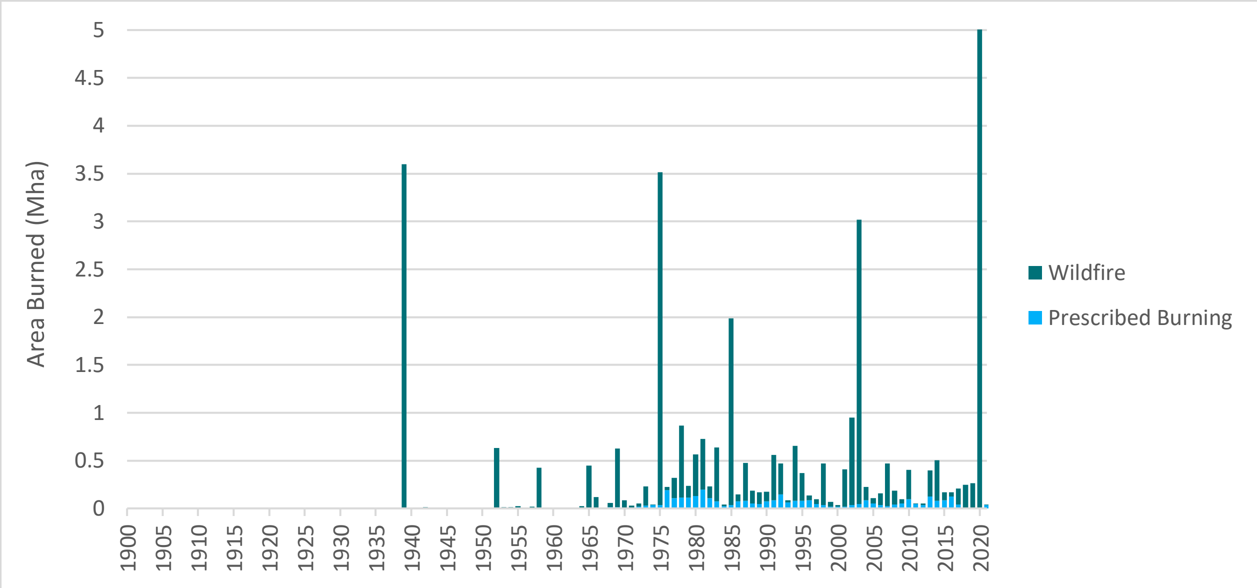

Figure 17 - Area burned (Mha) by year (1900-2021). 2018-2020 shows area in FESM data.

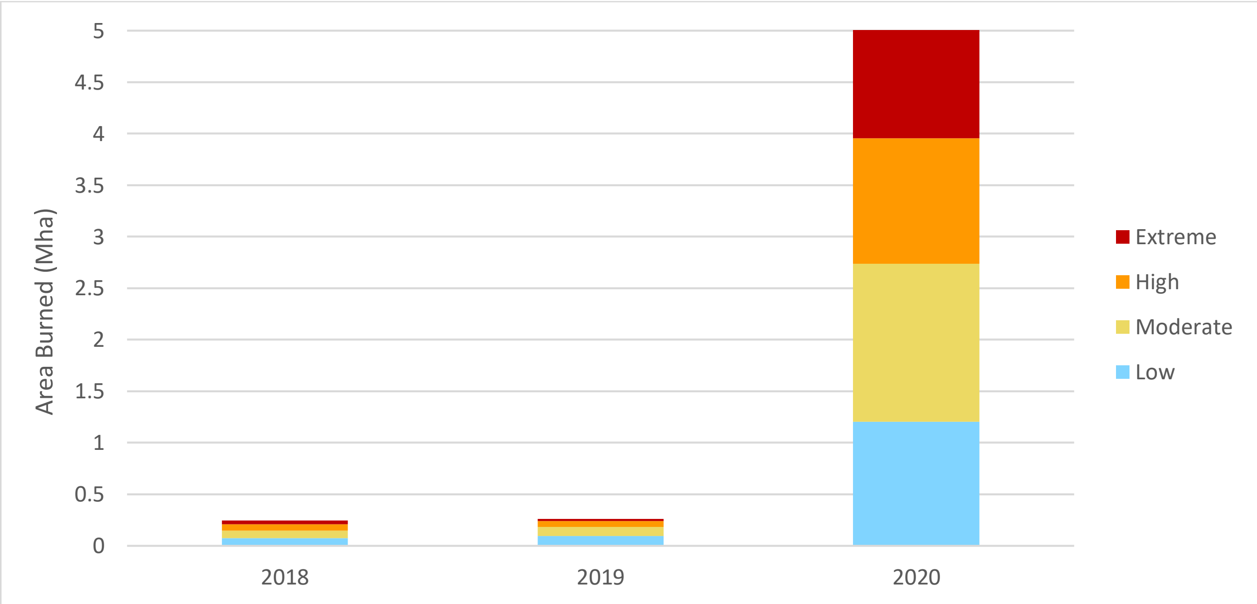

Figure 18 - Area burned (Mha) 2018-2020 by fire severity class from FESM data.

Fire Assumptions & Improvements

Assumptions

- There are only two forest fire types prior to 2017, wild-fire and hazard reduction burns.
- The entire area within the fire boundary is affected by the fire in a uniform manner

Improvements

- Expanding spatial-temporal data on fire severity class to incorporate vegetation type responses to improve the estimates of the impacts of fire on carbon pools. However, further research would be required to calibrate each of the NSW forest types.
- Implementation and calibration of standing dead pools and rates of post-fire recovery of biomass and fuel pools in NSW forests.
- Implementation of residue burning fire events in addition to hazard reduction and wildfire events
- Retrospective application of fire severity classes for entire modelling period once data is available

2.3.2. Forest clearing

Forest clearing is the 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 use. 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.

Forest clearing was identified from a land cover time-series dataset produced for the NGGI. This product identifies areas that are 'forest', which means the pixel is considered to have met the threshold canopy value of a forest. The NSW Forest Monitoring and Improvement Program has adopted the national definition of forest:

> *An area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding 2 metres and with existing or potential crown cover of overstorey strata about equal to or greater than 20 per cent. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands.*

Notably, the definition of forest includes land that has 'potential' to meet the canopy threshold, whereas the land cover product only identifies areas that have met the canopy threshold. Where a forest cover loss event occurs, a clearing regime is applied which moves biomass from the living biomass pools to the dead organic pools. It is assumed that debris is left onsite to decay.

As the model was configured to use the forest cover product as a 'point of truth' any misclassifications within the forest cover data will also be represented in the carbon outputs. Similarly, where there are large events that result in a temporary loss of forest cover, such as fire, will be modelled as a forest clearing event.

Forest Clearing Assumptions & Improvements

Assumption

- The forest cover product is the point of truth, in that where a pixel transitions from forest to non-forest in the forest cover product (NCAS) a forest clearing event modelled.
- Forest cover loss converts all living biomass to dead organic matter, where it is left on-site to decay

Improvements

- Only apply a forest clearing event where there is a transition of forest cover to non-woody biomass, as opposed to just when there is forest cover loss. While FLINTpro can model these changes, there is currently insufficient data on how the biomass would change through these transitions.
- 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 re-planting 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.

2.3.3. Replanting/Reforestation

In a similar way that forest clearing is detected, the system also detects replanting (re-establishment of forest cover on land that is under forest land use) and reforestation/afforestation (conversion of non-forest land use to forest). Remote sensing 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 2.1.1.

Importantly, a ‘replanted’ forest often takes up to 2-4 years before being detected by the remote sensing data. This is due to the very low canopy cover of very young forests (<20%). The amount of time between forest planting in reality and detection by the remote sensing data depends on the forest type and growing conditions. Where this occurs, the modelled growth will lag behind the true growth of the forest throughout the Run.

Reforestation Assumptions & Improvements

Assumption

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

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 would be needed.
- 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.

2.3.4. Harvesting

Harvesting is the activity of cutting down trees from forests, and moving biomass from living biomass pools to harvested wood products and dead organic matter. The effect of this event type is a reduction in carbon within the forest and an increase in the harvested wood products pool at the time of the event (See Harvested wood products section below), followed by an increase in carbon as the forest recovers. Notably, harvesting is distinguished from deforestation, as it does not result in a reduction in forest area (i.e. harvesting assumes that forests are replanted or regenerated).

The extent of harvesting of native forests is identified from spatial records provided by the Forestry Corporation of NSW. This includes 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 (Figure 19), allowing for a comprehensive modelling of the changes in forest carbon as a result of harvest activities on native state forests. While there is substantial temporal and spatial coverage of the data, the accuracy of the products used declines the further in the past they were created (i.e. accuracy of harvest mapping has improved over time). This includes not only the spatial extent of the harvesting, but also the modelled effect of the harvesting (proportion affected and destination of harvested timber). The older data used for modelling the harvest events is likely to include areas that were not harvested and therefore represents a broader area of interest associated with a harvest event. When this occurs, the impacts of each harvest event will be exaggerated, with areas being modelled as harvested that would not have been, such as streamside reserves.

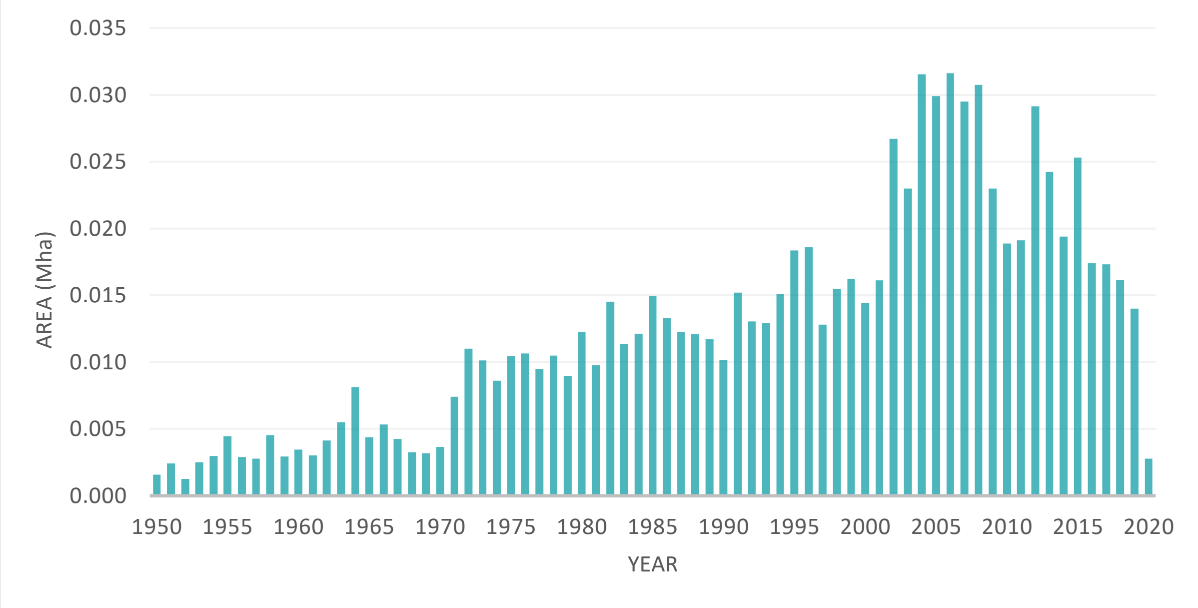

Figure 19 – Area harvested by year based on data provided by NSWFC.

Of the approximately 18,000 harvest areas that were identified in native state forests, there were 35 unique harvest operation types that were applied. These 35 types were further simplified into 13 distinct treatments. The simplification of harvest types was due to time constraints in compiling a full list of events. These events include specific product recovery rates, and proportion impacted.

A simplifying assumption was made that the percentage of basal area affected translated to the proportion of biomass affected with the harvest. It is recognised that this assumption may over or under-estimate the effect of timber harvesting on biomass, and further research is needed to determine an improved estimate. An improvement would be to introduce a dynamic relationship of wood volume and Forest Productivity layer (see 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.

Table 6 – Harvest types represented in the modelling, and an indication of the basal area removed.

Harvest Type	%BA removed
Australian Group Selection (AGS)	25%
Alternate Coupe	80%
Miscellaneous	10%
Non-Harvest	0%
Hardwood plantation CF	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%

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

Harvesting Assumptions and Improvements

Assumptions

- There are a limited number of harvest events (13) that were applied for the whole timeseries. Options exist to have temporally variable harvest events, although this would require research that is beyond scope of this project.
- That 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

- Improve the temporal changes in harvesting (i.e. changes in silviculture – historically and in future (e.g. post-2018 Coastal IFOA conditions) for public and private forests). The FLINTpro structure supports this, however the data was not available to support this functionality.
- Expand the silvicultural treatments that can be applied and ensure that the impacts of these treatments on growth responses is well calibrated.

2.3.5. Forest Treatment

Forest Treatments refer to specific events that modify the growth of the forest, such as fertiliser application. Similar to FullCAM, within FLINTpro, forest treatments modify the growth of the forest through increasing or decreasing the effective age of the forest. For example, the standard impact of a fertiliser application is to advance the forest 0.5 years of age over 1 year. The impact of this being that the forest will grow the equivalent of 1.5 years of standard growth within 1 year. For the Runs completed under this project, forest treatment (fertiliser) was only applied to plantations at the start of each rotation.

2.3.6. Combinations of Events

Through intersecting multiple spatial files, it is likely there will be an intersection of events. Including harvesting, fire, and forest clearing appearing in the same calendar year. Where multiple events occur within a single year, a sequence of events is triggered. For example, a fire in conjunction with a forest cover loss event will have a greater carbon impact than a fire without a forest cover loss event. Under these circumstances, where there is a fire and a forest cover loss event, the fire event is applied first based on type, with 100% of the remaining living biomass moved to the dead organic matter pool. This will create an overestimate in the impact of fire events where the fire was not completely stand replacing.

As the data being applied is annual, there are illogical event sequences, such as wildfire and forest cover gain within the same year. As it is not possible to determine the appropriate order of such events, simplifying assumptions were made. For example, where fire and forest establishment occur within one year, only the forest establishment is modelled. All events, rules, and sequences are described within the Database used in creating this output and can be improved incrementally through time.

Combined Events Assumptions and Improvements
Assumptions ● That forest cover loss events result in the 100% transfer of living biomass to dead organic matter, regardless of whether it occurs with other events, such as fire. **Improvements** ● Include more sophisticated delineation of forest loss events associated with fire from forest cover loss events caused by non-fire triggers.

2.4. Triggering Events

Events are managed by FLINTpro through disturbance modules that are triggered when a predefined set of conditions are met. These conditions are referred to as 'rules' and can be considered as a series of *if* statements – for example, *if* there is a forest cover loss detected in the remote sensing product, *then* apply a forest clearing event. In applying these rules, a combination of spatial and temporal data is used, allowing the flexible modelling of management events and natural disturbances within the landscape (Table 7). The rules are configured as a hierarchy from Activity Suites, to Activities, Regimes, and Events (Figure 20). Importantly, FLINTpro as a system is fully flexible in the spatial data that is used to define the rules, and through the database, any rule, assumption, or trigger can be modified by the user. In this context, any rule described below can be readily modified where improved data or approaches are available.

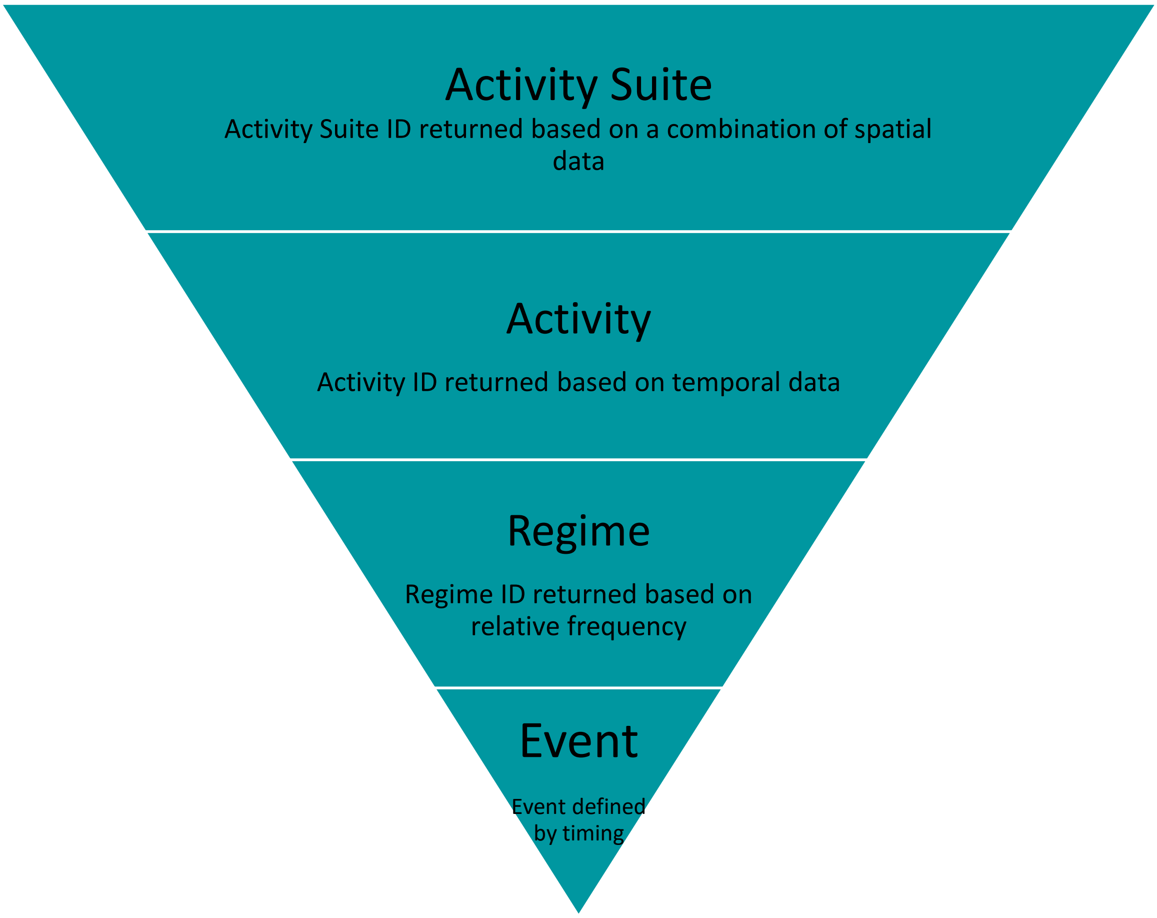

Figure 20 – A hierarchal approach that considers spatial, temporal, and statistical information to identifying the appropriate event to apply at a given point in time.

2.4.1. Activity Suites

The input database contains the information on the condition of each rule (i.e. *if* forest cover loss, *and* no fire, *then* apply Activity Suite 1). An Activity Suite consists of one or more temporally unique 'Activities'. Temporal uniqueness allows the modelling of changes in Activities based only on time. For example, where there is a shift in harvesting practices over time because of updates to management protocols.

For the NSW Configuration, six datasets were used for determining the appropriate activity suite. Based on the returned values from these data layers, the activity suite is identified. Through changing the data layer, or changing the values returned from the data, it is possible to quickly alter the Activity Suite and subsequent events. From the combination of input variables, 550,000 spatial rules were developed. Each of these rules map through to 230 Activity Suites.

Table 7 – Example of the relationships between Activity Suites, Activities, Regimes, and Events. Data is for illustrative purposes only.

Activity Suite	Activity	Start Year	End Year	Regime	Relative Frequency	Event	Timing (since trigger)
Mixed Eucalypt Timber Harvest	Single Tree Selection	1935	2000	Light	0.3	Light Harvest	0 Years 0 days
				Medium	0.5	Medium Harvest	0 Years 0 Days
				Heavy	0.2	Heavy Harvest	0 Years 0 Days
						Prescribed Fire	2 Years 180 Days
	Australian Group Selection	2000	2010	1st Cycle	0.8	AGS Harvest	0 Years 1 Days
						Prescribed Fire	0 Years 6 Days
				Thin	0.2	Thin	20 Years 0 Days
	Single Tree Selection	2010	2100	Medium	1.0	Medium Harvest	0 Years 0 Days

2.4.2. Activities

As described above, activities are a sub-unit of activity suites that are selected based on a specified time period. Activities relate to one or more regimes that are applied at a relative frequency for a specific point in time. This structure is designed to enable the application of multiple regimes to a single simulation unit. Temporal differentiation was not implemented in the project due to the absence of temporal data on changes in forest management. All activities were assumed to be valid for the entire simulation period.

2.4.3. Regimes

A regime is a specific temporal sequence of one or more events which is initiated by a trigger. Any subsequent events in a regime will have a timing trigger associated with it. For example, a plantation regime is initiated by a forest cover gain within a plantation boundary. The regime in this circumstance would be the planting of the forest, followed by a thinning event 12 years after the planting date. Events that are based on rules rather than spatial data are limited to event types that are not detectable using the spatial data. This is generally relevant to events that do not have an impact on the forest cover, such as pruning, thinning or low severity fires.

3. FLINTpro comparison with FullCAM

Forest Biomass Estimates

To compare FLINTpro and FullCAM modelling for forest biomass, a comparison of a homogenous FLINTpro simulation with FullCAM plot files was produced. This analysis uses a simplified forest growth curve (environmental planting) at a national scale for the comparison to ensure consistency in modelled outputs. There was a minor variation in forest biomass identified between FullCAM and FLINTpro, with the average difference in results being 0.21% (Figure 21). The difference is being driven by initial conditions for forest establishment. Within FullCAM, the planted biomass is set to 0.1 tonnes of biomass for each of the tree components, while within FLINTpro, the initial biomass is set from the planted age (0.5 in the circumstance of an environmental planting).

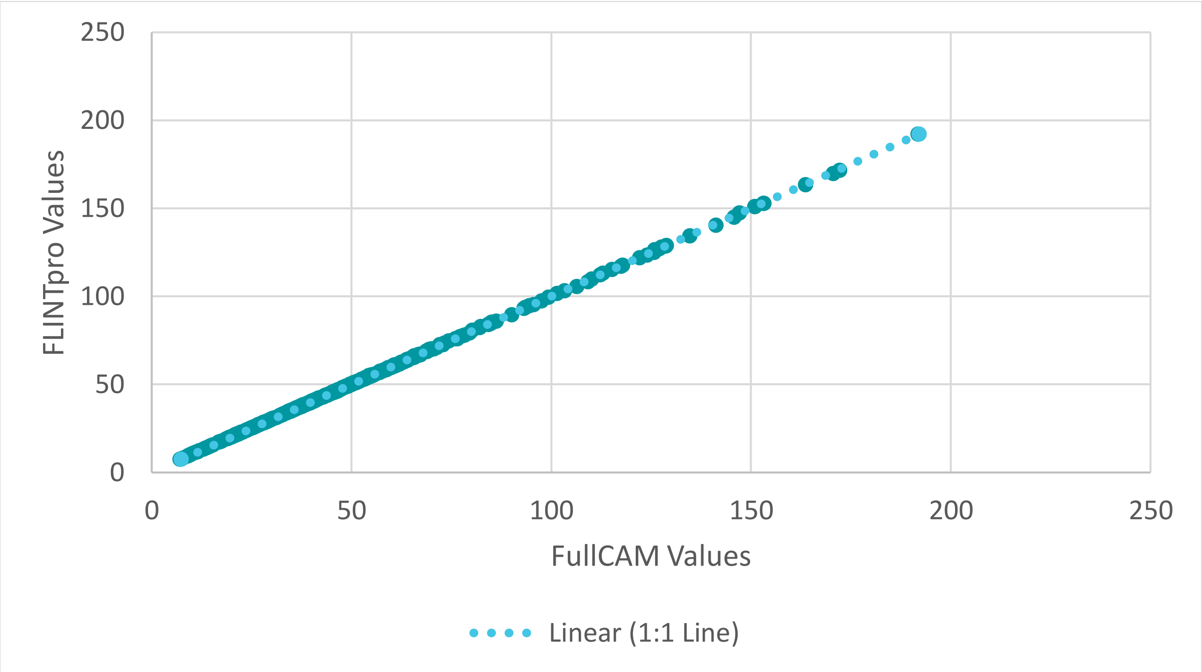

Figure 21 – Comparison of FLINTpro spatial outputs against and FullCAM point outputs for one point in time (25 years post growth).

To test the timeseries modelling, point based models were assessed. The results indicate that where the modelled parameters are comparable between FullCAM and FLINTpro, the modelled output are essentially identical (Figure 22).

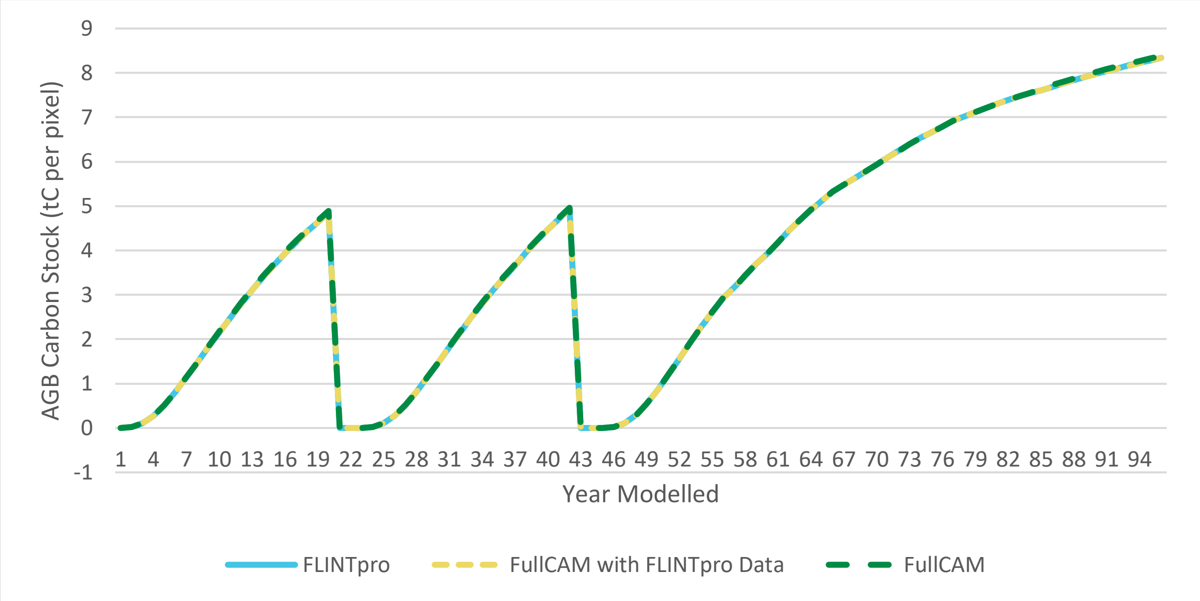

Figure 22 –Comparison of AGB Carbon Stock developed by FLINTpro, FullCAM with FLINTpro data and FullCAM outputs through time.

Soil Carbon

A comparison of FullCAM and FLINTpro outputs indicates strong correlation (Figure 23). There is a difference in the initial soil carbon conditions, which is reduced, but a difference remains between FLINTpro and FullCAM results. This difference occurs due to different initial soil conditions, in particular inert soil carbon and soil clay fractions. While FLINTpro is closely replicating FullCAM, the values that are being replicated appear problematic. The Soil carbon values from Gray et al (2019) for NSW don't exceed 100 tonnes of carbon per hectare, however, through the modelling, values exceeding 400 tonnes per hectare were calculated (Figure 24). It is expected that these values are being driven by turnover rates of the trees, in particular the leaf and fine root litter. Given the high divergence between the modelled outputs with the Gray et al (2019) results, it is recommended that further review of the FullCAM parameters be completed, and the assessment repeated before the modelled output is used.

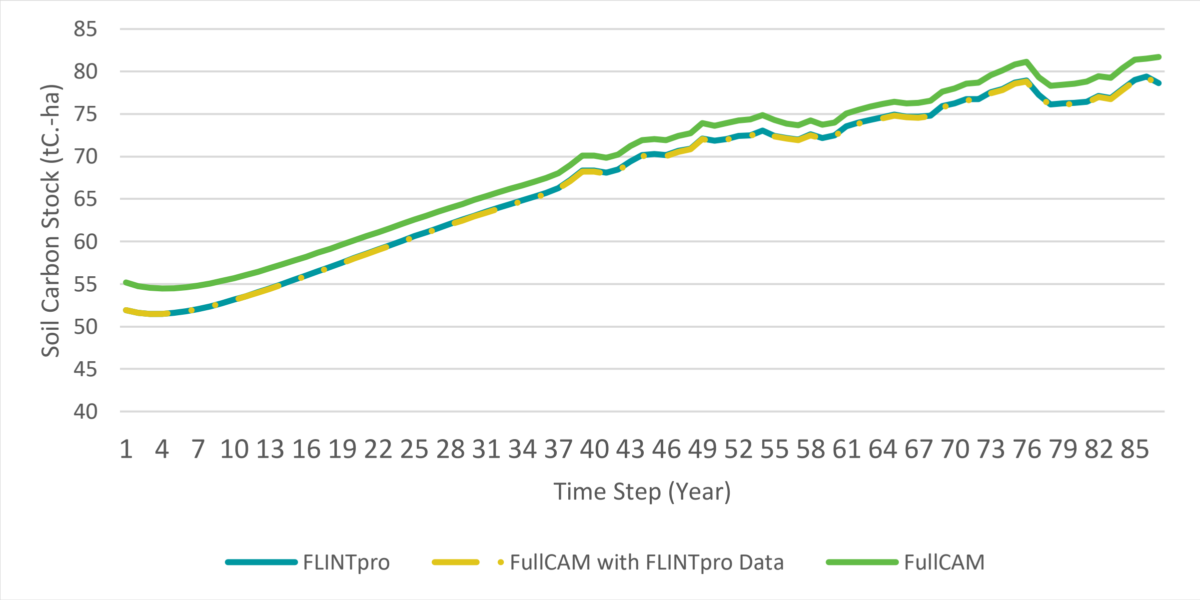

Figure 23 – Comparison of FLINTpro and FullCAM outputs through time. FullCAM with FLINTpro Data is where FullCAM was configured with data used in the FLINTpro simulation (climate, soil, tree parameters), while for FullCAM climate and soil parameters were used with FLINTpro tree parameters. The differences are created by NSW specific soil data being used for the FLINTpro simulation, with the maintained difference being driven by the initial carbon within the inert soil carbon pool.

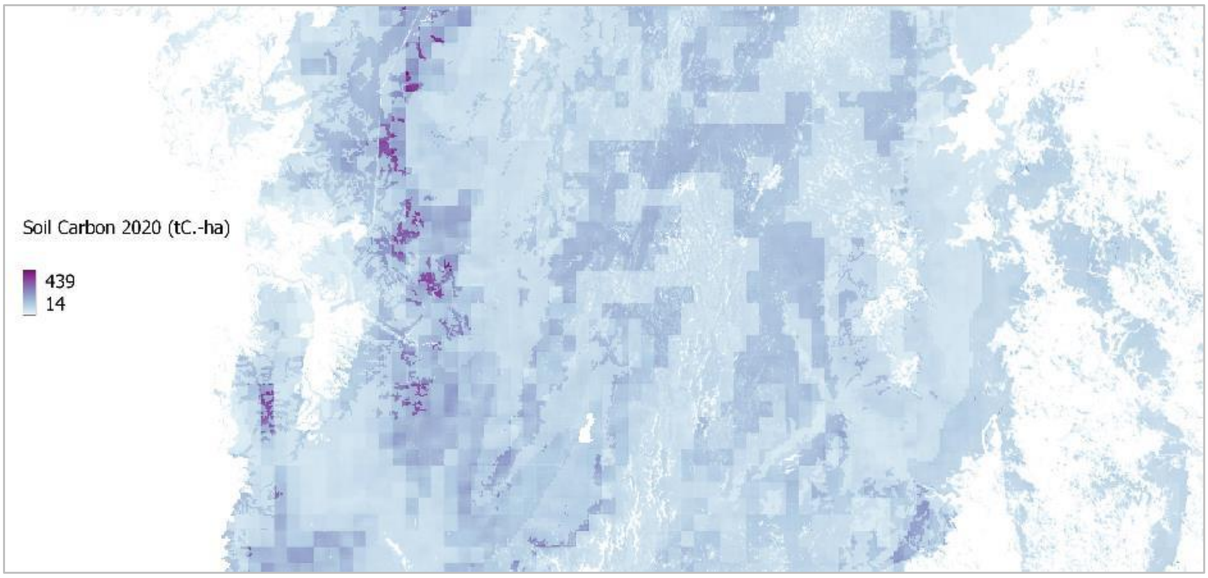

Figure 24 – Spatial Output of Soil Carbon for Southern RFA Region. The spatial output indicates high estimates of soil carbon, which appear to be significantly higher than other estimates. Areas that are never forest are not modelled.

4. Projections

Through FLINTpro in the current configuration, it is possible to complete projections of future changes in land use. However, these projections must be considered in the context of the modelling structure as described above. For example, the FullCAM growth model is not best suited for modelling the impacts of climate change, as biomass potential is static, and growth varies with some climate signals but excludes other relevant impacts, such as CO_2 fertilisation. For modelling more complex climate interactions, it will be necessary to move away from the NGGI based modelling approach to an alternative forest growth model. It is also necessary for any projections to account for future events, including timber harvesting, clearing/deforestation, and fire, which all have large impacts on the forest carbon. As the occurrence and precise extent of these events are unknown, the projections could be modelled through relative frequency of these events through time. FLINTpro is already configured for modelling in this manner.

5. FLINTpro Run & Outputs

To support different reporting requirements, four different spatial classifications were applied to the data:

- IBRA Regions
- Regional Forest Agreement Region boundaries
- National Park Boundaries
- State Forest Boundaries
- Plantation Extent

This allows the results to be reported separately for each of these sub-categories, or combinations thereof.

The completed Run spanned 1935 to 2020 and required analysis of 1.3 billion land units (pixels). The run required more than 25,000 hours, or nearly 3 years, of computer time, but was completed in under 1 day using FLINTpro's distributed cloud processing, resulting in over 300Gb of outputs.

5.1. Spatial Outputs

FLINTpro models annual time steps for every pixel within the Simulation Area, which equates to 1.3 billion pixels covering all of NSW. At the end of each time step, FLINTpro writes out a spatial file of the carbon stock or rate of every pool included within the Simulation. This can include aggregates of carbon pools, such as Aboveground Biomass (stem + leaves + branches + bark) or 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 25Figure 25 - 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.). The spatial outputs are beneficial in identifying spatial patterns in data, and greatly assist in developing an understanding of the underlying data.

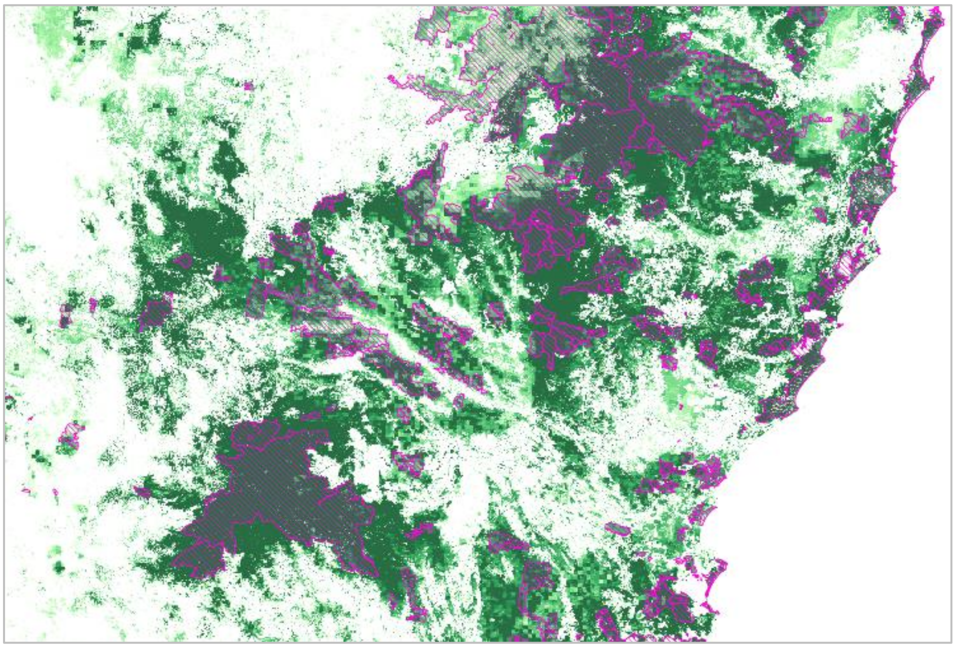

Figure 25 - FLINTpro outputs for Forest Carbon Stock (green) with the boundaries of national parks (Pink). Spatial outputs allow users to quickly identify patterns in the data.

5.2. Databases

In addition to spatial outputs, FLINTpro develops a database record which includes the aggregated results for a Run. 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. Spatial Filters are inputs into the Run that don't necessarily have an influence on the calculations but will be flagged against a carbon stock or flux. This allows one or more spatial files to be added to a Run and the results reported by the categories within the spatial files. For this Run, this included, Regional Forest Agreement regions, State Forest Boundaries, National Park Boundaries, Interim Biogeographic Regionalisation of Australia (IBRA) regions, and Plantation Extent. Notably, the database size will increase with the more spatial filters that are applied.

6. NSW Forest Carbon 1990-2020

6.1. Forest Carbon Balance

As described above, changes in forest carbon stock within NSW is only driven by processes and events triggered through forest cover gain events, cover loss events, fire or 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 2020 and the impacts of the 2020 fire season. This trend suggests that the state of NSW has transitioned from being a net source of carbon from forests, to being a net sink up to 2019. Following the 2020 fire season, NSW forests were a net source of emissions. The results indicate that the carbon in NSW forests is 164 million tonnes less in 2020 than in 1990 (Figure 26 - Figure 35Figure 28).

Figure 26- Estimates of total Forest Carbon Stock for NSW 1990-2020, 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 27- Repeat of Figure 21 with a non-zero scale, showing estimates of total Forest Carbon Stock for NSW 1990-2020 presented, 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.

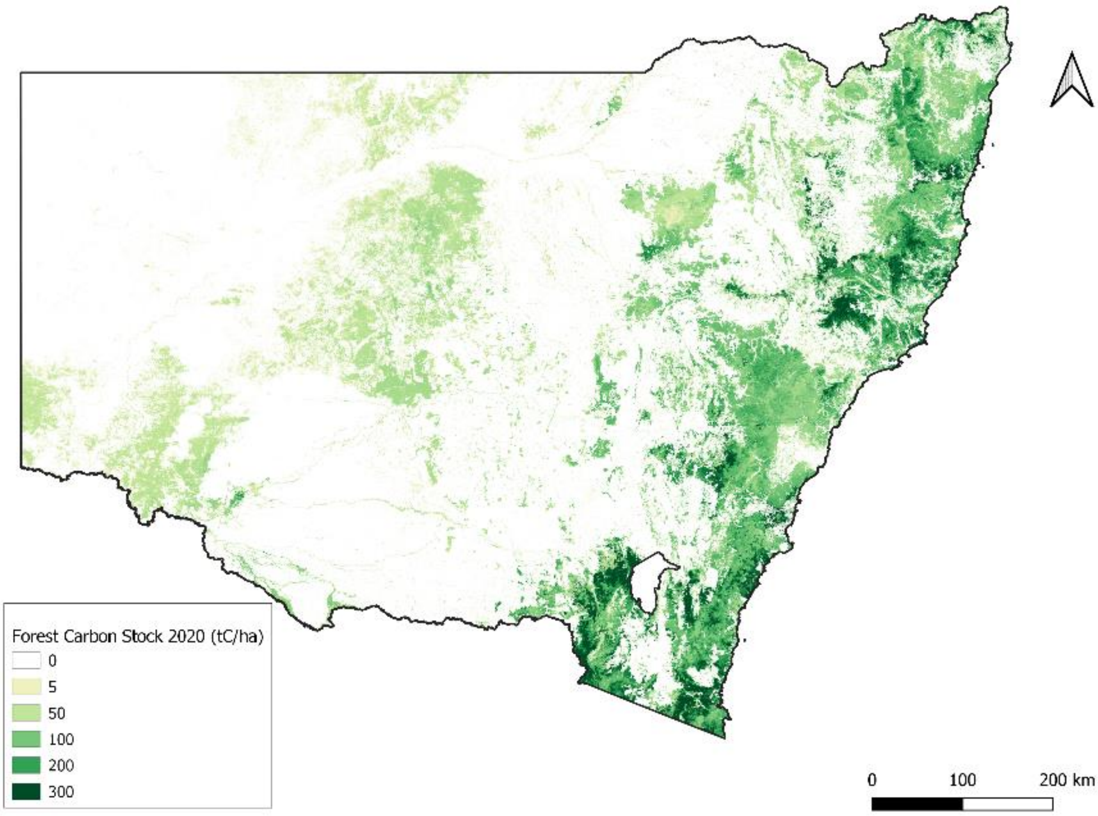

Figure 28 – Spatial Output of Forest Carbon for NSW in 2020, including aboveground biomass, belowground biomass, dead organic matter. Harvested wood products in use is not included in the spatial aggregation. Soil carbon and harvested wood products in landfill where not included. Developed with the 'Mid' forest growth rate where G=10.

Between 1990 and 2019, there was an average decline of close to 0.8MtC per annum (Figure 29 & Figure 30). There was a general decline in forest carbon stock from 1990 to 2010 of close to 4MtC per annum, and gain the average gain in forest carbon stock between 2010 and 2020 of 3MtC per annum.

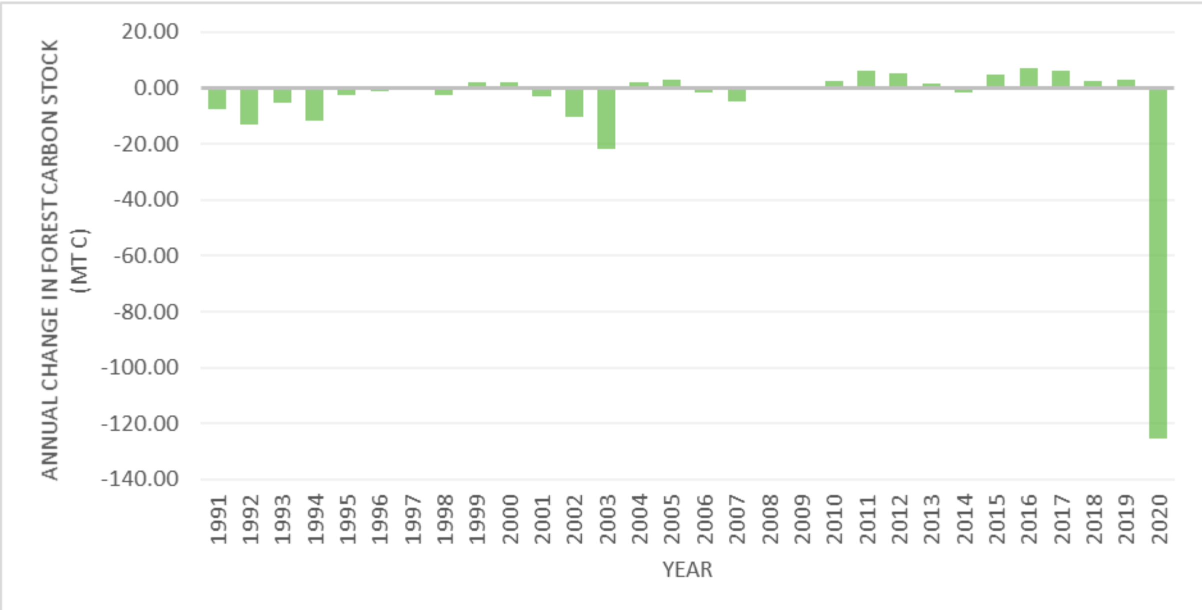

Figure 29 – Net Annual Change in Forest Carbon Stock 1990-2020, including aboveground biomass, belowground biomass, dead organic matter and harvested wood products in use. Negative numbers indicate a net loss in forest carbon, while positive numbers represent a net gain in forest carbon. Developed with the 'Mid' forest growth rate where G=10.

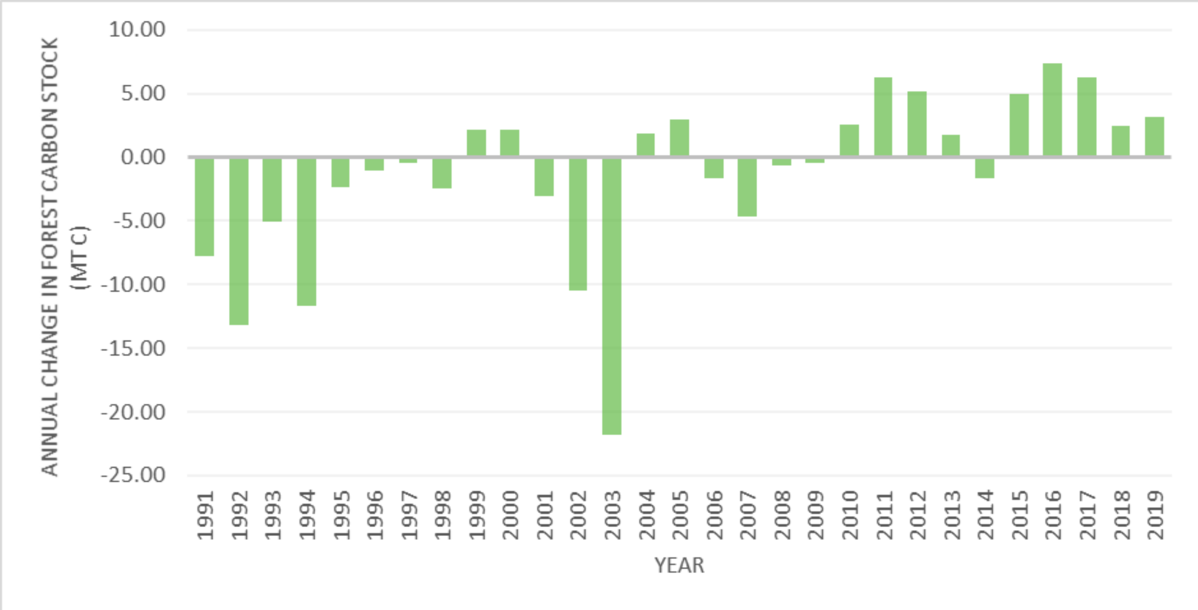

Figure 30 – Repeat of Figure 29 excluding 2020, showing the net Annual Change in Forest Carbon Stock 1990-2019, including aboveground biomass, belowground biomass, dead organic matter and harvested wood products in use. Negative numbers indicate a net loss in forest carbon, while positive numbers represent a net gain in forest carbon. Developed with the 'Mid' forest growth rate where G=10.

Changes in forest carbon were not spatially consistent, with regions of gain and loss spread across NSW (Figure 31). The forest carbon stock and carbon stock change also differ between land tenure. The forest carbon stock and change within State Forests and National Parks trending differently from forests outside of these management systems (Figure 32 & Figure 33). The results also indicate the significant relative contribution of plantation forests on the NSW forest carbon balance, in particular the softwood estate (Figure 34 & Figure 35).

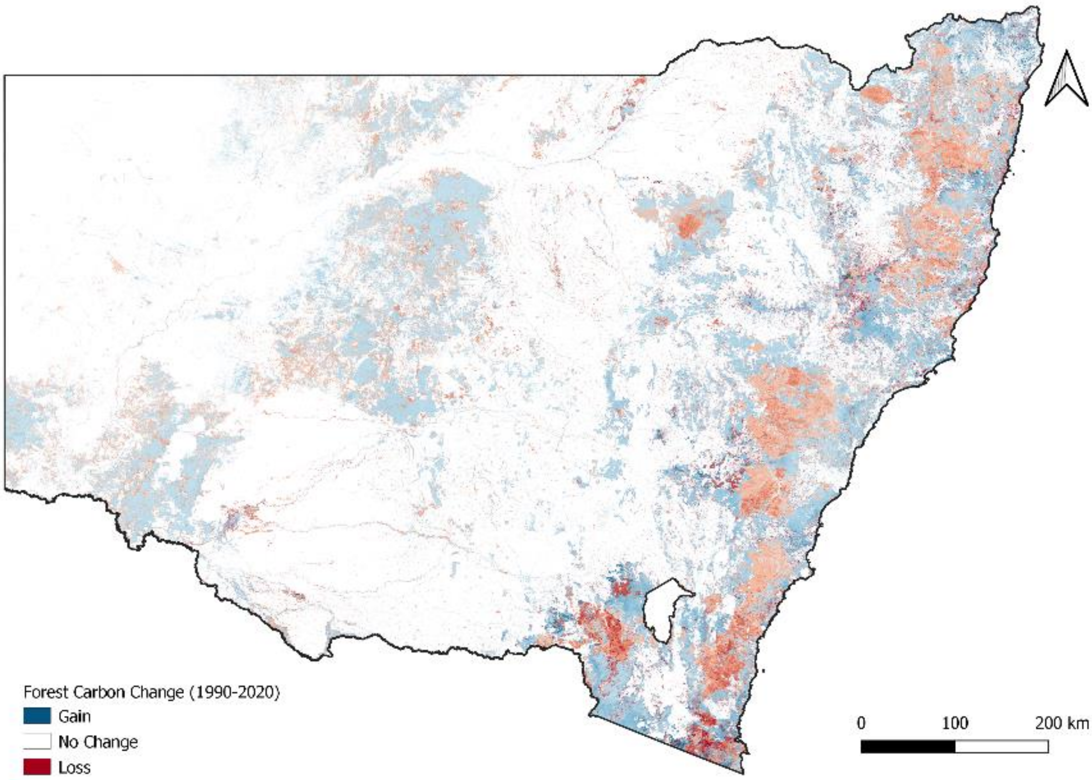

Figure 31 – Spatial output indicating the areas where forest carbon has increased (blue) and decreased (red) across NSW between 1990 and 2020. Developed with the 'Mid' forest growth rate where G=10.

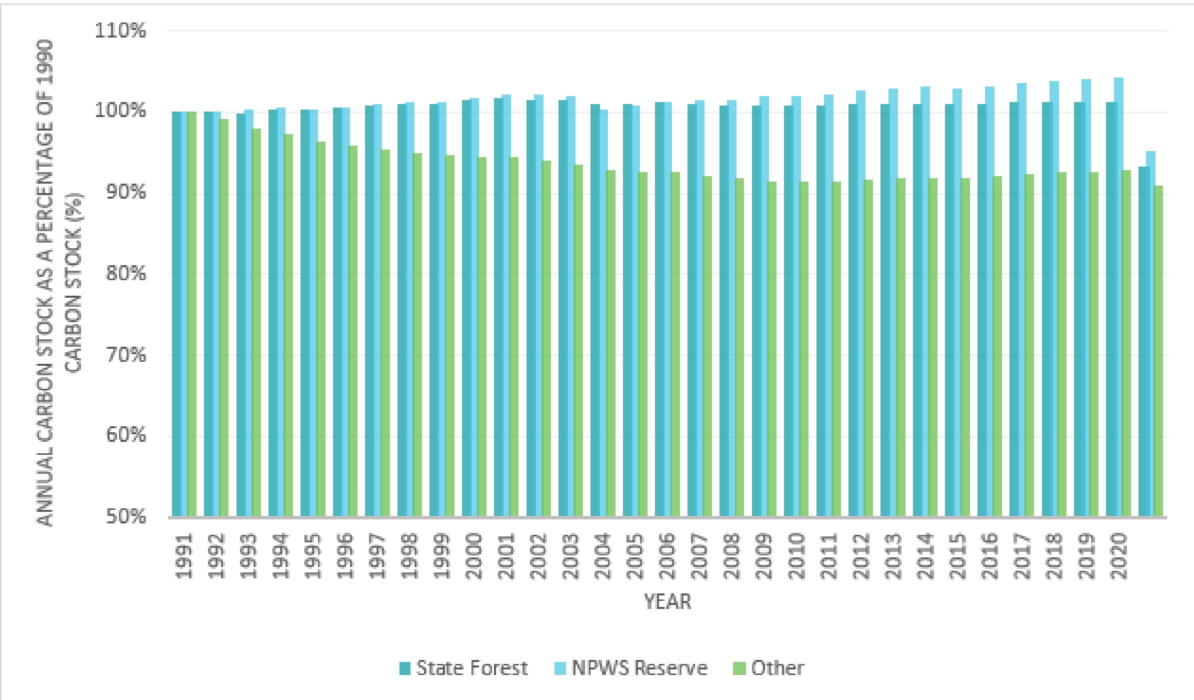

Figure 32 - Annual Carbon Stock of native forests relative to the 1990 carbon stock for the different Land Tenures. The graph indicates the temporal variation in carbon stock between land tenure. The cause of this variation was not analysed as part of this assessment. Estimates are based on current land tenure extent. Other forests refer to forests not within State Forests or National Parks. Developed with the 'Mid' forest growth rate where G=10.

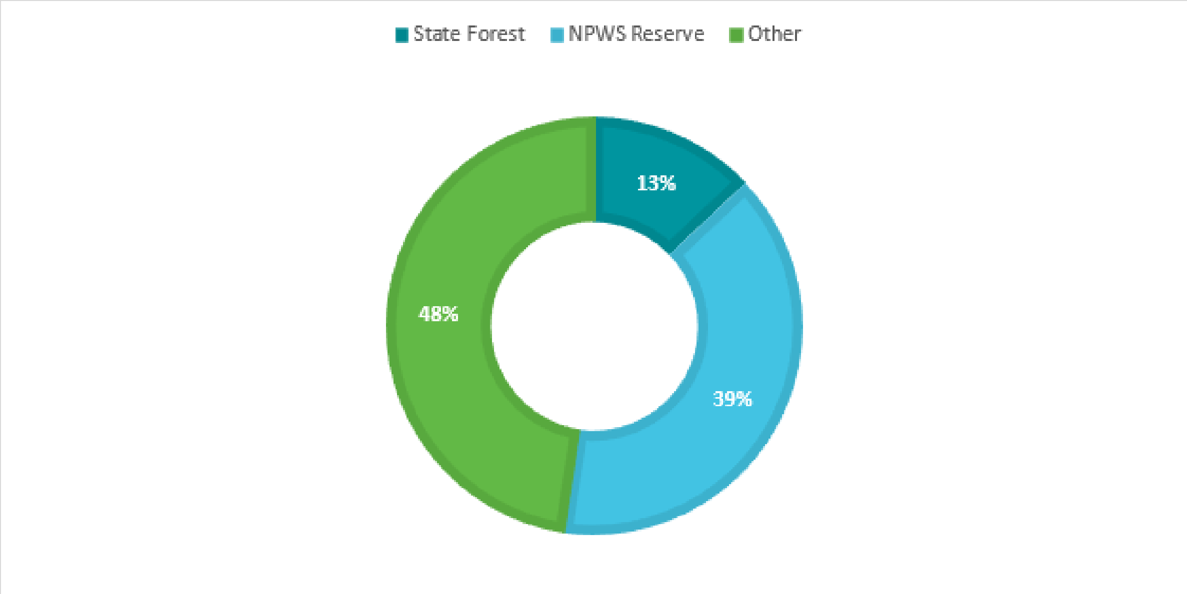

Figure 33 – Proportion of Forest Carbon Stock in 2020 in non-plantation forests by land tenure. Developed with the 'Mid' forest growth rate where G=10.

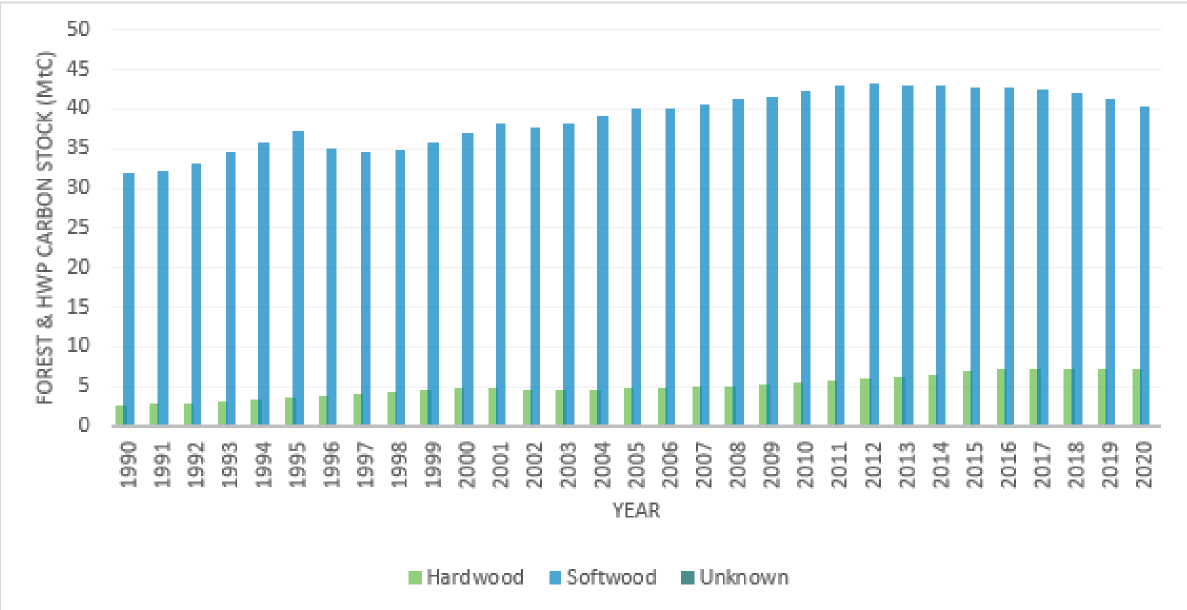

Figure 34 – Carbon stock estimates within Plantation Estate. Notably, any forest area within the 2016 Plantation Extent is modelled as a plantation from the start of the simulation. This assumption could be corrected with a timeseries of plantation extent. Developed with the 'Mid' forest growth rate where G=10.

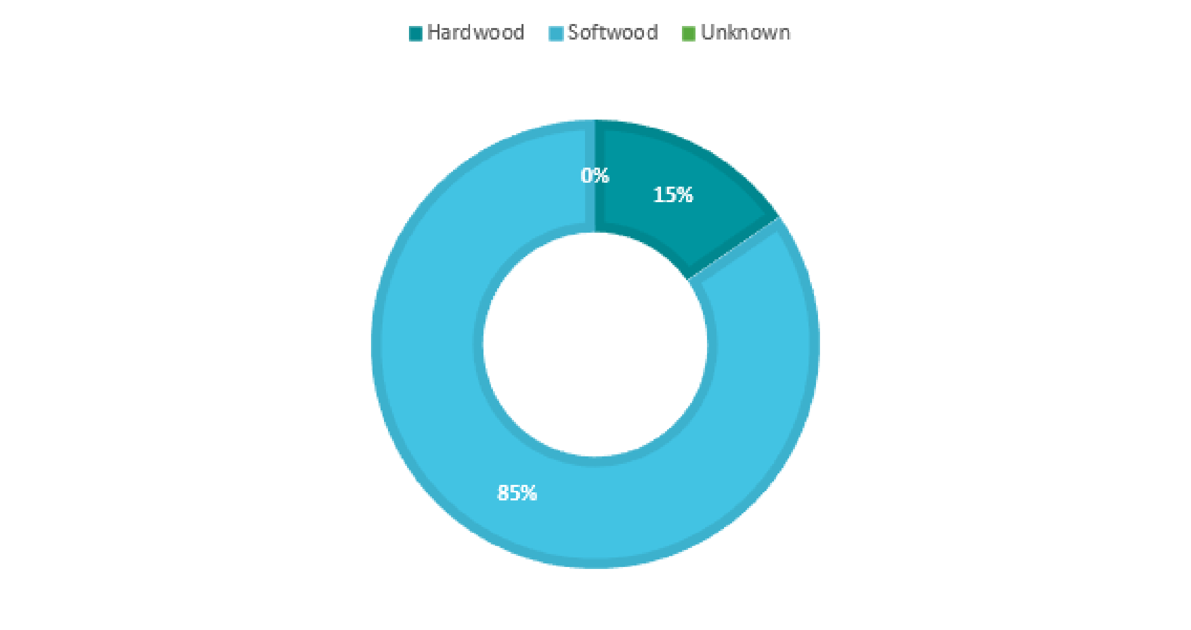

Figure 35 – Distribution of forest carbon by plantation forest type in 2020, indicating that the vast majority of forest carbon within plantations is within the softwood estate. Developed with the 'Mid' forest growth rate where G=10.

6.2. Soil Carbon

As described previously, while the simulation closely reflects the soil modelling within FullCAM 2020 release, there is low confidence in the soil carbon values. To demonstrate the difference between year 1, where results are largely influenced by the NSW DPI soil carbon data, and year 75, the year the NSW DPI data represents (2010), a comparison was created. The results indicate that the modelled results are an average of 62% higher in year 75 than year 1 (Figure 36 & Figure 37); however, this varies from a decrease of 30 percent to increases of over 700 percent. As unrealistic soil carbon numbers have been identified (>500 tonnes carbon per hectare in the top 30cm), only results for the Southern RFA region are presented here to illustrate the issues within the results. The increases in soil carbon appear to be driven by high amounts of carbon moving through the belowground biomass pools into the soil. The current FullCAM calibrations result in up to three times the carbon being turned over from the belowground biomass pools than the aboveground biomass pools. A further review of the forest and soil carbon interactions is required before full results can be presented.

There is current research being developed to improve data for modelling soil under forests. It is expected that these parameters will be released in 2022. FLINTpro can be updated once these details have been released.

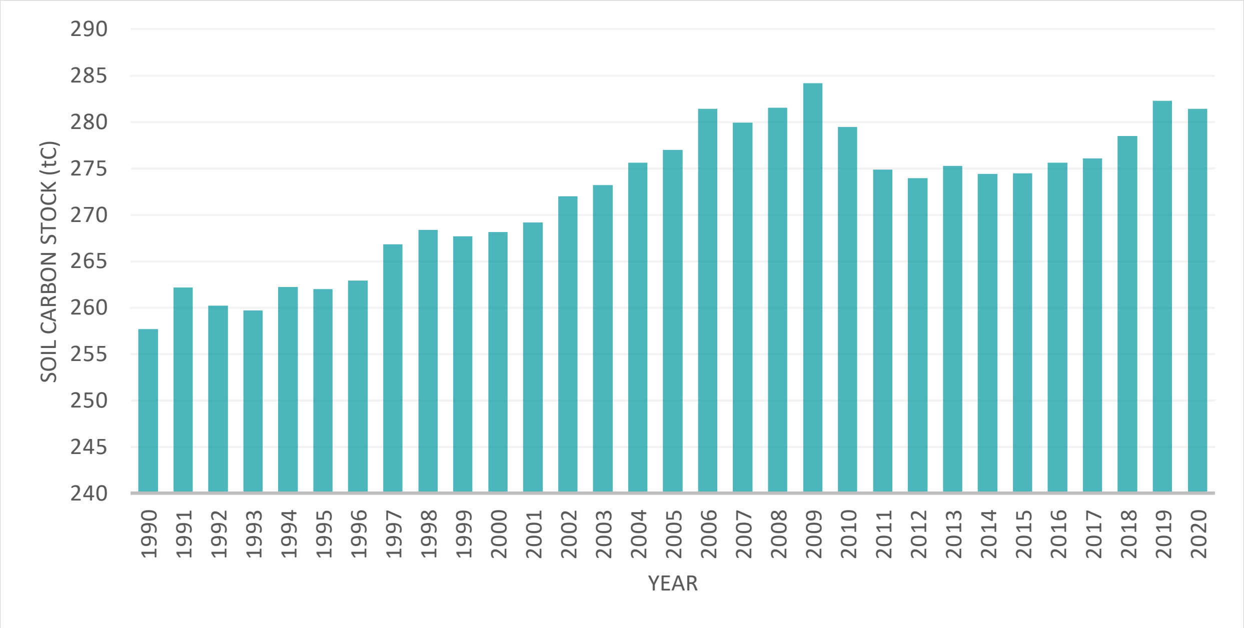

Figure 36 – Change in Soil Organic Carbon stock within the Southern RFA Region of NSW. The results indicate continual increases in soil carbon within the Southern RFA region; however, the outputs of the modelling do not well align with alternative estimates.

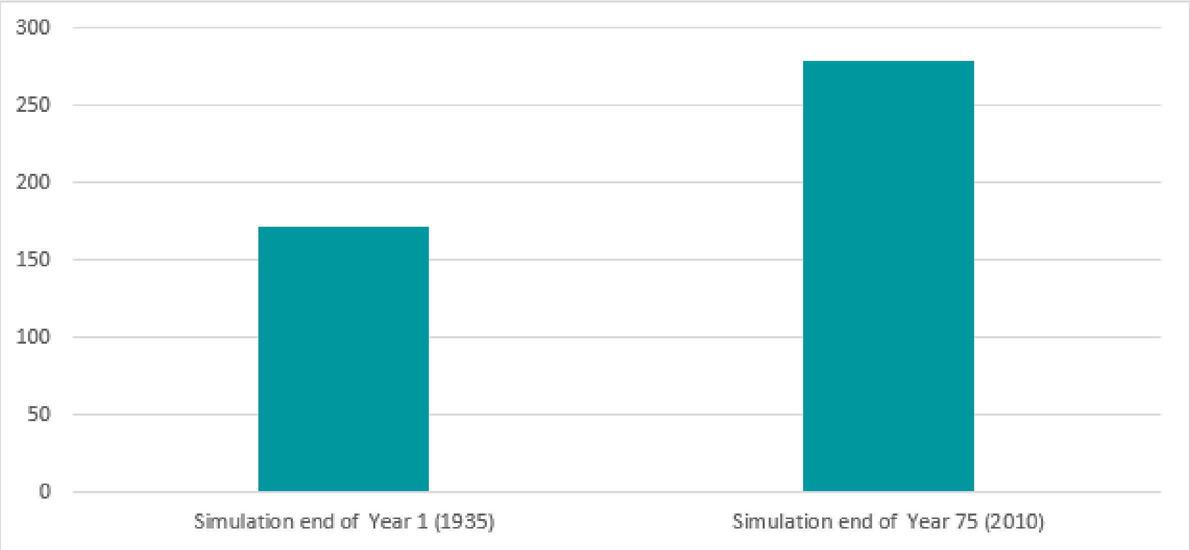

Figure 37 – Comparison of the Soil Organic Carbon estimates for Southern RFA Region at the end of year 1 and 75. Results at the end of Year 1 closely reflect the underlying NSW DPI data with one year of change, while 2010 is largely influenced by the modelled outputs. The results suggest there is an issue with components of the calibrations used in the models that is impacting on the soil organic carbon values.

6.3. Comparison of data inputs

6.3.1. Modifying Growth Rates

As described previously, FullCAM's TYF can be modified to increase or decrease growth rates of forests through modifying the G parameter. Lowering the value of G increases the rate of growth, while increasing G decreases the rate of growth. To test the sensitivity, the G parameters of 6.37, 10, and 12.53 were modelled, and given the scenario name of High, Mid, and Low respectively.

The results indicate that changing the G parameter changes the estimated carbon stock. The High scenario was, on average, 11 percent higher than the Mid scenario, while the Low scenario was, on average, 6 percent lower than the Mid scenario. While there is a change in the quantum, the trend in the data is generally consistent (Figure 38 & Figure 39).

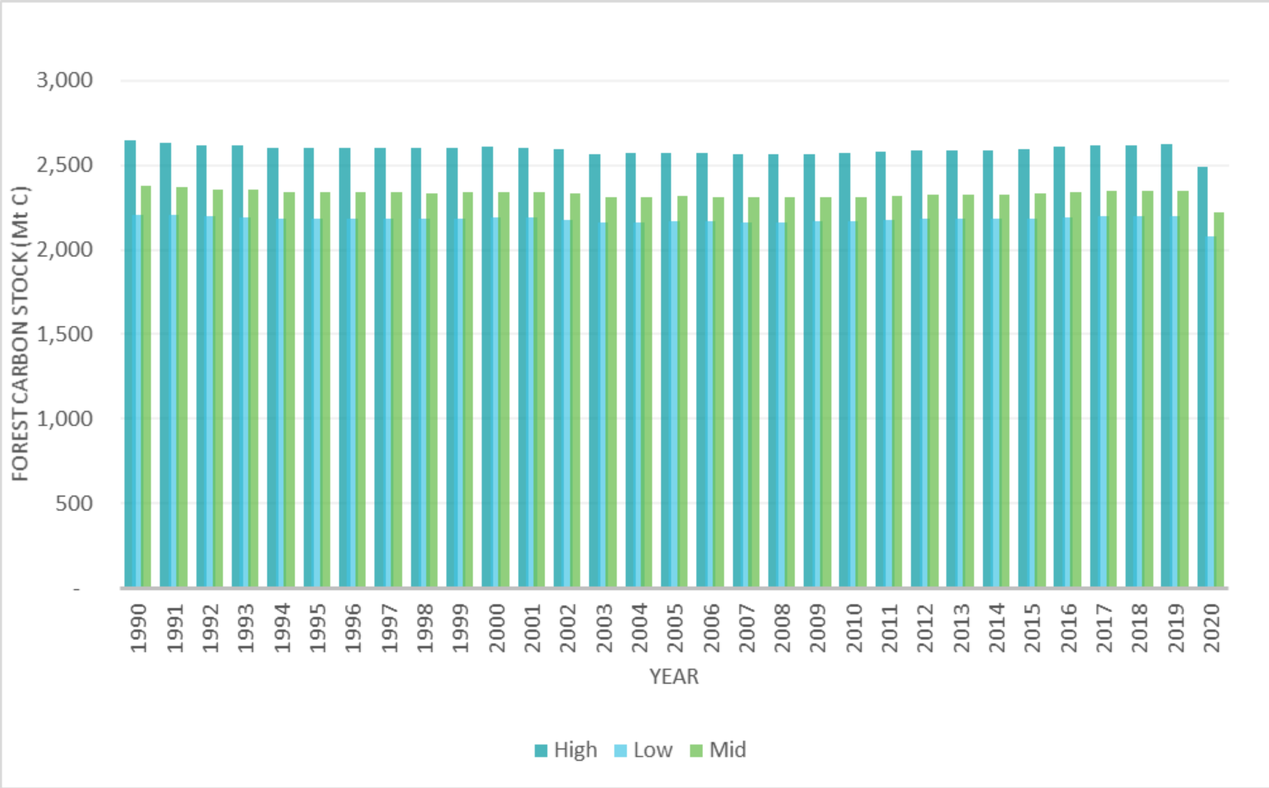

Figure 38 – Comparison of forest carbon stock estimates based on High (G=6.37), Mid (G=10) and Low (G=12.53) Scenarios for NSW.

Figure 39 - Comparison of net change in forest carbon stock based on the High (G=6.37), Mid (G=10) and Low (G=12.53) Scenarios for NSW.

6.3.2. Forest Cover Data

Through this project, the NSW forest extent data was used to replicate the Run for the Regional Forest Agreement (RFA) regions of NSW. The results indicate that there was a minor change in the forest carbon values between the NCAS and the NSW Forest Extent data (Figure 40**Error! Reference source not found.**). The results indicate there was an average difference of 2 percent between carbon stock estimates derived from the NSW Forest Extent data and the NCAS forest cover data. A deeper analysis into variation in carbon stock change and spatial variation was not conducted as part of this project.

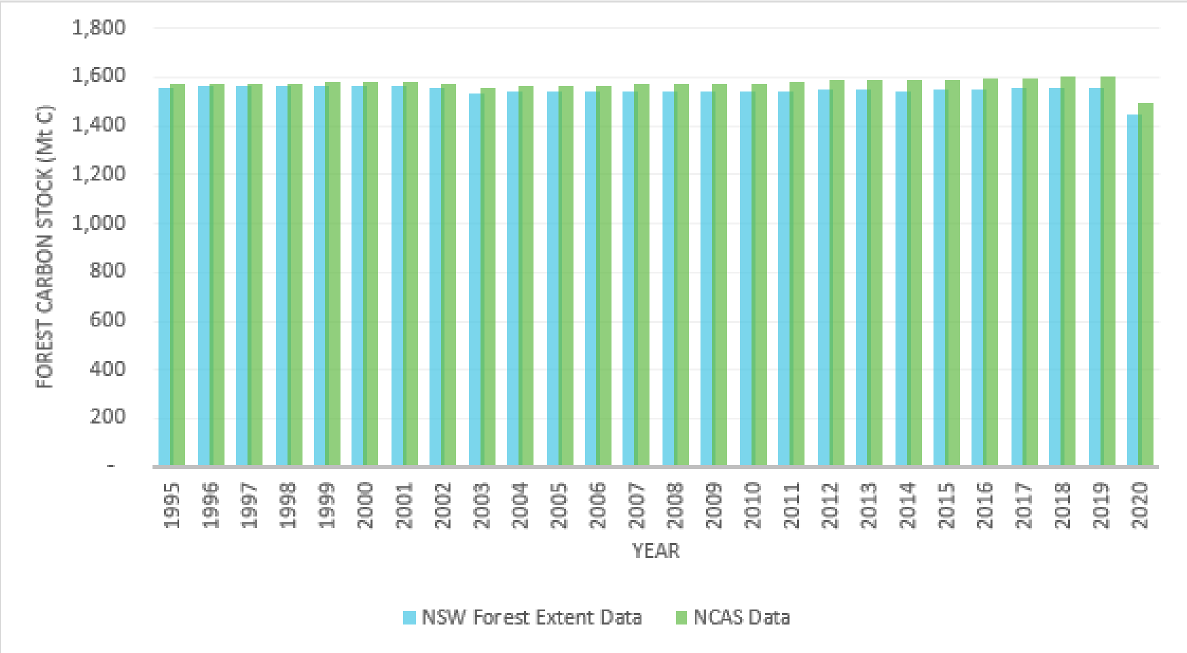

Figure 40 – Comparison of the forest carbon estimates using different forest cover products. Data provided from NSW Forest Extent Data and NCAS Data.

7. Drivers of Change

With the exception of 2003 and 2020 fire seasons, the majority of change in forest carbon stock across NSW was driven by forest cover loss and forest cover gain (Figure 41 & Figure 42). In general, most of the change occurred in areas outside of the NSW state forest and national park estate (Figure 43), which is reflected in the forest carbon stock estimates. The forest cover data also highlights the correlation between forest cover loss as detected by remote sensing and fire events. The high forest cover loss detected in national parks in 2020, for example, corresponds with the fire data (Figure 41).

Through the outputs database, it is not possible to distinguish harvesting from other tree removal events. At the state level, timber harvesting within NSW is a comparatively minor disturbance type in comparison to forest cover loss (Figure 44).

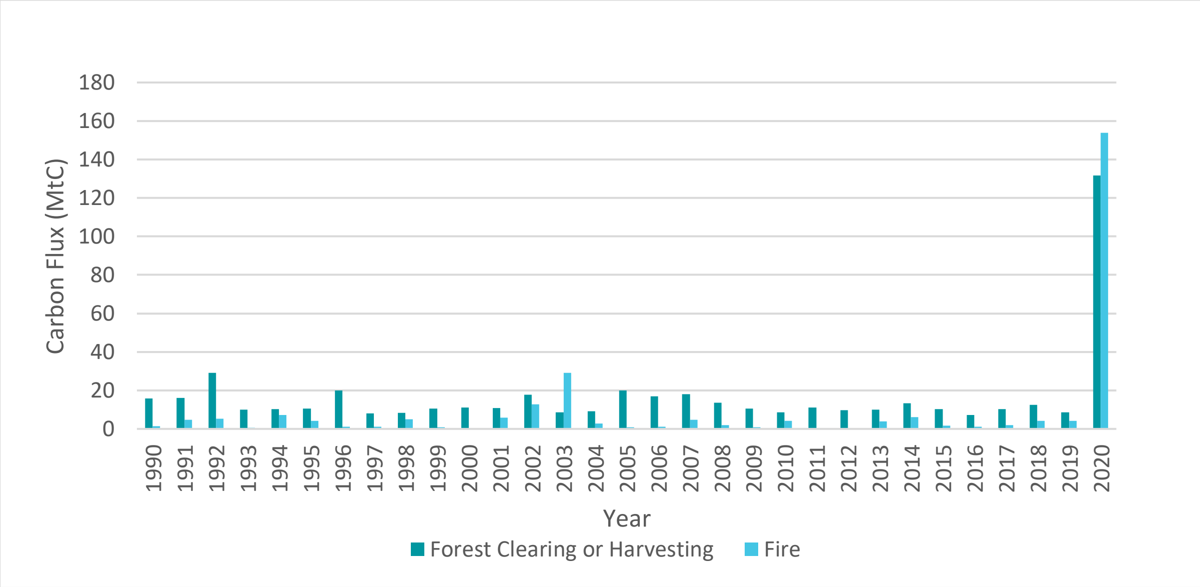

Figure 41 – Carbon Fluxes (movements) from clearing and harvesting and fire. Forest clearing or harvesting result in movements of carbon from Forest Aboveground Biomass and Forest Belowground Biomass to the Dead Organic Matter Pool or Harvested Wood Products Pools. Fire results in movements from Aboveground Biomass and Dead Organic Matter to the Atmosphere and Dead Organic Matter pools. The presented fluxes do not represent net emissions to the atmosphere.

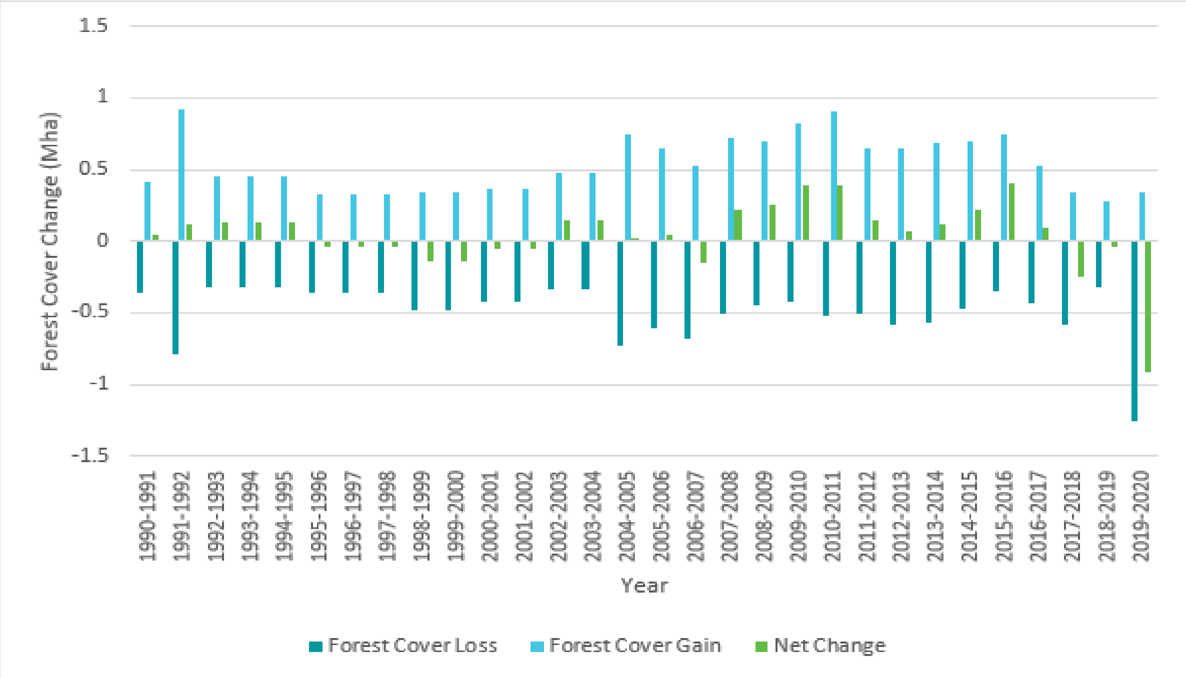

Figure 42 – Change in Forest Cover for NSW as determined from the NCAS forest cover data.

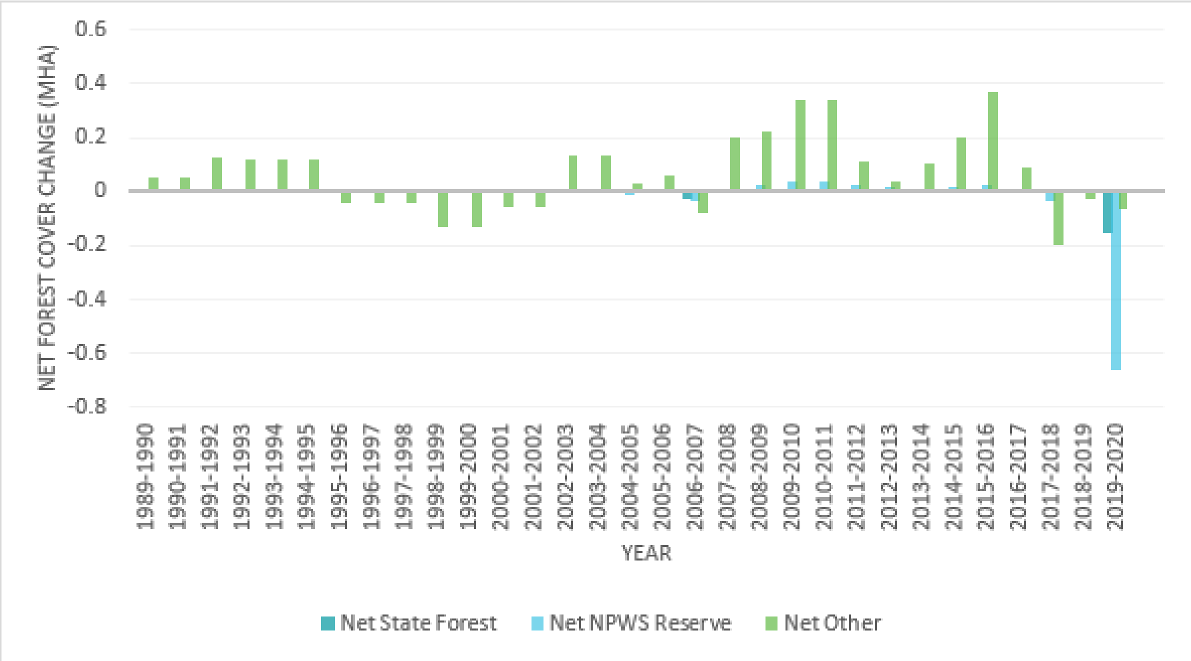

Figure 43 – Net change in Forest Cover by land tenure in NSW as determined from the NCAS forest cover data.

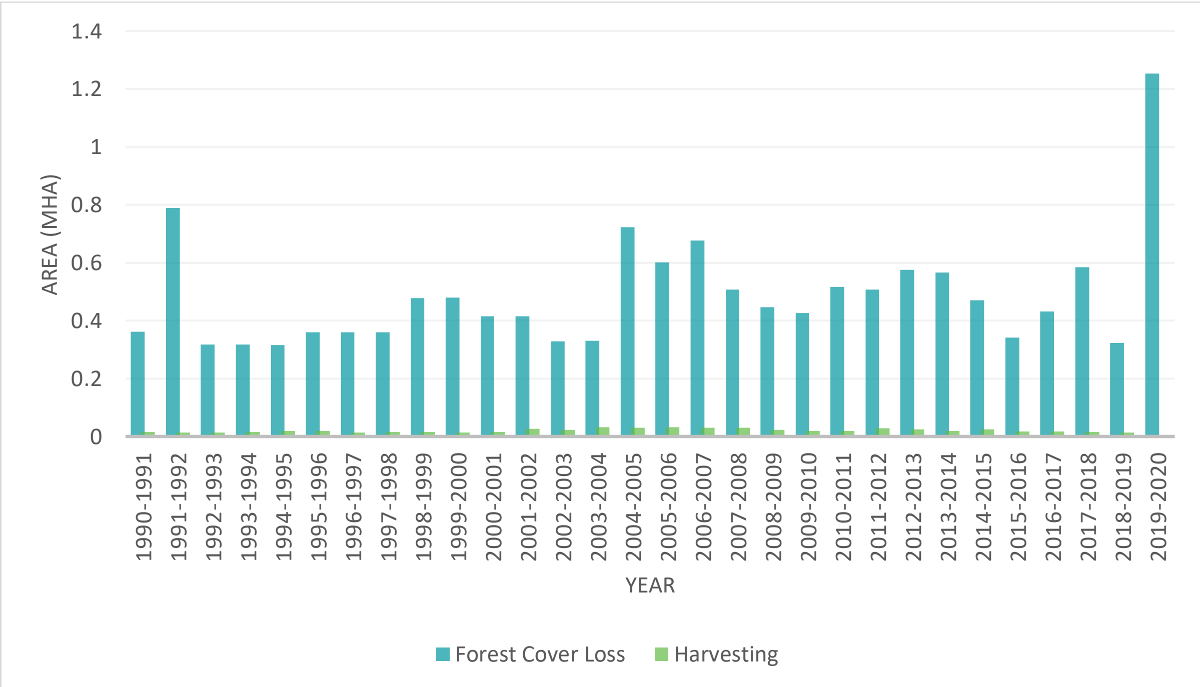

Figure 44 – Comparison of the area of forest cover loss in comparison with area harvested. Noting that harvest events in plantations are excluded from the harvest data. Forest cover loss data is derived from the NCAS data, while area harvested is from FCNSW harvest data, which excluded plantations.

7.1.1. 2019/2020 Fire Season

The impact of the 2019/2020 fire season on forest carbon represents the largest annual change in forest carbon across the 90 years modelled under this assessment. The fires are modelled to have directly resulted in 90 Mt carbon moving from the forest biomass (AGB & DOM) to the atmosphere, and an additional 63 Mt carbon from the living to the dead organic matter pools (Figure 45).

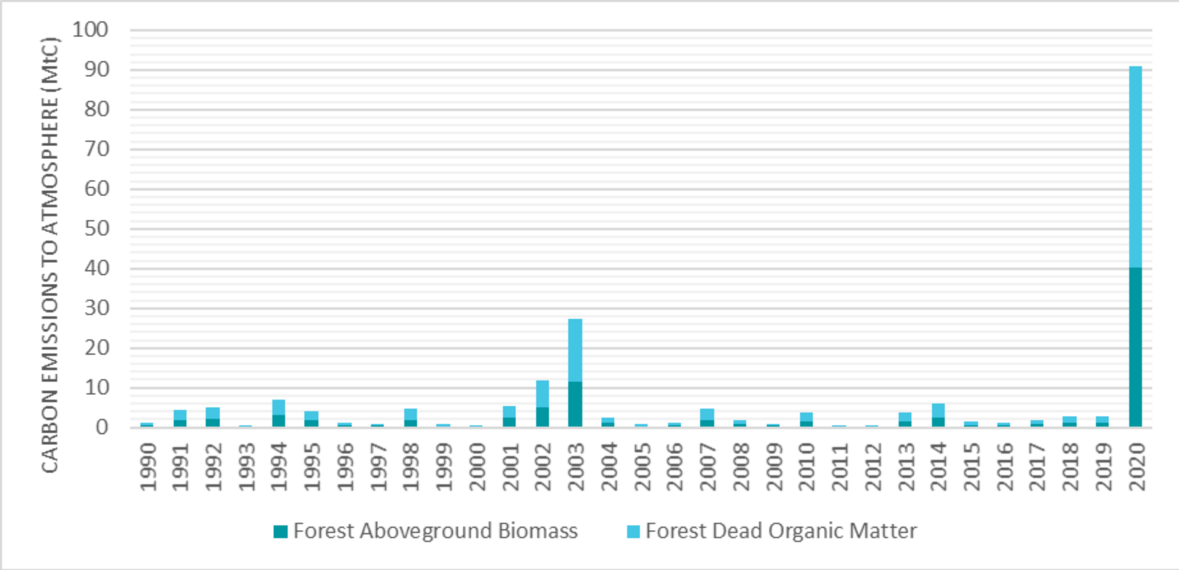

Figure 45 – Movements of carbon from forest aboveground biomass and dead organic matter to the atmosphere as a result of the 2019/2020 fire season.

There are some anomalies in the forest cover data associated with areas impacted by the 2020 fires, which will flow through to the forest carbon stock results for 2020 (Figure 46). This includes hard borders, regular shapes (circles and squares), and banding within the forest cover product for areas impacted by the 2020 fire season. These anomalies were caused through scene selection and masking process used in developing the national data products, where pre- and post-fire scenes were included in the layer (Furby, pers comms. 2021). It is expected that with the 2021 update, these anomalies will be reduced, and where they have not, could be improved through manual scene selection.

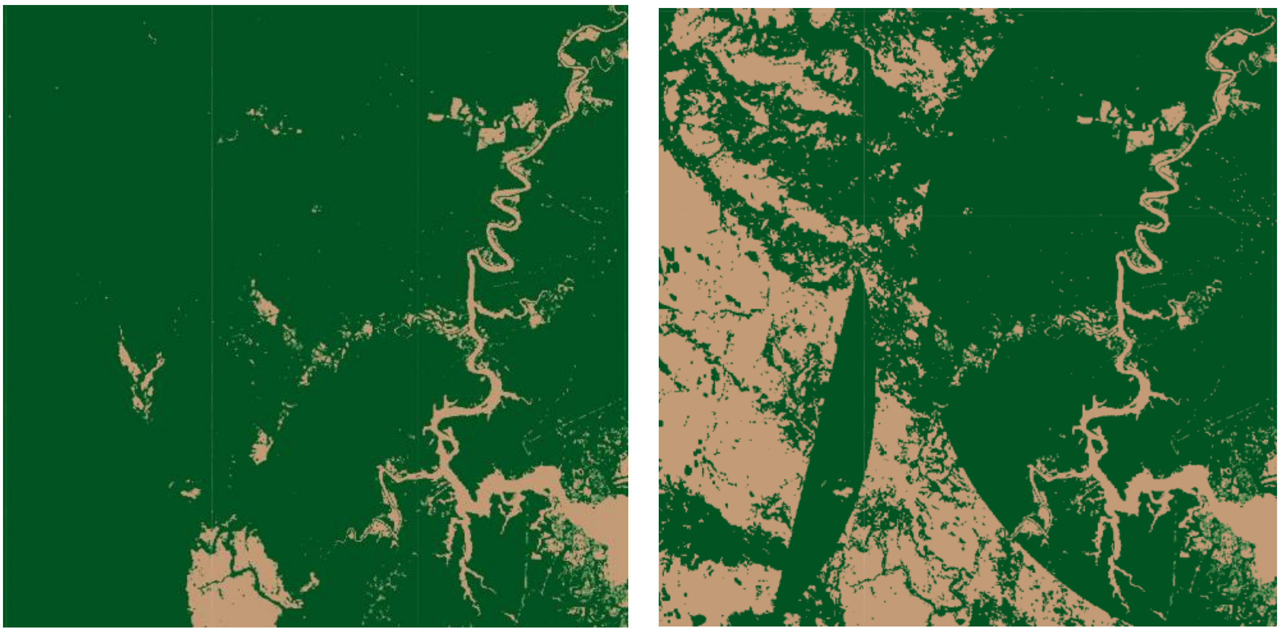

Figure 46 – Forest Cover data for a region of NSW in 2019 (left) and 2020 (right image), showing significant areas of forest cover loss post the 2020 fire, as well as anomalies in the data created through the image selection process (circles)

8. 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. 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 (DISER 2020). This relates largely to the modelling of multi-use forests. For forest land converted to grassland or cropland, or land converted to forest land, the uncertainty is reported to be +/- 3.5 per cent, with uncertainty on standing biomass of +/- 11.5 per cent (DISER 2020). While national parks are not necessarily included within the NGGI, 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 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 the measured data to assess accuracy of the output.

Updates from the Previous Version

A number of updates have been made to the database between the initial version of the Simulation (as reported in Version 4.1) and this version. Most of the updates critically relate to the treatment of fire and plantations post-thinning.

The incorporation of fire severity required additional Rules, modified some years of the previous run, and also provided the opportunity to revisit the original RFS data. The FESM data replaced the previous wild fire data for 2017 and 2018, which would impact on the carbon stock estimates for those years. Through the update to the run, additional fire years were also incorporated into the modelling extending fires from 1950 back to 1935.

Secondly, the biomass age adjustment was turned on for plantation forests. For the first iteration, the biomass age adjustment was not turned on for plantations forests following a thin event. In the re-simulation, this assumption was revisited and the biomass age adjustment was turned on for plantations forest after partial harvest events. These changes to how forests respond post thinning had minor impacts on the estimate of forest carbon stock (<1%), however it did materially change the estimate of change compared to a 1990 baseline (Figure 47).

The plantation calibrations will be updated again in 2022 for the NGGI and it is expected that the contribution of plantations will vary with further iterations of FullCAM. The update is expected to exclude the biomass age adjustment.

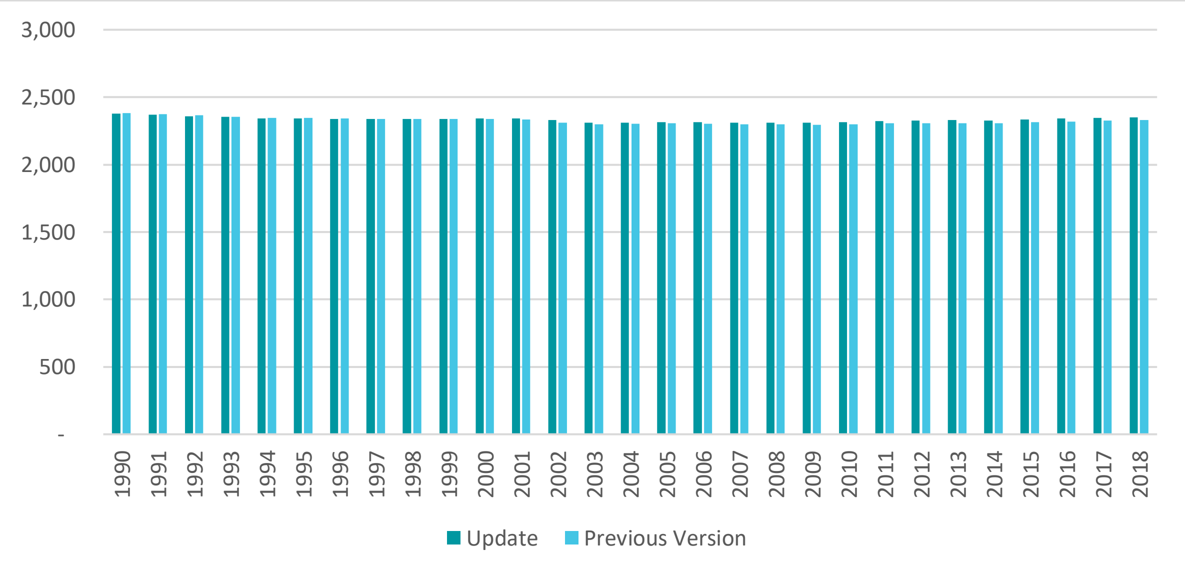

Figure 47 – Comparison of the Update (current) simulation for NSW compared with the previous version. The changes largely stem from changes to the biomass age adjustment in forests managed for timber production, both plantation and native forests.

9. Conclusion

Through this project we were able to develop an estimate of the forest carbon balance for NSW Forests from 1990 to 2020. The results indicate that 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 project demonstrates not only the importance of having a comprehensive forest monitoring system to provide insights into the system, it also highlights the importance of having an operational system for conducting the analysis.

While the output of this project represents a significant advancement in the understanding of the dynamics of forest carbon across NSW, the output would be significantly improved through improving data and expanding the model coverage. This includes taking advantage of new data sets being developed under the NSW Forest Monitoring and Improvement Program, as well as by research organisations independent of the monitoring program. It is recommended that the priority areas for improvement are:

- Attributing change in forest cover to have delineation between anthropogenic and natural disturbances.
- Improving Soil Organic Carbon predictions and incorporating the impacts of fire on Soil Organic Carbon
- Improved initial carbon stock estimates for native and plantation forests

As the largest changes in the forest carbon stock occur in forested areas outside of State Forests and the NSW Reserve system, it is recommended that forested areas on other crown land, private land and indigenous management areas be prioritised for data improvements.

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11. Annex 2 – Summary of Improvements to the Modelling System

Tree Biomass

- Update the TYF parameters for plantations and native forests when made, or if resources are available, use forest type specific calibrations reflecting NSW forest types, including calibration of parameters to datasets collated from NSW forest types (e.g. allocation of biomass, litterfall, decomposition of debris, and impacts of thinning and fire on carbon pools).

Representation of Species

- 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.
- When available, use updated FullCAM events for harvested native forests, including a re-classification of forest types and data-informed revision of model parameters (allocation, turnover, standing dead, debris, and soil carbon) and the impacts of different types of disturbances of differing severities on carbon dynamics.
- Exclude or modify database for modelling horticultural crops using NSW-specific land use masking data.
- Modify how Urban forests are modelled to better reflect the different growth capacity.

Soil Carbon

- Improved calibrations of inputs of carbon into the soil under forests, including using updated parameters of FullCAM when available to improve confidence in soil carbon values under forests (particularly plantation forests).
- Expand to include non-forest carbon sources (grassland and croplands)
- Set soil carbon stock in 2010 to values estimated by Gray et al (2019) and adjust initial soil carbon stock to be consistent with these values, and also assess whether a longer model ‘run-in’ is required to attain near equilibrium initial soil carbon values.
- Incorporate modifications to RothC for how topsoil moisture deficit is calculated

Model Initialisation

- 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. This may assist with introducing more spatial variation within the pre-1990 results.
- Back calculating the plantation ages for plantations present in 1988 based on observed harvest times.

- Developing a complete timeseries of forest cover from the earliest year possible
- Include a true timeseries of plantation extent from 1988 onwards.

Fire Modelling

- Expanding spatial-temporal data on fire severity class to incorporate vegetation type responses to improve the estimates of the impacts of fire on carbon pools. However, further research would be required to calibrate each of the NSW forest types.
- Implementation and calibration of standing dead pools and rates of post-fire recovery of biomass and fuel pools in NSW forests.
- Implementation of residue burning fire events in addition to hazard reduction and wildfire events
- Retrospective application of fire severity classes for entire modelling period once data is available

Forest Clearing Modelling

- Only apply a forest clearing event where there is a transition of forest cover to non-woody biomass, as opposed to just when there is forest cover loss. While FLINTpro can model these changes, there is currently insufficient data on how the biomass would change through these transitions.
- 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 re-planting 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.

Reforestation Modelling

- 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 would be needed.
- 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.

Harvest Modelling

- Improve the temporal changes in harvesting (i.e. changes in silviculture – historically and in future (e.g. post-2018 Coastal IFOA conditions) for public and private forests). The FLINTpro structure supports this, however the data was not available to support this functionality.
- Expand the silvicultural treatments that can be applied and ensure that the impacts of these treatments on growth responses is well calibrated.

Harvested Wood Products

- Model temporal cohorts to better represent the life cycle of harvested wood products in use
- Model the movement of harvested wood products into landfill and long-term carbon dynamics

Combination of Events

- Include more sophisticated delineation of forest loss events associated with fire from forest cover loss events caused by non-fire triggers.

12. Annex 3 – Data Requirements

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

Dataset Name	Type	Description
FullCAM_RothC_DB V43 -Mid -G10	SQLite Database (.sqlite)	Classification: Database. Dataset Name: FullCAM_RothC_DB V43 -Mid -G10.sqlite ID: f1c21c37be7b4899b4153d9e3ec91c62 Data Type: SQLite Database (.sqlite). The sqlite database has been created by the Mullion Group.
FullCAM_RothC_DB V43 - Low -G12.53	SQLite Database (.sqlite)	Classification: Database. Dataset Name: FullCAM_RothC_DB V43 - Low -G12.53.sqlite ID: 4e31dde2d56f442cbad41e02df09391b Data Type: SQLite Database (.sqlite). The sqlite database has been created by the Mullion Group.
FullCAM_RothC_DB V43 - HIGH -G6.317.sqlite	SQLite Database (.sqlite)	Classification: Database. Dataset Name: FullCAM_RothC_DB V43 - HIGH -G6.317.sqlite ID: 4e31dde2d56f442cbad41e02df09391b Data Type: SQLite Database (.sqlite). The sqlite database has been created by the Mullion Group.
NSW State Boundary	Vector - Geojson (.geojson)	Classification: Administrative Boundary (Level 3). Dataset Name: NSW State Boundary. ID:b29c86380a6b47eb89e1ba2ff1986d51. 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 Pre-1750	Raster - Tiff (.tif)	Classification: Ecological Zone. Dataset Name: MVG 5.1 Pre-1750. ID:41703737eb654dd2abff6ba32eb7ce6a. Data Type: Raster - Tiff (.tif). National Vegetation Information System V6.0 © 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 Annual Fire - 2 Class	Raster Time-Series - Tiff (.tif)	Classification: Annual Fire. Dataset Name: NSW Annual Fire - 2 Class. ID:9c10ee403dc147d38dc3dcf573b8a655. Data Type: Raster Time-Series - Tiff (.tif). Description Combined datasets of fire extent from RFS and Forestry Corporation converted to tiff raster format. 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
Harvest Time Series - With Projection (1950-2030)	Raster Time-Series - Tiff (.tif)	Classification: Annual Harvest. Dataset Name: Harvest Time Series - With Projection (1950-2030). ID:20527c53a77c424f95c59c043535c1a2. Data Type: Raster Time-Series - Tiff (.tif). Description Forestry Corporation dataset of annual harvest extent converted to tiff raster format. Harvest events within State Forests between 1990-2019 projected to 2020-2030. ©Forestry Corporation Accessed at: Acquired from NSWFC

Plantation Extent 2016 (Mapped as 1935)	Raster Time-Series - Tiff (.tif)	Classification: Plantation Extent. Dataset Name: Plantation Extent 2016 (Mapped as 1935). ID:02210067df344ff9af7bfe1aa117be0c. Data Type: Raster Time-Series - Tiff (.tif). Description: 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 International. Accessed at: https://www.data.gov.au/dataset/ds-dga-61351472-9ab5-45e4-a90b-3bf18ce51caf/details?q=2016%20plantation
NSW_NPI_Regions	Vector - Geojson (.geojson)	Classification: National Plantation Inventory Regions. Dataset Name: NSW_NPI_Regions.geojson ID: 88b5398fd4e446f79d95f03778ee1a8b Data Type: Vector - Geojson (.geojson). Description: National Plantation Inventory Regions, developed by ABARES, clipped to NSW Creative Commons Attribution 4.0 International. Accessed at: https://www.data.gov.au/dataset/ds-dga-61351472-9ab5-45e4-a90b-3bf18ce51caf/distribution/dist-dga-bf9e7853-2051-4cd2-9c2a-bd29cf50bc36/details?q=NPI
NCAS Forest/Non-Forest 2020	Raster Time-Series - Tiff (.tif)	Classification: Forest/Non-Forest Cover. Dataset Name: NCAS Forest/Non-Forest 2020. ID:e771c3e47d1f4dd6bcfe02fb0fb6e4f1. Data Type: Raster Time-Series - Tiff (.tif). **Description:** Forest Cover data from 1988 to 2020 adapted from National Forest and Sparse Woody Vegetation Data (Version 3, 2020 Release) created by Department of the Environment and Energy. Sparse Woody vegetation was converted to non-forest land cover. Accessed under Creative Commons Attribution Share Alike 4.0 International. Accessed at: https://data.gov.au/data/dataset/d734c65e-0e7b-4190-9aa5-ddbb5844e86d

NSW Forest Extent Data Forest/Non-Forest 1995-2020	Raster Time-Series - Tiff (.tif)	Classification: Forest/Non-Forest Cover. Dataset Name: NSW Forest Extent Data Forest/Non-Forest 1995-2020 ID: 6b8f4a3295ae4e91960ecde0b0deb024 Description: Forest Cover data for NSW RFA regions from 1995-2020. Data provided by Spatial Vision. Based on Wood_Extent_Base.Zip.
Average Forest Productivity Index (V2.0 - 2019)	Raster - Tiff (.tif)	Classification: Forest Productivity Index (Long Term Average). Dataset Name: Average Forest Productivity Index (V2.0 - 2019). ID:82484315eb1346818f25c8d7178750b0. Data Type: Raster - Tiff (.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 - Tiff (.tif)	Classification: Potential Forest Aboveground Biomass. Dataset Name: ERF Potential Forest Aboveground Biomass (V2.0 - 2019). ID:c60d8123282b48958950bd5dda64ee81. Data Type: Raster - Tiff (.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
FPI Time-Series	Raster Time-Series - Tiff (.tif)	Classification: Forest Productivity Index (Time Series). Dataset Name: FPI Time-Series. ID:0fe591b7a7e743d2b632260ad486f11c. Data Type: Raster Time-Series - Tiff (.tif). Product acquired from Australian Government Department of Industry, Science, Energy and Resources. Adaptation of dataset included merging tiles. Accessed at: Acquired from DISER
Monthly Rainfall	Raster Time-Series - Tiff (.tif)	Classification: Monthly Rainfall. Dataset Name: Monthly Rainfall. ID:5e0f8373f637419589fdd486c7fc436b.

		Data Type: Raster Time-Series - Tiff (.tif). Product acquired from Australian Government Department of Industry, Science, Energy and Resources. Adaptation of dataset included merging tiles. Accessed at: Acquired from DISER
Monthly Air Temperature	Raster Time-Series - Tiff (.tif)	Classification: Monthly Air Temperature. Dataset Name: Monthly Air Temperature. ID:3f4157b9204f43cc817c7d4ac6b2c58f. Data Type: Raster Time-Series - Tiff (.tif). Product acquired from Australian Government Department of Industry, Science, Energy and Resources. Adaptation of dataset included merging tiles. Accessed at: Acquired from DISER
Open-Pan Evaporation	Raster Time-Series - Tiff (.tif)	Classification: Monthly Open-Pan Evaporation Dataset Name: ANUClimate 2.0 pan evaporation ID: 27098dfeeb0a49ffb6fe863803c23863 Data Type: Raster Time-Series - Tiff (.tif). Description: Monthly class A pan evaporation for the Australian continent from 1970 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 pan evaporation is the total pan evaporation for each month, as recorded at each of around 200 to 300 stations 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 pan evaporation is modelled by expressing each value as a ratio anomaly with respect to the 1976-2005 monthly mean pan evaporation as interpolated by a thin plate smoothing spline function 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. 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 pan evaporation grids. Automated quality assessment for the period 1970-2017 rejected on average 2.7 data values per month (1.2%) with extreme studentised residuals. Point-wise cross validated values of the fitted spline surfaces for the period 1970-2017 gave mean bias of 0.3 mm (0.2% of the mean), a mean absolute predictive error of 17 mm (11% of the mean) and a root mean square predictive error of 23 mm (15% of the mean). Accessed at: Acquired from ANU
RPM Initial Mass	Raster - Tiff (.tif)	Classification: Initial Soil Carbon (RPM) Dataset Name: RPM Initial Mass ID: 13a21dd74b674638bde5d49b0ba65603 Description: Initial Mass of RPM based on POC values from NSW DPI . The dataset contains digital soil maps of three principal soil organic carbon (SOC) fractions across NSW: particulate organic carbon (POC), humic organic carbon (HOC) and resistant organic carbon (ROC), which represent fractions of increasing bio-chemical stability. The 100 m resolution rasters cover depth intervals 0-10 cm, 10-30 cm and 0-30 cm. Maps for mean, lower 5% and upper 95% confidence intervals are provided. They were derived from random forest modelling of 427 profile points across NSW from 2008-09 with mid-infrared (MIR) derived carbon fractions and a set of 16 predictor variables. The products are important for modelling soil carbon dynamics for carbon accounting, and as a potential indicator of soil quality. The products are more fully described in: Gray JM, Karunaratne SB, Bishop TFA, Wilson BR, Veeragathipillai M 2019, Driving factors of soil organic carbon fractions over New South Wales, Australia. Geoderma 353, 213-226. https://doi.org/10.1016/j.geoderma.2019.06.032
HUM	Raster - Tiff (.tif)	Classification: Initial Soil Carbon (HUM) Dataset Name: HUM.tif ID: 701577aebe5d400aae85787010515ff8 Description: Initial Mass of HUM based on HOC values from NSW DPI . The dataset contains digital soil maps of three principal soil organic carbon (SOC) fractions across NSW: particulate organic carbon (POC), humic organic carbon (HOC) and resistant organic carbon (ROC), which represent fractions of increasing bio-chemical stability. The 100 m resolution rasters cover depth intervals 0-10 cm, 10-30 cm and 0-30 cm. Maps for mean, lower 5% and upper 95% confidence intervals

		are provided. They were derived from random forest modelling of 427 profile points across NSW from 2008-09 with mid-infrared (MIR) derived carbon fractions and a set of 16 predictor variables. The products are important for modelling soil carbon dynamics for carbon accounting, and as a potential indicator of soil quality. The products are more fully described in: Gray JM, Karunaratne SB, Bishop TFA, Wilson BR, Veeragathipillai M 2019, Driving factors of soil organic carbon fractions over New South Wales, Australia. Geoderma 353, 213-226. https://doi.org/10.1016/j.geoderma.2019.06.032
Inert	Raster - Tiff (.tif)	Classification: Initial Soil Carbon (Inert) Dataset Name: Inert.tif ID: e65cb87687c04f5a961218545ec93f5b Description: Initial Mass of Inert based on ROC values from NSW DPI . The dataset contains digital soil maps of three principal soil organic carbon (SOC) fractions across NSW: particulate organic carbon (POC), humic organic carbon (HOC) and resistant organic carbon (ROC), which represent fractions of increasing bio-chemical stability. The 100 m resolution rasters cover depth intervals 0-10 cm, 10-30 cm and 0-30 cm. Maps for mean, lower 5% and upper 95% confidence intervals are provided. They were derived from random forest modelling of 427 profile points across NSW from 2008-09 with mid-infrared (MIR) derived carbon fractions and a set of 16 predictor variables. The products are important for modelling soil carbon dynamics for carbon accounting, and as a potential indicator of soil quality. The products are more fully described in: Gray JM, Karunaratne SB, Bishop TFA, Wilson BR, Veeragathipillai M 2019, Driving factors of soil organic carbon fractions over New South Wales, Australia. Geoderma 353, 213-226. https://doi.org/10.1016/j.geoderma.2019.06.032
DPM	Raster - Tiff (.tif)	Classification: Initial Soil Carbon (DPM) Dataset Name: DPM - Initial Stock of 0 ID: f1a59bc2a43d49879d8d4767bdd1f3a0 Description: Zero biomass assumed for DPM, holding data created for this purpose.
BIO-S	Raster - Tiff (.tif)	Classification: Initial Soil Carbon (BIO-S) Dataset Name: Initial Bio-S.tif ID: ec67450f36f24663a9ddeefbefd75ec9 Description: Zero biomass assumed for BIO-S, holding data created for this purpose.

BIO-F	Raster - Tiff (.tif)	Classification: Initial Soil Carbon (BIO-F) Dataset Name: Initial Bio-S ID: ec67450f36f24663a9ddeefbefd75ec9 Description: Zero biomass assumed for BIO-F, holding data created for this purpose.
Clay Frac	Raster - Tiff (.tif)	Classification: Soil Clay Fraction Dataset Name: Clay Frac ID: c6b1c9a77b65492da7ed07c0b2b7aad0 Description: Soil Clay Fraction provided by NSW DPI

13. Annex 4 - Summary of known data issues

In developing the output, a number of errors in the input data were identified that create errors in the outputs. These errors affected 1,363 hectares of NSW, which will not be sufficient to confound the results presented (Figure 48); however, if a similar assessment was to be repeated, it is recommended that these issues be rectified.

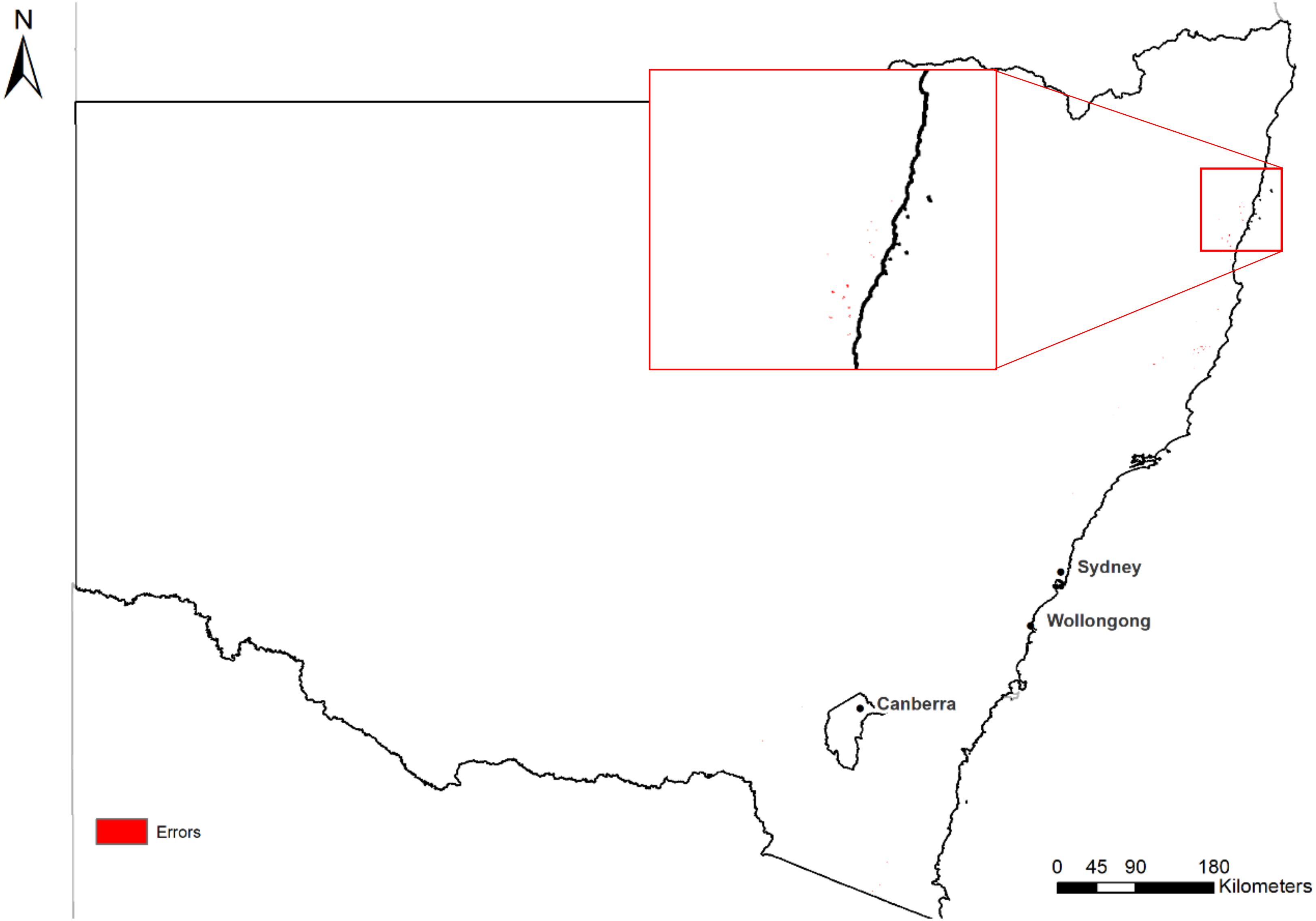

Figure 48 – Spatial output highlighting areas where errors occurred within the Run (red on the map).

Table 8 – Issues within the input data that created errors within the Run

Data Layer	Issue	Impact
NSW Parks & State Forest Boundaries	Overlapping boundaries	When assessed in isolation, there will be a small double counting of land.
Harvest Data & Plantation Extent	Areas mapped as plantation are subject to native forest harvest events, creating an illogical sequence.	Pixels where there is an illogical combination of spatial data are not simulated.