Downscaling – The role of forestry in enhancing the Australian land CO2 sink

19 April 2023

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The Net Zero Australia (NZAu) project is a collaborative partnership between the University of Melbourne, The University of Queensland, Princeton University and management consultancy Nous Group. The study examines pathways and detailed infrastructure requirements by which Australia can transition to net zero emissions, and be a major exporter of low emission energy and products.

Net Zero Australia

Downscaling – The role of forestry in enhancing the Australian land CO_2 sink

19 April 2023

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1 Introduction

Globally, an important role has been identified for natural ecosystem carbon sequestration and storage processes in mitigating climate change through net carbon dioxide (CO_2) removals (IPCC, 2018, 2019). Within the forestry sector, the main activities with potential for providing emissions abatement are:

- Reforestation and afforestation of land,
- Reductions in (or avoidance of) deforestation.
- Improving forest management,
- Increasing retention of carbon in harvested wood, and
- Increasing use of woody biomass waste and residues for bioenergy.

These various forestry-based activities have different abatement potentials, as well as different levels of uncertainty in estimates of carbon accounting, barriers to adoption and technical and social feasibility. These various factors are explored in this report, in the context of *Net Zero Australia's* (NZAu) modelled pathways to net zero GHG emissions.

In recent years Australia's land use, land-use change, and forestry (LULUCF) sector has been a net sink of carbon dioxide, accounting for −25.1 Mt-CO_2e in the 2019 GHG inventory (DISER, 2021). Projections of business-as-usual activity suggest that while current trends of net sequestration of CO_2 may continue in coming years, the rate of this net CO_2 removal can be expected to reduce due to the aging of forests and resulting lower rate of carbon uptake in trees, and the increasing occurrence of disturbances such as bushfires (Abram et al., 2021; Canadell et al., 2021). However, with a concerted effort, Australia's land sector (agriculture and forestry) may contribute to country-wide emissions abatement through the uptake of activities that, in aggregate, remove CO_2 from the atmosphere and offset residual anthropogenic GHG emissions elsewhere in the domestic system.

Net Zero Australia has therefore developed initial estimates of net emissions trajectories within the LULUCF sector from 2020 to 2050 resulting from abatement strategies of reducing deforestation and a concerted afforestation of a portion of suitable agricultural land. The specific assumptions relating to these two strategies are detailed in the NZAu Methods, Assumptions, Scenarios & Sensitivities (MASS) document (Net Zero Australia Project, 2022), and are briefly outlined below.

This report explores the geospatial implications of NZAu's estimates of afforestation, through analysis of the prospective lands that may host such new tree plantings and potential land use impacts. This detail is valuable, due to the significant regional variation of land suitability and its potential availability, as well as the importance of other factors, such as social, industrial and governmental acceptance and adoption, as well as the continued development of our capabilities to monitor carbon.

2 Recent Trends

Australia's national greenhouse inventory (DISER, 2021) accounts for net LULUCF emissions due to land use and land use changes between:

- forest land,
- cropland,
- grassland,
- wetland, and
- settlements,
- as well as an estimation of net emissions associated with harvested wood products.

Historical trends (1990 – 2019) in GHG emissions from these land use types and changes (DISER, 2021) (Figure 1) show that the LULUCF sector has gradually moved from being a net source to a net sink of GHG emissions over the last 30 years. Detailed description of these trends within each land use and land use change category is provided in the NZAu MASS document (Net Zero Australia Project, 2022). Here, we highlight trends in the most significant source and sink categories only.

The largest contributor to emissions has been anthropogenic forest loss represented in the *land converted to cropland* and *grassland* categories, with *land converted to grassland* resulting in average annual emissions of +44 Mt-CO_2e/year over the last 10 years. It is important to recognise this is permanent conversion to other uses. Deforestation does not include areas where tree cover is temporarily absent due to cycles of timber harvesting and reforestation or wildfire and natural regeneration. Policy reforms promoting biodiversity conservation and land protection have resulted in regulations to end broadscale conversion of remnant native forest and a significant decrease in net emissions due to this activity over recent years.

The category generating the largest sink of CO_2 (or net removals from the atmosphere) in the last 10 years is *land converted to forest land*. This is primarily conversion of other land types (mostly grasslands) to forest land. This includes new commercial plantations, environmental plantings and human-induced natural regeneration, with new commercial plantations established between 1995 and 2010 dominating. Over the past ten years (2010–2019), an estimated average of −39 Mt-CO_2e/year has been removed from the atmosphere due to these activities. However, under business-as-usual, this forest sink is projected to diminish in the coming years because there has been little new tree planting in the last 10 years, and because the rates of removal associated with existing forests will approach zero as environmental plantings reach maturity and plantations move into stable cycles of harvest and replanting.

Net emissions trends associated with land use and land use change over the years 2010 – 2019 are highly variable across the country (Figure 2). This is due to several factors including regional climates, state-based vegetation policies and the focus of plantation investment by Managed Investment Scheme companies operating between 1995 and 2009. The largest sinks for lands converted to forest land are in southern WA, NSW, VIC and TAS. The largest source of emissions is QLD from *land converted to grassland*.

Figure 1 | Trends in (top) historical net annual GHG emissions of Australian Land Use, Land Use Change, and Forestry (LULUCF); and (bottom) average net annual GHG emissions over 2010-2019, by land use and land use change category. The black line and circles show the net annual GHG emissions.

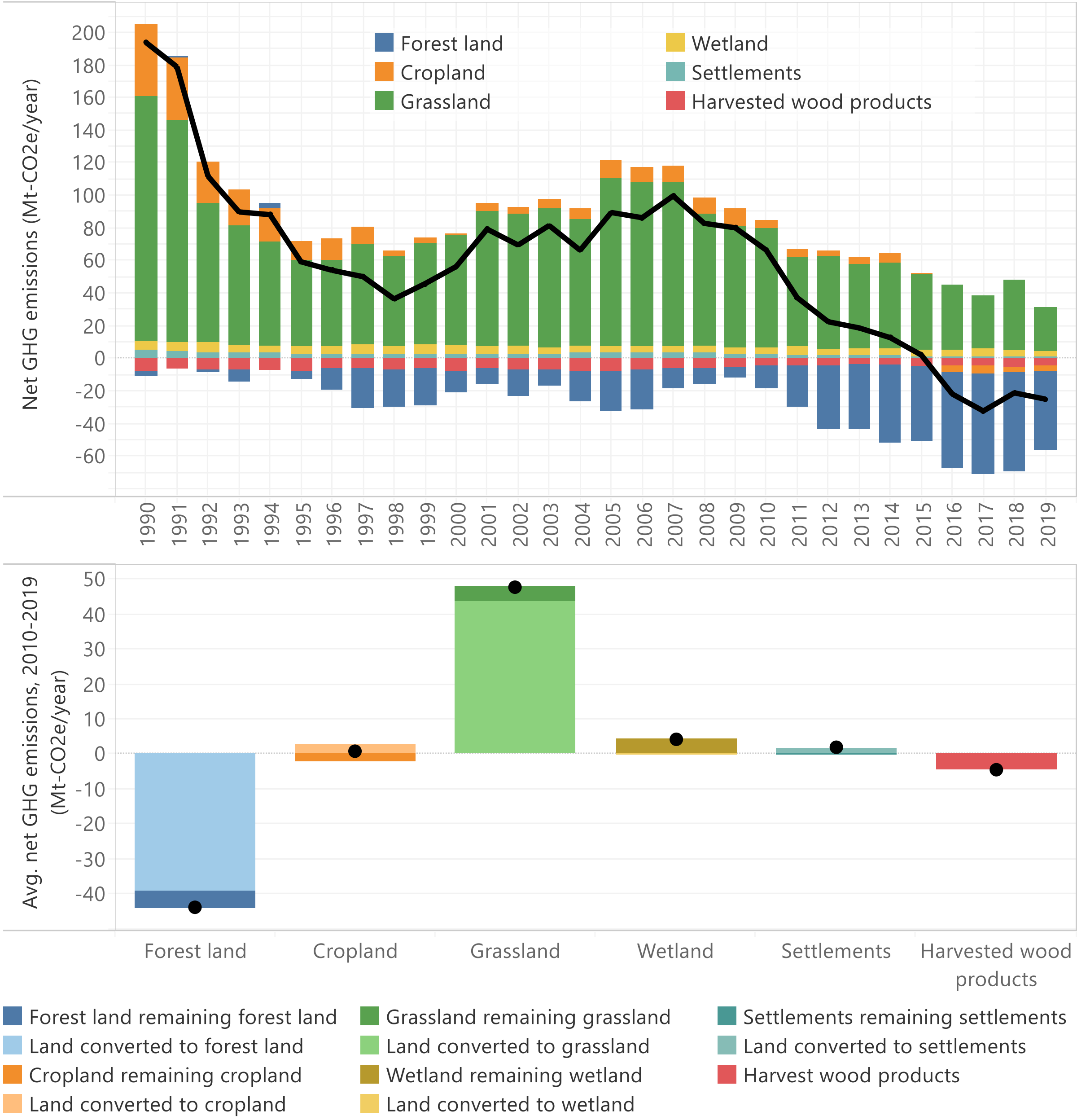
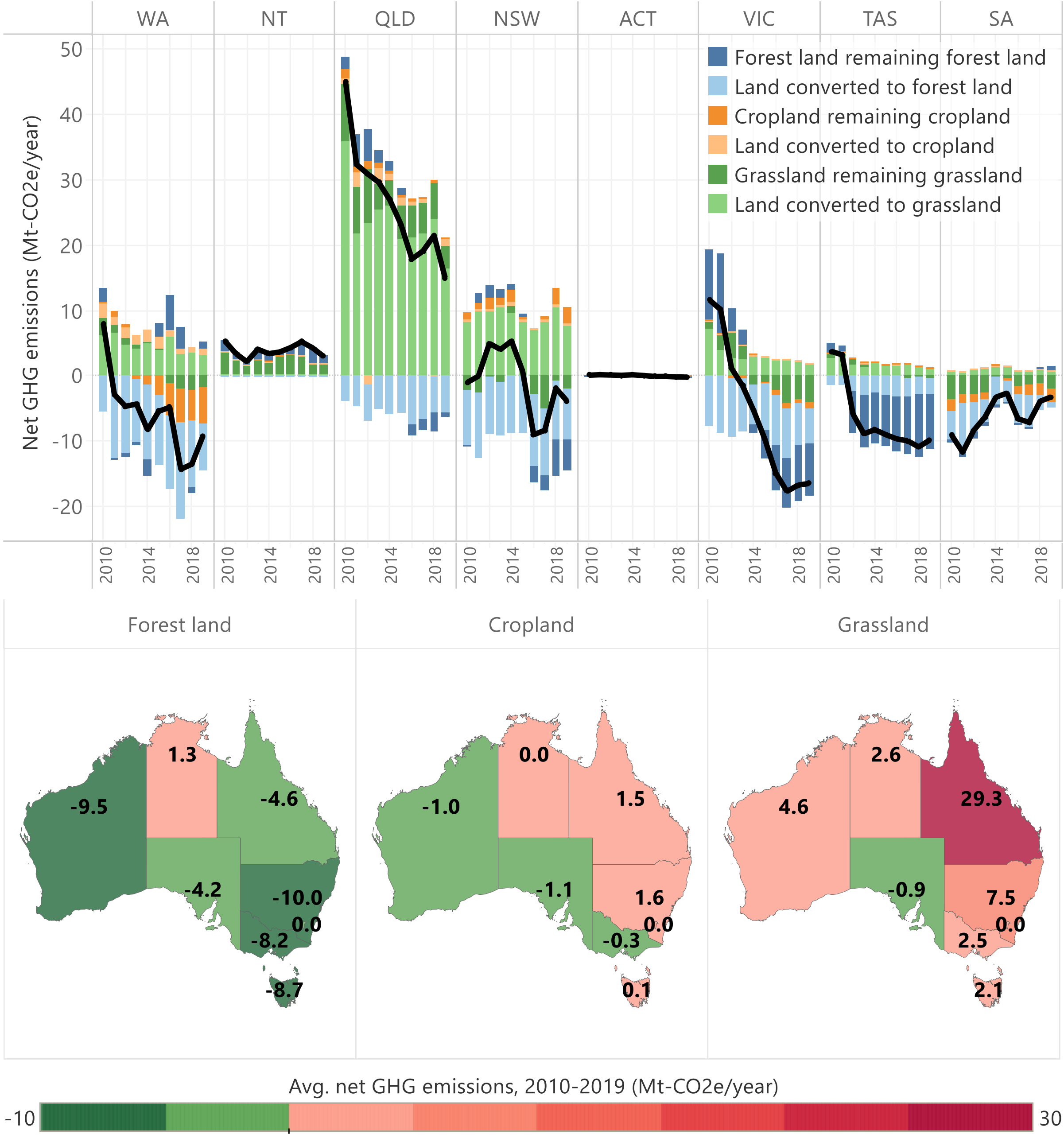


Figure 2 | Trends in recent forest land, cropland and grassland net annual GHG emissions, (top) by year, and (bottom) averaged over 2010-2019 by Australian state/territory. The black line shows the net annual GHG emissions.



3 National projections of forestry sector contribution to LULUCF emissions abatement

Net Zero Australia has developed estimates of future emissions trajectories for the various LULUCF sector categories described above. The basis for these projections is the National Inventory Report (DISER, 2021), with assumptions on future trends drawn from expert advice.

The two main forestry-sector emissions abatement strategies considered in this work are:

- reducing deforestation; and
- afforestation.

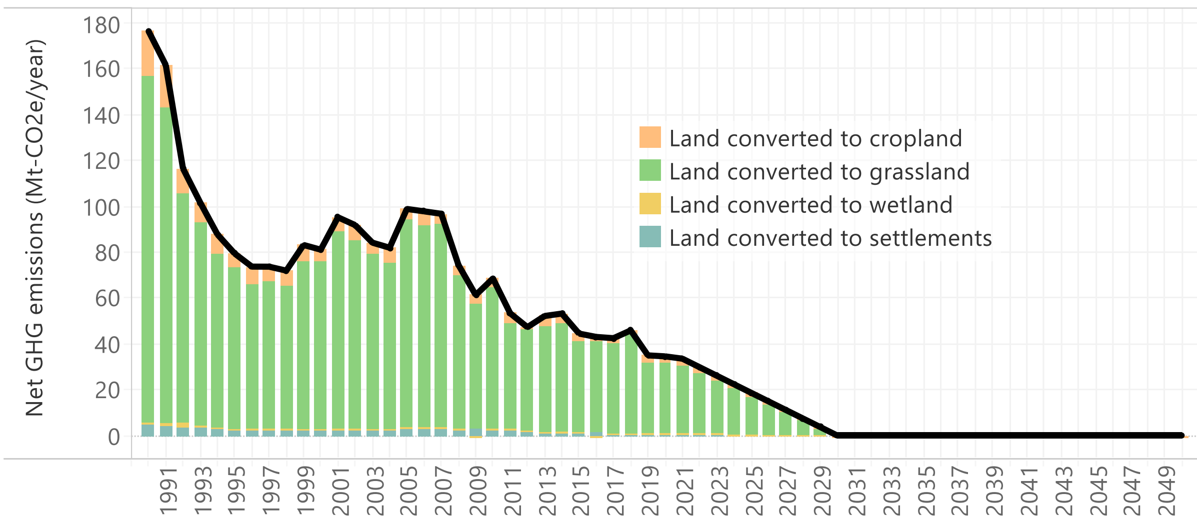
These strategies relate to the activities of *land converted to cropland/grassland/wetland/settlement*, and *land converted to forest land* of the LULUCF sector, respectively, with specific assumptions outlined below.

Net emissions from other land categories (lands remaining as grasslands, croplands, wetlands and settlements) have fluctuated around net zero emissions in recent years. For this study, we assume this trend will continue, with annual net emissions in each of these categories being equal to the average of the previous 10 years' (2010 – 2019) annual emissions. This is a simplifying assumption, noting that the actual net emissions will vary between years, due to differences in climate, climate policies, economic growth rates, etc.

3.1 Reduction in deforestation

We assume a concerted effort to reduce deforestation with net emissions from *land converted to cropland/grassland/wetland/settlement* emissions projected to decline to zero by 2030 (Figure 3). This significant emissions abatement was assumed to result from an increase of regulatory control and from market drivers (e.g. Meat and Livestock Australia's CN30 target) that will lead to reduced land clearing rates. This approach is consistent with the recent Australian Government commitment in Glasgow COP26 (UK COP26, 2021).

Figure 3 | Historical and projected Australian net emissions from the *land converted to other uses* categories within the LULUCF sector.



3.2 Afforestation

Re-/Afforestation describes the conversion of non-forest land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources to result in withdrawal of CO_2 from the atmosphere.

Our analysis assumes that a concerted effort involving tree planting on agricultural and grazing land or human-induced natural regeneration would result in an additional net sink of −51 Mt-CO_2e of annual sequestration by 2050 compared with a projected business-as-usual trajectory. This projection involves new investment to expand the forest area through a combination of trees integrated with farming, environmental plantings, commercial plantations and human-induced regeneration. This would require cultural change in the farming community, new investment and technology development to support more efficient establishment and more rapid tree growth.

The assumed annual rate of new tree or forest establishment (Figure 4) increases from the current low level near zero to an annual rate of 200,000 ha/year by 2030, which continues to 2050, resulting in a total new forest area of 5.1 million hectares (M ha). The average rate of carbon dioxide sequestration in these new forests is assumed to be 10 t-CO_2/ha/year, resulting in −51 Mt-CO_2e of annual sequestration by 2050 compared with the BAU trajectory (Figure 5). The estimate of 10 t-CO_2/ha/year sequestration rate for new forests lies within the range of estimates from other studies and the range of 7-15 t-CO_2/ha/year considered in the Net Zero America Project (Birdsey, 2021). We provide estimates of the regional variability of the annual sequestration rate below, and future work could explore projected sequestration in more detail.

Figure 4 | The projected annual rate and cumulative area of new tree planting on agricultural land.

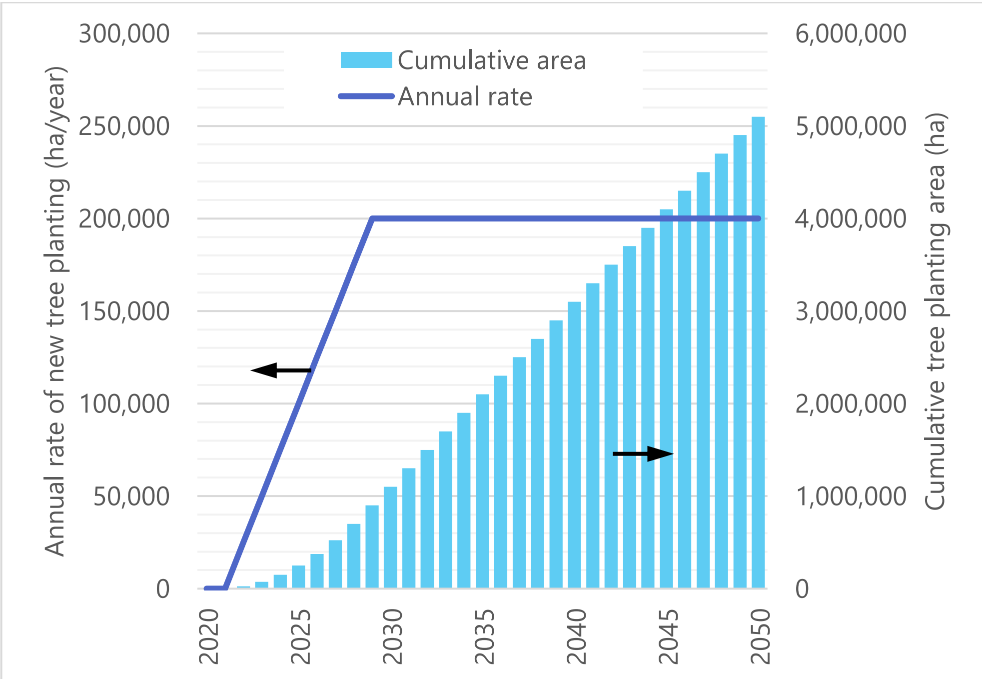
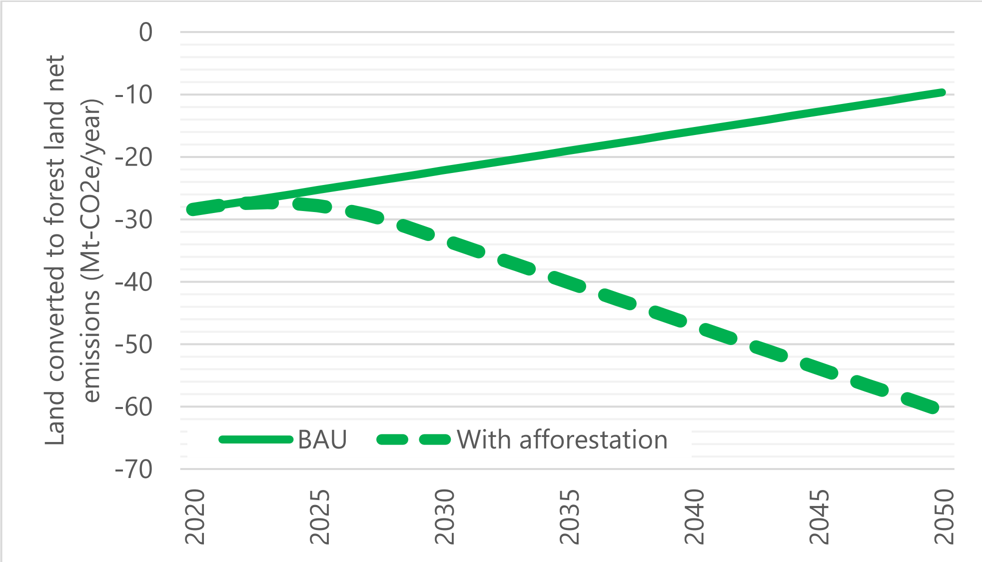


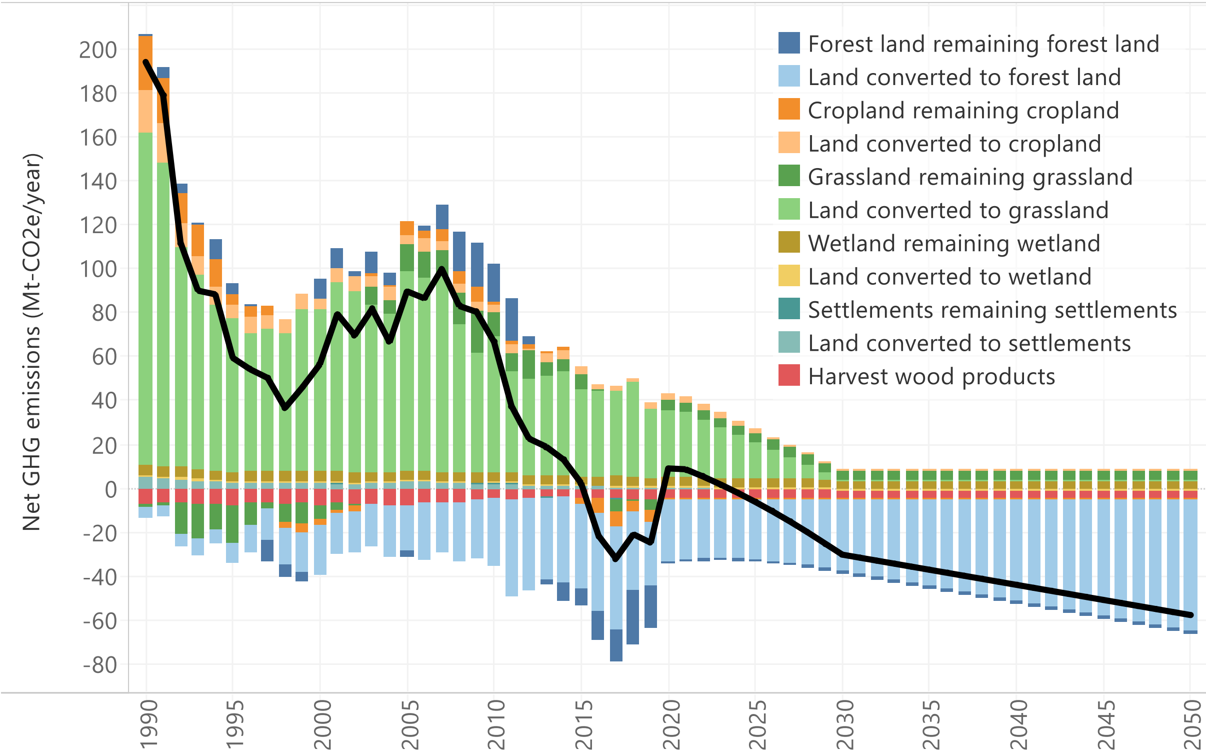
Figure 5 | The projected national emissions trajectory for the *land converted to forest land* category, with the projected afforestation assuming an average CO_2 sequestration rate of 10 t-CO_2/ha/year.



3.3 LULUCF projections

Bringing together the historical and projected net emissions from the LULUCF sector with the reduced deforestation and afforestation emissions abatement measures (Figure 6) shows LULUCF is projected to be a net sink of −58 $MtCO_2e$/year by 2050.

Figure 6 | Historical (1990 – 2019) and projected (2020 – 2050) GHG emissions from LULUCF sector with the assumed mitigation measures outlined in the NZAu MASS document (Net Zero Australia Project, 2022).



4 Downscaling of afforestation

In this section we describe an initial assessment of potential locations and land use types where the 5.1 M ha of new tree plantings might occur. We consider that these trees are located predominantly on land designated by the Australian Bureau of Statistics (ABS) as *land mainly used for intensive cropping and improved pastures*, which currently extends over 77 M ha (Australian Bureau of Statistics, 2022). We excluded irrigated land use types and sugar from this analysis due to their higher value and smaller total land area. The focus is integrating trees and other vegetation into productive farming systems – generally termed agroforestry – but we also consider a proportion of new commercial timber plantations consistent with recent government policy and industry objectives. If designed appropriately, agroforestry can have minimal impact on farming production and integrating trees can generate significant potential co-benefits to the farm operation, such as improved livestock production through the provision of shade and shelter, reduced soil erosion, improved water quality, mitigation of wind erosion and reduced dryland salinity (Farine et al., 2012; Fitch et al., 2022). Trees also have significant aesthetic benefits and may improve land value (Polyakov et al., 2015). Different forms of agroforestry can also generate additional potential revenue streams from timber or non-timber products, and from carbon or biodiversity payments (Nuberg et al., 2009).

4.1 Current land type coverage and afforestation land availability

The Dynamic Land Cover Dataset Version 2.1, provided by Geoscience Australia (Lymburner et al., 2015) was used to characterise current land cover and use types. This provides geospatial data across Australia with standard land cover classification in 250m × 250m pixels. We use here the data set characterising land cover over the period January 2014 to December 2015, omitting the classes *Trees – sparse* and *Trees – scattered* and focussing on land areas covered in trees with an open and closed canopy (*Trees – closed* and *Trees – open*)[1] and land areas used for irrigated and rainfed cropping, pasture and sugar in 2014-15 (Figure 7 and Figure 8)[2].

The 5.1 M ha of new trees in 2050 constitutes an estimated 9% of current land used for rainfed cropping and pasture (Table 1). The Geosciences Australia dataset from 2014-15 is considered to be representative of 'current' land cover and use types, while noting that in the years since this dataset was compiled, cropping and pasture land use areas may have changed. For example, the most recent Australian Bureau of Statistics *Agricultural Commodities Statistics 2020-21* reports the total *land mainly used for crops* to be 31.6 M ha and *land mainly used for grazing on improved pasture* to be 45.2 M ha (Australian Bureau of Statistics, 2022).

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[1] The geospatial dataset used defines the different classes of canopy cover as follows.

- Closed: greater than 70% canopy cover.
- Open: between 30% and 70% canopy cover.
- Sparse: between 10% and 30% canopy cover.
- Scattered: less than 10% canopy cover.

[2] The land cover types assessed here are described in the geospatial dataset as follows.

- Cropping: Production of plant species usually managed as a monoculture for food and/or fibre. Native vegetation has largely been replaced by introduced species as a result of clearing and sowing new species, the application of fertilisers or the dominance of volunteer species. Dryland and irrigated cropping are defined. Includes production of annual and perennial species.
- Pastures: Pasture and forage production, both annual and perennial, is based on a significant degree of modification or replacement of the native vegetation. Areas are cultivated or maintained for the production of food for animals, whether harvested or grazed directly. Dryland and irrigated are defined.
- Trees: Native and non-native woody plants more than 2 metres tall usually with a single stem or branches well above the base. Not always distinguishable from large shrubs.

These land use categories are not entirely consistent with those reported by Lymburner et al. (2015) and summarised in Table 1, but regional distributions of agricultural land use types were found to be similar.

Table 1 | Summary of current land cover and use area across Australia (Lymburner et al., 2015).

Land cover/use type	Land area (M ha)
Trees – closed	24.3
Trees – open	40.3
Irrigated cropping	1.0
Irrigated pasture	0.3
Irrigated sugar	0.2
Rainfed cropping	30.0
Rainfed pasture	28.8
Rainfed sugar	<0.1
Total trees (closed & open)	**64.6**
Total rainfed cropping & pasture	**58.8**

We assume the land that is suitable and potentially available for tree planting to be some proportion of the land designated as *rainfed cropping* and *rainfed pasture*, which has a total current land area of 58.8 M ha. The CSIRO has similarly recently evaluated the potential land availability for environmental planting, finding a total of 63.3 M ha distributed across the same areas shown for rainfed cropping and pasture in Figure 8 (Fitch et al., 2022). However, tree planting is likely to focus on land that is 'marginal' for agricultural commodity production at the farm scale and on broadacre areas where soil fertility or climate limit agricultural profitability. The precise definition of such marginal agricultural land is uncertain, and therefore the availability of land for increased tree cover is also uncertain.

Figure 7 | Australian land area designated as covered by trees with open and closed canopies in 2014-15 (Lymburner et al., 2015).

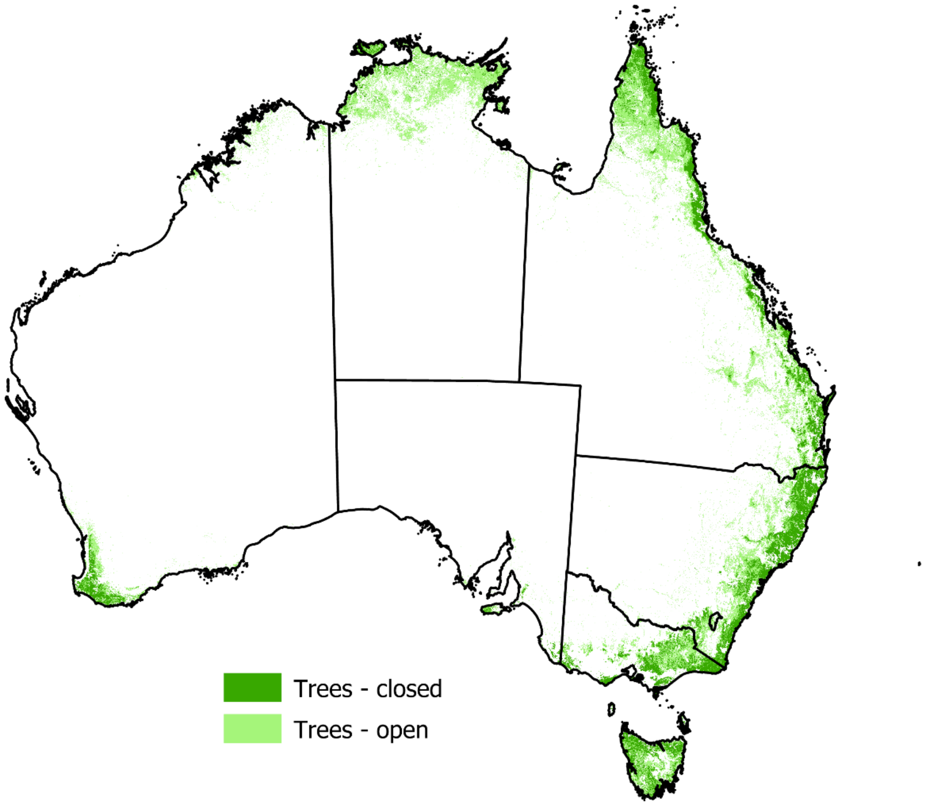
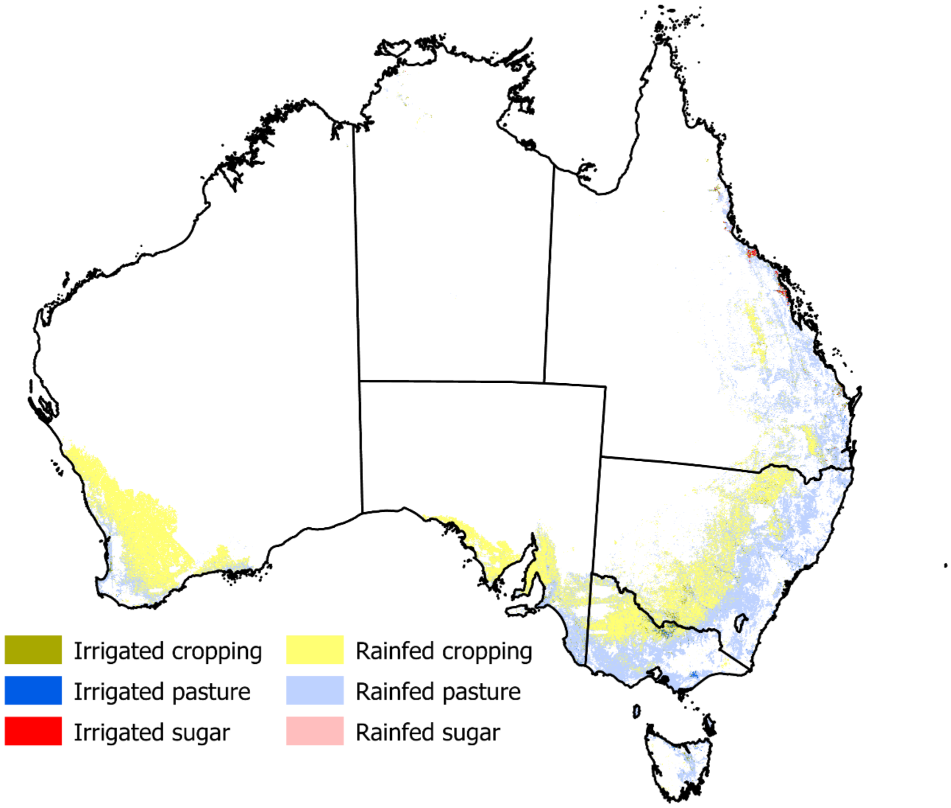


Figure 8 | Australian land area designated as used for irrigated and rainfed cropping, pasture and sugar in 2014-15 (Lymburner et al., 2015).

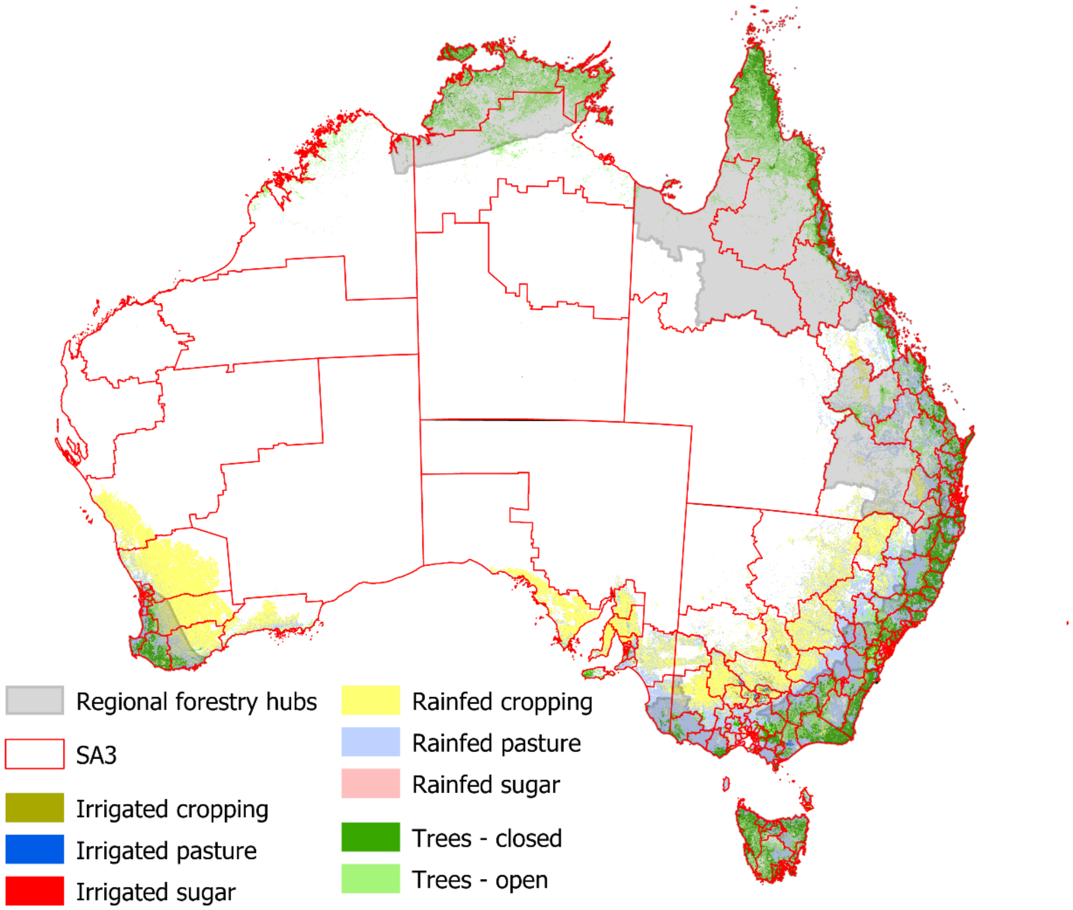


4.2 Spatial bases for downscaling

We use two geospatial bases for assessing land use impacts of new environmental planting and plantations on Australian farmland.

First, we consider the ABS' level 3 statistical areas (SA3) as the basis of land impact assessment. The geographic boundaries for the SA3 regions are shown in Figure 9, where each of the 359 SA3 regions is described by the ABS as being functional areas of regional towns and cities with a population in excess of 20,000 or clusters of related suburbs around urban commercial and transport hubs within the major urban areas (Australian Bureau of Statistics, 2021). Most SA3 areas have populations between 30,000 and 130,000 people. For the purposes of this downscaling analysis, the farming land types within a given SA3 are considered to have similar agricultural production, economic and social, and climatic characteristics.

Figure 9 | Geographic boundaries of the ABS' level 3 statistical areas (SA3) (Australian Bureau of Statistics, 2021), with an underlay of the land cover and use types relevant to this downscaling (Lymburner et al., 2015).



Second, we assess the establishment of tree plantations in areas designated as Regional Forestry Hubs (ABARES, 2022). The Australian Government has recently established 11 Hubs, under the National Forest Industries Plan, with each hub encompassing regions with existing concentrated forestry activity (ABARES, 2022). Figure 10 presents the geographic boundaries of these Regional Forestry Hubs, while Table 2 summarises the current land cover and use types within those hubs.

In assessing the proportion of the 5.1 M ha of new tree planting that may constitute commercial timber plantations in these regions, we account for regional variations in annual rainfall using the 30-year mean average rainfall data from the Bureau of Meteorology, averaged over each SA3 area (Figure 11). The SA3 rainfall data is shown in Figure 11 as an average across the area of the SA3, calculated from Australian Bureau of Meteorology gridded data at 5 km resolution (Commonwealth of Australia Bureau of Meteorology, 2022).

Figure 10 | Geographic boundaries of the 11 defined Regional Forestry Hubs (ABARES, 2022), with an underlay of the land cover and use types relevant to the present downscaling (Lymburner et al., 2015).

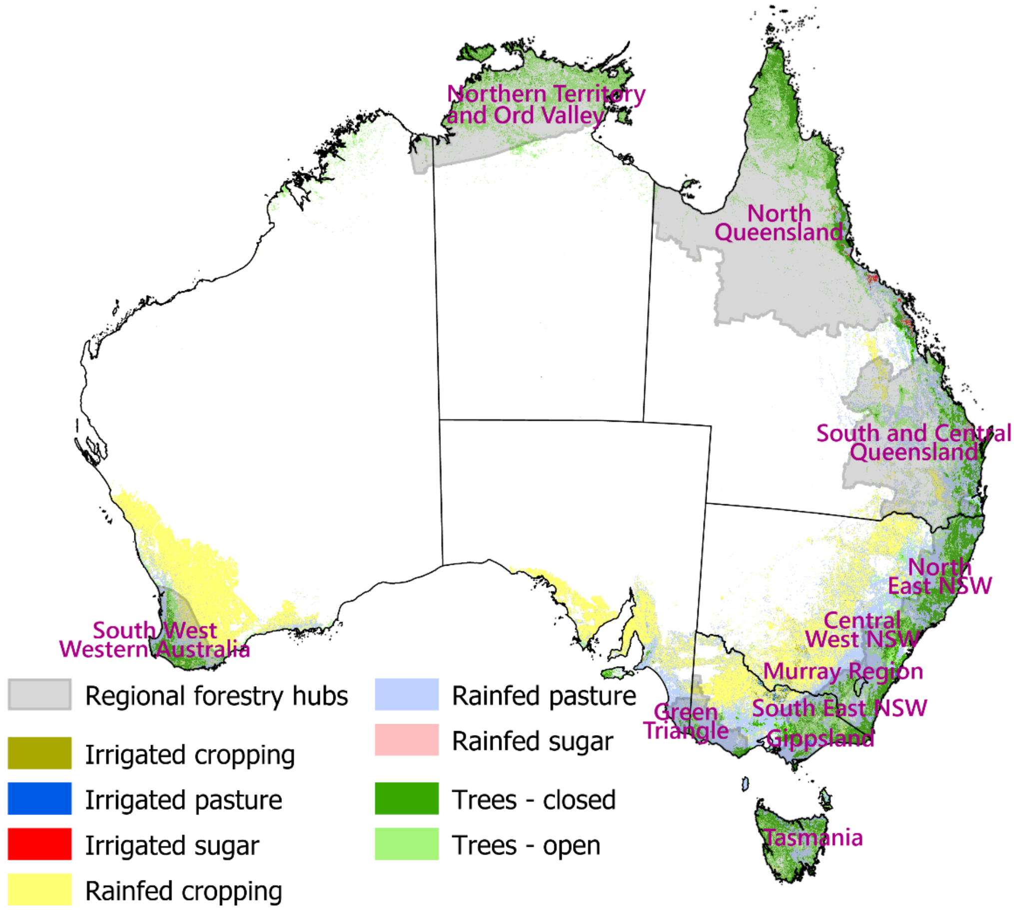
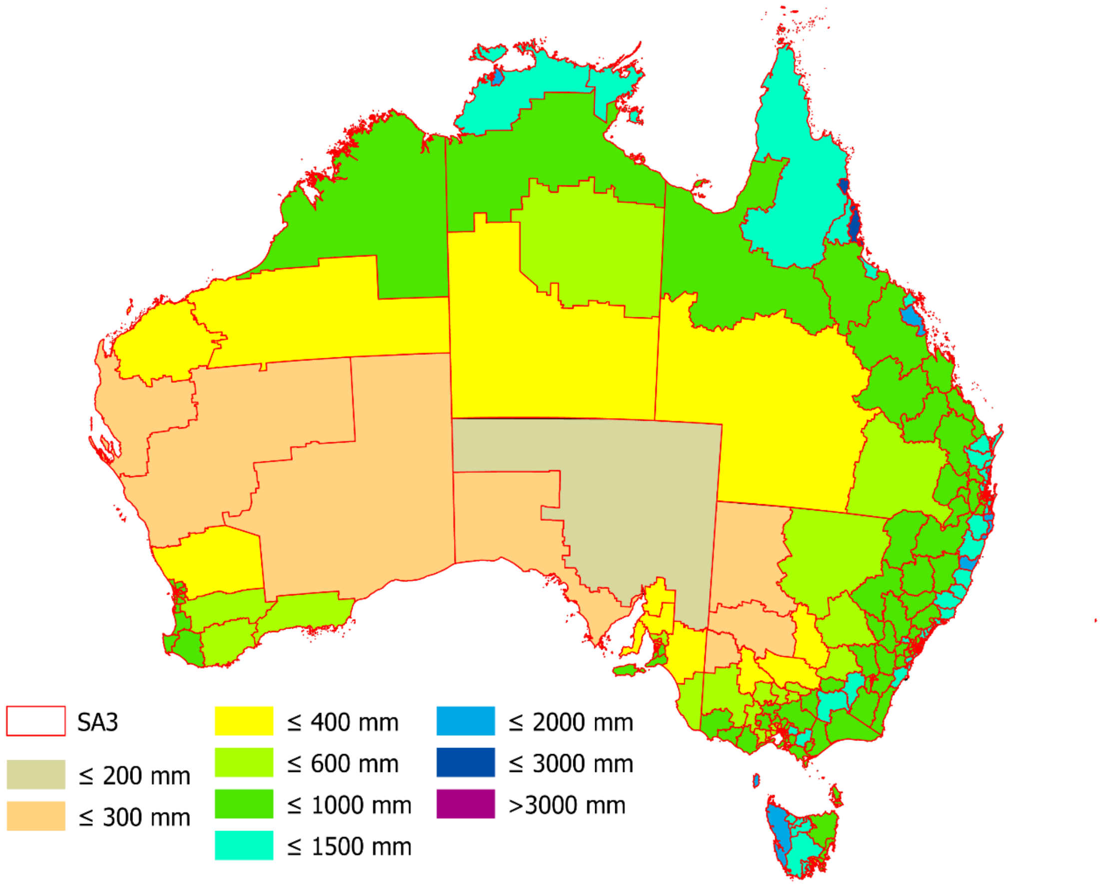


Table 2 | Summary of the current land area cover and use types within the 11 defined Regional Forestry Hubs.

Regional forestry hub	Total land area (M ha)	Total area (M ha) covered by		Proportional area covered by	
		Rainfed cropland and pastureland	Trees – open & closed	Rainfed cropland and pastureland	Trees – open & closed
Central West NSW	2.3	1.1	1.0	48%	44%
South East NSW	4.7	1.2	2.8	26%	59%
Gippsland	4.1	1.0	2.8	24%	68%
Green Triangle	4.7	3.1	0.9	66%	19%
North East NSW	9.7	2.4	6.8	24%	70%
North Queensland	59.9	0.7	13.8	1%	23%

Regional forestry hub	Total land area (M ha)	Total area (M ha) covered by		Proportional area covered by	
		Rainfed cropland and pastureland	Trees – open & closed	Rainfed cropland and pastureland	Trees – open & closed
Northern Territory and Ord Valley	26.5	0.0	10.9	0%	41%
Murray Region	3.4	1.1	2.0	34%	59%
South West Western Australia	6.2	2.3	2.9	38%	47%
Tasmania	6.5	0.8	4.7	13%	73%
South and Central Queensland	31.9	3.9	7.8	12%	24%
Total	**159.9**	**17.7**	**56.4**	**11%**	**35%**

Figure 11 | Mean annual rainfall within each SA3 region over the years 1981-2010 (Commonwealth of Australia Bureau of Meteorology, 2022).



4.3 Siting of afforestation

As indicated, afforestation for this study comprised two types. The dominant type was permanent environmental plantings integrated with Australian farmland (agroforestry), the other was timber plantations, also located on current Australian farmland but preferentially within the defined regional forestry hubs.

We consider uptake of these two types of afforestation are likely to be greater on rainfed pasture land than on rainfed cropland, which reflects a number of factors influencing the relative prospects of land afforestation uptake. Firstly, cropland is, in general, distributed across lower rainfall regions of Australia than pasture land, and would therefore have lower CO_2 sequestration rates. Second, cropping activity uses large machinery, which inhibits significant integration of trees. Finally, the co-benefits of locating trees on pastureland are more significant than for cropland.

With this downscaling we also evaluate the impact of a potentially greater afforestation uptake on lands within the defined regional forestry hubs. Regions with existing forestry activity are more likely to be a focus for new trees on existing farmland, either as environmental plantings or as timber plantation, because of availability of supporting infrastructure (nurseries, planting crews) and presence of markets for timber. Furthermore, these regions have greater annual rainfall than regions outside of the hubs and are therefore likely to have greater CO_2 sequestration rates making them more attractive for carbon projects or farmers with net zero emission objectives.

We therefore examine two strategies for siting the 5.1 M ha of new trees by 2050:

- Siting across SA3 regions, with 20% of new plantings located on rainfed cropland and 80% on rainfed pastureland across the country (section 4.4); and
- Siting across SA3 regions, with 50% greater rate of afforestation in SA3 regions within Regional Forestry hubs, and with 20% of new plantings located on rainfed cropland and 80% on rainfed pastureland across the country (section 4.5).

The siting of afforested land according to these two strategies is presented in the following sub-sections, and is summarised in Table 3.

Table 3 | Summary of land cover impacts between 2020 and 2050 from tree establishment with the 2 different proposed strategies.

	Strategy 1 – Across national farmland	Strategy 2 – Across national farmland with a focus on forestry hubs
Total afforested land area in 2050	+5.1 M ha	+5.1 M ha
30-year change in cropland coverage	−1.0 M ha (−3.4%)	−0.9 M ha (−2.9%)
30-year change in pastureland coverage	−4.1 M ha (−14%)	−4.2 M ha (−15%)
30-year change in forest land coverage	+5.1 M ha (+7.9%)	+5.1 M ha (+7.9%)

Note: Here, forest land refers only to the land cover designated as Trees – closed & open, as shown in Figure 7.

The following data inputs for each of 359 SA3 regions shown in Figure 9 are used:

- total land area;
- proportion of total land area within a Regional Forestry Hub;
- mean annual rainfall; and
- current land cover/use area across the categories *Rainfed Cropping*, *Rainfed Pasture*, *Trees – Closed*, *Trees – Open*, *Other*.

We then calculate the absolute land cover/use change in each SA3 required for a total increase of 5.1 M ha of new trees nationally, given the assumptions of the 2 siting strategies outlined above, i.e.

$$\sum_i \left[x z_i A_i^{\text{cropland}} + y z_i A_i^{\text{pasture land}}\right] = 5.1 \text{ M ha}, \qquad \forall i \in \{\text{SA3 regions included in analysis}\},$$

where A_i^{cropland} and $A_i^{\text{pasture land}}$ are the current land area of cropland and pasture land in a given SA3 region i, x and y are the modelled proportional uptake of new trees on cropland and pasture land, and z_i is a multiplier of the nominal uptake for SA3 regions within regional forestry hubs.

In the siting Strategies 1 and 2, the nominal establishment of new trees on pasture land is four times greater than that on cropland ($y/x = 4$) across all SA3 regions. For strategy 1, no multiplier is used for the uptake of trees in regional forestry hubs ($z_i = 1$), while for strategy 2, a multiplier of $z_i = 1.5$ is used for SA3 regions within regional forestry hubs. In both siting strategies $z_i = 1$ for SA3 regions that are not within regional forestry hubs. For SA3 regions that straddle regional forestry hub boundaries, the z_i multiplier is adjusted to account for only the SA3 area that lies within the regional forestry hub.

We further note that this analysis excludes SA3 regions with total land area less than 0.01 M ha, and those with total rainfed cropland and pastureland comprising less than 5% of the SA3 land area.

4.4 Results for Strategy 1 – Across national farmland

We find that the conversion of 3.4% of cropland and 14% of pasture land would be required to establish 5.1 M ha of new trees with strategy 1 over 30 years (Figure 14). This represents a 7.9% increase in all land covered in trees with an open and closed canopy. The regional distribution of this afforested land area is shown in Figure 12, with state/territory-based changes shown in Figure 13 and Table 4. Afforested land is preferentially located in in the wheat belt of Western Australia, the central west of New South Wales, and the Green Triangle region of Victoria and South Australia. Detailed land cover change for each significant region is shown in Figure 25 in Appendix A.

Figure 12 | Farmland area afforested by 2050 across all SA3 regions for Strategy 1.

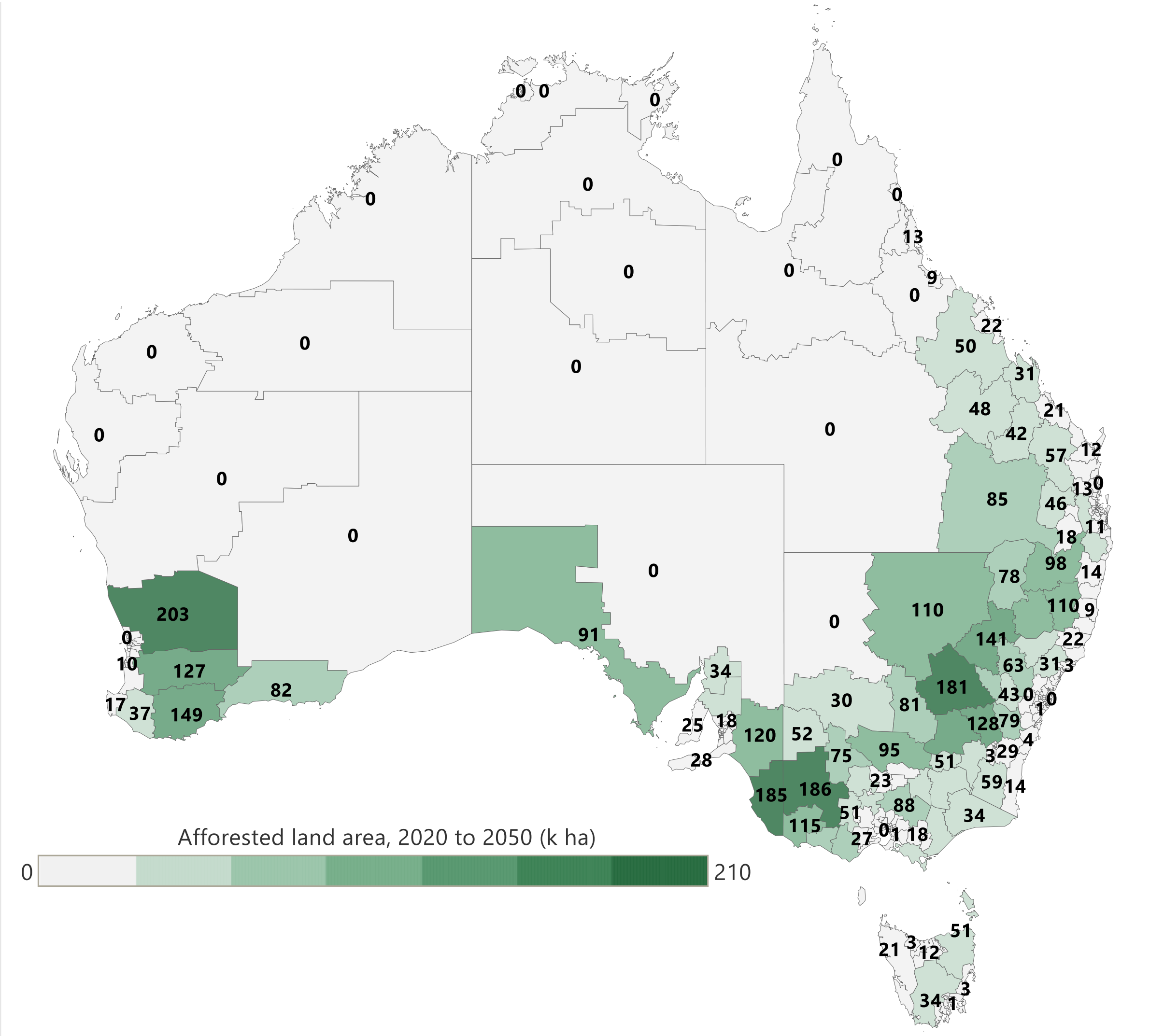


Table 4 | Total farmland afforestation by state/territory for Strategy 1.

State/territory	Farmland afforestation
WA	0.66 M ha
NT	0.00 M ha
QLD	0.59 M ha
NSW and ACT	2.0 M ha
VIC	1.2 M ha
TAS	0.13 M ha
SA	0.57 M ha

Figure 13 | Land cover and use types across Australian states/territories for Strategy 1.

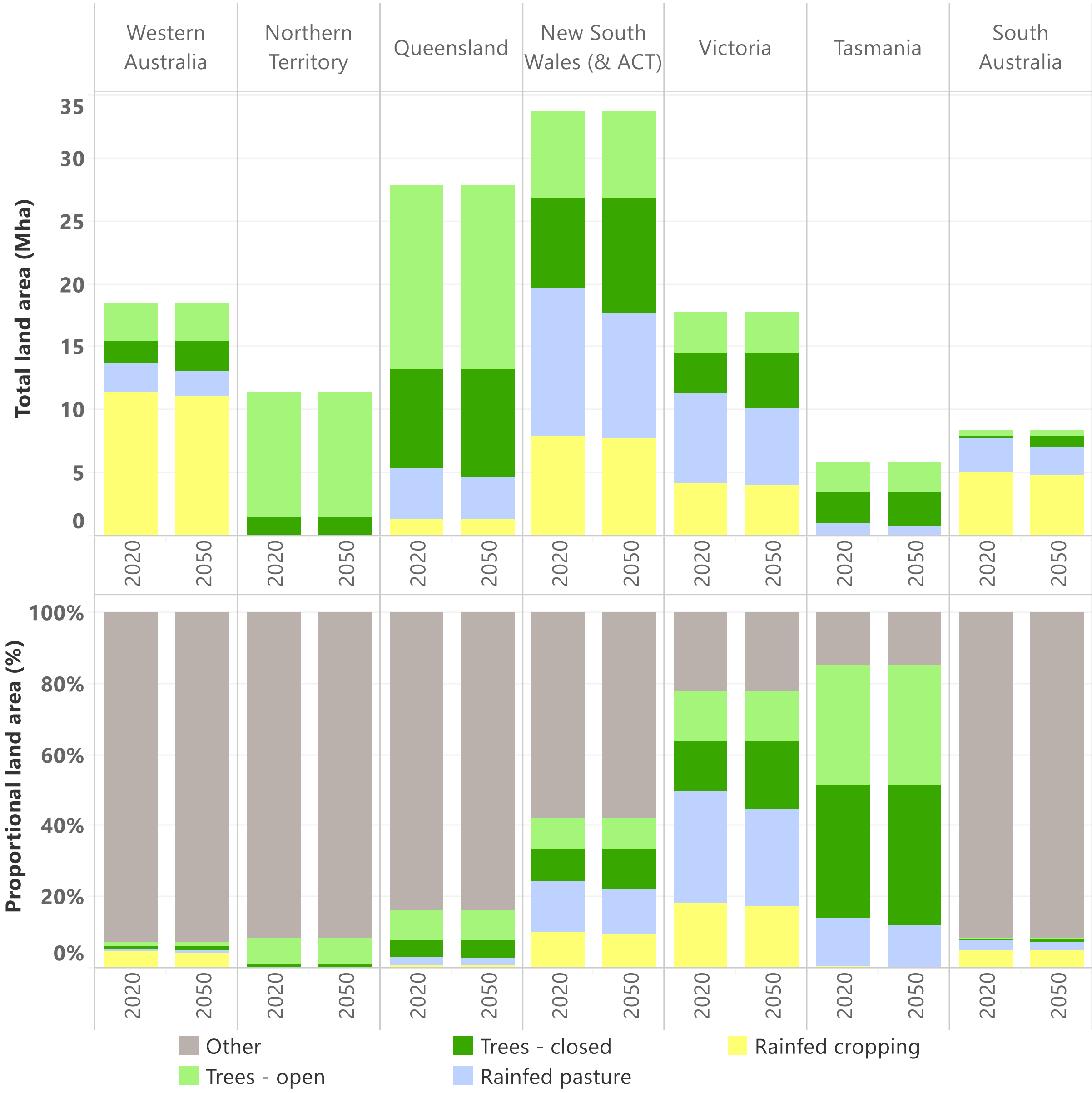
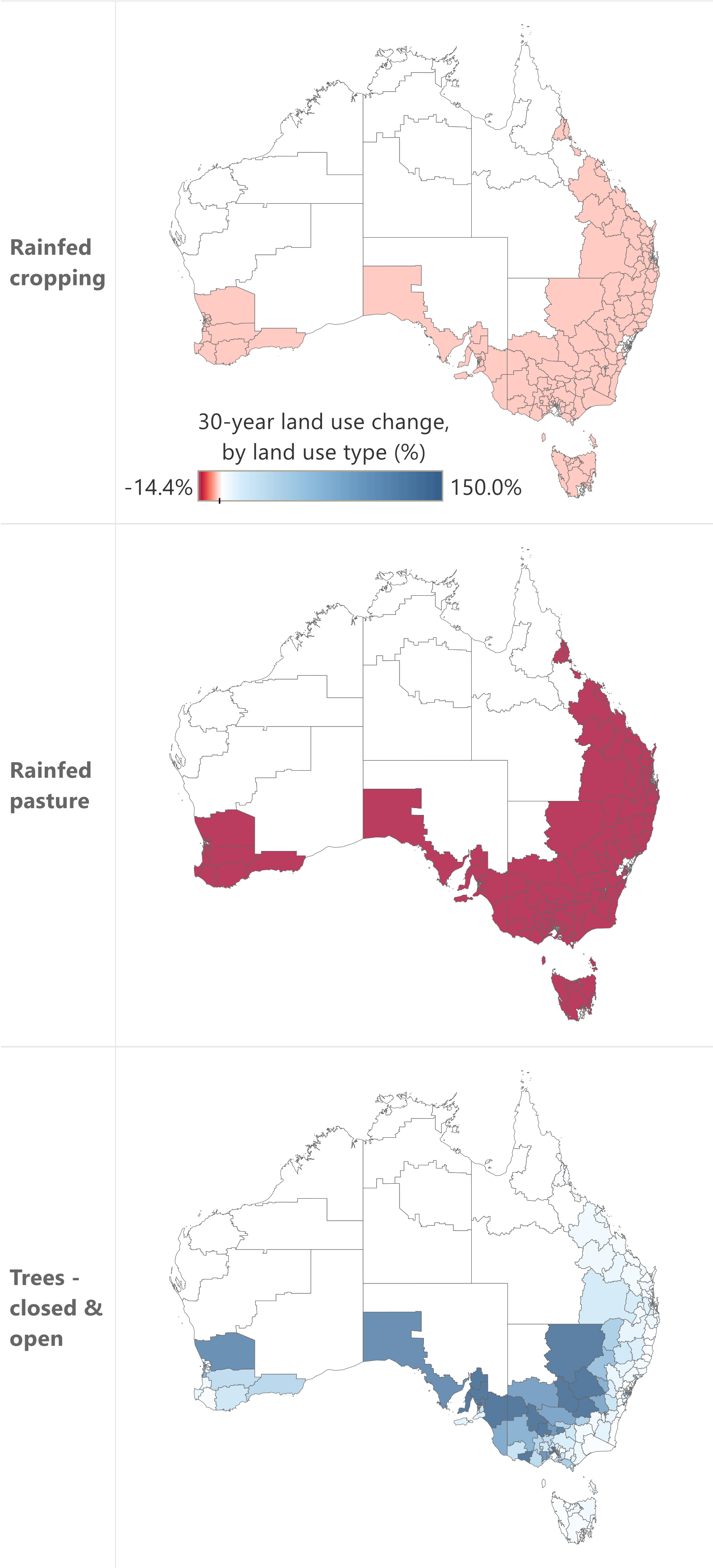
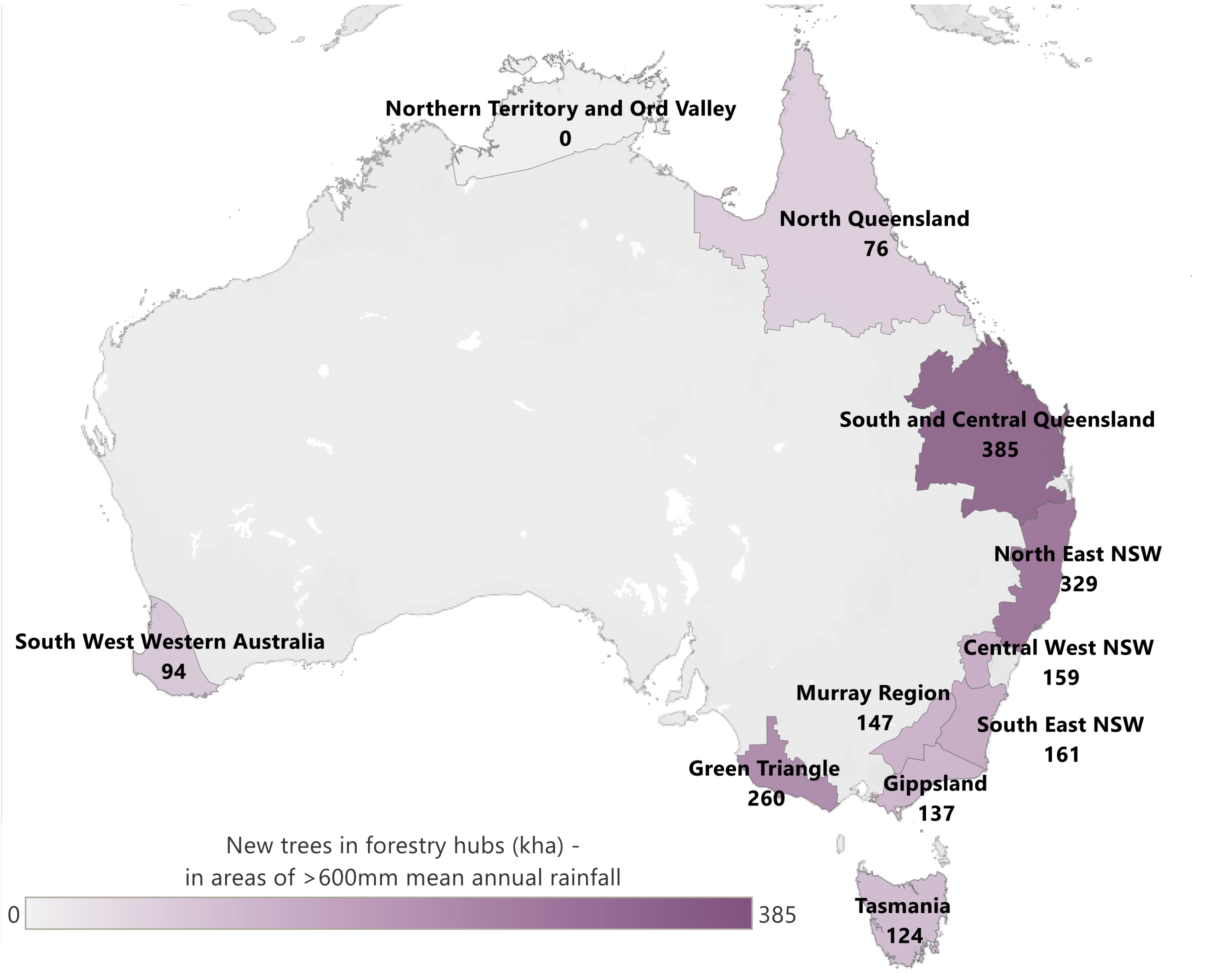


Figure 14 | Change in land use for rainfed cropping, rainfed pasture and trees (closed & open canopies) from 2020 to 2050 across all SA3 regions for Strategy 1.



We find that, even without focusing on afforestation within regional forestry hubs, 1.9 M ha of the new trees sited with strategy 1 are located on farmland within the Australian Government's defined Regional Forestry Hubs in areas of greater than 600 mm mean annual rainfall (Figure 15). This suggests some of the 5.1 M ha of new trees established could be timber plantations, which could provide regional economic benefit, as well as potentially increased sequestration rates. We provide estimates of potential plantation establishment in these hubs and resulting CO_2 sequestration in section 5 below.

Figure 15 | New trees sited in 2050 within regional forestry hubs in areas of >600 mm mean annual rainfall for Strategy 1. Total area 1.9 M ha, of which some proportion may be commercial timber plantations.



4.5 Results for Strategy 2 – Across national farmland with a focus on forestry hubs

We now consider a 50% greater uptake of afforestation on farmland that lies within the Australian Government's defined Regional Forestry Hubs. This strategy continues to use the 20% cropland and 80% pasture land split across the country.

The regional distribution of afforested land area with this Strategy is shown in Figure 16, with state/territory-based changes shown in Figure 17 and Table 5. This results in increased afforestation in QLD and TAS, reduced afforestation in WA and SA, while NSW and VIC have similar levels. Detailed land cover change with Strategy 2 for each region of Australia is shown in Figure 25 in Appendix A.

We also find that 2.9% of national cropland is converted to trees over 30-years with this greater focus on afforestation within hubs; a lower conversion rate than was found in Strategy 1. This is due to the lower representation of cropland in the Hubs than in the national average. This also leads to the 30-year conversion of pasture land being greater than in Strategy 1, accounting for 14.7% of all pasture land. With this greater focus on afforestation in Hubs we find that 30-year absolute afforestation occurs on 4.6% of cropland and 18.3% of pasture land within the Regional Forestry Hubs, while afforestation occurs on 3.1% of cropland and 12.2% of pasture land outside of the Hubs (Figure 18).

Figure 16 | Farmland area afforested by 2050 across all SA3 regions for Strategy 2.

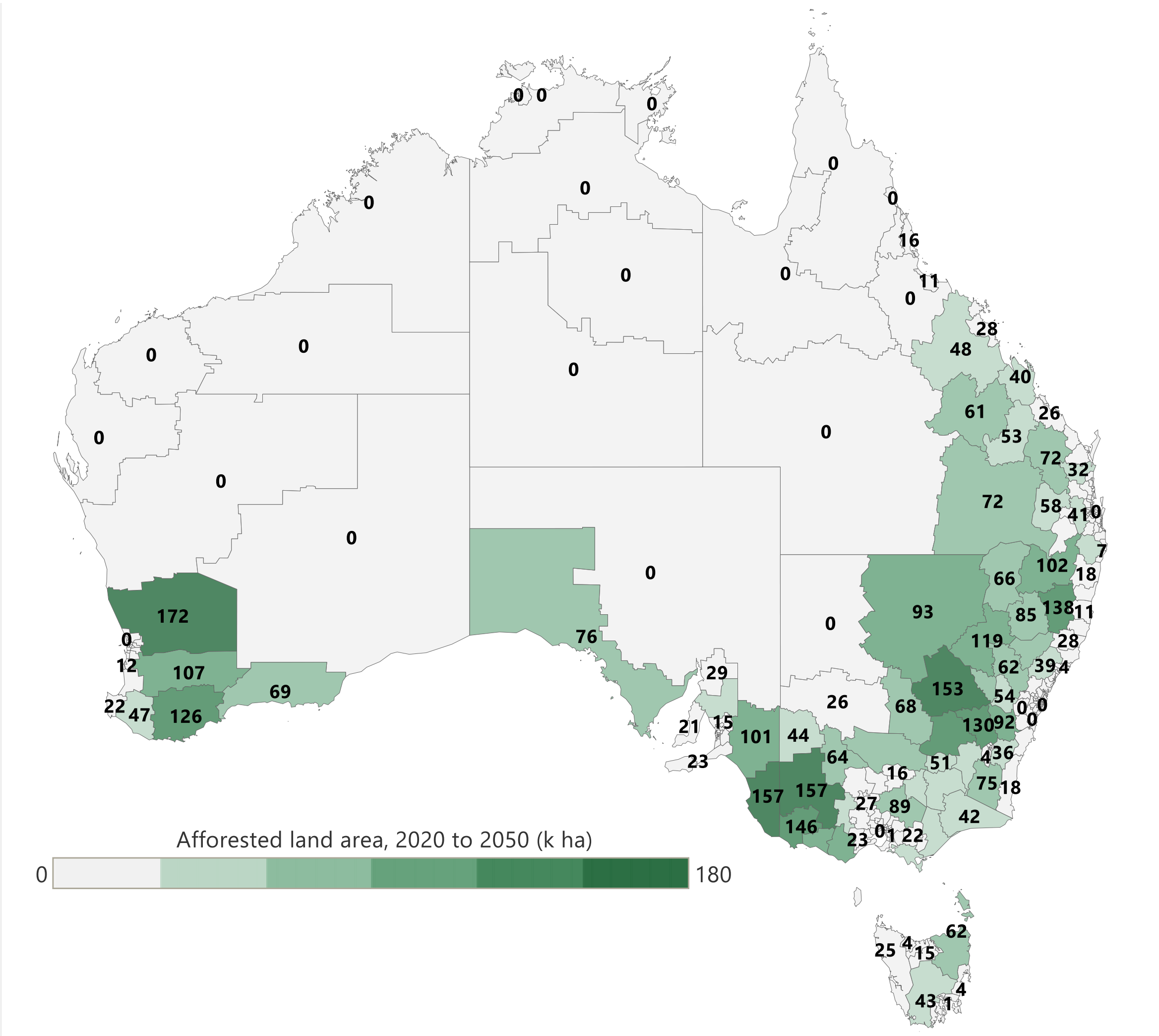


Table 5 | Total farmland afforestation by state/territory for Strategy 2.

State/territory	Farmland afforestation
WA	0.60 M ha
NT	0.00 M ha
QLD	0.70 M ha
NSW & ACT	1.9 M ha
VIC	1.2 M ha
TAS	0.17 M ha
SA	0.48 M ha

Figure 17 | Land cover and use types across Australian states/territories for Strategy 2.

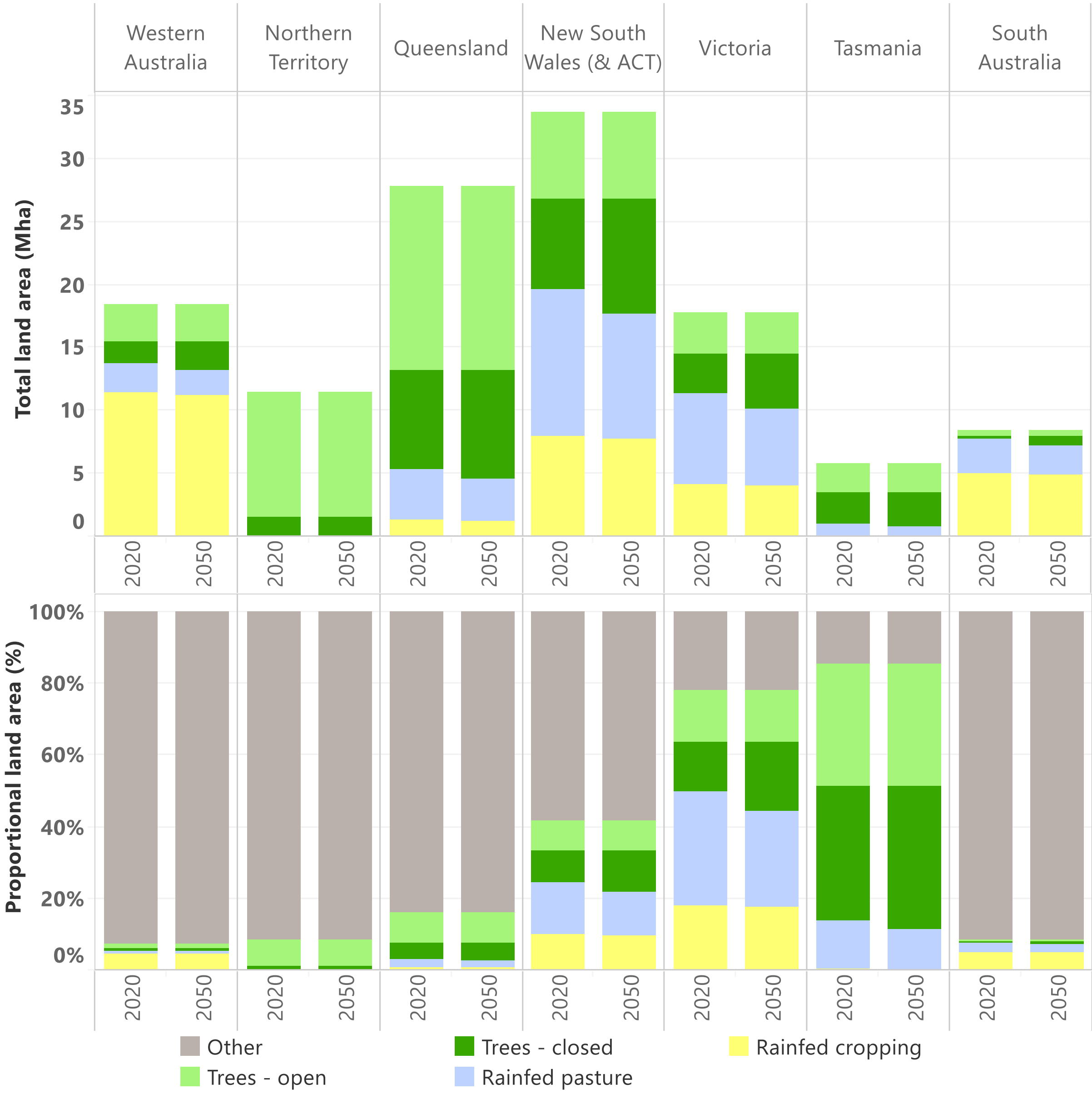
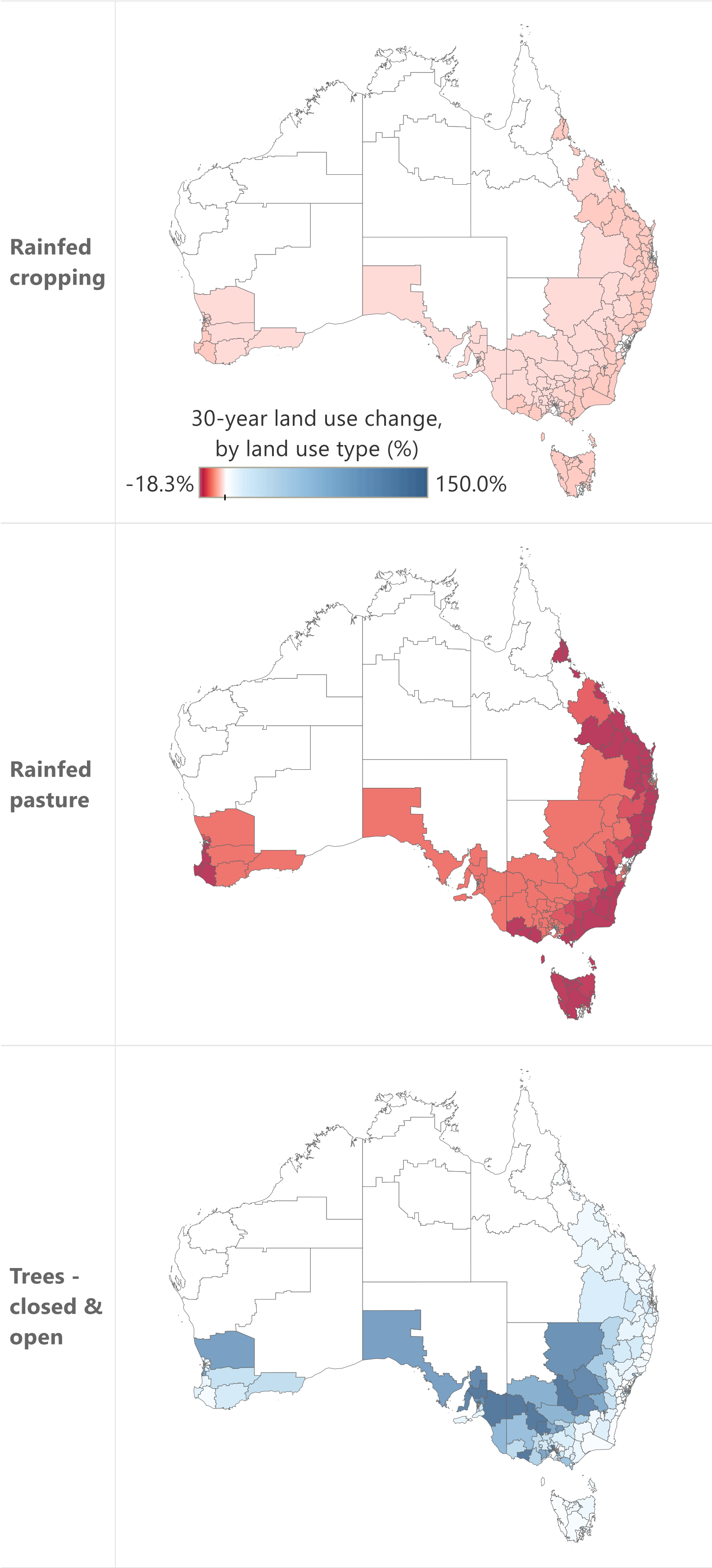
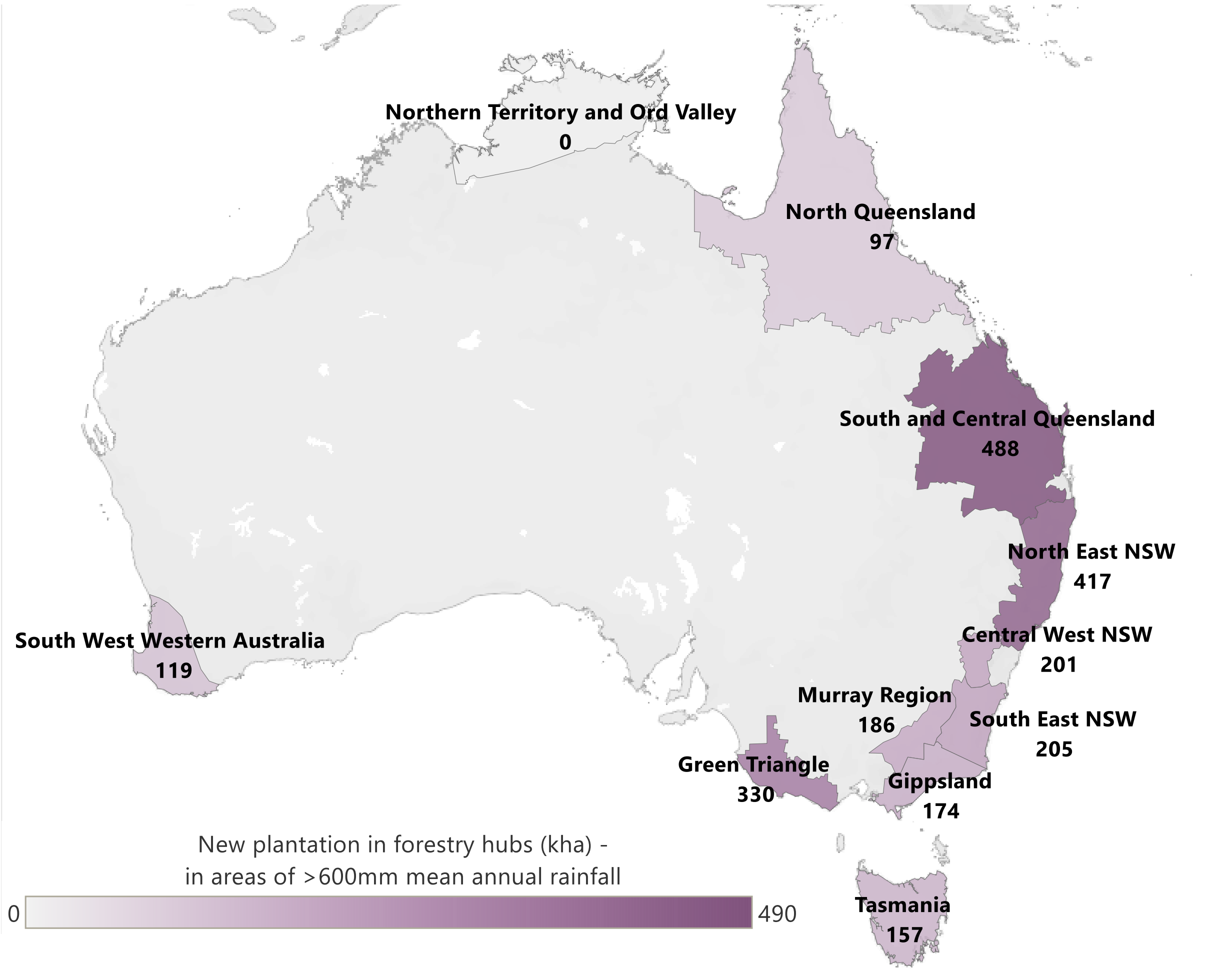


Figure 18 | Change in land use for rainfed cropping, rainfed pasture and trees (closed & open canopies) from 2020 to 2050 across all SA3 regions for Strategy 2.



We also find that under Strategy 2, 2.4 M ha of the new trees are sited within Regional Forestry Hub areas, in areas of greater than 600 mm mean annual rainfall (Figure 19). This represents almost half of the new trees modelled in this work and a significant opportunity for some portion of new trees to be established as timber plantations. See estimates of potential plantation establishment in these hubs and resulting CO_2 sequestration in section 5 below.

Figure 19 | New trees sited in 2050 within regional forestry hubs in areas of >600 mm mean annual rainfall for Strategy 2. Total area 2.4 M ha, of which some proportion may be commercial timber plantations.



5 Estimating regional sequestration on afforested land

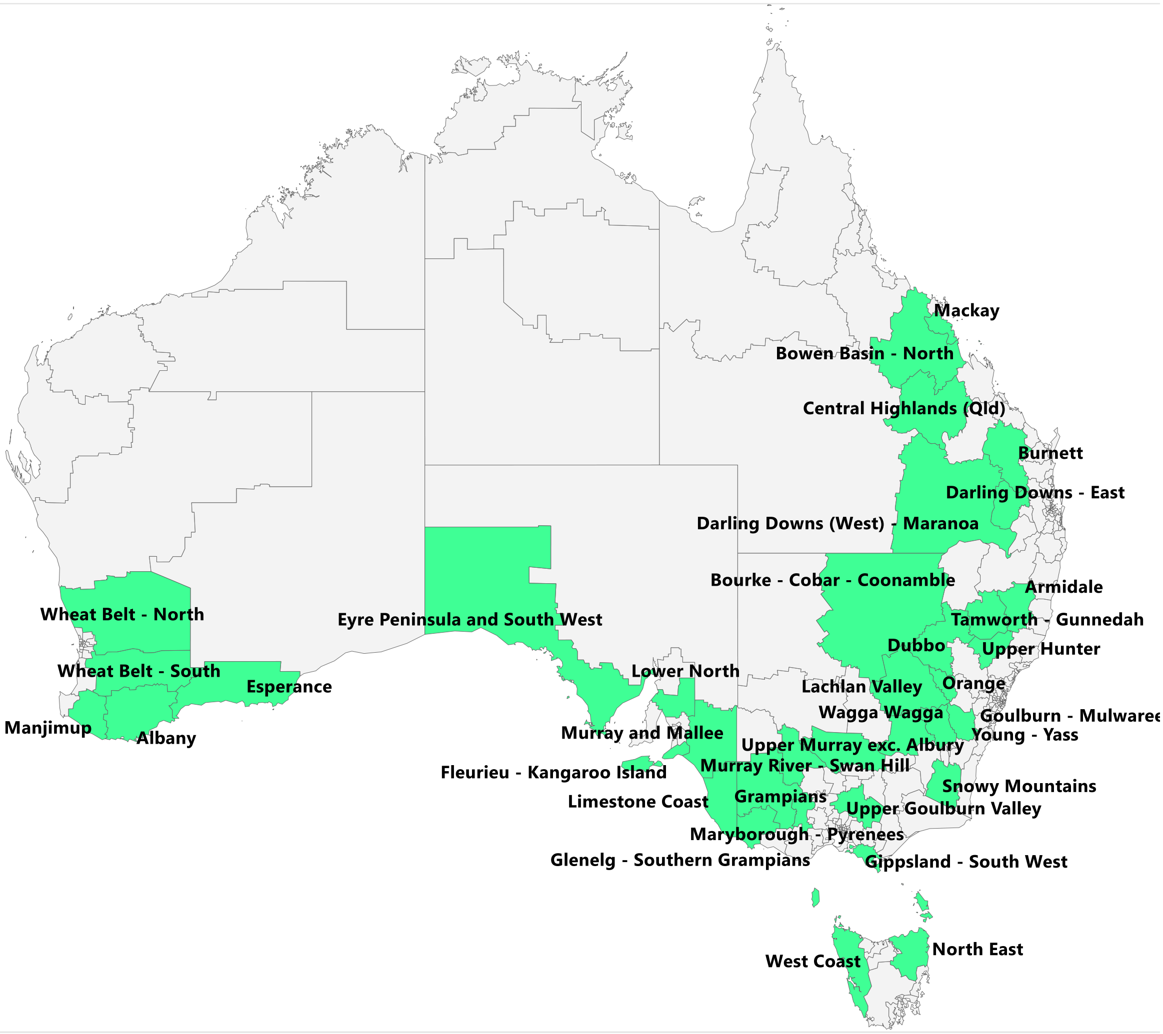
The initial estimates of a potential abatement outlined in section 3.2 above assumed an average rate of carbon dioxide sequestration in new forests of 10 t-CO_2/ha/year, so that the 5.1 M ha of new trees in 2050 would sequester −51 Mt-CO_2/year. However, the sequestration rate will vary with climate, with the maturity of any new forests, and numerous other factors. Here we provide estimates of the regional variation in sequestration rate using the Australian Commonwealth Scientific and Industrial Research Organisation's LOOC-C tool (CSIRO, 2022).

5.1 Representative regions, projects and estimation method

We assess the sequestration potential for several representative regions across the country that were found in section 4 to host a significant portion of new trees. These representative regions (Figure 20) account for 50% of the total afforested land area in Strategy 1 above, and 48% in Strategy 2. These representative SA3 regions span areas that might host mostly agroforestry (environmental planting) projects and those that might host new commercial timber plantations.

Specifically, estimates of CO_2 sequestration potential are calculated at the centroid of the representative SA3 regions (Figure 20) using the LOOC-C tool's estimation method for *Reforestation by environmental or mallee plantings* (CSIRO, 2022). This method of afforestation involves "establishing and maintaining native vegetation such as trees or shrubs on land that has been clear of forest for at least five years. Plantings can either be a mix of trees, shrubs and understory species native to the local area, or species of mallee eucalypts" (CSIRO, 2022). The LOOC-C CO_2 sequestration estimates with the environmental planting method use the forest growth and decay equations of the Full Carbon Accounting Model (DCCEEW, 2020) and account for above- and below-ground living and dead biomass.

Figure 20 | Representative SA3 regions used to estimate 30-year average CO_2 sequestration.



5.2 Sequestration results

Sequestration rates vary from 0.8 t-CO_2/ha/year in the Bowen Basin in QLD, to 4-7 t-CO_2/ha/year across Australia's main cropping regions, to greater than 20 t-CO_2/ha/year in regions of high rainfall (Figure 21). The average estimated sequestration rate weighted by the modelled afforested land area in Strategy 1 was found to be 8.0 t-CO_2/ha/year, assuming all new trees are environmental planting agroforestry projects. This finding aligns with those recently published by CSIRO who found 25-year average rates of technical sequestration potential on 63.3 M ha of farmland to be 7.6 t-CO_2/ha/year (Fitch et al., 2022). CSIRO further found that sequestration rates for environmental plantings in high stocking density shelterbelts could have average sequestration rates of 11.7 t-CO_2/ha/year (Fitch et al., 2022).

It is also plausible that some portion of the afforested land would be established as timber plantations which would sequester CO_2 at greater rates than the environmental plantings, with some estimates suggesting sequestration may be greater by a factor of 3 (Fitch et al., 2022). CSIRO's recent estimates found 25-year average rates of technical sequestration potential of plantation forestry on 20.75 M ha of suitable farmland with annual rainfall >600mm to be 30.42 t-CO_2/ha/year (Fitch et al., 2022). They noted the land area that is likely to be economically-favourable for plantation forestry is 2.6–9.8 M ha with average sequestration rates 29.3–31.8 t-CO2/ha/year.

5.2.1 Strategy 1

We suggest that for Strategy 1, 10% (0.51 M ha) of afforested land could be established as timber plantation in areas of greater than 600 mm mean annual rainfall and within the Regional Forestry Hubs. These plantations would account for 27% of the afforested farmland within the high rainfall regions of the Hubs and assuming the rates of sequestration to be 2.5× the modelled sequestration rates of environmental plantings in those SA3s (Figure 21), following the estimates of Fitch et al. (2022).

Taken together, for Strategy 1, the average environmental planting (90% of all afforestation) sequestration rate would be 7.7 t-CO_2/ha/year and the plantation (10% of all afforestation) sequestration rate would be 30.3 t-CO_2/ha/year. This gives an area-weighted average national CO_2 sequestration rate of 9.9 t-CO_2/ha/year (Table 6), which is approximately equal to our initial estimates made in section 3.2.

5.2.2 Strategy 2

For Strategy 2 with the greater focus on the Regional Forestry Hubs, the siting in section 4.5 modelled 2.4 M ha of afforested farmland within the high rainfall regions of the Hubs. We again suggest that 27% of this afforested farmland could be established as timber plantation, accounting for 0.6 M ha with 2.5× the modelled sequestration rate of environmental plantings in those SA3s (Figure 21).

Therefore, for Strategy 2, the average environmental planting (87% of all afforestation) sequestration rate would be 8.1 t-CO_2/ha/year and the plantation (13% of all afforestation) sequestration rate would be 30.3 t-CO_2/ha/year. This gives an area-weighted average national CO_2 sequestration rate of 10.9 t-CO_2/ha/year (Table 6). This value is greater than that for Strategy 1 because for Strategy 2 more afforested land is within Hub regions with greater mean rainfall than other regions and because Strategy 2 has more plantation area.

Figure 21 | Estimated 30-year average annual sequestration of environmental plantings sited at the centroid of 36 representative SA3 regions.

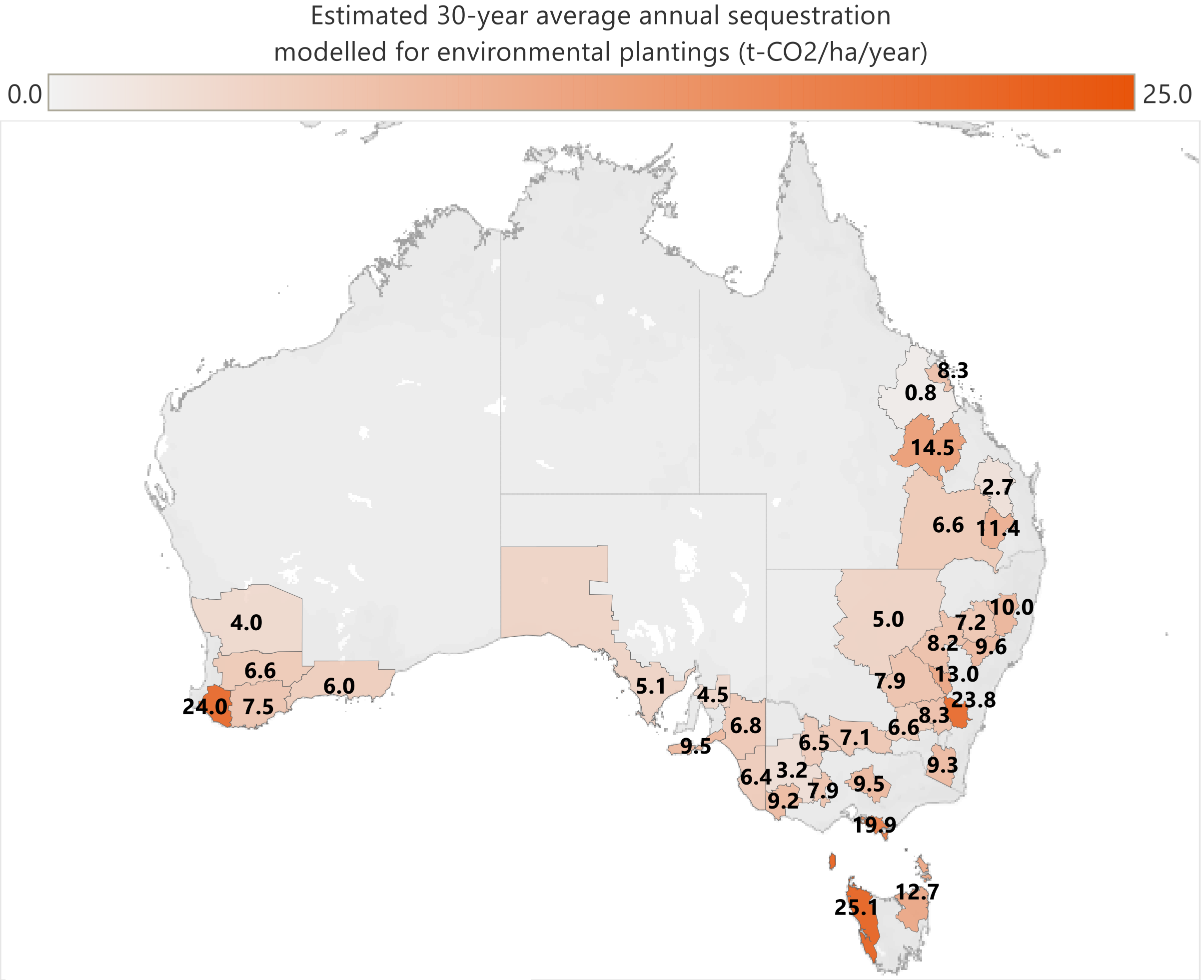


Table 6 | The division of afforested land area between environmental planting and timber plantations, and estimated CO_2 sequestration potential for the two siting strategies.

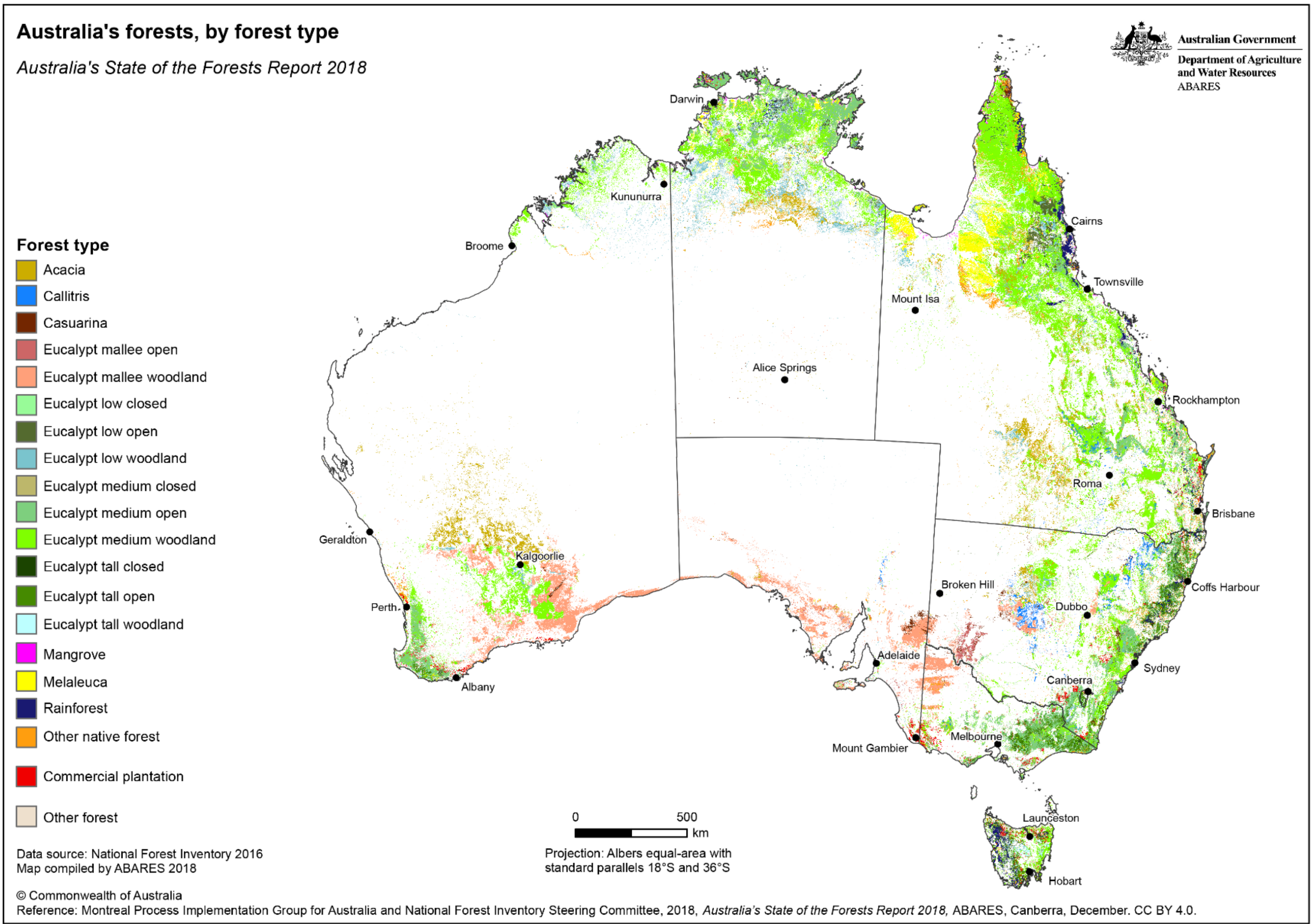
	Strategy 1	Strategy 2
Total area of new trees	5.1 M ha	5.1 M ha
Total area of new trees in Hubs in areas of >600 mm mean annual rainfall	1.9 M ha	2.4 M ha
Total environmental plantings area	4.6 M ha	4.5 M ha
Total timber plantations area	0.5 M ha	0.6 M ha
Representative area-weighted estimated sequestration potential – environmental plantings	7.7 t-CO_2/ha/year	8.1 t-CO_2/ha/year
Representative area-weighted estimated sequestration potential – plantations	30.3 t-CO_2/ha/year	30.3 t-CO_2/ha/year
National average estimated sequestration potential	9.9 t-CO_2/ha/year	10.9 t-CO_2/ha/year

5.3 Which type of trees are required?

Figure 22 presents the distribution of different types of Australian forest (ABARES, 2018). It can be expected that the majority of environmental plantings established on existing farmland would follow a similar distribution of forest types with the majority being comprised of native Australian species, such as various eucalypts. In many cases the tree species established will need to be those that are well-suited to medium to low rainfalls, particularly those established on existing cropping land.

Existing plantations are approximately evenly distributed between hardwood and softwood species (Figure 22) (ABARES, 2016). Australia's hardwood plantation species are dominated by the *Tasmanian blue gum* and *shining gum* predominantly located in Western Australia, the Green Triangle around the southern Victoria-South Australia border, and Tasmania. The main species making up Australia's softwood plantations are *radiata pine* and *southern pines* mostly in the Murray Valley, the Green Triangle, the Central Tablelands in NSW, Tasmania and South-East Queensland. Any new plantation area established would likely be comprised of these species.

Figure 22 | Current Australian land area covered in forest, coloured by forest type (ABARES, 2018).



6 Summary and additional considerations for forestry sector emissions abatement

This report has examined the potential farmland impact of a concerted afforestation effort to enhance Australia's forest CO_2 sinks, as part of Net Zero Australia's country-wide net zero emissions pathway modelling. We have found that 5.1 M ha of new trees could be sited on current Australian farmland, predominantly located in southern and eastern Australia, and preferentially on Australian pasture land. Depending on the siting strategy used, 2.9–3.4% of cropland would be required over 30 years to host new trees, while 14–15% of pastureland would be required. We have also shown that a national average of 10 t-CO_2 of annual sequestration per afforested land area is plausible, assuming that environmental plantings are adequately managed to maintain sequestration rates, and that some small portion of the afforested land area (~10%) is established as timber plantations in areas with higher annual rainfall.

There are several considerations that any program seeking to establish the uptake of trees on Australian farmland should consider, in addition to those characterised in this report. These relate to the impact of natural disturbances, the impact of climate change on future sequestration and survival, the need for carbon monitoring improvement, the value of alternative options for emissions abatement or sequestration, and the impacts on stakeholders, notably farmers and Indigenous Australians. Some of these considerations are briefly discussed below.

6.1 Uncertainty, inter-annual variability and susceptibility of negative CO_2 fluxes

The negative CO_2 fluxes (removals) modelled in this work are inherently uncertain and will vary between years, particularly with longer term climate variability and change, as well as the potential for emissions through natural disturbances – such as bushfires – which can release significant amounts of CO_2. Such disturbances are likely to increase in prevalence and extent in southern Australia, and the implications of these disturbances will need thorough consideration, accounting and risk management.

Furthermore, market mechanisms to fund emissions removals will often preference the lowest cost solutions. In the case of carbon sequestration through afforestation of farmland, these mechanisms may incentivise projects with less certain levels of sequestration and permanence. These factors will need to be addressed in mechanism design, accounting and reporting (Australian Academy of Science, 2022; Chubb et al., 2022).

6.2 Other options for emissions abatement and increased sequestration

The forest and tree abatement options considered in this work can only contribute to net-zero emissions goals if they are additional to existing natural carbon sinks. Here, we have considered only those activities that reduce emissions or enhance anthropogenic carbon sinks, namely reduced deforestation and a specified level of farmland afforestation. However, other natural ecosystem activities can reduce emissions and increase sequestration, but the potential and the additionality of such measures is uncertain.

Firstly, there is potential to improve forest management and enhance the existing forest sinks, in the *forest land remaining forest land* category of the national GHG emissions inventory. Improving forest management incorporates many activities, each of which can have a small emissions impact compared with the afforestation considered here in detail (Birdsey, 2021). Some of these activities are:

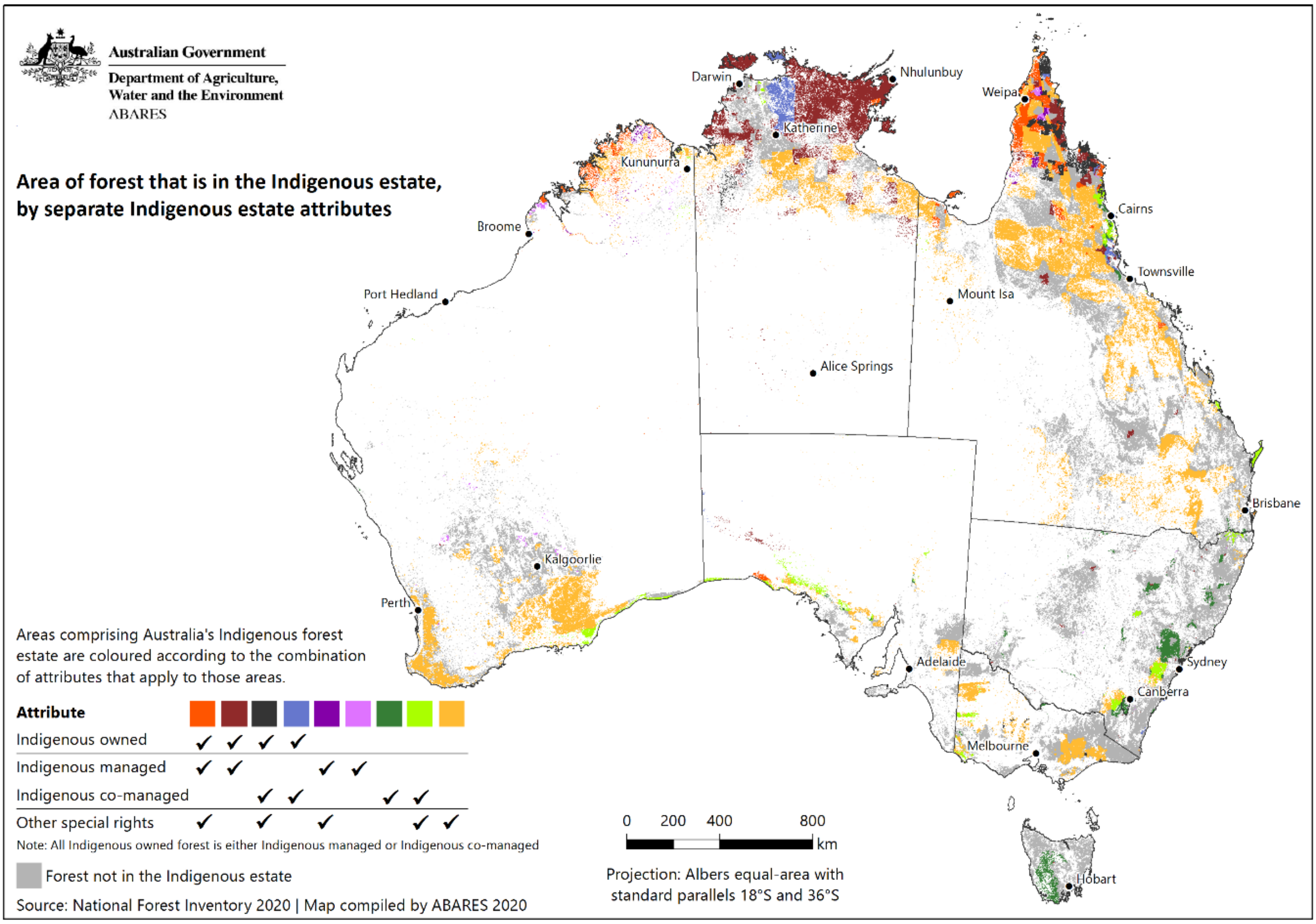
- accelerating regeneration of forests after disturbances through seeding, tree planting and control of competing vegetation;
- restoring degraded forests to increase sequestration rates;
- improving productivity or changing the quantum of sequestration of plantations through silvicultural techniques; and
- optimising the amount of carbon stored in long-lived wood products.

The impact of such improved forest management practices has been examined elsewhere, particularly for Australia in CSIRO's recent carbon sequestration potential report (Fitch et al., 2022), and for the USA as part of the Net Zero America study (Birdsey, 2021).

Savannah fire management across Australia has also been used to avoid emissions from large-scale high-intensity bushfires and increasing carbon sequestration in dead and living organic matter (Fitch et al., 2022; Russell-Smith et al., 2013). Such practice has been undertaken by Indigenous Australians for thousands of years to reduce fire intensity by reducing tropical grass biomass and reducing fire impacts on woody biomass (Wurster et al., 2021). This practice is widely applied in northern Australia, with a number of positive social and environmental impacts, including employment opportunities for indigenous communities (Fitch et al., 2022) and biodiversity improvement (Russell-Smith et al., 2013).

While the present report has focussed on afforestation of Australia's current farmland, some of which is within the indigenous forest estate shown in Figure 23, there is also significant potential to enhance the forest land sink in other regions of indigenous land ownership. Emissions abatement strategies on these forest lands can include reductions in deforestation, improved forest management, and savannah fire management, as discussed above. The benefits of such activities include biodiversity improvement, income through working on Country and practising culture, managing bushfire risk, and stimulating native seed production (Gebbie et al., 2021).

Figure 23 | Current Australian forested land area that is in the Indigenous estate, coloured by different estate attributes and sourced directly from ABARES (2020).



6.3 Possible emergence of other options for enhancing the land sink – the Land+ sensitivity

It is possible that, in addition to those land-based emissions abatement strategies used in the core scenarios of the Net Zero Australia project, and the forestry sector options for emissions sequestration discussed previously, several other options for reducing emissions or enhancing the land CO_2 sink may emerge in the coming years. These are, however, currently characterised by greater levels of uncertainty in estimates of carbon accounting, additionality, barriers to adoption and technical and social feasibility.

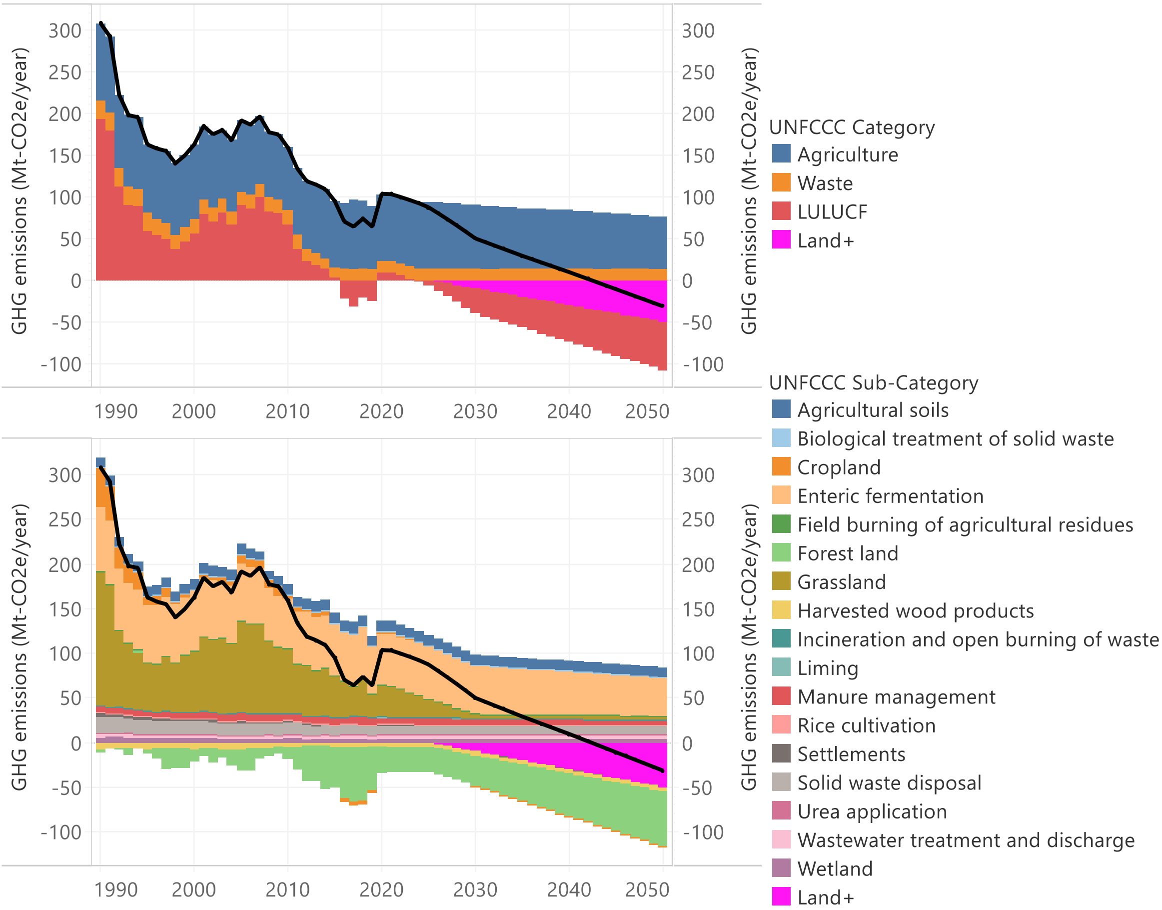
The Net Zero Australia project accounts for the possible emergence of other options for enhancing the Australian CO_2 sink with its *Land+* Sensitivity (Figure 24). This sensitivity is used to explore the wider energy system and environment impacts of the land sector reaching modest levels of net emissions removal, which are detailed elsewhere. Here we provide a brief outline of the strategies that this *Land+* sensitivity could constitute.

Options for enhancing the Australian land CO_2 sink

- A whole of landscape restoration approach, including:
    - integrated savannah burning (Cooke and Meyer, 2017; Russell-Smith et al., 2013); and
    - feral animal control (Drucker et al., 2010).
- Human-induced (re)generation of deep-rooted plant species (greater use of deep-rooted legumes in extensive rangeland and cropping, greater incorporation of forage shrubs (e.g. Eremophylia that also reduces livestock methane).
- Early life rumen microbiota engineering – in which animals are weaned on a methane inhibitor to establish a microbiota that results in the animal producing lower levels of methane over the animal's lifetime (Meale et al., 2021).
- Reductions in over-grazing (e.g. drought preparedness) and continuous cropping (reduced soil disturbance)

A number of these represent nascent options for emissions abatement, whose potential is uncertain. In exploring the possible implications of these options, we assume in this *Land+* sensitivity a linear increase in CO_2 sequestration from these options from 2025, reaching −50 Mt-CO2e/year by 2050 (Figure 24). This results in the combined land sector reaching −31.5 Mt-CO_2e/year in 2050.

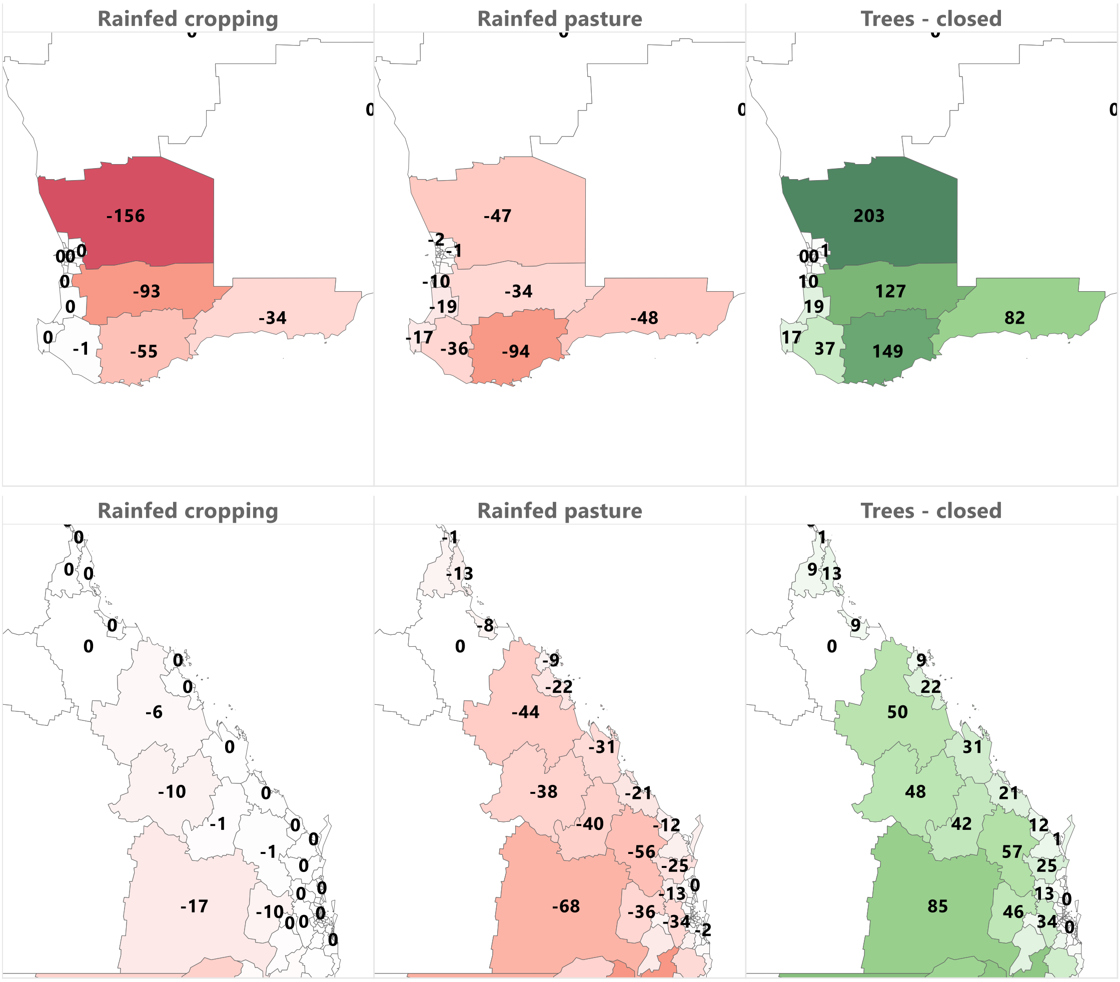
Figure 24 | Net land (agriculture, waste and LULUCF) sector emissions trajectories used in the Land+ sensitivity, aggregated by (top) UNFCCC category and (bottom) UNFCCC sub-category. These show additional options for enhancing the Australian land CO_2 sink (Land+) contributing −50 Mt-CO_2e/year of net sequestration by 2050, with the combined land sector reaching −31.5 Mt-CO_2e/year in 2050.



Appendices

Appendix A: Detailed land cover change for significant regions

Figure 25 | Strategy 1 – 30-year absolute land use change (2020 to 2050) of rainfed cropping, rainfed pasture land, and trees (closed & open canopies), across select SA3 regions in southern WA, southern QLD, eastern NSW, eastern VIC and TAS, and western VIC and south-eastern SA.



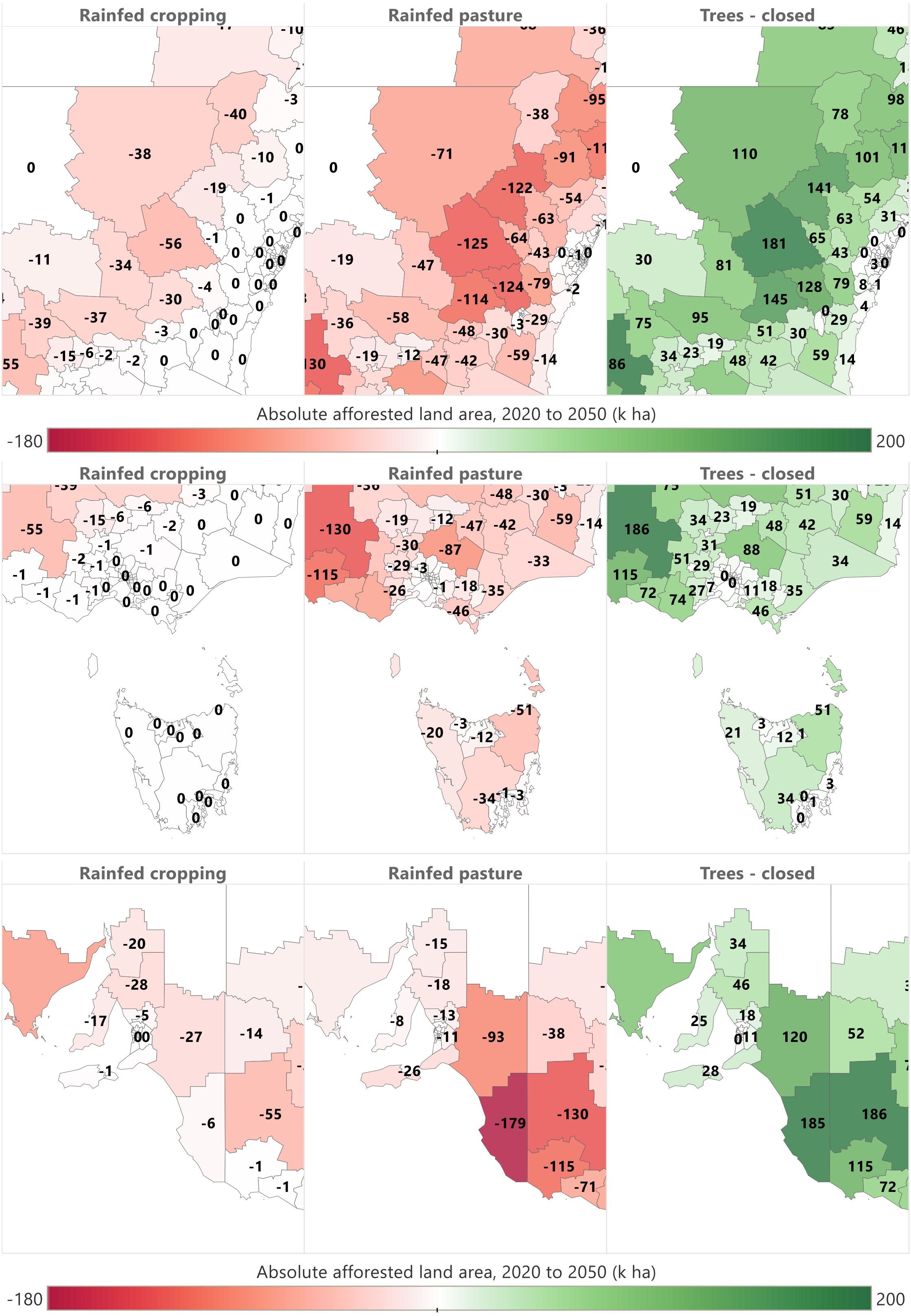
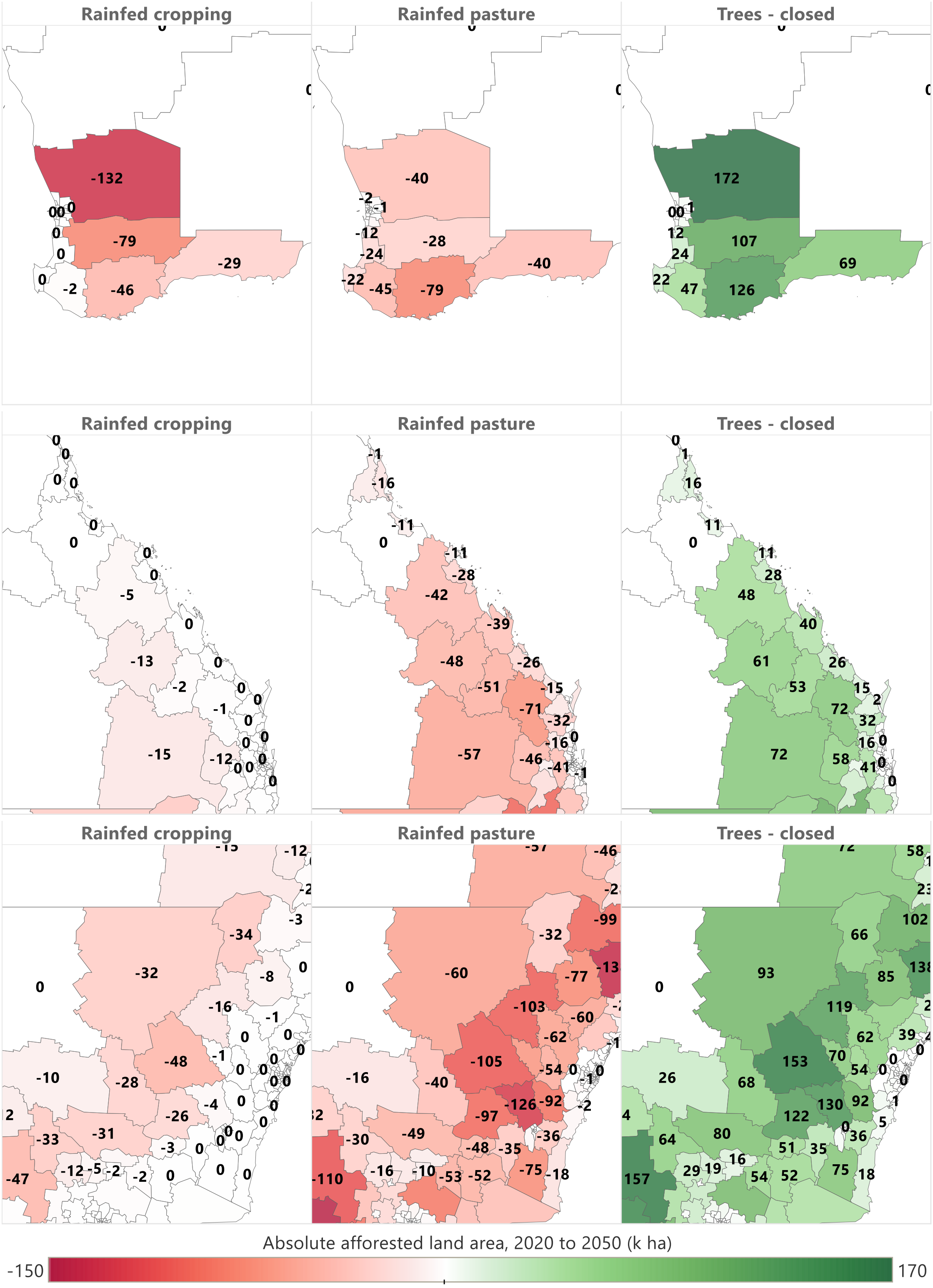
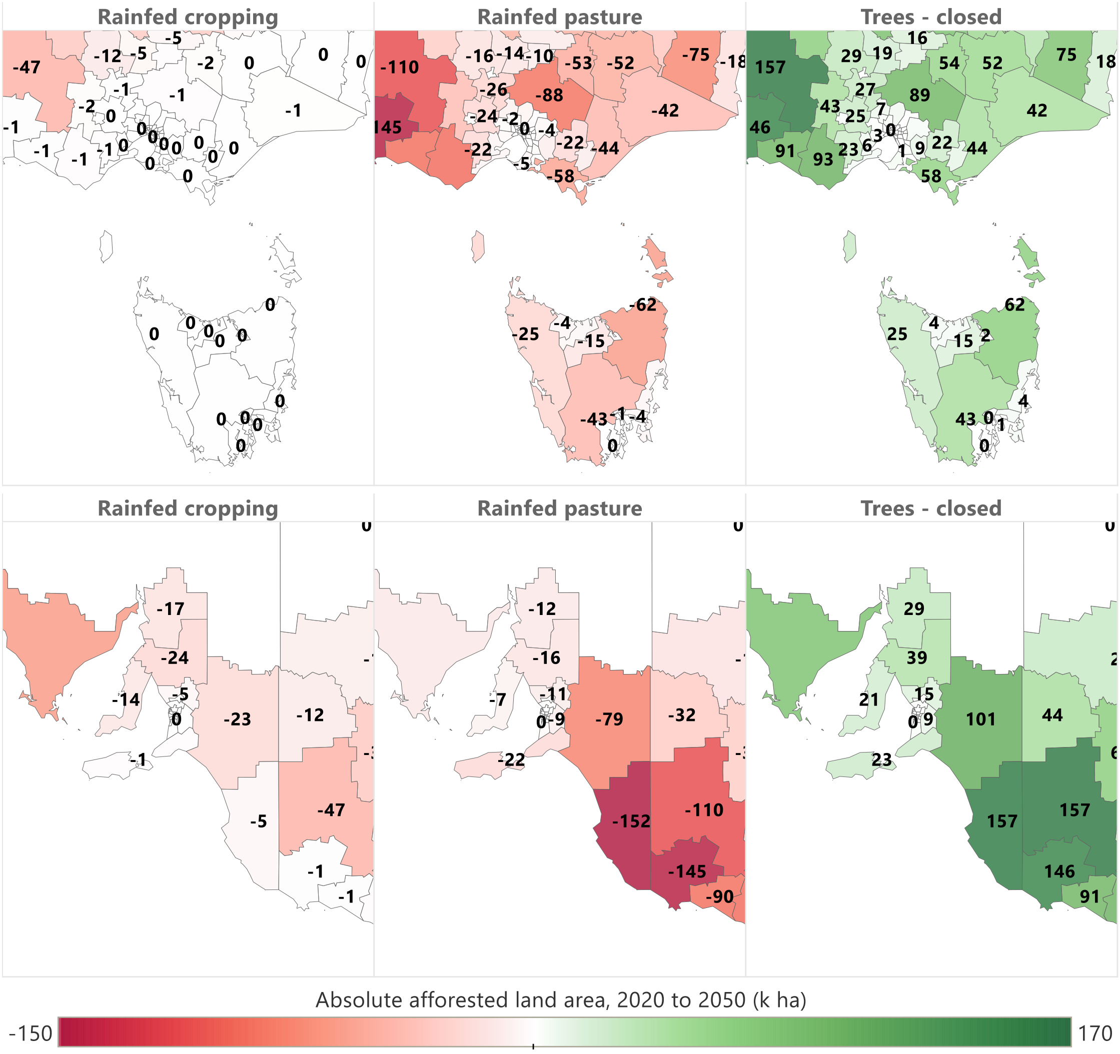

Rainfed cropping
Rainfed pasture
Trees - closed
Absolute afforested land area, 2020 to 2050 (k ha)
-180
200
Rainfed cropping
Rainfed pasture
Trees - closed
Rainfed cropping
Rainfed pasture
Trees - closed
Absolute afforested land area, 2020 to 2050 (k ha)
-180
200

Figure 26 | Strategy 2 – 30-year absolute land use change (2020 to 2050) of rainfed cropping, rainfed pasture land, and trees (closed & open canopies), across select SA3 regions in southern WA, southern QLD, eastern NSW, eastern VIC and TAS, and western VIC and south-eastern SA.




Rainfed cropping
Rainfed pasture
Trees - closed
Rainfed cropping
Rainfed pasture
Trees - closed
Absolute afforested land area, 2020 to 2050 (k ha)
-150
170

Appendix B: Detailed land cover change for significant regions

Table 7 | Representative SA3 regions used to estimate 30-year average CO_2 sequestration for representative Agroforestry environmental planting projects across the country.

SA3 code	SA3 name	State	Regional Forestry Hub	Mean annual rainfall (mm)	Strategy 1 afforestation (kha)	Strategy 2 afforestation (kha)	Estimated CO_2 sequestration (t-CO_2/ha/year)
10103	Snowy Mountains	New South Wales	South East NSW	740	59	75	9.3
10105	Goulburn - Mulwaree	New South Wales	Central West NSW	716	79	92	23.8
10106	Young - Yass	New South Wales	South East NSW	684	128	130	8.3
10302	Lachlan Valley	New South Wales		497	181	153	7.9
10304	Orange	New South Wales	Central West NSW	741	65	70	13.0
10501	Bourke - Cobar - Coonamble	New South Wales		409	110	93	5.0
10503	Dubbo	New South Wales		633	141	119	8.2
10604	Upper Hunter	New South Wales	North East NSW	764	54	60	9.6
10903	Upper Murray exc. Albury	New South Wales		389	95	80	7.1
11001	Armidale	New South Wales	North East NSW	894	110	138	10.0
11004	Tamworth - Gunnedah	New South Wales		724	101	85	7.2
11303	Wagga Wagga	New South Wales	Murray Region	572	145	122	6.6
20103	Maryborough - Pyrenees	Victoria		570	51	43	7.9
20401	Upper Goulburn Valley	Victoria	Murray Region	896	88	89	9.5
20503	Gippsland - South West	Victoria	Gippsland	947	46	58	19.9
21501	Grampians	Victoria	Green Triangle	453	186	157	3.2
21503	Murray River - Swan Hill	Victoria		341	75	64	6.5
21701	Glenelg - Southern Grampians	Victoria	Green Triangle	681	115	146	9.2
30701	Darling Downs (West) - Maranoa	Queensland	South and Central Queensland	567	85	72	6.6
30702	Darling Downs - East	Queensland	South and Central Queensland	650	46	58	11.4
30801	Central Highlands (Qld)	Queensland	South and Central Queensland	630	48	61	14.5
31201	Bowen Basin - North	Queensland	North Queensland	655	50	48	0.8
31202	Mackay	Queensland	North Queensland	1509	22	28	8.3
31902	Burnett	Queensland	South and Central Queensland	710	57	72	2.7

SA3 code	SA3 name	State	Regional Forestry Hub	Mean annual rainfall (mm)	Strategy 1 afforestation (kha)	Strategy 2 afforestation (kha)	Estimated CO_2 sequestration ($t\text{-}CO_2$/ha/year)
40502	Lower North	South Australia		384	46	39	4.5
40601	Eyre Peninsula and South West	South Australia		238	91	76	5.1
40701	Fleurieu - Kangaroo Island	South Australia		602	28	23	9.5
40702	Limestone Coast	South Australia	Green Triangle	570	185	157	6.4
40703	Murray and Mallee	South Australia		344	120	101	6.8
50103	Manjimup	Western Australia	South West Western Australia	875	37	47	24.0
50901	Albany	Western Australia	South West Western Australia	505	149	126	7.5
50902	Wheat Belt - North	Western Australia		363	203	172	4.0
50903	Wheat Belt - South	Western Australia	South West Western Australia	409	127	107	6.6
51101	Esperance	Western Australia		415	82	69	6.0
60203	North East	Tasmania	Tasmania	817	51	62	12.7
60403	West Coast	Tasmania	Tasmania	1880	21	25	25.1

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