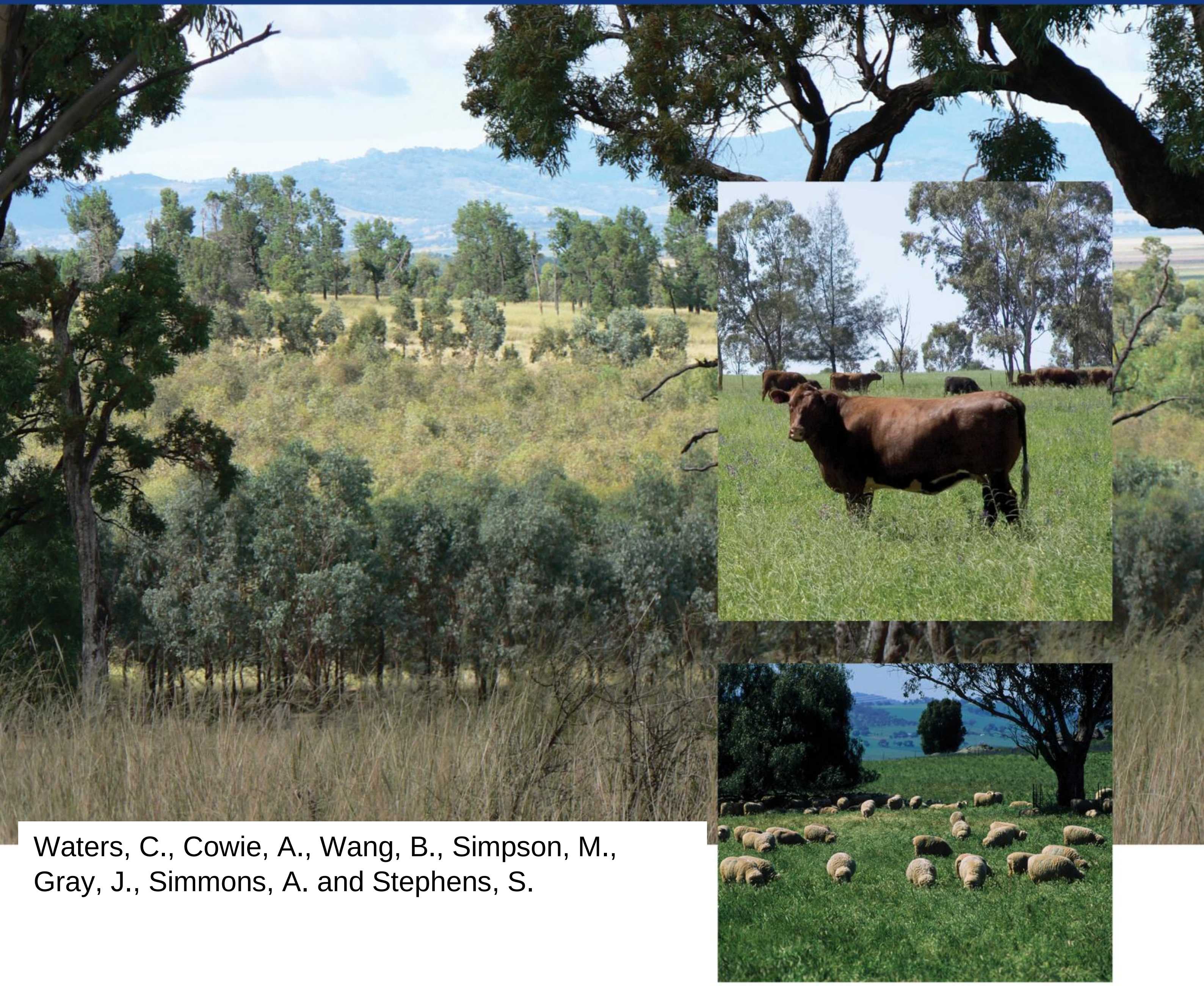
Abatement opportunities from the agricultural sector in New South Wales

Modelling to support the development of the Primary Industries Productivity and Abatement Program



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Glossary of terms

AGB	Above ground biomass
AD	Avoided Deforestation
ADE	Avoided Deforestation activities in eastern NSW
ADW	Avoided Deforestation activities in western NSW
AC	Avoided Clearing
ACCU	Australian Carbon Credit Unit
AD	Avoided Deforestation
ALFA	Australian Lot Feeders Association
AGEIS	Australian Greenhouse Emissions Information System
BGB	Below ground biomass
C	Carbon
CEAs	Carbon Estimation Areas
CER	Clean Energy Regulator
CMI	Carbon Market Institute
CMIP6	Sixth phase of the Coupled Model Intercomparison Project, of the World Climate Research Programme
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
CH_4	methane
C-stock	Carbon stock
DISER	Department of Industry, Science, Energy and Resources
DMPP	3,4-Dimethylpyrazole phosphate (a nitrification inhibitor)
EF	Emissions factor
ERF	Emissions Reduction Fund
FullCAM	Full Carbon Accounting Model
GCM	Global Climate model
HIR	Human-induced regeneration

INS	Invasive native scrub
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle Assessment
LLS	Local Land Services
MEP	Mixed species, environmental plantings
MEPT	Mixed species, environmental plantings (Temperate areas)
MLA	Meat and Livestock Australia
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous oxide
NIR	(Australia’s) National Inventory Report (to the UNFCCC)
3-NOP	3-Nitrooxypropanol (a feed additive that reduces enteric methane)
PIPAP	Primary Industries Productivity and Abatement Program
SOC	Soil Organic Carbon
SSP245	Shared socioeconomic pathway 2, under Representative Concentration Pathway 4.5. That is, a “middle of the road” scenario with respect to social, economic, and technological trends, and moderate emissions.
SSP585	Shared socioeconomic pathway 5, under Representative Concentration Pathway 8.5. That is, a scenario modelling a high-tech, energy intensive future with high emissions associated with ongoing fossil fuel use.
UNFCCC	United Nations Framework Convention on Climate Change

Executive summary

The Primary Industries sector presents a myriad of opportunities for emissions abatement. Agriculture is a major source of emissions as well as delivering significant abatement through vegetation-based sequestration. The sector is well-placed to play a significant role in contributing to both short (2030) and long term (2050) emissions reduction targets and hence contribute to a pipeline of abatement that is desirable from State and National perspectives.

This report provides estimates of the amount of sequestration and emissions reduction from agriculture that could be delivered in 2030. Most importantly, we also identify feasible opportunities for the co-delivery of agricultural production which will benefit regional communities, create positive environmental outcomes as well contribute to the NSW Net Zero ambition.

The Net Zero Plan Stage 1: 2020-2030 (NZ Plan) is foundational for the NSW Government's action on climate change and goal to reach net zero emissions by 2050. The NSW and Commonwealth governments are jointly funding over $2 billion in energy and emissions reduction initiatives. The NZ Plan aims to strengthen the prosperity and quality of life of the people of NSW, while helping the state to deliver a 35% cut in emissions by 2030 compared to 2005. The Primary Industries Productivity and Abatement Program (PIPAP) is one of seven programs under the memorandum of understanding (MoU) between the NSW and Commonwealth Governments on energy and emissions reduction.

In transitioning to the long term 2050 target, the NSW NZ Plan aims to support economic growth and reduce the 2005 NSW emissions by 35% by 2030. There are several benefits in supporting the delivery of abatement from the agricultural sector including:

- **Large abatement potential:** The extensive nature of agricultural land-use means there is the potential to deliver a large pool of abatement through sequestration
- **Strong linkages between sustainable agricultural production and abatement:** Increased abatement in agriculture will allow the sector to secure long-term access to international markets which increasingly require the demonstration of sustainable land management and environmental stewardship
- **Additional income streams for farmers:** Carbon farming provides an alternative income stream which can increase resilience of the farm enterprise, rural communities and landscapes
- **New regional jobs:** The Carbon Market Institute estimates that by 2030, the Australian carbon market will generate $AUD 10-24 billion and create between10,500 and 21,000 new jobs.
- **Opportunity to 'stack' abatement activities to amplify returns:** Co-deliver economic, abatement and environmental outcomes
- **Multiple environmental benefits:** Opportunity to reverse land degradation, increase the extent and quality of habitat for biodiversity through abatement activities

Our Approach

Vegetation and associated soil carbon pool sequestration estimates were based on an identification of suitable areas for alternative management approaches to determine the potential abatement. The FullCAM (Full Carbon Accounting Model) was used to model the spatial delivery of abatement across NSW under current climate for 100 years (2020 to 2119). We have constrained vegetation-based abatement by applying a low adoption rate (1 to 10%) to safeguard the production of food and fibre but recognise that agricultural land-use trade-offs may be minimal at up to 20% on-farm adoption.

Spatial estimates of soil carbon change associated with management of woody vegetation were also derived using FullCAM but considered unreliable due to limited field-based validation. The potential abatement estimates provided in this summary are based on biomass growth (above and below ground) and do not include soil carbon sequestration associated with vegetation growth, thus providing an underestimate of the potential abatement. A second modelling exercise using a mixed modelling approach was used to create a benchmark soil carbon map for NSW from which a 10% change in cover (woody vegetation and ground cover) was used to estimate the potential sequestration through soil carbon management.

To estimate the potential soil carbon sequestration from agricultural land-use we used the conservative default values provided by the Commonwealth Government to assess soil carbon change under modified crop management activities and compared these to published values for NSW.

Estimated abatement from emissions reduction was quantified with respect to a baseline representing the projected emissions in 2030 without intervention. This allowed estimation of the technical abatement potential through a range of strategies including reducing enteric methane through feed additives and herd management and stabilising organic carbon through pyrolysis to produce biochar.

For each of the sequestration and emissions reduction strategies, we have also provided an analysis of the current constraints to adoption (including those associated with methods developed under the Emissions Reduction Fund) to determine the adoption potential and quantify feasible abatement. Emissions reduction technologies and management practices were assessed with respect to technology readiness, regulatory, economic and social barriers to production, to determine feasible abatement. Approaches and activities to overcome these barriers were also identified.

Contribution to the NSW Net Zero Plan

We found that creating a pipeline of abatement activities can be achieved initially through vegetation and soil-based sequestration activities and more long-term abatement coming from emissions reductions activities as technologies are commercialised and costs decline (**Figure i**). Each source of abatement is summarised in **Figure ii**.

The potential to deliver a large amount of abatement in biomass (~57.8 Mt CO_2 e) from management of vegetation by 2030 was identified (**Figure ii**). Large abatement opportunities (31.9 Mt CO_2 e) in biomass can be delivered from enhancement of existing ERF Avoided Deforestation project areas (6.9 Mt CO_2 e) and incentivising retention of native vegetation by 2030 (25.1 Mt CO_2 e). In addition, ERF Environmental plantings (as well as non-ERF market activities such as tree planting or management of native regrowth) could provide ~17.9 Mt CO_2 e of abatement over the next 10 years. These estimates are summarised in **Table i**. Significant additional sequestration from soil carbon associated with vegetation management can be achieved. Conservative estimates for ERF Modelled Soil Carbon method suggest 20.0 Mt CO_2 e can be sequestered by 2030 in agricultural managed areas (croplands and grazing systems) (**Table ii**). Increasing vegetation cover (woody and ground cover) by 10% across NSW could potentially sequester 7.5 to 10 t ha^{-1} soil carbon which is equivalent to potential carbon sequestration of 452.8 Mt soil C (1.6 Mt CO_2 e) across most of NSW (agricultural and non-agricultural areas) (**Figure iii**.). Indicative estimates suggest as much as 5.5 Mt CO_2 e soil carbon sequestration can be achieved in central western NSW with a 10% increase in vegetation cover (**Table iii**).

The agricultural sector can also support emissions reduction of ~ 3.92 to 4.68 Mt CO_2 e in 2030 (**Table iv**).

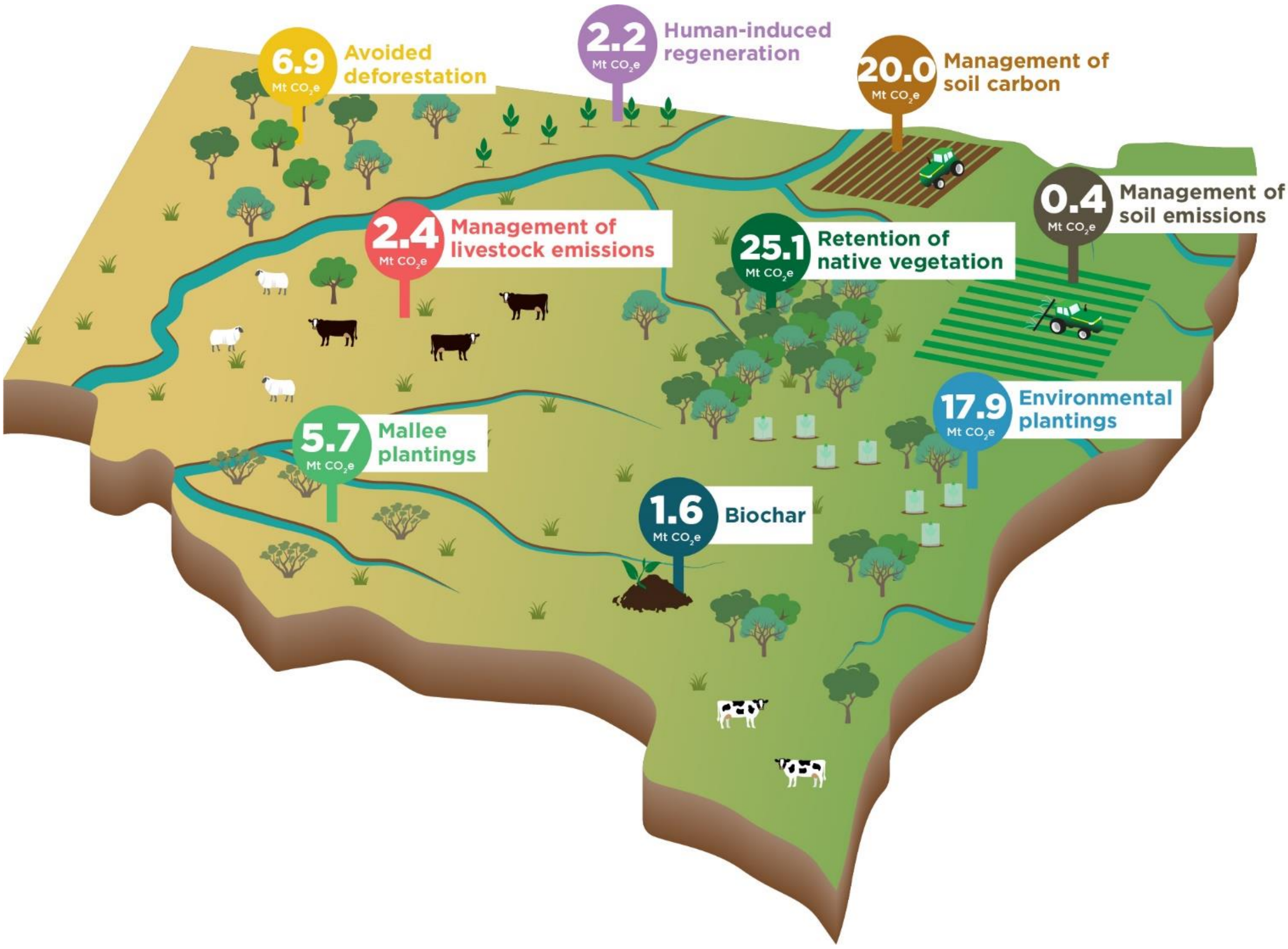


Figure i. Feasible abatement estimates delivered over 10 years (2020 to 2030) from NSW agriculture. Activities are ranked based on their ability to be integrated into existing agricultural land-use and generate income streams for farmers. For vegetation-based sequestration (natural regeneration, environmental and Mallee plantings, avoided clearing) values are cumulative, estimated from activities commencing 2020 and for biomass only. Additional sequestration in soil carbon from vegetation is not indicated. For emissions reduction activities, the value given is the estimated abatement in the year 2030.

Highlights

20.0 M t CO_2e delivered from the management of soil carbon

We provide conservative estimates of sequestration potential through soil carbon management, based on regional Commonwealth Government default values. The greatest sequestration potential was identified for sustainable intensification through grazing native vegetation and conversion of croplands to pastures in north-western NSW. In these areas, opportunities to deliver abatement as well as providing climate change adaptation were identified. Additional sequestration from stubble retention across the cropping and mixed farming zones was also identified.

We have assumed a 10% industry adoption rate which reflects the interest and willingness by industry to participate in carbon markets through soil sequestration. Options to modify Emissions Reduction Fund soil carbon methods have been identified which would unlock considerable additional abatement. There is an expectation that the sequestration potential identified from these conservative estimates underestimates potential abatement opportunities.

Opportunities to sequester soil carbon from a 10% increase in cover (woody and ground cover) across NSW were identified and would have the additional benefit of reducing the risk of losses in soil carbon from erosion.

2.2 M t CO_2e delivered from natural regeneration

Natural regeneration is considered one of the most cost-effective vegetation-based sequestration activities. The management of native vegetation regrowth includes regrowth management that can be associated with rehabilitation of degraded or low productivity areas and the enhancement of remnant vegetation. The greatest opportunities for sequestration are in western NSW. Strategic prioritisation of zones within a farm such as riparian, floodplain or drainage lines may support the greatest sequestration rates in semi-arid areas.

We have assumed a 5 % industry adoption rate as well as an on-farm adoption of 20%, giving 33,337 ha of natural regeneration in NSW. The large number of registered projects for the *Human-induced Regeneration* ERF method suggests greater rates of adoption may be achieved.

17.9 M t CO_2e delivered from Environmental Plantings

Environmental plantings provide one of the largest sequestration opportunities and also deliver agricultural production benefits. Activities include reforestation and afforestation through e.g. direct seeding or planting tube-stock of mixed native species as shelter belts, for rehabilitation of degraded areas and for amenity purposes. Targeted activities that enhance remnant vegetation, riparian areas and drainage lines, provide erosion control and reverse land degradation may positively impact livestock production.

We confined our assessment to the temperate areas of NSW only, where sequestration rates are relatively high and rainfall is reliable. In these areas we have assumed a 5 % industry adoption rate and an on-farm adoption of 20% giving 135,000 of environmental plantings in NSW. While these areas offer the highest rates of sequestration, expansion of these activities to more marginal areas e.g. mixed farming zone of central and northern NSW will further increase abatement opportunities.

Additional environmental benefits include increased landscape connectivity of native vegetation and the creation of wildlife corridors. Rehabilitation of areas for dryland salinity control and nutrient management may also provide additional productivity benefits.

2.0-2.8 M t CO_2e delivered through reduced emissions from livestock

Enteric methane, emitted by ruminant livestock, contributes 75% of the NSW agriculture sector emissions.

Strategies to reduce enteric methane include dietary additives and herd management to enhance productivity. Promising feed additives, that can reduce emissions by over 50% per unit of feed intake, are expected to become commercially available within 2-5 years. Dietary strategies are most applicable to livestock on supplementary feed or full rations (dairy and feedlot cattle). Strategies to reduce enteric methane from grazing animals include pasture management and breeding. Herd management approaches are estimated to reduce methane emissions by 5-25% and are most applicable in grazing systems. Based on projected size of the NSW cattle herd in 2030, the feasible abatement through a combination of dietary additives and herd management is estimated at 1.5-2.0 Mt CO2-e per year in 2030. The estimated feasible abatement for enteric methane from sheep is estimated at 0.4-0.5 Mt CO2-e. The total abatement estimated represents a 20% reduction in livestock emissions projected for 2030.

Further emissions reduction in 2030 in the livestock sector were estimated 0.12-0.20 Mt CO2-e though modified management of manure.

5.7 M t CO_2e delivered from Mallee plantings

These activities include the establishment and management of any species from the genus *Eucalyptus* that has multiple stems, by direct seeding or planting of tube stock. Mallee plantings can provide shelter belts, rehabilitation or restoration of degraded areas (salinity control and nutrient management) as well as amenity benefits to the farm. The assessment of potential for Mallee plantings was confined to the low rainfall areas in southern NSW, consistent with ERF eligibility requirements for Mallee planting projects. In these areas, where crop production is becoming increasingly challenged under future climates, Mallee plantings may provide addition production benefits where climate adaptation strategies include transitioning from cropping to mixed farms enterprises.

In our estimations we have assumed a 5 % industry adoption rate and on-farm adoption of 20% giving 121,948, 14,963 and 30,791 ha for establishment of *Eucalyptus kochii*, *E. loxophleba and E. polybractea* respectively.

1.56 M t CO_2e Biochar

The production of biochar and its use as a soil amendment would stabilise carbon in organic matter and has the potential to reduce N_2O and methane emissions from decomposition of organic residues and reduce N_2O emissions from soil. The stabilisation of organic matter may also provide further emissions reduction in the energy sector, through production of renewable heat and electricity.

Feasible abatement in 2030 through biochar, considering only the carbon stabilisation component, is estimated at 1.56 Mt CO2-e.

Further emissions reduction in 2030 in the cropping sector were estimated at 0.27 Mt CO_2-e from reduction in N_2O from soil, through management of inorganic fertilisers and crop residues, and 0.1 Mt CO_2-e through delayed flooding of rice, to reduce CH_4 emissions.

32 M t CO_2e delivered by incentivising retention of native vegetation

Consistent with the published literature, reforestation and avoided deforestation provide the largest short-term abatement opportunities. Natural climate solutions such as natural regeneration and avoiding deforestation are recognised globally as providing some of the most cost-effective climate change mitigation pathways. However, incentivising the retention of native vegetation (avoiding clearing), is likely to be delivered with a trade-off against crop production and a lesser trade-off with livestock production. While the magnitude of trade-offs would need to be considered within the individual farm context, we identify that a large opportunity to avoid emissions from clearing exists in eastern areas of NSW.

There is also opportunity to deliver abatement through the modification of existing Emissions Reduction Fund methods to enhance the sequestration from established ERF project areas in western NSW.

Opportunities to deliver abatement from the agricultural sector

In order that the abatement potential from agriculture is realised, a suite of high impact strategies to remove barriers and increase opportunities for market-based (Emissions Reduction Fund, ERF) and non-carbon-market activities (outside the ERF which may require financial incentives) were identified. Early stage activities may include:

- **Spatial prioritisation and optimisation:** Development of regional blueprints which identify spatial prioritisation for abatement opportunities that optimise land-use for carbon, production and biodiversity, whilst considering mitigation strategies for unintended impacts (e.g. currently most ERF activity is geographically clustered in the semi-arid rangelands of western NSW increasing the risk of abatement activities to regional climate conditions). These blueprints can be used to support ongoing stakeholder consultation, tailor regional program implementation as well as informing program evaluation; and
- **Developing alternative models that capture small scale abatement:** Identify and develop business cases for partnerships (e.g. Local Land Services, Landcare, Greening Australia, Local Governments), to facilitate aggregation of small-scale abatement activities and/or options for the role of the NSW

Government in developing market and non-market mechanisms. Spatial prioritisation and optimisation can be used to facilitate business case development

There are two major priority areas identified from our analyses of opportunities and barriers:

Undertake regional demonstrations and pilots to reduce uncertainties and costs

- Demonstrate and evaluate abatement management practices (including regenerative practices) and technologies
- Promote regenerative management practices that increase soil carbon and deliver co-benefits of improved productivity and drought resilience
- Develop an on-farm optimisation tool to support decisions that maximise synergies and minimise trade-offs between production and carbon
- Harness lighthouse examples from key farmer innovators and ERF project developers
- Demonstrate and provide training to help farmers navigate complexities in project development and management, show how carbon income can be managed as an additional enterprise contributing to farm diversification (including training/forums in legal, financial planning and tax treatment)
- Pilot incentive programs to lower transaction costs and deliver secure abatement
- Pilot incentive programs to 'value-stack' carbon projects through the identification and valuing of environmental co-benefits

Prioritise and accelerate Emissions Reduction Fund method modifications

- Develop business cases for new ERF methods, and modified methods to overcome identified barriers in current methods
- Work with carbon project developers to test and validate proposed method modifications (developed as part of above)
- Modification of the ***Estimating Sequestration of carbon in Soil using Default Values*** method to provide a workable, low-cost method which adopts a hybrid, modelled-measured approach to baseline and quantify soil carbon changes. Current modelled (default value) estimates are low (reducing the value of a carbon project) and direct measurement costs restrict adoption of the ***Measurement of Soil Carbon Sequestration in Agricultural Systems*** method
- Develop a mechanism to 'overlay' or 'nest' multiple ERF methods on the one site.
- Modification of ***Human-induced revegetation*** and ***Avoided Deforestation*** methods to recognise management leading to sequestration in vegetation and soils not currently recognised in methods e.g. regrowth at sites with <20% canopy cover
- Expansion of the ***Avoided Clearing*** method to capture areas '*at risk*' of clearing
- Modification of the ***Human-induced revegetation*** method to capture canopy change rather than depending on age of woody vegetation, for use in semi-arid, rangeland environments
- Modification of the ***Beef Herd Management*** to include sheep flock management

Table i. Overview of feasible sequestration in biomass (accumulated sequestration 2020 to 2030) from NSW agricultural sector, derived from FullCAM. Activities associated with Emissions Reduction Fund methods (carbon markets) and comparable non-market practices.

ERF method	Practice	Area (ha)	% Adoption rate	% of farm (ha)	Assumptions	Cumulative sequestration t C (biomass & soil)	Cumulative sequestration t C (biomass)
						2030	2030
Avoided clearing of native vegetation							
Avoided Deforestation	Recognising vegetation < and > 20% cover; ecological thinning	(Western NSW) 299,455 (Western NSW) 119,782	5 1	-	Most activities in western NSW; recognised method enhancement and expansion opportunities realised	1,796,730 359,346	1,577,166 311,433
		M t CO_2 e (2030)				**7.90**	**6.92**
	Reduced clearing rates	(Eastern NSW) 409,500	-	-	Dis-incentivising current rate of clearing in eastern NSW	6,961,500	6,838,650
		M t CO_2 e (2030)				**25.52**	**25.07**
		M t CO_2 e (2030)				**33.42**	**31.99**
Vegetation regrowth management							
Human-induced regeneration	Natural regeneration	33,337	5	20	Uptake of current adoption continues	1,700,537	597,591
		M t CO_2 e				**6.24**	**2.19**
Reforestation and Afforestation							
Environmental Plantings	Planting paddock boundaries and remnant enhanced; rehabilitation and restoration, shelter belts, amenity plantings	(Temperate NSW) 135,337	5	20	Cost barriers are removed; adoption targets temperate areas of NSW; co-sharing costs of mixed native species by direct seeding and tube stock planting are in place	11,503,654	4,872,132
		M t CO_2 e (2030)				**42.18**	**17.86**
Mallee *Eucalyptus kochii*		(Low rainfall NSW) 21,948	5	20	Adoption targets marginal areas of the southern cropping zones where cropping is becoming increasingly more marginal	1,163,244	476,272
Mallee *E. loxophleba*		14,963	5	20		912,743	366,593
Mallee *E. polybractea*		30,791	5	20		1,939,833	723,588
		M t CO_2 e (2030)				**14.72**	**5.7**
		M t CO_2 e (2030)				**56.95**	**23.56**
					Total M t CO_2e	**96.61**	**57.74**

Table ii. Overview of estimated feasible sequestration from soil in agricultural landscapes (accumulated sequestration 2020 to 2030). Activities associated with Emissions Reduction Fund method- "Estimating sequestration of carbon in soil using default values method (model-based soil carbon)" only.

ERF method	Practice	Area (ha)	% Adoption rate	% of farm (ha)	Assumptions	Cumulative sequestration T C 2030
Soil carbon						
Default values	Conversion of cropland to pasture	1,373,406	10	-	Based on the current rates of conversion to pastures and incentivising conversion to perennial grass and legumes pastures	904,056
	Stubble retention	1,294,358	10	-	Based on current potential area for adoption of retention of stubble in croplands	505,678
	Sustainable intensification e.g. grazing management, pasture enhancement, nutrient management; soil acidity management; new irrigation; pasture renovation	10,740,034	10	-	Industry uptake across a broad range of activities	4,049,458
					Total	**5,459,192**
					M t CO_2e	**20.0**
						Cumulative sequestration T C

Table iii Potential SOC sequestration by LLS Region (with 10% absolute vegetation cover increase)

LLS Region	**Area (km2)**	**Mean (t/ha)**	**Potential seq (Mt)**	**CO_2 equiv. (Mt)**
Central Tablelands	30,265	8.1	24.5	89.8
Central West	87,375	8.6	75.0	275.0
Greater Sydney	11,453	6.1	6.9	25.3
Hunter	30,905	7.5	23.1	84.7
Murray	41,372	7.4	30.5	111.8
North Coast	29,553	8.1	24.0	88.0
North West	76,807	8.8	67.8	248.6
Northern Tablelands	36,819	7.1	26.1	95.7
Riverina	65,656	7.5	49.5	181.5
South East	54,422	6.6	36.1	132.4
Western	296,818	5.3	158.3	580.4
NSW	**761,444**	**7.4**	**521.8**	**1913.3**

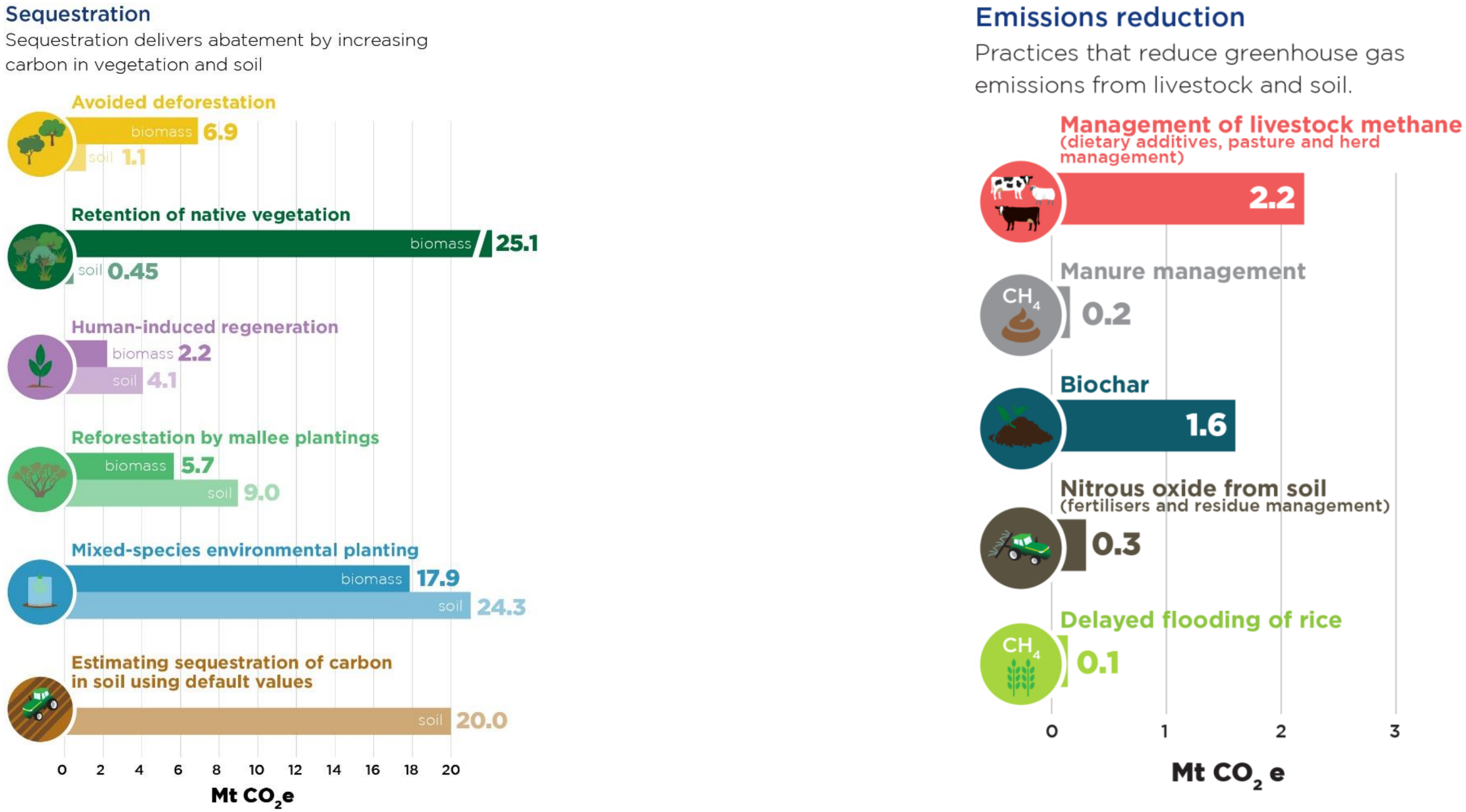
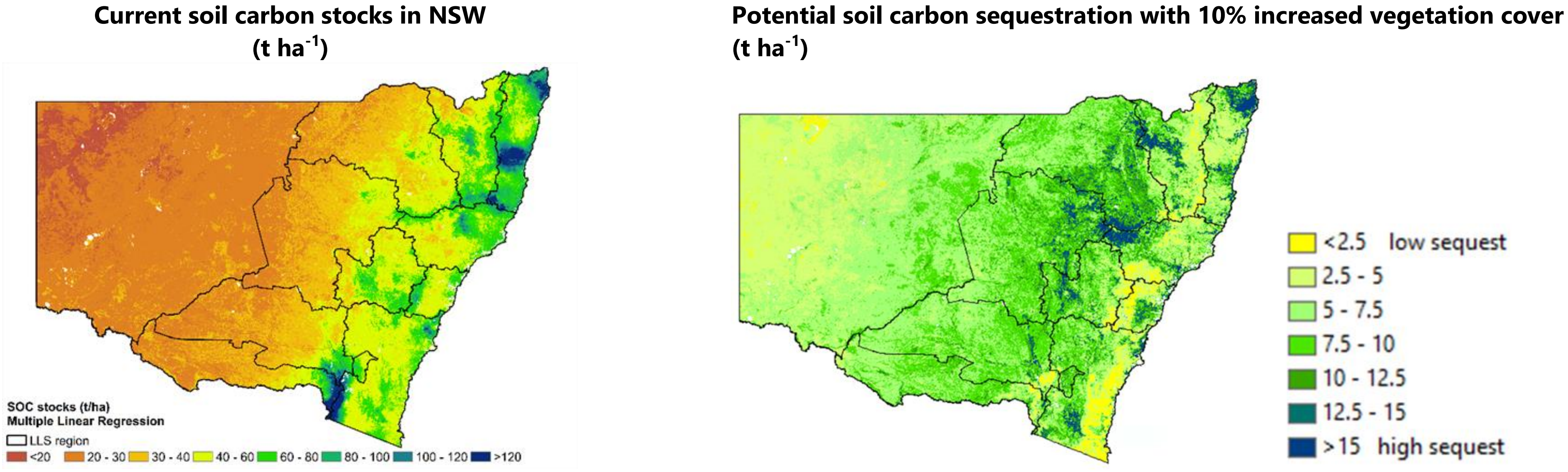


Figure ii. NSW abatement potential (2020-2030) includes sequestration in biomass and soil and emissions reduction practices includes management of livestock and soil.



Current soil carbon stocks in NSW (t ha^{-1})

Potential soil carbon sequestration with 10% increased vegetation cover (t ha^{-1})

Figure iii. Current soil carbon stock (t ha^{-1}, left) and potential soil carbon sequestration with a 10% (absolute) increase in vegetation cover (woody and ground cover).

Table iv. Overview of feasible emissions reduction (in 2030) from NSW agriculture. Adoption rate is estimated on the assumption of a market incentive that removes cost barriers, and no regulatory barriers hindering adoption.

Emissions source	Practice	Scale of sector in 2030	Technical potential (% reduction)	% Adoption rate	Assumptions	2030 Mt CO_2 e
Enteric methane reduction						
Beef, feedlot	Feed additive	350,000-650,000 head	50	60-80	Feedlot numbers continue current upward trend. Most promising feed additive (*Asparagopsis*) approved for use, affordable and accepted by the beef industry. Limited additional mitigation through herd management in this already intensive system	0.18 to 0.33
	Herd management		5	80		
Beef grazing	Feed additive	4.65-5.85 million head	50	2-30	Herd based on range 1990-2015. Moderate uptake of nitrate feed additive (ERF method already available). Widespread adoption of “best practice” herd management (culling unproductive animals, improved genetics, supplementary feeding, improved pasture and grazing management)	1.05 to 1.31
	Herd management		15	80		
Dairy	Feed additive	250,000-350,000 head	50	40-60	Dairy herd continues current downward trend. Most promising feed additives (*Asparagopsis* and 3-NOP) approved for use, affordable and accepted by the dairy industry. Additional mitigation through herd management particularly supplementary feeding	0.28 to 0.39
	Herd management		20	80		
Sheep	Feed additive	25-35 million head	50	20	Flock based on range 2000-2015. Moderate uptake of nitrate feed additive (ERF method already available). Widespread adoption of “best practice” flock management (culling unproductive animals, improved genetics, supplementary feeding, improved pasture and grazing management)	0.37 to 0.52
	Flock management		10	50		

Total enteric methane						**1.87 to 2.55**
Soil emissions of nitrous oxide						
Inorganic fertilisers	Nitrification inhibitors, Fertiliser management	345 Gg N fertiliser, applied to 5.6 m ha crops	50 20	70 10	ERF method available that provides incentive for widespread adoption in cropping systems of the DMPP product that is already commercially available	**0.22**
Crop residues	Remove for biochar/bioenergy	8.4 Mt cereal residues	40	10	Residues in excess of 1.5 t/ha can be removed from cereal crops without impacting productivity. Bioenergy and biochar industries become established, such as though regional biohubs.	**0.05**
Total soil N_2O						**0.27**
Biochar						
Avoided decomposition	Pyrolysis of biomass to produce biochar for soil amendment	11 Mt feedstock	6 Mt CO_2-e	10 straw, 50 manure 90 processing residues	Regulatory barriers to production and use of biochar are overcome.	**1.56**
Other						
Methane, Nitrous oxide from manure	Covered ponds, biogas flared or used; Pyrolysis of litter	400,000-600.000 pigs	70 (covered ponds) 50 (pyrolysis of feedlot manure)	50% uncovered ponds and drylot feedlots	Numbers of pigs remain stable at the range seen 2010-2017; feedlot numbers continue to increase. Available technology for anaerobic digestion and covered ponds adopted more widely. Regulatory barriers to production and use of biochar overcome.	**0.12-0.20**
Methane from rice production	Delayed flooding	94,000 ha	50	50	Modified stubble management and delayed flooding reduce emissions by 50% and will be adopted by 50% of growers	**0.10**
					M t CO_2 e at 2030	**3.92 to 4.68**

1. Background

The agricultural sector of NSW contributed to 15 per cent of the state's total greenhouse gas (GHG) emissions in 2016/17 (NSW Environment & Heritage, 2020). The primary source of agricultural emissions is livestock methane, which accounted for 73 per cent of all NSW agricultural emissions over this period. The balance of agricultural emissions include manure, nitrous oxides from fertiliser use, crop waste decomposition, rice cultivation and stubble burning. As well as being a major source of emissions, agriculture providing significant abatement through vegetation-based sequestration. In NSW, agricultural land-use currently supports around 26 per cent of the national land sector abatement through vegetation-based sequestration activities. This makes NSW primary producer's major stakeholders in the delivery of long-term national abatement.

The Net Zero Plan Stage 1: 2020-2030 (NZ Plan) is foundational for the NSW Government's action on climate change and goal to reach net zero emissions by 2050. The NSW and Commonwealth governments are jointly funding over $2 billion in energy and emissions reduction initiatives. The NZ Plan aims to strengthen the prosperity and quality of life of the people of NSW, while helping the state to deliver a 35% cut in emissions by 2030 compared to 2005. The Primary Industries Productivity and Abatement Program (PIPAP) is one of seven programs under the memorandum of understanding (MoU) between the NSW and Commonwealth Governments on energy and emissions reduction.

The PIPAP program relates to the following NZ Plan objectives

- regional economies are diversified, supported and invigorated through the transition to net zero by taking advantage of opportunities and avoiding adverse impacts
- key sectors act to stay competitive in a global transition to net zero, offering low emissions products and services and reducing the risk of stranded assets.

A major focus of the PIPAP Program includes supporting the uptake of new emissions reduction technologies which may also reduce farm costs and increase primary production, reduce on-farm emissions intensity, secure new income streams through carbon sequestration (in soils and vegetation) and maximising revenue from carbon offset programs (Department of Planning Industry & Environment, 2020).

Major benefits of sequestration activities from primary industries (agriculture, forestry and fisheries) include:

- Linkages between sustainable agricultural production and abatement
- A large carbon sink potential
- Strengthened regional economic growth and development. The Carbon Market Institute suggests that by 2030, the Australian carbon market will generate between $AUD 10-24 billion and create between10,500 - 21,000 new jobs.
- The creation of additional income streams for farmers which are linked to increased resilience of the farm enterprise and the landscape (Cowie et al. 2019; Baumber et al. 2020).
- The opportunity to stack benefits (production, biodiversity and carbon)
- Assist primary industries to secure long-term market share and grow new emerging markets by demonstrating sustainable land management and environmental stewardship
- Enhance the natural resource base (soil quality and benefits to biodiversity through habitat enhancement)
- Opportunities to reverse land degradation

These opportunities have been recognised by industry lobby groups and research and development corporations, many of which have, or are developing Net Zero emissions targets, demonstrating sustainable production and advocating the multiple benefits to farmers, regions and biodiversity. Some examples are provided below:

Value-stacking carbon farming

Recognising that additional benefits are derived from undertaking carbon farming practices which are beyond a carbon sequestration or emissions reduction benefit. These can be benefits to the agricultural production system (e.g. increased lamb survival with planting shelter belts), biodiversity (e.g. regrowth of native vegetation that increases the structural complexity of vegetation and habitat features), social benefits (e.g. greater well-being and resilience) as well as broader environmental benefits (e.g. increased vegetation cover and reduced rates of erosion).

- Meat & Livestock Australia. https://www.mla.com.au/research-and-development/Environment-sustainability/cn30/
- Australian Wool Innovation (Wiedemann et al. 2019)
- Clean Energy Regulator http://www.cleanenergyregulator.gov.au/csf/Pages/method-soil-carbon.html
- National Farmers Federation https://nff.org.au/wp-content/uploads/2020/02/NFF_Roadmap_2030_FINAL.pdf
- NSW Farmers Association https://www.nswfarmers.org.au/NSWFA/Posts/The_Farmer/Environment/Improving_pasture_growth_with_carbon_grazing.aspx
- Farmers for Climate Action https://www.farmersforclimateaction.org.au/carbon_storage
- Carbon Farmers of Australia https://carbonfarmersofaustralia.com.au/carbon-farming/

Agriculture is a major source of emissions as well as providing significant abatement through vegetation-based sequestration. Abatement is currently being delivered through the Emissions Reduction Fund (ERF) which represents a key mechanism for delivering Australia’s commitment of 26-28% reduction on 2005 emissions levels by 2030 under the 2015 Paris Agreement. ERF methods are Commonwealth legislated instruments that specify the rules for accounting for emissions reduction and sequestration through project implementation. ERF methods are designed to encourage abatement that is able to be used to meet Australia’s international mitigation targets. ERF projects generate Australian Carbon Credits (ACCUs) that may be purchased by the Commonwealth through reverse auction or traded on the voluntary market.

Carbon farming employs different agricultural practices or land use management under ERF methods to either increase carbon stored in vegetation and soil (sequestration) or reduce greenhouse gas emissions from livestock, soil and vegetation clearing (emissions reduction) or a combination of both. In the past five years there has been a rapid uptake of carbon farming practices by the agricultural sector across Australia. Farmers have benefited from participation in carbon markets under the ERF which has provided a new income stream through the generation of ACCUs and resulted in increased agricultural productivity and increased farm profitability (Baumber et al. 2020). In western NSW carbon farming has demonstrated potential co-benefits that both enhance socio-ecological resilience by introducing new income streams, as well as providing opportunities for sustainable land management to enhance soil and vegetation (Cowie et al. 2019). However, the literature further identifies broader opportunities for carbon farming to deliver a range of ecosystem services such as biodiversity, improved soil quality which reduces land degradation (CMI, 2019) as well as generating economic benefits (Evans, 2015). The quantification and verification of environmental co-benefits can also provide opportunities to enhance the value of export markets with environmental branding of agricultural products securing long-term market access (Beef Sustainability Framework, 2019).

As net zero ambitions from state governments and the corporate sector (mining, aviation, energy) are also scaling up, understanding the volumes and pipeline of future ACCU supply from different sectors will be important to develop pathways to net zero. In transitioning to the long term 2050 target, the NSW NZ Plan aims to co-deliver economic growth and reduce the 2005 NSW emissions by 35% by 2030. Agricultural industries can play a significant role in contributing to both short (2030) and long term (2050) emissions reduction targets by creating a pipeline of abatement activities. These activities will include but are not limited to sequestration in the land sector as well as the reduction in emissions from livestock.

The objectives of this report were to:

1. Provide estimates of potential emissions reduction and sequestration from the agricultural sector, and
2. To identify feasible opportunities for the agricultural sector to co-deliver economic growth for regional NSW and contribute to the NSW Net Zero ambition.

The report is structured to provide:

- An outline of the current situation in terms of emissions from agriculture as well as delivery of abatement and an overview of the assessment framework
- An estimate of the technical and feasible sequestration and emission reduction potential from agriculture as well as a synthesis of current knowledge to underpin pathways to maximise the delivery of abatement

2. Current abatement activity

Australian agricultural land-use currently dominates the Australian Government's Emissions Reduction Fund (ERF) with abatement being delivered through vegetation management and agricultural activities (**Figure 1**). In 2017-2018, it has been estimated that across Australian agricultural areas, 8.7 million tonnes of abatement with an approximate value of $105 million was delivered. Compared to the value of farm-gate products this puts carbon credits just outside the top 50 Australian agricultural products (AgriFutures Australia 2019).

Between 2015 and 2020, the adoption of ERF methods in western NSW has resulted in extensive (>3.6 million ha), recent (2015-2020), land-use change (**Figure 1b**). The concentration of vegetation-based ERF projects in the low rainfall, semi-arid rangelands of NSW has resulted from the low opportunity cost of agricultural production in the rangelands. This means that NSW abatement activity is geographically exposed (e.g. regional climatic risks) and any expansion of activities outside the rangelands will reduce the risk of this exposure. Notwithstanding the rapid uptake of carbon off-set projects across the agriculture sector, the adoption of different ERF methods has been inconsistent (**Table 1**). Most of the uptake has involved the regeneration or protection of native vegetation in rangeland grazing systems and limited uptake of other agricultural or revegetation methods. Other agricultural methods include storing carbon in soils avoiding carbon emissions through a reduction of enteric methane from livestock and manure methane from piggeries and avoiding nitrogen emissions from fertiliser (**Table 1**).

In NSW a total of 57,719,067 t CO_2-e has been contracted from vegetation-based methods with 53% having been delivered (September 2020). A further 455,777 t CO_2-e from manure management in piggeries and 235,000 t CO_2-e from soil sequestration is also under current contract with around 61% (275,882 t CO_2-e) of current contracts delivered from piggeries. As at September 2020, no sequestration from soils has been delivered in NSW1.[1]

NSW has been a significant beneficiary of the Federal governments $2.55 billion Emissions Reduction Fund with approximately $695 million invested in the western Division (CER, 2020a). Given there is evidence that carbon farming income is being reinvested on-farm and in some cases used to undertake land restoration activities and employ local contractors there is considerable scope for abatement activities to also enhance socio-economic and system resilience (Baumber et al 2020; Cowie et al. 2019; Cross et al. 2019).

The rapid expansion of carbon farming in NSW has been primarily driven by the ERF which is close to being exhausted. In 2019, the Australian government announced a further $2 billion (Carbon Solutions Fund) which will effectively continue the ERF to 2029 (CER 2020b). This provides some certainty around continued access to the fund at the same time as demand is growing for carbon credits beyond government purchasing.

The ERF will provide ongoing opportunities to deliver abatement, however broader opportunities for abatement are not being captured through the ERF. These unrealised opportunities include small-scale, on-farm activities which can often complement agricultural production and collectively will provide significant abatement.

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[1] figures are the amount of credits issues for all registered projects and exclude multi-state projects

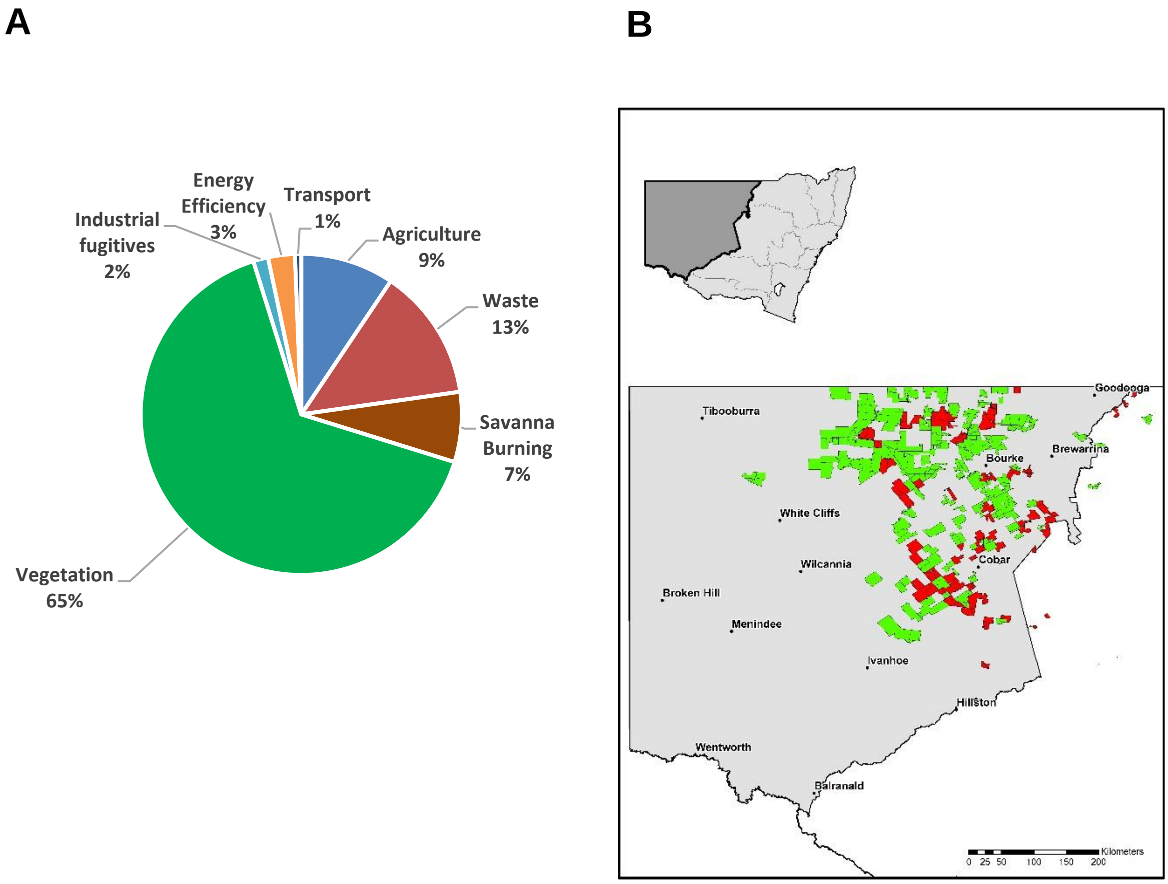


Figure 1. Australian agricultural land use (vegetation, savannah burning, Agriculture methods) is currently contributing to more than 80% of the national abatement from Emissions Reduction Fund (ERF) abatement activities (A). There is a dominance of vegetation-based ERF activities in western NSW under two methods Avoided Deforestation (red) and Human-induced revegetation (Green). Areas depicted are a slight over estimation as they represent property boundaries rather the project boundaries.

Table 1. Emissions Reduction fund activity from the land sector in September 2020 across NSW; Vegetation category includes ERF methods Avoided Deforestation (AD), Human-induced Regeneration (HIR), Environmental and Mallee Plantings and Plantation Forestry methods (EP); Agriculture category includes ERF methods Manure management in Piggeries (Manure), Herd Management (Herd), Measurement of Soil Carbon Sequestration in Agricultural Systems (Soil)

Sector	Approx. area in NSW (ha)	Number of contracted projects	ACCUs committed under contract	ACCUs issued to contracted projects (Sept 2020)	Approx. value ($) (Ave price $12.07)
Vegetation	**3,973,119**	**155**	**58,219,067**	**25,450,195**	**702,704,139**
- **HIR**	**3,003,256**	**86**	**30,908,933**	**10,607,797**	**373,070,821**
- **AD**	**964,121**	**59**	**26,040,789**	**14,451,684**	**314,312,323**
- **EP**	**5,742**	**10**	**1,269,345**	**390,714**	**15,320,994**
Agriculture	**18,103**	**10**	**1,074,777**	**212,777**	**12,968,277**
- **Manure**	**-**	**5**	**455,777**	**196,777**	**5,501,228**
- **Herd**	**-**	**1**	**184,000**	**-**	**2,220,880**
- **Soil**	**18,103**	**4**	**435,000**	**16,000**	**5,250,450**

3. Current emissions from agriculture

The primary industries sector makes a substantial contribution to the greenhouse gas (GHG) inventory of NSW. In 2018, the agriculture sector contributed 18Mt CO_2-e, 13.6% of NSW total emissions of 131.7 Mt CO_2-e. By far the largest emissions source is methane (CH_4) from ruminant livestock (70%), followed by nitrous oxide (N_2O) from soils (17%) and manure management (8%) (**Figure 2**). The remainder comprises carbon dioxide (CO_2) from liming and urea application, CH_4 from rice cultivation and GHG emissions from residue burning (**Figure 2**). Emissions from on-farm energy use and upstream activities such as fertiliser manufacture are reported in the energy sector (see below).

Deforestation is an additional source of emissions, reported separately – about 4.6Mt CO_2-e in 2018, mostly for agriculture. On the other hand, vegetation management (through reforestation, revegetation, cropland and grazing land management) sequestered approximately 21Mt CO_2-e, leading to net 16.4 Mt CO_2-e sequestration in the LULUCF sector in 2018.

GHG emission reporting for the agriculture sector

Following the national greenhouse gas inventory, which is in turn based on IPCC guidance for reporting to the UNFCCC, the emissions and removals from agricultural activities are reported in three inventory sectors:

- Emissions of methane and nitrous oxide from agricultural activities such as raising livestock and using fertiliser, are reported in the Agriculture sector

- Emissions of carbon dioxide (CO2) and CO2 removals (carbon sequestration) associated with land clearing, reforestation and other land use practices that influence vegetation and soil carbon on all land tenures are reported in the Land Use, Land Use Change and Forestry (LULUCF) Sector. This sector also includes carbon in wood products.

- Energy use on farm, including fuel and electricity, is reported in the Energy sector. Energy use associated with activities upstream of the farm, such as fertiliser manufacture, are also reported in the energy sector.

Non-CO_2 GHGs are converted to units of CO_2-equivalent (CO_2-e) using global warming potentials provided by the IPCC that express the warming effect of each gas relative to that of a pulse of CO_2, calculated over 100 years. The GWPs used currently, from the IPCC's 2007 Fourth Assessment Report, are 1 for CO_2, 25 for CH_4, and 298 for N_2O. Future reporting, under the Paris Agreement, will use updated values.

The Australian national inventory includes a separate report presenting accounts under the Kyoto Protocol, which includes a subset of emissions and removals in the LULUCF sector relating to deforestation, afforestation and reforestation since 1990, plus emissions and removals associated with forest management, cropland management, grazing land management and revegetation.

This report deals with emissions in the Agriculture and LULUCF sectors, excluding commercial forestry and wood products.

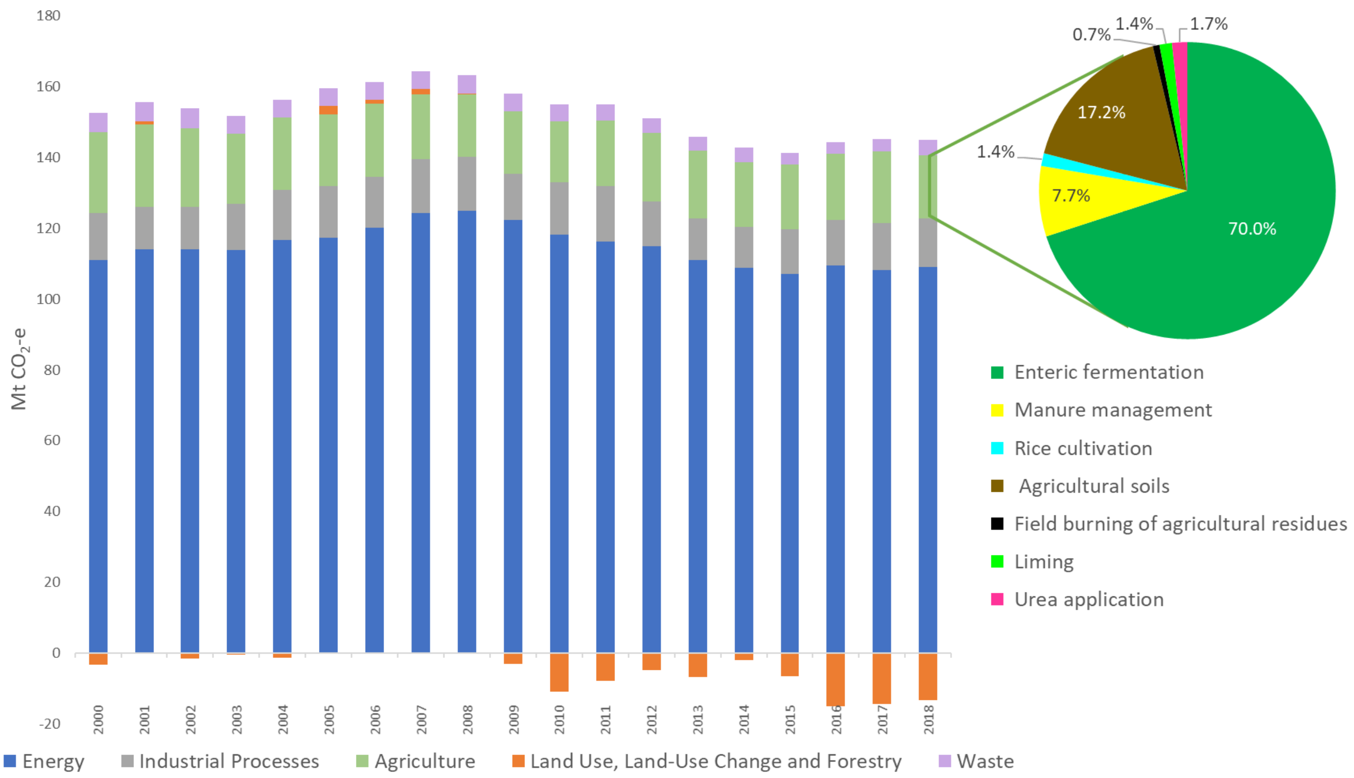


Figure 2. NSW emissions, highlighting contribution of agricultural sector in 2018. Negative values for Land use, land use change and forestry occur in years when sequestration exceeds emissions from land clearing. *Source: AGEIS, DISER*

Methane emissions produced by ruminant livestock (cattle and sheep "enteric fermentation") vary over time according to the number of livestock, which is influenced by seasonal conditions, but have generally declined from 1990 to 2018 due to falling numbers of livestock during the drought (**Figure 3**). Agricultural soil emissions comprise N_2O, a potent GHG released through microbially-mediated cycling of nitrogen derived from fertiliser, livestock excreta and crop residues. A small fraction of N from fertiliser and manure is volatilised as ammonia or lost through leaching, and leads to indirect N_2O emissions, that are also included in this source. Soil N_2O has been steady since 1990 (**Figure 3**). Methane emissions from rice cultivation make a small contribution that varies markedly from year to year, depending on the availability of water for irrigation (**Figure 3**).

Manure emissions have been constant over the period 1990-2018 (**Figure 3**). Prior to the 2018 inventory, the major contributions to emissions from manure management came from piggeries, dairies and beef feedlots. A new calculation method introduced in the 2018 inventory has led to a doubling of manure sector emissions, due to a new assumption that 5% of manure from grazed cattle and sheep is deposited in farm dams, with an associated emissions factor around 100 times higher than the EF for manure deposited on pasture. The evidence base for this change is limited to the observation that farm dams have higher methane emissions in grazing than cropping areas (DISER, 2020a); research is required to confirm this observation and identify the source, to ensure that this change to the inventory is warranted. It seems highly unlikely that 5% of manure from rangeland cattle, or from sheep, is deposited in farm dams.

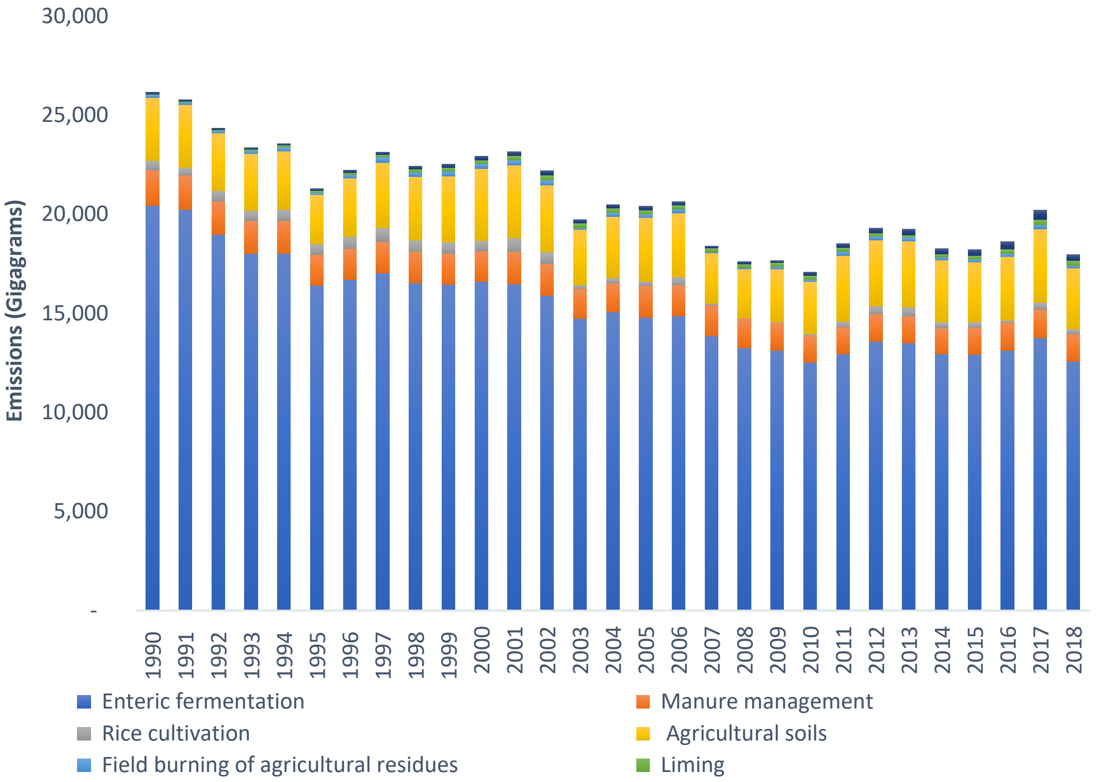


Figure 3. Trend in agriculture sector emissions for NSW, 1990-2018 *Source: AGEIS, DISER.*

The land use, land use change and forestry sector was a source of emissions in the early nineties when rates of land clearing were high, but has been a net sink most years since 1993 (inclusive) (**Figure 4**). The Kyoto Protocol accounts (**Figure 5**) and areas of land conversion (**Figure 6**) also illustrate the decline in land clearing since 1990 and show that the major sink in the LULUCF sector is forest management. Grazing land management has also made a significant contribution to sequestration in some years, while cropland management has been a source of emissions (Figure 4). The area of land cleared (**Figure 5**, **Figure 6**) diminished sharply from 1990 to 1995, and picked up ahead of the introduction of the Native Vegetation Act 2005, after which it declined further, although it has recently increased. While primary land clearing has remained low since 1995, clearing of secondary regrowth (on land cleared since 1970) has fluctuated but is generally balanced by a similar area of regrowth (**Figure 6**, **Figure 7**).

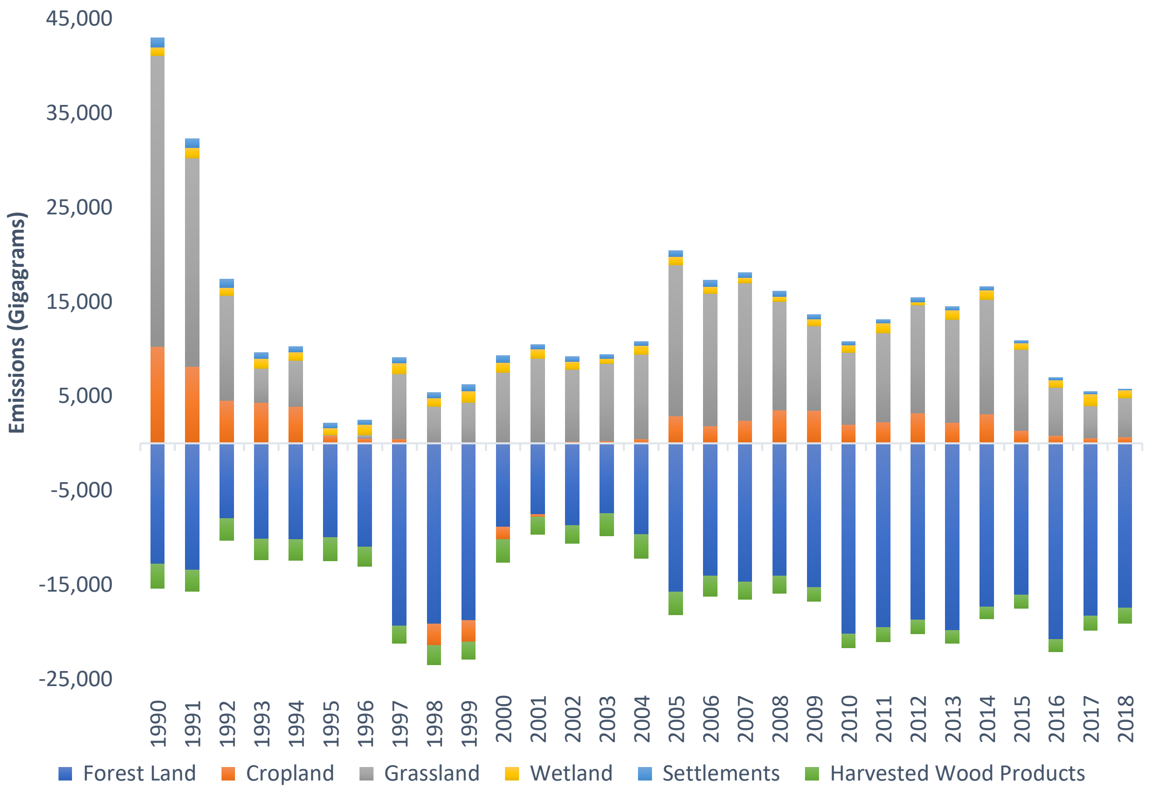


Figure 4. Trend in agriculture sector emissions for NSW, 1990-2018 *Source: AGEIS, DISER.*

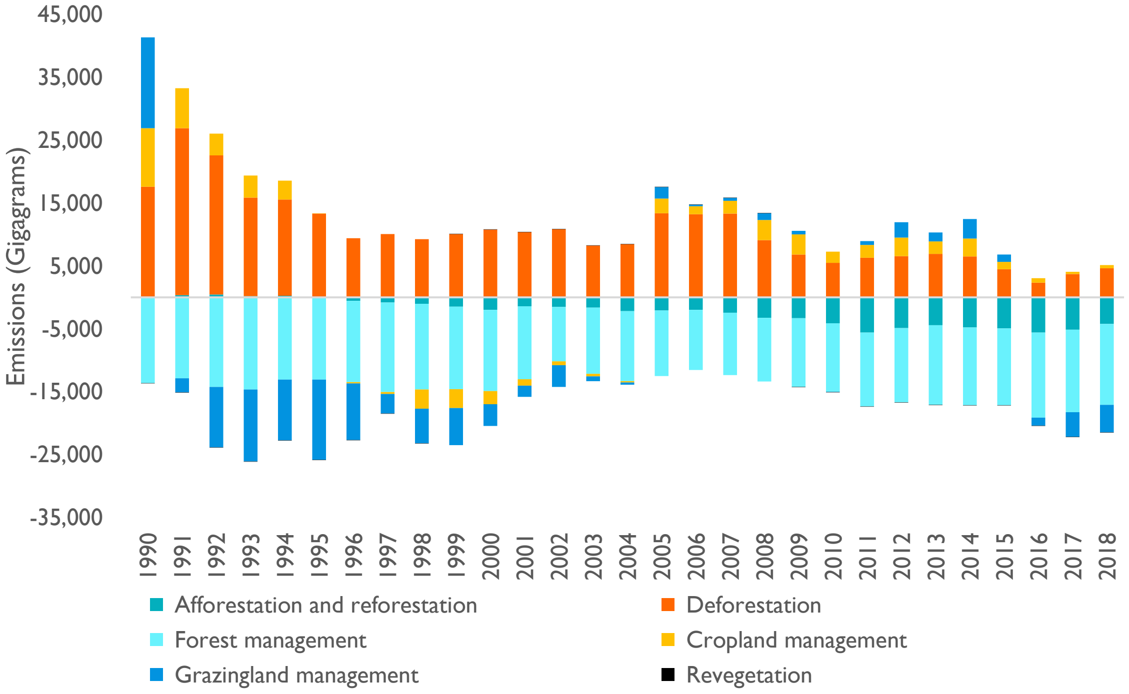


Figure 5. Trend in land-use, land-use change and forestry emissions for NSW, Kyoto Protocol accounts *Source: AGEIS, DISER.*

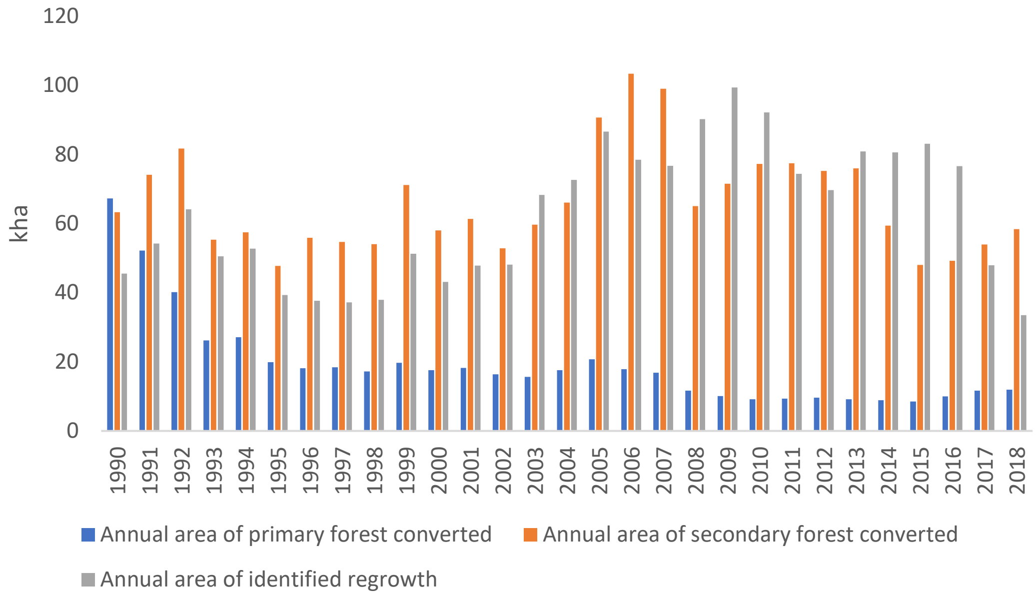


Figure 6. Annual areas of NSW forest (thousand ha) converted to other land-use categories
Source: AGEIS, DISER.

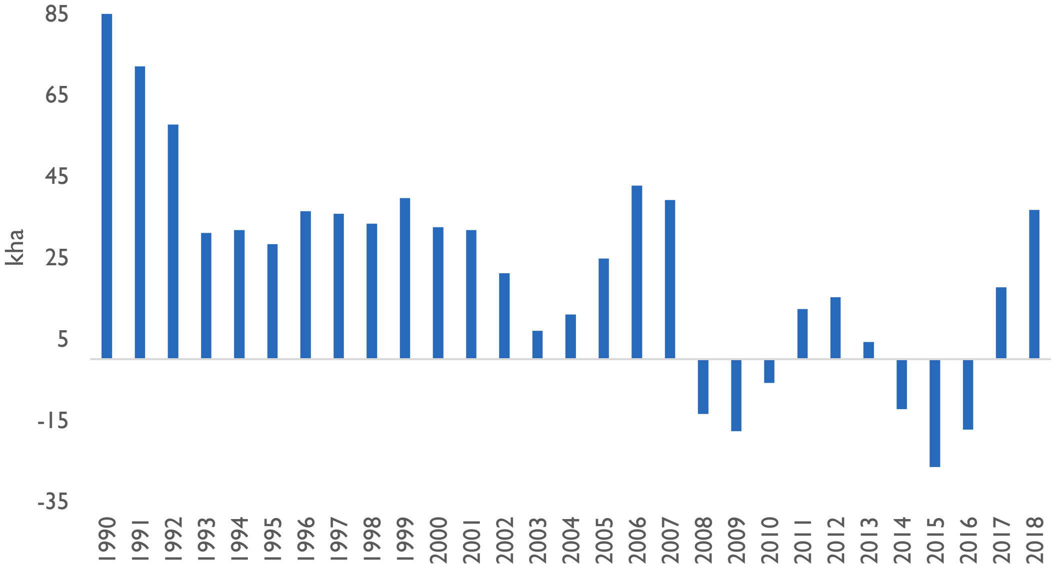


Figure 7. Net clearing of NSW forests (thousand ha). Conversions identified less regrowth.
Source: AGEIS, DISER.

4. Overview of assessment framework

We considered there to be two implementation pathways for increased uptake of abatement activities in agricultural systems:

- participation in ecosystem service markets such as the ERF, and
- land management practice change which results in abatement but is not of sufficient scale to enter into an ERF market (referred to as non-market activities)

Each pathway will require different approaches to address barriers to adoption, but detailed analysis of these alternative pathways is beyond the scope of this report. Sequestration activities in agricultural systems were considered under four broad categories of vegetation and soil management. Both market (ERF) and non-market activities are considered under each category:

- **Clearing of native vegetation:** ERF methods ***Avoided Deforestation*** and ***Avoided Clearing***; non-market activities include incentivising retention of native vegetation
- **Vegetation regrowth management:** ERF method ***Human-induced Regeneration***; non-market activities include natural regeneration for vegetation enhancement, the restoration of degraded or low productivity areas or the enhancement of remnant vegetation
- **Reforestation and Afforestation:** ERF methods include ***Reforestation by Environmental and Mallee Plantings***; non-market activities include planting of shelter belts, amenity plantings, and environmental plantings for habitat or amelioration (e.g. erosion control, dryland salinity or nutrient management), small scale farm forestry and bioenergy plantings
- **Soil carbon sequestration:** ERF activities ***include Estimating Sequestration of Carbon in Soil using Default Values and Measurement of Soil Carbon Sequestration in Agricultural Systems***; non-market activities align to ERF methods e.g. conversion of croplands to pasture, stubble retention and sustainable intensification (nutrient management, soil acidity management, new irrigation, renovation/establishment and maintenance of pasture). Other activities include grazing management, remediation of degraded landscapes, reduced tillage and the incorporation of legumes in perennial pastures.

Emissions reduction potential was assessed for the source categories:

- **Enteric methane**: Feed additives and herd/flock management approaches were considered. ERF methods include ***Beef cattle herd management***, ***Reducing greenhouse gas emissions by feeding nitrates to beef cattle***, and ***Reducing greenhouse gas emissions by feeding dietary additives to milking cows***.
- **GHG from soils:** Nitrous oxide (N_2O) released from soil is derived from synthetic and organic fertilisers, crop residues, symbiotic nitrogen fixation by legumes and excreta from livestock. ERF method ***Reducing greenhouse gas emissions from fertiliser in irrigated cotton*** relates to reduction in nitrous oxide (N_2O) through modified fertiliser and irrigation management". Practices that are not currently covered by ERF methods include use of nitrification inhibitors, fertiliser management in crops other than cotton, and application of biochar.
- **Emissions from manure management:** Current ERF method ***Animal effluent management*** covers new facilities for treatment of effluent from piggeries and dairies to destroy or avoid emissions of methane and nitrous oxide**.**
- **Biochar:** We assessed a potential additional category of avoided oxidation of organic matter, through pyrolysis to produce biochar. While this abatement mechanism is not currently included in the national inventory, the IPCC's 2019 refinement of guidelines for national greenhouse gas inventories (IPCC, 2019) provides a method for the calculation of carbon stabilised in biochar, that could be implemented in the national inventory, and could form the basis of a future ERF method.

Technical abatement potential: The assessment framework first calculated the technical sequestration and emissions reduction potential for ERF and non-ERF activities from agriculture across NSW. For sequestration, this was founded on multi-criteria suitability mapping to define the areas (ha) where ERF methods could be applied. This allows for spatial representation of abatement options as well as the quantification of abatement. The cumulative sequestration in vegetation (and associated soil carbon pool) was modelled using FullCAM for three time periods (2030, 2050 and 2119) to predict potential sequestration. Potential soil carbon sequestration within agricultural systems was modelled using two approaches: spatial estimates from the DISER (Department of Industry, Science, Energy and Resources) and a mixed modelling approach. Soil carbon estimates were based on conservative values (default values) provided by DISER. We assigned these estimates to land use categories and assessed estimates against the published literature for studies undertaken in NSW. We also developed a current soil carbon benchmark map for NSW and determined the potential to increase soil carbon through a 10% increase in vegetation cover (woody and ground cover) across NSW.

Baseline estimates of enteric methane emissions for 2030, with no abatement measures, were derived using the algorithms applied in Australia's national greenhouse gas inventory, as described in the National Inventory Report (NIR) (DISER, 2020a), and the livestock numbers obtained as described in **Section 8.**

Assessment Framework

*(i) **Potential abatement:** For sequestration this involved mapping of areas suitable for activities and the quantification of sequestration potential using either FullCAM or mixed modelling approaches to determine the technical potential for sequestration. For emissions reduction, base-line estimates for no abatement activities were assessed against industry adoption rates*

*(ii) **Adoption rate:** Industry adoption rates accounted for trade-offs between carbon sequestration or emissions reduction activities as well as other barriers to adoption (including technology readiness)*

*(ii) **Feasible abatement:** For sequestration the amount of industry adoption x area suitable for activities x proportion of on-farm adoption. For all abatement activities consideration of the risks to the long-term security of sequestration for emissions reduction was also given*

Adoption rate: Different abatement practice (ERF or non-ERF) and technologies were assessed using two categories. A "*Production trade-off*" rank (positive, neutral, negative) reflects the likely impact of the activity on agricultural production. A second "*Security Risk*" category recognises activities under the ERF or another carbon offset certification scheme (Gold Standard, Verified Carbon Standard) as having a greater security of delivering abatement (*high*) than non-ERF activities (*low*).

The industry adoption rate was assessed based on a consideration of the barriers to adoption of sequestration activities for each category of vegetation and soil management. Consideration was given to the current approaches being developed by the Federal Government and the carbon market industry to address barriers to adoption or method expansion. For sequestration activities, these barriers were also informed by stakeholder consultation and surveys undertaken as part of ongoing research (e.g. Cross et al. 2019) and past NSW DPI research (Cowie et al. 2019). This was supplemented with additional feedback from carbon project developers in NSW (Jennifer Sinclair (Green Collar), Skye Glenday and Zoe Ryan (both Climate Friendly) and Brad Kerin (Carbon Market Institute). The details of these adoption barriers and justification for adoption rates are provided in **Part A** of this report for each broad category of vegetation and soil management activities.

Adoption rates for emissions reduction activities were informed by published literature and expert judgement which considered risks, trade-offs with production and the ease in which practices could be incorporated into production systems. Additional detail is provided in **Part B**.

Feasible abatement: Feasible abatement assumed any regulatory barriers were overcome and adoption rates accounted for production impacts.

Feasible sequestration was quantified as:

Industry adoption rate X the suitable areas X sequestration rate

For vegetation regrowth and management, and afforestation activities an 'on-farm factor' which accounted for the proportion of the specific land-use on-farm (20%) was further applied. Here, we assumed that 20% of an existing farm could be used for carbon without negative impact on production. No 'on-farm' factors were applied to other abatement activities.

Feasible emissions reduction was quantified as:

Industry adoption rate X technical potential.

PART A: Sequestration

5. Methodological approach

5.1 Suitability mapping

A detailed outline of each ERF method and the vegetation/soil management activities associated with each method, and summary flowcharts for the derivation of each suitability map, are given in **Appendix I**. We used a multi-criteria approach when we developed spatial layers following the eligibility rules for each ERF method outlined by the Clean Energy Regulator (CER, 2020a).

To provide confidence in the results of suitability mapping we compared existing ERF project areas (Carbon Estimation Areas) under Avoided Deforestation (AD) and Human-induced regeneration (HIR) methods in western NSW to the suitability maps. An example of this comparison (**Figure 8**) is provided for the HIR method and it shows good agreement at the fine spatial scale.

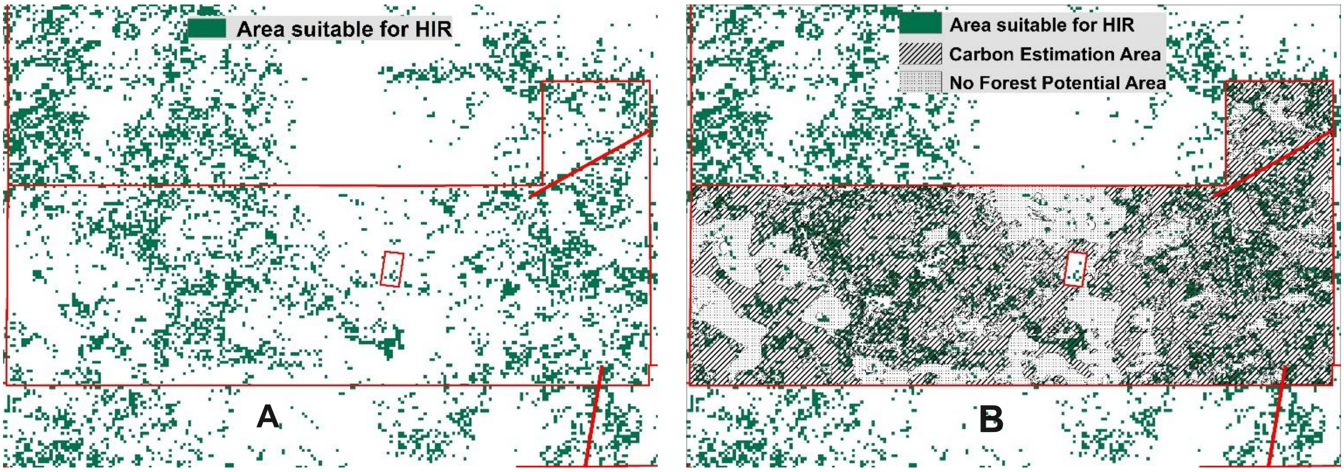


Figure 8 NSW DPI mapped suitable areas for Human-induced revegetation (HIR) are shown in green. **A.** Property boundary areas are shown in red and mapped suitable areas in green. **B.** The actual carbon estimation area (CEA, shaded) and predicted areas (green) shows good alignment of the suitability mapping with a slight underestimation of the potential area. *Source:* CEA provided by GreenCollar

An overview of the spatial distribution of areas in NSW currently being managed under ERF projects as well as the areas suitable for expansion of each ERF activity are given in **Figure 9**. It should be noted that the suitability mapping shows areas that are "technically suitable" for potential expansion of ERF activities without accounting for the price of carbon/value of production from existing land use. In addition, some eligibility rules for ERF methods cannot be captured by spatial mapping.

Prior to applying FullCAM to estimate sequestration potential, the existing areas of ERF activity (red, **Figure 9**) were removed from the areas mapped as suitable (blue, **Figure 9**), and the resultant spatial file used for sequestration modelling.

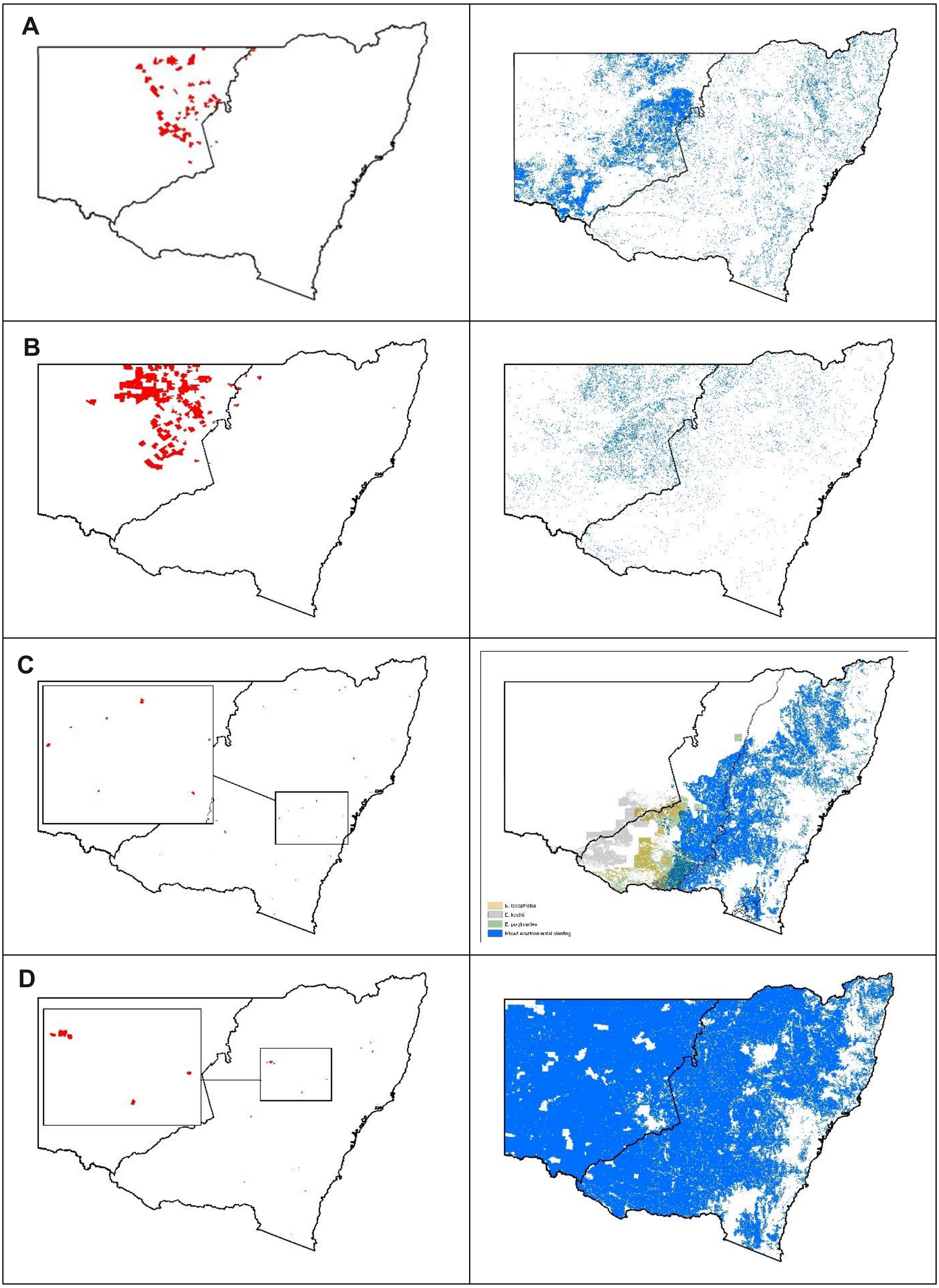


Figure 9. Current extent (red) and theoretical potential (blue) of Australian government Emissions Reduction Fund (ERF) carbon farming activities in New South Wales: (A) Avoided Deforestation (AD)[1]; (B) Human-induced Regeneration (HIR)[1.] (C) Environmental or Mallee Plantings[2.] (EP) and (D) Sequestering Carbon in Soils in Agricultural Systems (Soil). The black line indicates the boundary for western NSW (rangelands) and the black dotted line (C), the 600 mm rainfall isohyet[2]. Under current eligibility rules, there is no further expansion of AD but we have presented area where there is potential for vegetation to be cleared. *Adapted* from Baumber *et al* (2020).

1. The actual extent of a current project activity (red), known as the carbon estimation area (CEA), is a sub-set of the mapped areas which is defined by rules set out for each ERF method. A project can contain one or many CEA's e.g. may have both AD and HIR projects. The mapped areas are property boundaries and therefore may be a slight over-estimate of carbon estimation area.
2. Under the ERF, Mallee planting projects are restricted to ≤ 600 mm long-term average annual rainfall for three Mallee species *Eucalyptus loxophleba*, *E. kochii* and *E. polybractea*. We restricted Environmental Plantings to the temperate rainfall zone as successful seeding and replanting is likely to be more reliable in these higher rainfall zones

5.2 Potential sequestration

5.2.1 FullCAM-derived sequestration in vegetation

The FullCAM (Full Carbon Accounting Model) is used to construct Australia's National Greenhouse Gas Inventory for the land sector. We used the 2020 Public Release version of FullCAM (DISER 2020b), to model sequestration potential under the current climate for four broad categories of vegetation sequestration activities. The 2020 FullCAM version has increased functionality that allows automation of batches to produce sequestration estimations for 100 years over large spatial areas. Importantly, the 2020 version of FullCAM also has revised model calibrations which remove erroneous predictions from the previous version. Adjustments in this new FullCAM calibration now account for configuration of environmental plantings, adjustments for natural regeneration including impacts of ground water availability and adjustments for alternative grazing management.

FullCAM predicts the accumulation of above-ground biomass (dry matter, DM) (AGB, t DM ha^{-1}), below-ground biomass (BGB, t DM ha^{-1}) and soil organic carbon (SOC, t C ha^{-1}) under woody vegetation. FullCAM models forest growth over time at a site, based on site productivity which is calibrated against field-based, observed data.

We present the predicted cumulative sequestration from 2020 to 2030, 2050 and 2119. FullCAM was parameterised following the ERF method specific guidelines from the DISER (2020b, with settings summarised below) and predictions were made for sites within each of the areas mapped as suitable. Spatial maps for sequestration in biomass across NSW for 2119 are presented in **Appendix II** and all other time periods are presented in Section 6.

Vegetation management	Abbreviation	Suitable area (km^2) in NSW	FullCAM tree species	Planting year	Abatement calculated for each grid cell (1 km^2) as
Avoided Deforestation (western NSW)	ADW	59,891	Natural regeneration <500mm rainfall	2000	Δ AGB/BGB/soil carbon in 2030/2050/2119 = AGB/BGB/soil carbon in 2030/2050/2119 - AGB/BGB/soil carbon in 2020
Avoided Deforestation (eastern NSW)	ADE	35,119	Natural regeneration >500mm rainfall	2000	As for ADW
Human-induced regeneration	HIR	33,385	Mixed species environmental planting	2020	AGB/BGB/soil carbon in 2030, 2050 and 2119
Mixed species environmental plantings (temperate areas)	MEPT	135,337	Mixed species environmental planting	2020	AGB/BGB/soil carbon in 2030, 2050 and 2119
Mixed species environmental plantings (Mallee spp.)	Mallee Eucalyptus kochii	21,948	Mallee eucalypt species	2020	AGB/BGB/soil carbon in 2030, 2050 and 2119
	Mallee Eucalyptus polybractea	30,761	Mallee eucalypt species	2020	AGB/BGB/soil carbon in 2030, 2050 and 2119
	Mallee Eucalyptus loxophleba	14,963	Mallee eucalypt species	2020	AGB/BGB/soil carbon in 2030, 2050 and 2119

AGB: the mass of aboveground tree components (t DM/ha), BGB: the mass of belowground tree components (t DM/ha), Soil carbon: C mass of forest soil (t C/ha)

5.2.2 Soil carbon sequestration

The FullCAM modelling provides soil carbon sequestration estimates under various vegetation ERF methods as described in Section 5.2.1. Spatial maps for FullCAM predicted soil sequestration (associated with each vegetation ERF method) are found in **Appendix III.** As FullCAM is not parameterised for soil carbon methods, we needed to take an alternative approach to model potential sequestration from soils. We undertook two approaches to predicting soil carbon sequestration:

i. **Estimating potential in Agricultural systems:** Here, conservative estimates were used based on ERF default values: DISER provides conservative estimates of changes in soil carbon under specific practices for different regions in NSW (DISER, 2020b). We assigned these estimates to land use categories and reviewed these estimates against the published literature for studies undertaken in NSW. This allowed determination of the potential to increase soil carbon under different agricultural management practices.

ii. **Estimating the potential from vegetation cover change:** Here, the sensitivity to vegetation cover change (woody and ground cover) across NSW was compared relative to a soil carbon benchmark map to determine the sequestration potential from cover management. Detail of these modelling approaches is provided in **Appendix IV** and summarised below (**Figure 10**).

    Management practices to increase cover may include increasing cover of woody vegetation (trees and shrubs) or increasing ground cover layer (perennial grasses). To create the soil carbon benchmark map (which reflects an estimate of the current soil carbon in NSW) we compared the use of two different modelling approaches (Multiple Linear Regression - MLR and Random Forests - RF), and model performance was assessed against common statistical metrics. The MLR benchmark map was then used to examine the soil sequestration potential based on a 10% increase vegetation cover (biomass and ground cover). A 10% increase in cover was considered a realistic achievement. These maps were then 'sense-checked' using several regional examples and predicted potential sequestration for each LLS region were determined. The soil sequestration potential from a 10% increase in vegetation cover for each LLS region is provided in **Appendix V**.

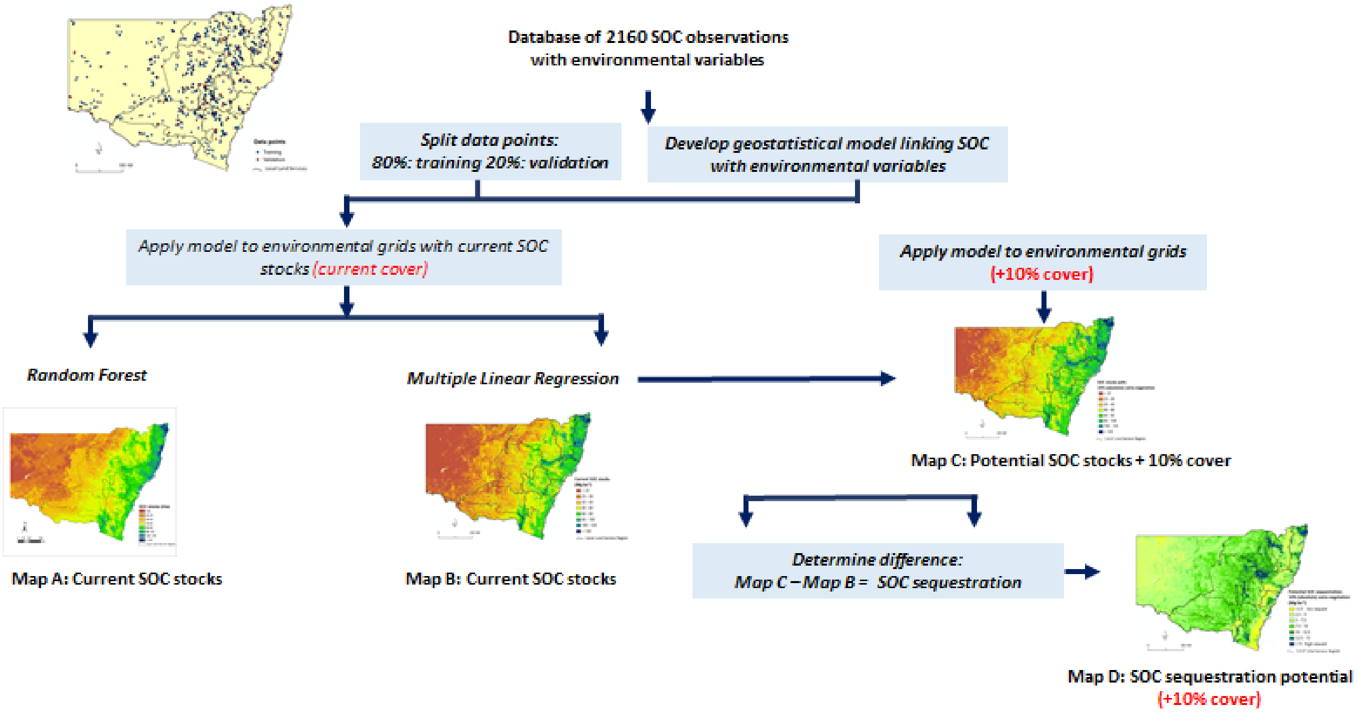


Figure 10. Overview of approach to determine current soil organic carbon stock (SOC stock) and potential SOC sequestration based on an addition 10% vegetation cover (+10% cover)

6. Feasible sequestration potential

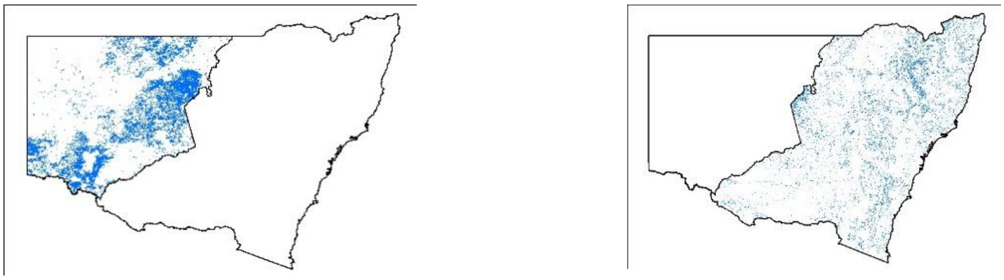
6.1 Avoided clearing of native vegetation

These activities involve the avoided clearing of native vegetation for which a clearing permit has been approved. These can include ERF methods ***Avoided Deforestation*** and ***Avoided Clearing*** or non-ERF activities. Further details are provided in **Appendix 1**.

6.1.1 Analysis

The total area calculated as suitable for ERF Avoided Deforestation (AD) was 9,503,100 ha, of which 964,121 ha is currently being managed for sequestration (**Table 1**). This leaves some 8,543,492 ha which could potentially be applicable for AD, Avoided Clearing (AC) methods or non-ERF activities that incentivise the retention of native vegetation.

From the areas mapped as potentially suitable for AD we separated NSW into the Western Division where there are relatively low levels of landscape fragmentation (limited historical clearing and virtual continuous cover of native vegetation) compared to eastern NSW where landscapes are highly fragmented (**Figure 11**). Therefore, there should be greater opportunities (and environmental benefits) in avoiding clearing in eastern NSW compared to western NSW where the enhancement of existing AD project areas and further expansion of AD methods provide the greatest opportunities.



Avoided Deforestation western NSW (ADW)

Avoided Deforestation eastern NSW (ADE)

Figure 11. Areas where clearing of native vegetation can be avoided in the west (left), 5,989,100 ha and in the east (right) 3,511,900 ha. There is a difference of 2,100 ha between total area suitable for AD and the sum of ADW (AD western) and ADE (AD eastern) due to overlapping pixels

The spatial mapping showed the greatest potential sequestration rates to occur in eastern NSW with total cumulative sequestration rates (biomass and soil) of approximately 17 t C ha^{-1} (2030) and 39 t C ha^{-1} (2050) (**Tables 4 and 5**) compared to western NSW which had approximately 6 t C ha^{-1} (2030) and 15 t C ha^{-1} (2050) (**Table 2** and **3**). Cumulative sequestration in biomass for 2020-2030 ranged from 5.2 t C ha^{-1} (**Table 2)** in western NSW to 16.7 t C ha^{-1} in eastern NSW (**Table 4).**

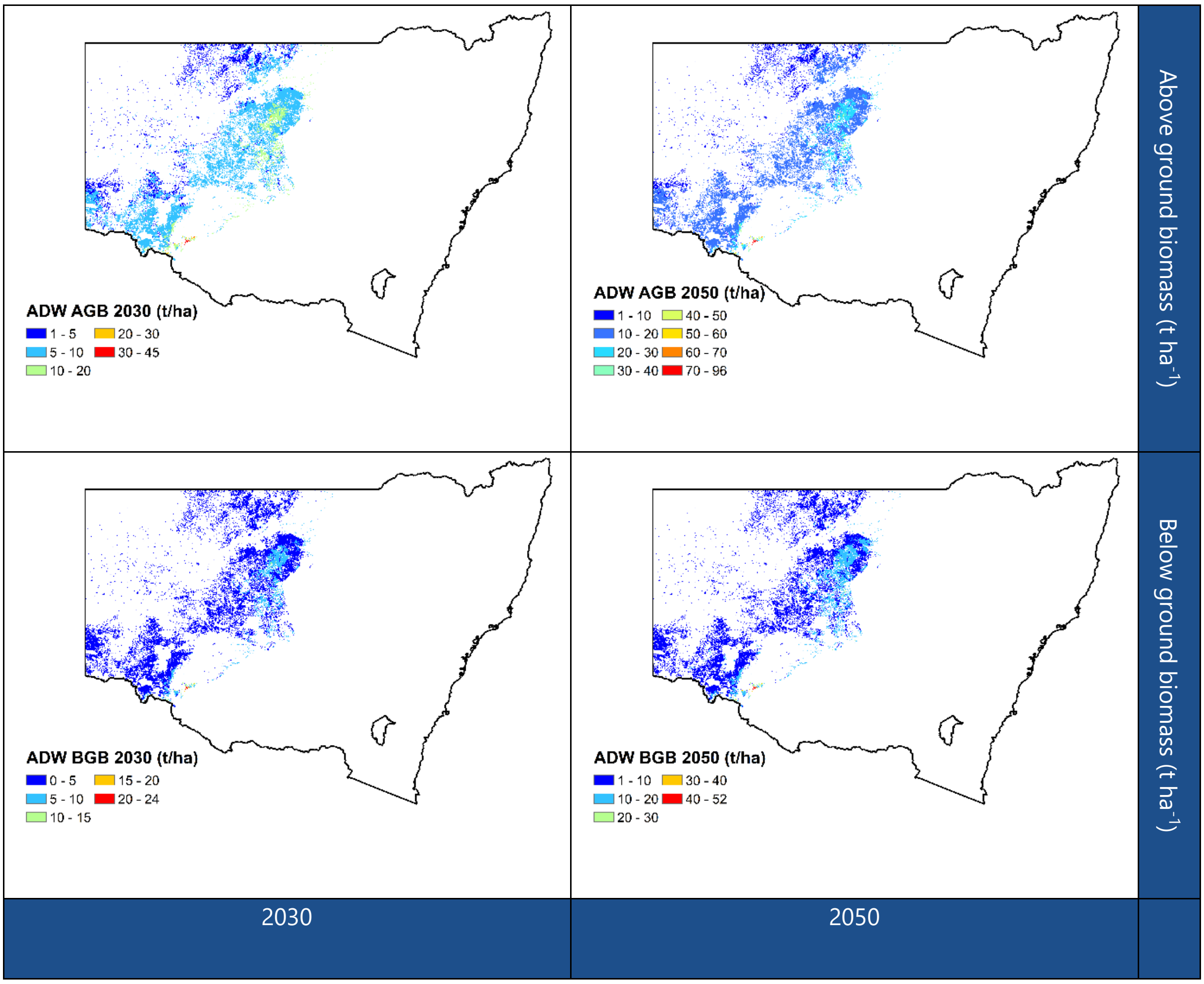


Figure 12. Avoided Deforestation in western NSW (ADW), FullCAM modelled cumulative above ground biomass (AGB, t ha^{-1}) and below ground biomass (BGB, t ha^{-1}) for 2030 and 2050.

Table 2. Cumulative predicted carbon (t C biomass) from 5,989,100 ha of suitable areas for AD in western NSW

	2030	2050	2119
AGB (t biomass)	40,292,915	86,525,402	141,243,150
BGB (t biomass)	21,696,185	46,590,601	76,054,004
Total	61,989,100	133,116,003	217,297,154
Total (t C biomass)	**30,994,550**	**66,558,002**	**108,648,577**
Cumulative t C ha^{-1}	5.2	11.1	18.1

Table 3. Cumulative predicted carbon (t C, soil) from 5,989,100 ha of suitable areas for AD in western NSW

	2030	2050	2119
Total (t C soil)	**4,805,082**	**20,352,321**	**55,678,222**
Cumulative t C ha^{-1}	0.80	3.40	9.30

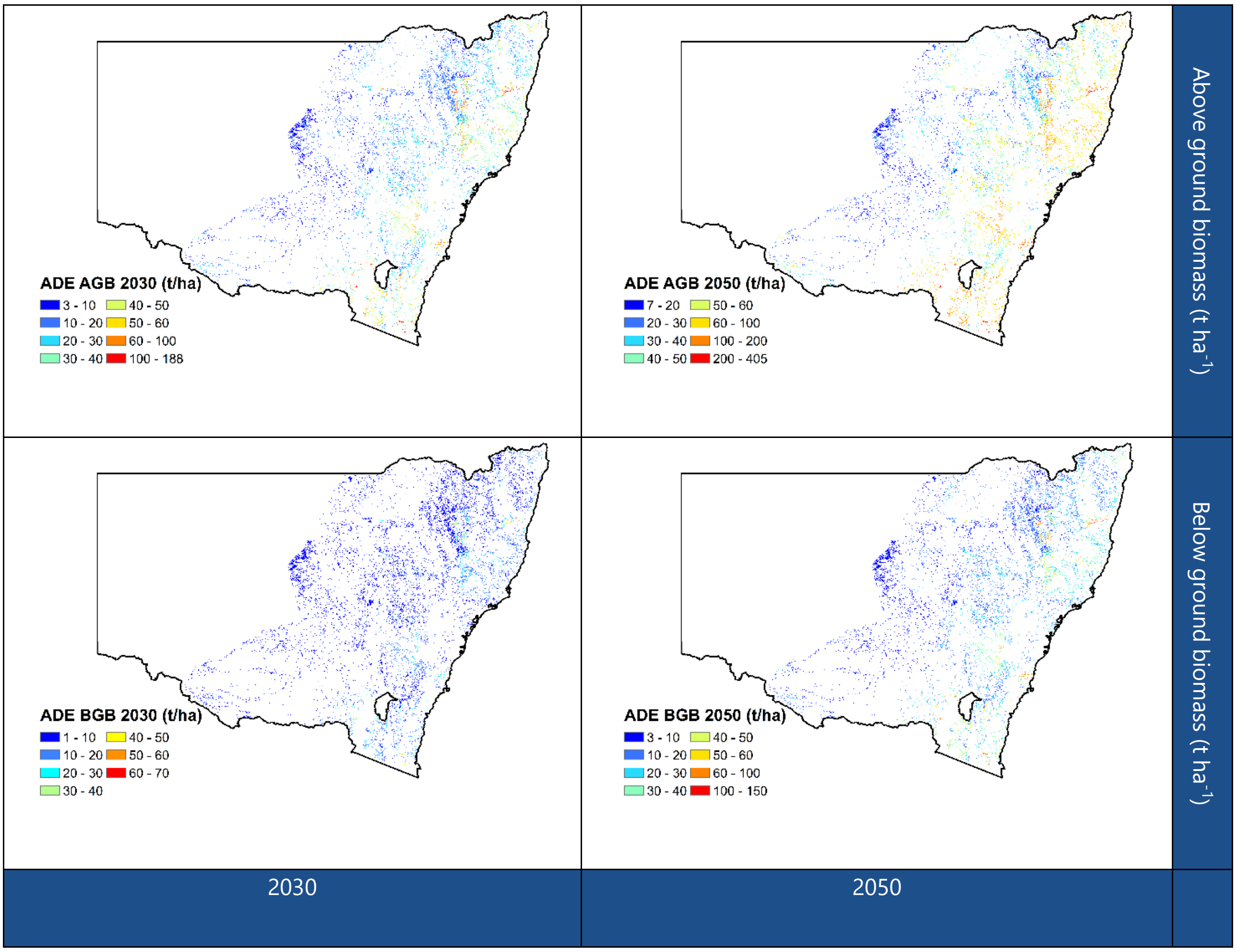


Figure 13. Avoided Deforestation in eastern NSW, (ADE) FullCAM modelled cumulative above ground biomass (AGB, t ha^{-1}) and below ground biomass (BGB, t ha^{-1}) for 2030 and 2050 in eastern NSW.

Table 4. Cumulative predicted carbon (t C biomass) from 3,511,900 ha of suitable areas for AD in eastern NSW.

	2030	2050	2119
AGB (t biomass)	85,386,418	183,359,635	299,314,326
BGB (t biomass)	31,581,278	67,817,948	110,705,299
Total	116,967,696	251,177,583	410,019,625
Total (t C biomass)	**58,483,848**	**125,588,792**	**205,009,813**
Cumulative t C ha^{-1}	16.7	35.8	58.4

Table 5. Cumulative predicted carbon (t C, soil) from 3,511,900 ha of suitable areas for AD in eastern NSW.

	2030	2050	2119
Total (t C soil)	**1,088,573**	**10,329,755**	**34,152,367**
Cumulative t C ha^{-1}	0.3	2.9	9.7

6.1.2 Opportunities and barriers

Eligibility rules currently preclude further expansion of Avoided Deforestation (AD) and Avoided Clearing (AC) ERF-methods. For further adoption of this method, method modification would need to include the removal of eligibility criteria requiring evidence for past clearing events and intervals between events (AC method). A modification of the AC and AD methods that includes dis-incentivising the clearing of vegetation in areas where there is a high risk of clearing has been proposed (Green Collar, *pers. comm*). This method employs an approach to identify areas of 'clearing risk' that has been developed by the Queensland Herbarium (D Butler *pers. comm*).

Further expansion of sequestration opportunities in NSW using non-ERF sequestration may include resolving the policy disconnection between biodiversity conservation, climate change abatement opportunities and unregulated clearing in NSW. The NSW Auditor recorded an increasing rate of loss of woody vegetation in NSW; from 9,200 ha in 2013-14 to 20,200 ha in 2016-17 and a five-year peak of 27,300 ha in 2017-18 (Audit Office of NSW, 2019). This accelerated rate of clearing of native vegetation could be significantly slowed if sequestration opportunities were to be recognised and farmers could generate income from hosting significant patches of existing vegetation. The approach suggested by GreenCollar for AC and AD method modification could also be used to identify areas for incentivising the retention of vegetation for carbon benefits using non-ERF mechanisms. In this way a '*clearing risk*' determination may be applied to both ERF and non-ERF activities. The applicability of this approach is currently being examined by NSW Department of Primary Industries in conjunction with GreenCollar and Queensland Department of Environment and Science.

Additional opportunities to enhance sequestration may be achieved within existing ERF AD areas and include:

- Recognising management that results in changes in woody vegetation above and below the 'forest cover' threshold (20%), e.g. management of grazing intensity. Here, changes in canopy cover for non-forest (ie: <20% canopy cover) and forest (>20% canopy cover) within carbon estimation areas (CEA) could then be counted as sequestration. These are currently excluded under the AD method.
- Ecological thinning to increase the maximum attainable carbon as well as biodiversity value of these areas (Waters et al 2017a; Gonsalves et al. 2018; NSW Government 2019).

6.1.3 Production trade-offs

- The net financial impact on rangeland areas currently being managed for AD has been positive as these areas have relatively low income from livestock production (Cockfield, et al. 2019). In some cases, carbon income has been directed into intensification of other rangeland areas which has resulted in off-setting lost production and higher productivity across the whole farm enterprise (Cross et al. 2019; Baumber et al. 2020).
- For areas currently being managed under the AD method there is likely to be a positive impact on the agricultural enterprise through ERF method modification that recognises forest (>20% cover) and non-forest (<20%) components within carbon estimation areas. This would provide additional income from management practices which increase sequestration below and above the forest cover threshold. Further enhancement of AD areas through ecological thinning may provide abatement benefits but an economic assessment of the costs of this activity would need to be made. It is feasible that thinning

which targets low carbon density, shrubby species combined with biochar produced from thinnings may enable some offset of costs and also result in further abatement potential being realised from not only increased tree growth (greater carbon accumulation) but also from biochar use (Simmons et al., *in review*).

Ecological thinning

In situations where there is a high density of small stems, thinning can result in increased tree growth rates, increased tree recruitment rates but also change structural features and available food sources which will benefit some species.

- The production impacts from retaining woody vegetation will be dependent on the desired land use post clearing as well as the current condition of the landscape. For low productivity landscapes, production trade-offs may be minimal as evidenced by the uptake of AD projects in western NSW. Where clearing is undertaken for the purposes of cropping this is likely to incur a greater financial penalty compared to clearing and sowing pasture for livestock production. For example, lower levels of vegetation cover may result in subtle increases in the value of croplands (Chancellor et al. 2019). In situations where croplands were converted to permanent, perennial pastures the resulting impact of livestock emissions as well as sequestration potential would need to be considered (see Section **6.5.1**). Linking clearing permits to the latter option will likely support more favourable emissions scenarios.
- Overall the impacts on production are likely to be neutral to negative.

6.1.4 Adoption rate

In western NSW, we have assumed a 5% (2030) adoption within existing ERF project areas. Here, management which leads to unaccounted regrowth and growth from woody cover in the < 20% and >20% cover classes in non-CEA areas represent a further abatement opportunity. It has been assumed that no changes in woody cover would occur beyond 2030, a point at which canopy closure is likely to be achieved. Based on a total cumulative sequestration rate in biomass of 5.2 t C ha^{-1} (**Table 2**), >1.57M t C can be sequestered by 2030 across 299,455 ha (**Table 7**).

The rate of adoption of thinning activities to enhance existing AD areas in western NSW is expected to be low (1%) because any increased carbon accumulation from thinning undertaken in 2020 is not realised until 2050. This may be considered high-risk activity, resulting from long payback periods to achieve post thinning sequestration. This would deliver >0.7 M t C (2050) and 1.1 M t C (2119) based on total cumulative sequestration rates in biomass of 11 and 18 t C ha^{-1} respectively, across a total of 59,891 ha (**Table 7**).

Further, an assumed 1% adoption rate (2030, 2050) for AD/AC ERF methods in western NSW would be driven by method modification to include more workable eligibility rules (AD Expansion, **Table 7**). Across 59,891 ha in western NSW, this would deliver >0.3 M t C (2030), 0.7 M t C (2050) and 1.1 M t C (2119), based on total cumulative sequestration rates in biomass provided in **Table 2**.

In eastern NSW, where landscapes are fragmented, we have assumed prioritisation on reduced clearing through rectification of conflicts with clearing policy or incentivising the retention of native vegetation. We have assumed that at least 50% of the area cleared in 2017/18 (27, 300 ha) would be incentivised to retain existing native vegetation, which is at high risk of clearing, each year to 2030. This assumption is based on a return to a rate of clearing ~9,200 ha yr^{-1} (2013–14) with further avoided clearing from 'unexplained clearing' (in the order of ~5,000 ha, 2013-2014, Audit Office of NSW, 2020). That is a total of 409,500 ha between 2020 and 2030 where clearing will be avoided. Following 2030 it is assumed due to changes in the policy environment and the incentives to sequester carbon on farm there will be little appetite for clearing and therefore no further adoption is identified. At an average total sequestration rate in biomass of approximately 17 t ha^{-1} (**Table 4**) this amounts to >6.8M t C (**Table 7**) through incentivising retention of native vegetation.

This underestimates abatement potential from this activity as emissions from diesel and burning have not been included.

In total some 31.9M t CO_2e (2030), 4.87M t CO_2e (2050), 7.94M t CO_2e (2119) sequestration in biomass is estimated to be achieved by avoiding deforestation and retaining native vegetation.

Table 6. Feasible cumulative sequestration (**t C biomass and soil**) from managing clearing of native vegetation (Avoided Deforestation, AD and Avoided Clearing) (t C) across NSW based on a total of 5,989,100 ha of suitable areas in western NSW and 3,511,900 ha in eastern NSW.

Retention of native vegetation	**Adoption %**	**Adoption Area (ha)**	**2030**	**2050**	**2119**
Enhanced AD[1] (Western)	5	299,455	1,796,730		
Enhanced AD[2] (Western)	1	59,891	nil	868,419	1,641,013
AD expansion[3] (Western)	1	59,891	359,346	868,419	1,641,013
Reduced clearing (Eastern)	n/a	409,500	6,961,500	Nil	Nil
		t Carbon	9,117,576	1,736,838	3,282,026
		M t CO_2 e	33.43	6.37	12.03

[1] Recognising sequestration below and above the 20% forest cover threshold [2] Ecological thinning [3] Expansion of eligibility rules, identification of areas at high risk of clearing

Table 7. Feasible cumulative sequestration (**t C in biomass**) from managing clearing of native vegetation (Avoided Deforestation, AD and Avoided Clearing) (t C) across NSW based on a total of 5,989,100 ha of suitable areas in western NSW and 3,511,900 ha in eastern NSW.

Retention of native vegetation	**Adoption %**	**Adoption Area (ha)**	**2030**	**2050**	**2119**
Enhanced AD[1] (Western)	5	299,455	1,577,166		
Enhanced AD[2] (Western)	1	59,891	nil	664,790	1,084,027
AD expansion[3] (Western)	1	59,891	311,433	664,790	1,084,027
Reduced clearing (Eastern)	n/a	409,500	6,838,650	Nil	Nil
		t Carbon	8,727,249	1,329,580	2,168,054
		M t CO_2 e	31.99	4.87	7.94

6.2 Vegetation regrowth management

Native vegetation regrowth management includes activities associated with the ERF ***Human-induced Regeneration (HIR)*** method (detailed in **Appendix 1**). Non-ERF activities include the active management of regrowth for rehabilitation associated with degraded or low productivity areas or the enhancement of remnant vegetation. Management practices include the strategic removal or the control of livestock grazing intensity, cessation of regrowth control and weed/pest suppression for revegetation or rehabilitation.

The total area calculated as potentially suitable for HIR was 3,338,500 ha, of which 3,003,256 ha (**Table 1**) is currently being managed for sequestration, however, much of this area has not yet delivered its potential abatement.

6.2.1 Analysis

The spatial distribution maps (**Figure 14**) show that the largest abatement opportunities occur across extensive areas in western and northern NSW. These maps also reveal that the soil carbon pool associated with regrowth is greatest for northern NSW (**Appendix III**). The total cumulative sequestration rates (in biomass and soil) across NSW are 51 t ha^{-1} (2030), 83 t ha^{-1} (2050) and 128 t ha^{-1} (2119), with the soil carbon pool delivering almost twice the amount of carbon as the biomass pool across each time period (**Table 8** and **9**).

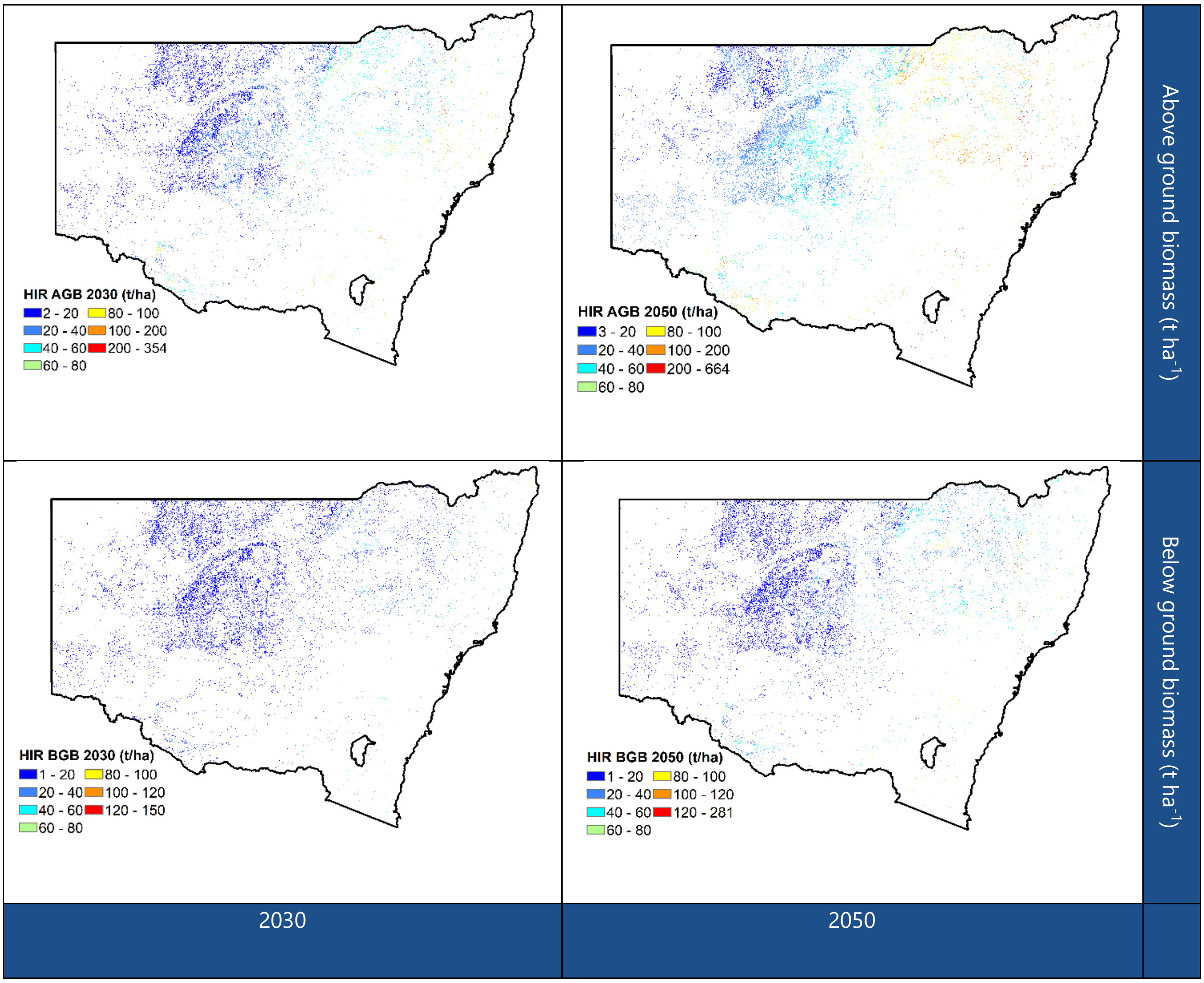


Figure 14. Human-induced regeneration (HIR), FullCAM modelled cumulative above ground biomass (AGB, t ha^{-1}) and below ground biomass (BGB, t ha^{-1}) for 2030 and 2050.

Table 8. Cumulative predicted carbon (t C, biomass) from 3,338,500 ha of suitable areas for HIR in NSW

	2030	2050	2119
AGB (t biomass)	83,993,380	156,662,400	200,468,100
BGB (t biomass)	35,593,600	66,298,830	84,808,250
Total	119,586,980	222,961,230	285,276,350
Total (t C Biomass)	**59,793,490**	**111,480,615**	**142,638,175**
Cumulative t C ha^{-1}	17.9	33.4	42.7

Table 9. Cumulative predicted carbon (t C, soil) from 3,338,500 ha of suitable areas for HIR in NSW

	2030	2050	2119
Total (t C Soil)	**110,260,200**	**164,069,500**	**283,750,800**
Cumulative t C ha^{-1}	33.0	49.1	84.9

6.2.2 Opportunities and barriers

There has been a relatively large uptake of natural regeneration under the HIR method, in part due to relatively low opportunity cost in the rangelands and low transactional costs associated with this method. In addition, HIR areas can be strategically grazed to provide some livestock income and to-date many project areas have been established on low productivity sites (Cockfield et al. 2019). However, the rate of accumulation of AGB and the maximum amount of carbon sequestered will determine the financial value of a carbon project and its value proposition for the farmer.

The amount of carbon accumulated will be dependent on species specific responses (recruitment, growth and mortality) to seasonal conditions, particularly the timing of rainfall events. Growth response times may also be contingent on the capacity of the soil seedbank to respond to rainfall events as well as interactions with weed competition. Where landscapes are fragmented, or where there has been a history of fertiliser application (particularly phosphorous), the response of native species can be slow or impeded. Generally, the response from soil seedbanks of Australian species is poorly understood, leading to considerable uncertainty around anticipated germination rates.

While stand age and site quality are important factors in the amount of sequestration achieved, recent studies have highlighted the importance of the position in the landscape and access to ground water in maximising potential carbon accumulation (Paul and Roxburgh 2019). This appears to be particularly important for more arid areas where riparian or floodplain zones may support increased sequestration compared to surrounding areas (Paul and Roxburgh 2019). As riparian areas and drainage lines can often be managed for erosion control and where best practice includes the fencing these areas and periodical grazing by livestock, it may be expected that widespread uptake of sequestration activities in these areas of a paddock would occur. These 'wet' areas will also form important sites as refugia for species under climate change. However, such activities would be at small scale, precluding access to carbon markets through the current aggregation and auction process. There is a clear potential to recognise co-benefits associated with the restoration of habitat for biodiversity in addition to the carbon benefits from planting in these 'wet' areas.

For semi-arid and arid plant species, size is generally a poor indicator of age (Grice at al. 1997). Currently in FullCAM modelling there is a dependency on knowing the age of stands to determine sequestration potential. Therefore, modifications to the HIR method which capture changes in canopy size rather than age may better reflect changes in carbon accumulation in drier environments. A major carbon project developer, Climate Friendly, is proposing a method modification where FullCAM biomass is based on canopy change rather than stand age for semi-arid environments (Z. Ryan pers. comm). The Forest Management Indicators Program run by NSW DPI Forest Science team are developing and employing remotely sensed methods, e.g. foliar projective cover (FPC) to measure woody cover density, developed through the Queensland Government Statewide Landcover and Trees Study (SLATS program) (AusCover 2020). In addition, Airborne Laser Scanning – UAV-based photogrammetry - is also being used to quantify both vegetation cover as well a height. Each of these options can be explored to measure changes in canopy (C Stone *pers. comm*).

6.2.3 Production trade-offs

- Natural regeneration is considered the most cost-effective option for sequestration.
- The economic benefits of HIR projects are primarily dependent on the price for carbon and achievable sequestration rates and is less sensitive to livestock prices or modest increases in livestock carrying capacity (Cockfield et al. 2019). For rangeland systems, under current price and policy settings, forgone income from livestock will only be significant in the long-term (multiple decades) (Cockfield et al 2019). Re-directing some of the income from carbon farming to farm improvements (e.g. total grazing pressure fencing) has been shown to allow intensification of production (increased carrying capacity)

elsewhere on the farm which has potential to offset lost livestock productivity (Cross et al. 2019; WLLS, 2019, Baumber et al. 2020)

- It is generally accepted that a negative relationship between pasture and woody growth exists (e.g. Pellegrini et al. 2016). For rangeland systems, it has been well established that high levels of woody cover or INS (Invasive Native Species) require control to increase livestock production (e.g. WLLS, 2019). Here, INS is seen as a symptom of over grazing. Recent anecdotal evidence in the rangelands of western NSW is showing that the control of grazing intensity may be more important than the competitive interactions between woody cover and pasture to restore livestock productivity (Waters et al. 2020). However, woody cover thresholds are likely to vary depending on the vegetation community. For example, in rangeland systems, Mulga (*Acacia aneura*) communities may support up to 40% canopy cover, above which pasture growth rapidly declines as herbaceous production is minimal (WLLS, 2020, R. Grant *pers. comm*).
- There is evidence that the regrowth of woody shrubs (e.g. Mulga) provides the greatest competition to pasture growth but also provides the least sequestration benefit compared to trees (Waters et al. 2017b). This suggests that management that favours the regrowth of carbon dense tree species may increase carbon and have reduced impact on production.
- Some grazing can occur with management of regrowth but again in mixed species regrowth, the responses to grazing will vary with palatability and the timing/frequency of grazing events.
- Overall, the impacts on production are likely to be neutral to positive.

6.2.4 Adoption rate

The on-farm adoption rate recognises that not all farms will convert the total area to carbon sequestration activities. We have assumed a 20% on-farm adoption, at a 5% industry adoption rate, which results in an overall adoption rate of 1%. We also acknowledge that depending on the size of a farm and the condition of the landscape, the 20% on-farm adoption value may be higher or lower. We estimate between ~6,000 and 66,000 ha, representing a 1 and 10% industry adoption rate, respectively, can feasibly deliver 1.25 to 12.49 M t CO_2 e (biomass and soil) abatement in 2030 (**Table 10**) including 0.44 to 2.19 Mt CO_2 e (biomass) in 2030 (Table 11). This range is provided as we expect natural regeneration to allow for periodic grazing which will likely increase industry adoption (evidenced by the high number of active HIR-ERF projects, **Table 1**).

Table 10. Feasible cumulative sequestration (**t C biomass and soil**) from managing vegetation regrowth (HIR) across NSW based on a total of 3,338,500 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from vegetation regrowth management (**t C biomass and soil**) based on **1% adoption** across NSW

			t carbon		
Adoption (%)	**Area of farm applied (%)**	**Adoption area (ha)**	**2030**	**2050**	**2119**
1	20%	6,677	340,107	554,191	854,656
		M t CO_2-e	1.25	2.03	3.14

b. Future feasible sequestration from vegetation regrowth management (**t C biomass and soil**) based on **5% adoption** across NSW

Adoption (%)	**Area of farm applied (%)**	**Adoption area (ha)**	**2030**	**2050**	**2119**
5	20%	33,385	1,700,537	2,755,501	4,263,890
		M t CO_2-e	6.24	10.10	15.63

c. Future feasible sequestration from vegetation regrowth management (**t C biomass and soil**) based on **10% adoption** across NSW

Adoption (%)	**Area of farm applied (%)**	**Adoption area (ha)**	**2030**	**2050**	**2119**
10	20%	66,770	3,405,270	541,910	8,546.56
		M t CO_2-e	12.49	20.33	31.37

Table 11. Feasible cumulative sequestration (**t C biomass**) from managing vegetation regrowth (HIR) across NSW based on a total of 3,338,500 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from vegetation regrowth management (**t biomass**) based on **1% adoption** across NSW

			t carbon		
Adoption (%)	**Area of farm applied (%)**	**Adoption area (ha)**	**2030**	**2050**	**2119**
1	20%	6,677	119,518	223,011	285,107
		M t CO_2-e	0.44	0.82	1.05

b. Future feasible sequestration from vegetation regrowth management (**t C biomass**) based on **5% adoption** across NSW

Adoption (%)	**Area of farm applied (%)**	**Adoption area (ha)**	**2030**	**2050**	**2119**
5	20%	33,385	597,591	1,115,059	1,425,539
		M t CO_2-e	2.19	4.09	5.23

c. Future feasible sequestration from vegetation regrowth management (**t C biomass**) based on **10% adoption** across NSW

Adoption (%)	**Area of farm applied (%)**	**Adoption area (ha)**	**2030**	**2050**	**2119**
10	20%	66,770	1,195,183	2,230,118	2,851,079
		M t CO_2-e	4.38	8.18	10.45

6.3 Reforestation and afforestation

Reforestation by ERF methods, ***Mixed-species Environmental or Mallee Plantings*** as well as non-ERF activities such as shelter belts, amenity and environmental plantings for habitat or amelioration of environmental problems (erosion control, dryland salinity or nutrient management) offer the largest sequestration potential from agricultural systems in NSW.

Reforestation
Increasing regrowth or replanting an existing forest or woodland
Afforestation
Adding to trees by replanting or managing regrowth where there is no current forest

6.3.1 Analysis

Across NSW, a total of 13,533,700 ha is potentially suitable for reforestation activities, of which 5,419 ha is currently being managed for sequestration (**Table 1**).

We assessed the potential for ***Mixed-species Environmental Plantings*** within temperate areas only. Expansion of this ERF method/activities to other areas, particularly the marginal and mixed farming areas of NSW will magnify the potential sequestration. The temperate areas of NSW, the tablelands and coastal areas provide the greatest potential for high sequestration rates and less risk of establishment failure than drier environments. However, larger-scale activities will occur in the mixed farming zones of central NSW (**Figure 15**). Reforestation/afforestation activities offer the greatest rates of sequestration (biomass and soil), 85 t C ha^{-1} (2030), 149 t C ha^{-1} (2050) and 234 t C ha^{-1} (2119) (**Table 11** and **12**) including of 36 t C ha^{-1} (2030), 67.5 t C ha^{-1} (2050), 86.4 t C ha^{-1} (2119) in biomass. (**Table 11**).

For Mallee species the rate of sequestration (biomass and soil) are limited by species distribution patterns, confined to south-western NSW (**Figures 16** to **18**) with rates of between 53-63 t C ha^{-1} (2030), 104-118 t C ha^{-1} (2050) and 190-211 t C ha^{-1} (2119) (**Tables 13** to **18**). Sequestration rates in biomass ranged from 21.7 to 24.5 t C ha^{-1} (2030) to 40.6 to 45.6 t C ha^{-1} (**Tables 13, 15, 17)**.

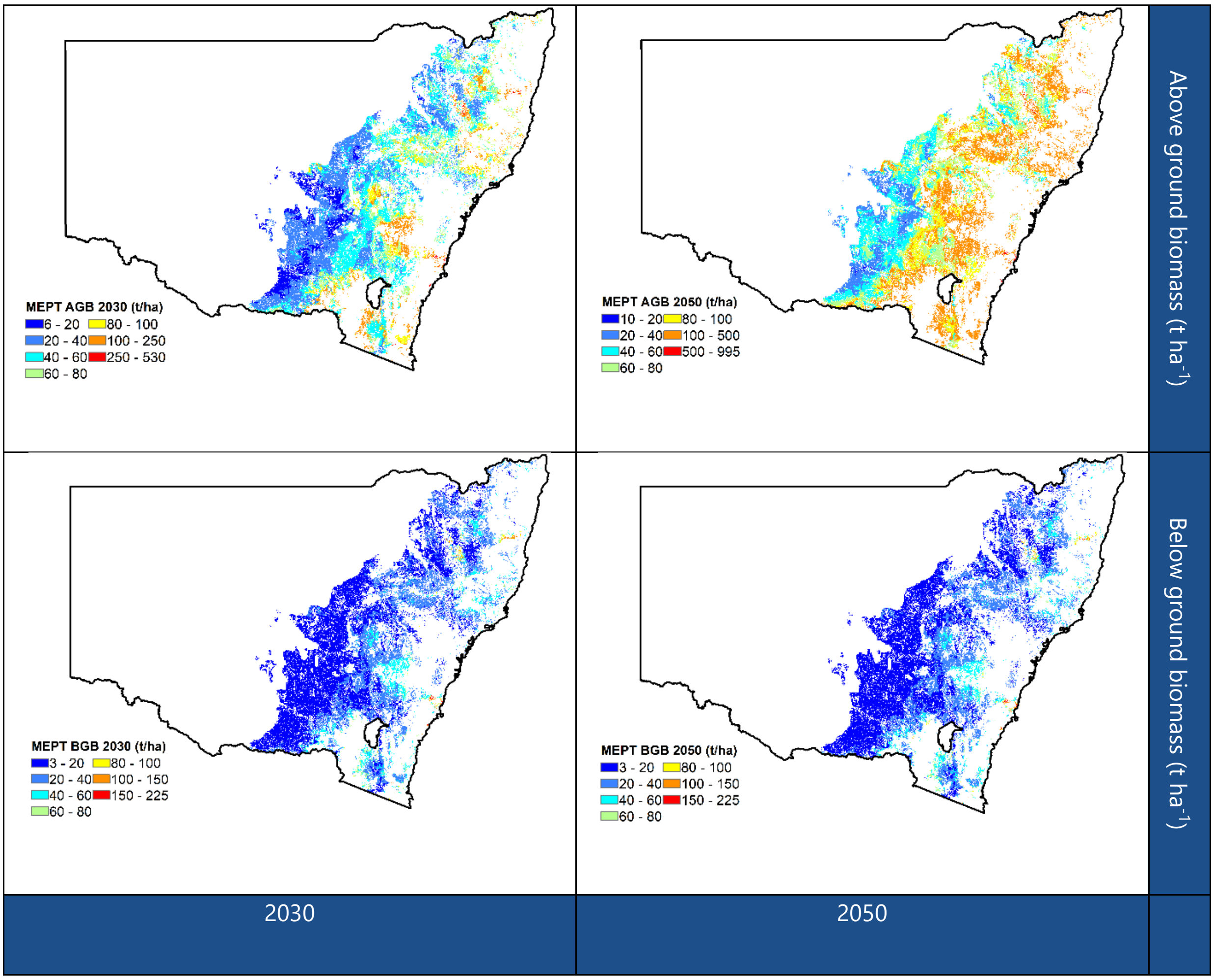


Figure 15. Mixed-species Environmental Planting in temperate areas, (MEPT), FullCAM modelled cumulative above ground biomass (AGB, t ha^{-1}) and below ground biomass (BGB, t ha^{-1}) for 2030 and 2050.

Table 11. Cumulative predicted carbon (t C, biomass) in 13,533,700 ha of suitable areas for **MEPT** in NSW

	2030	**2050**	**2119**
AGB (t biomass)	684,799,000	1,282,082,600	1,642,131,000
BGB (t biomass)	289,771,100	542,144,400	694,277,500
Total	974,570,100	1,824,227,000	2,336,408,500
Total (t C biomass)	**487,285,050**	**912,113,500**	**1,168,204,250**
Cumulative t C ha^{-1}	36	67.5	86.4

Table 12. Cumulative predicted carbon (t C, soil) in 13,533,700 ha of suitable areas for **MEPT** in NSW

	2030	**2050**	**2119**
Total (soil t C)	**667,042,300**	**1,103,579,300**	**2,003,459,500**
Cumulative t C ha^{-1}	49	81.5	148.0

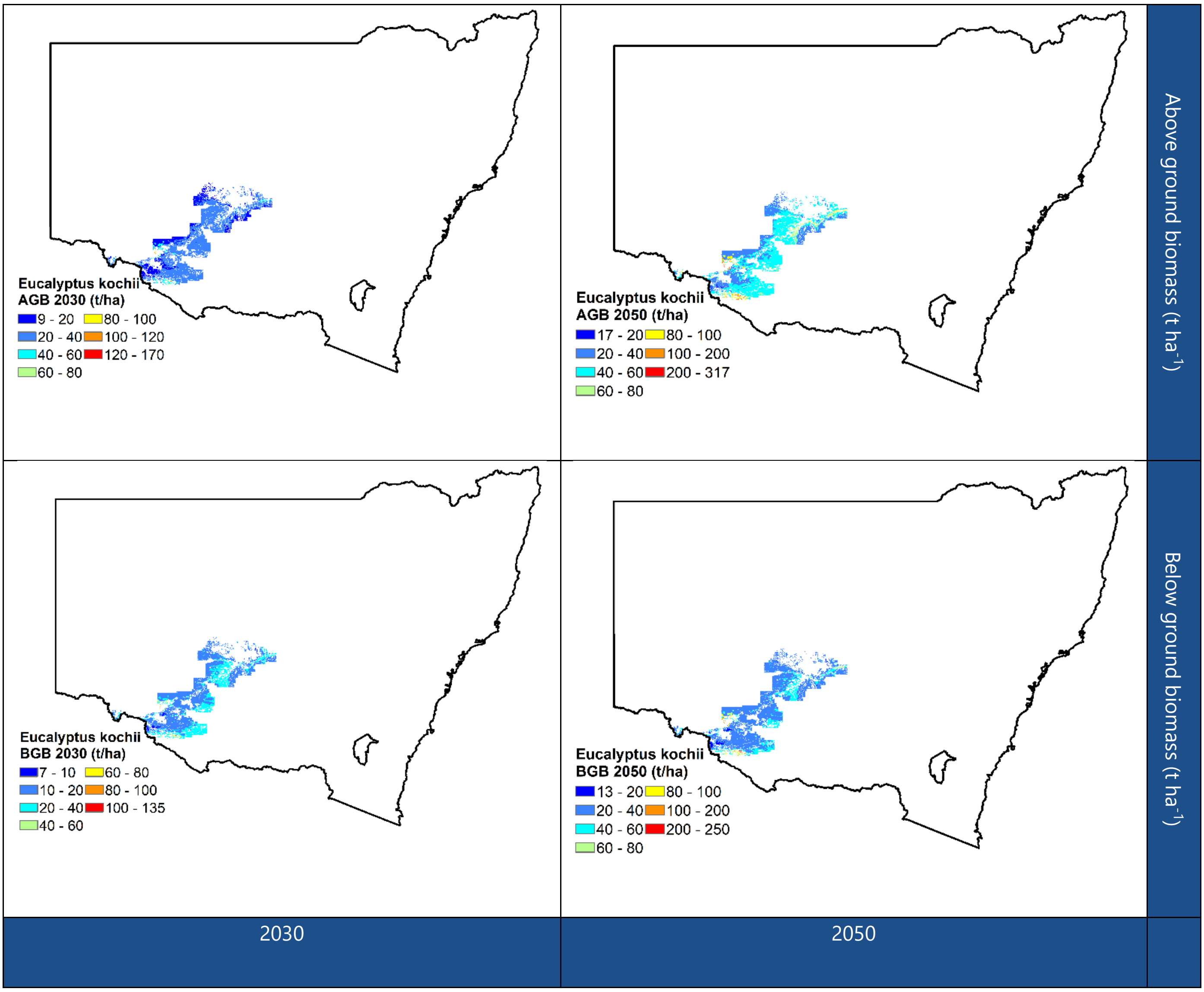


Figure 16. Mallee (*Eucalyptus kochii*) plantings, FullCAM modelled cumulative above ground biomass (AGB, t ha^{-}) and below ground biomass (BGB, t ha^{-1}) for 2030 and 2050.

Table 13. Cumulative predicted carbon (t C biomass) in 2,194,800 ha of suitable areas for *E. kochii* in NSW

	2030	2050	2119
AGB (t biomass)	53,228,410	99,252,480	126,996,200
BGB (t biomass)	42,319,350	79,138,610	101,333,600
Total	95,547,760	178,391,090	228,329,800
Total (t C biomass)	**47,773,880**	**89,195,545**	**114,164,900**
Cumulative t C ha^{-1}	21.7	40.6	52.0

Table 14. Cumulative predicted carbon (t C soil) in 2,194,800 ha of suitable areas for *E. kochii* in NSW

	2030	2050	2119
Total (biomass C)	**67,551,440**	**138,726,200**	**301,803,300**
Cumulative t C ha^{-1}	30.8	63.2	137.5

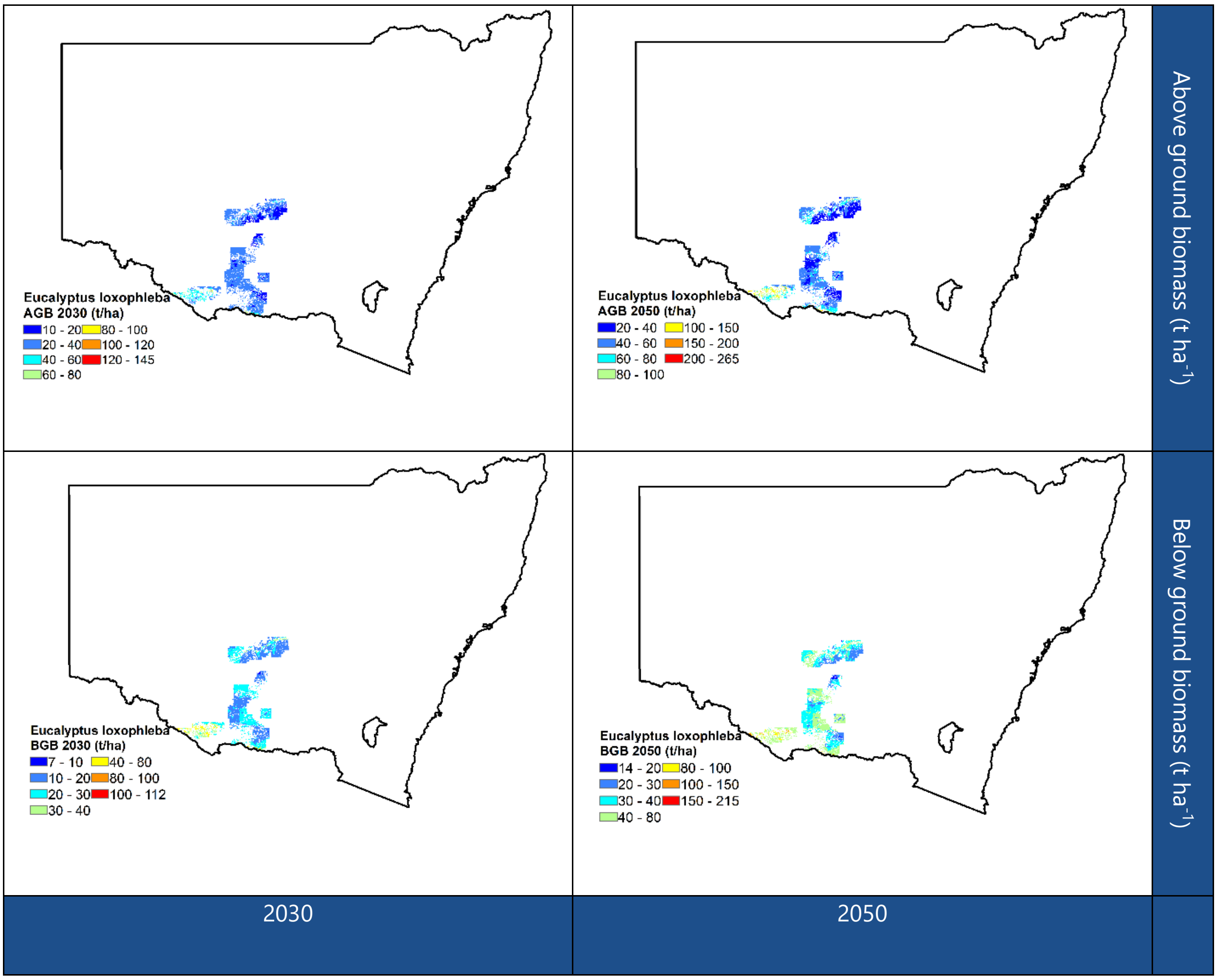


Figure 17. Mallee (*Eucalyptus loxophleba*) plantings, FullCAM modelled cumulative above ground biomass (AGB, t ha^{-1}) and below ground biomass (BGB, t ha^{-1}) for 2030 and 2050.

Table 15. Total potential carbon (t C Biomass) from 1,496,300 ha of suitable areas for *E. loxophleba* in NSW

	2030	**2050**	**2119**
AGB (t biomass)	40,817,810	76,176,700	97,491,390
BGB (t biomass)	32,474,690	60,761,800	77,813,560
Total	73,292,500	136,938,500	175,304,950
Total (t C biomass)	**36,646,250**	**68,469,250**	**87,652,475**
Cumulative t C ha^{-1}	24.5	45.6	58.6

Table 16. Total potential carbon (t C Soil) from 1,496,300 ha of suitable areas for *E. loxophleba* in NSW

	2030	**2050**	**2119**
Total (t C soil)	**54,543,460**	**108,106,200**	**227,887,400**
Cumulative t C ha^{-1}	36.4	72.2	152.3

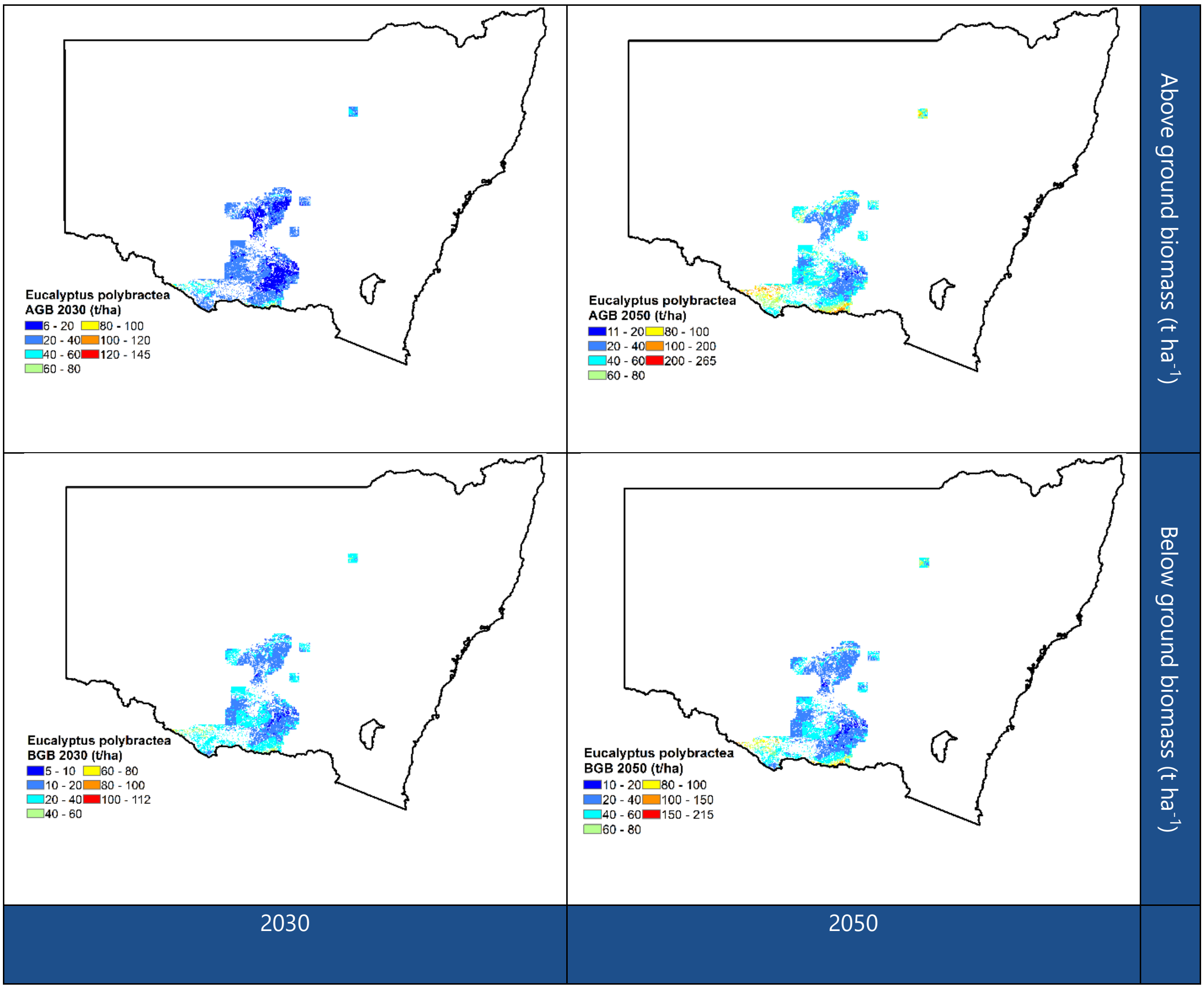


Figure 18. Mallee (*Eucalyptus polybractea*) plantings, FullCAM modelled cumulative above ground biomass (AGB, t ha^{-1}), below ground biomass (BGB, t ha^{-1}) and soil carbon (t C ha^{-1}) for 2030 and 2050.

Table 17. Cumulative predicted carbon (t C, biomass) from 3,079,100 ha of suitable areas for *E. polybractea* in NSW

	2030	2050	2119
AGB (t biomass)	80,570,160	150,321,900	192,368,900
BGB (t biomass)	64,087,000	119,888,400	153,526,000
Total	144,657,160	270,210,300	345,894,900
Total (t C biomass)	**72,328,580**	**135,105,150**	**172,947,450**
Cumulative t C ha^{-1}	23.5	43.9	56.2

Table 18. Cumulative predicted carbon (t C, soil) from 3,079,100 ha of suitable areas for *E. polybractea* in NSW

	2030	2050	2119
Total (t C soil)	**120,031,500**	**220,413,100**	**439,754,100**
Cumulative t C ha^{-1}	38.9	71.6	142.8

6.3.2 Opportunities and barriers

There has been a long history of direct seeding or the planting of tube stock within agricultural landscapes (e.g. Vesk and Dorrough 2006). Farmers recognise the utility and amenity value of afforestation and reforestation activities. These values include;

- Improved livestock weight gain and survival from shade and shelter provided by trees (Gregory 1995),
- Pasture and crop protection (Reid and Landsberg 1999),
- Facilitating integrated pest management and pollination services (e.g Cunningham *et al*. 2002)
- Connecting habitats to create corridors for wildlife (Manning *et al*. 2006), and
- Addressing land degradation e.g. dryland salinity, nutrient management (Yates and Hobbs, 1997).

However, reforestation and afforestation activities are generally supported by a mix of incentive funding (e.g. Landcare Australia – 20 Million Trees Program) and private co-funding. This recognises both the public and private benefit of reforestation and afforestation and the required sharing of the significant costs of site preparation, establishment and on-going management. A major barrier to the adoption of the ERF methods like ***Mixed-species Environmental Plantings*** has been the costs associated with developing projects at a sufficient scale to represent a viable proposition to farmers.

Greening Australia (GA) has had a long history of revegetation activities, aiming to balance native, biodiverse plantings with agricultural production and forestry. In 2014, GA priced direct seeding costs at \$520 ha^{-1} for fencing/labour and \$450 ha^{-1} associated with site preparation, weed management and labour (Greening Australia 2014). Currently GA commercial prices for establishment vary from \$2,500 (direct seeding) to \$5,000 ha (tube stock planting) for the restoration native endemic species of diverse structure (James McGregor *pers. comm*). The availability of genetic material (particularly endemic native species) for direct seeding or as tube stock may also limit where and when planting may occur as well as the scale of plantings.

In a relatively new initiative and a new opportunity for small-scale abatement activities, GA has developed a *Biodiverse Carbon Conservation* (BCC) product. BCC represents partnerships between farmers, biodiverse carbon farming and Australian companies. Through these partnerships, small scale projects that would otherwise be unviable within the ERF may allow farmers to participate in carbon markets. As such, this commercial model provides an approach to remove some of the barriers around participation for small-scale projects in carbon markets while also supporting additional biodiversity benefits. A model for GA to partner with LLS is currently under consideration within Regional NSW.

As described in section **6.2.2**, the on-farm placement of plantings in ‘wet’ areas will maximise the abatement potential. Both the configuration of tree plantings on farm as well as the proportion of the farm that can be reforested without negatively impacting agricultural production will be important to identifying on-farm spatial opportunities. Belt plantings rather than blocks have greater sequestration potential (Paul et al, 2019) and belt configuration will also accommodate paddock boundary plantings as well as within-paddock shelter for livestock.

6.3.3 Production trade-offs

- The diverse benefits from tree planting to the farm enterprise have been listed above e.g. shelter belts for livestock production and lamb survival, restoration and amelioration is associated with is a production benefit.
- Where environmental plantings are associated with ecological restoration, salinity and nutrient management, additional benefits to the farm enterprise can be gained. We suggest that the greatest benefits to production from environmental plantings will occur in highly modified or degraded landscapes.
- Additional value of environmental plantings can result where palatable shrubs such as saltbush (*Atriplex nummularia)* or edible seed pods and foliage (e.g. *Acacia spp)* are included in plantings for livestock fodder reserves.

- The notion that as woody density increases, the capacity to utilise pastures will be reduced and negatively impact enterprise profitability may not always be the case. For example, in detailed economic analyses of 16 commercial livestock enterprises in the Grassy-box Woodland communities of NSW, healthy woodlands (associated with 20-30%cover) provided higher levels of income from livestock during dry periods compared to degraded woodlands. In addition, healthy woodlands also provided alternative cash income streams associated with ecosystem services (native grass seed harvesting, pollination services) as well as greater levels of wellbeing among farmers (Ogilvy et al. 2018). The additional benefits of healthy woodlands in supporting climate change adaptation through more resilient ecosystems have been highlighted for several Australian woodland communities (Lavorel et al. 2015). A study undertaken by Field et al. 2006 (pg 36) and cited by Hassall (2008), describes a significant correlation between tree cover and land value. Here, 5-50% tree cover was associated with a 25% increase in property values relative to a similar cleared property.
- As discussed for HIR (**6.2.2**), the impacts of changes in woody cover on production will be dependent on multiple factors including species and agricultural production as well as the initial starting condition of the landscape.
- Environmental plantings can also co-deliver wood products under farm forestry. Where carbon-forestry projects target marginal lands, carbon prices > \$18 t CO_2 e constitute a viable farm forestry enterprise (Paul et al. 2013). Farm forestry may however negatively impact cropping enterprises (Cleugh et al., 2002).
- Environmental benefits through the provision of feed sources for wildlife (nectar and pollen) are most beneficial from remnants and where endemic species are planted (Keogh et al. 2010). While relatively little is known about the role of native pollinators in Australian agriculture, the role of environmental plantings to increase pollinator habitat and resources is likely to be increasingly important under ongoing biosecurity and climate change threats (see O'Grady and Mitchell 2017).
- Overall, the impacts on production are likely to be neutral to positive.

6.3.4 Adoption

We considered that the clear production value in investing in trees on farm as well as the legacy from adoption of reforestation activities will support high levels of industry adoption. However, we have provided a range of conservative adoption rates (1-10%) because adoption rate will likely vary between different crop and livestock systems. For temperate areas of NSW, relatively 'reliable' rainfall reduces the risk of establishment failure which may occur in more marginal areas of the mixed farming zone. For temperate areas, we have assumed an adoption rate of at least 5% (2030, 2050) but for cropping enterprises the adoption rate may be lower. In the southern cropping areas of NSW, climate change impacts on future wheat yields indicate considerable uncertainty around the long-term viability of grain production (Feng et al. 2020; Wang et al. 2020). Conversion of cropland to pastures or at least diversification into mixed farming may represent an adaptation strategy in these areas. In this region, there may be greater rates of adoption of mallee plantings in more marginal, semi-arid environments.

For all afforestation and reforestation activities we have applied a 20% on-farm adoption factor for the same reasons outlined in section **6.2.4**.

Within the temperate areas, based on a 5% industry adoption rate and 20% on-farm adoption, some 135,337 ha could feasibly deliver > 11.5 M t C (2030), >20.1 M t C (2050) and >31.7 M t C (2119) based on sequestration rates (biomass and soil) of 85 t ha^{-1} (2030), 149 t ha^{-1} (2050) and 234 t ha^{-1} (2119) (**Table 19**). Biomass sequestration potential is estimated at 17.8 M t CO_2 e (2030), 33.5 M t CO_2 e (2050) and 42.9 M t CO_2 e (2119) (**Table 20**)

In the semi-arid areas of southern NSW, 2,194,800 ha is potentially suitable for replanting Mallee species (*Eucalyptus kochii*). Based on a 5% industry adoption rate and 20% on-farm adoption, >33,000 ha could feasibly deliver >1.16 M t C (2030), 2.2 M t C (2050) and > 4.76 M t C (2119) based on sequestration rates (biomass and soil) of 53 t ha^{-1} (2030), 104 t ha^{-1} (2050) and 190 t ha^{-1}(2119) (**Table 21**). Sequestration potential in biomass is estimated at 1.8 M t CO_2 e (2030), 3.27 M t CO_2 e (2050) and 4.18 M t CO_2 e (2119) (**Table 22**).

For Mallee species, *Eucalyptus loxophleba* a total of 1,496,300 ha is potentially suitable for replanting. At a 5% industry adoption rate and 20% on-farm adoption, > 14,000 ha could feasibly deliver sequestration. Based on sequestration rates (biomass and soil) of 61 t ha^{-1} (2030), 118 t ha^{-1} (2050), 211 t ha^{-1}(2119) the amount of sequestration predicted is > 0.9 M t C (2030), >1.7 M t C (2050) and >3.1 M t C (2119) (**Table 24**). Sequestration potential in biomass is estimated at 1.34 M t CO_2 e (2030), 2.50 M t CO_2 e (2050) and 3.22 M t CO_2 e (2119) (**Table 25**).

For Mallee species, *Eucalyptus polybractea* a total of 3,079,100 ha is potentially suitable for replanting. At a 5% industry adoption rate and 20% on-farm adoption, 30,791 ha could feasibly deliver sequestration. Based on sequestration rates of 63 t C t ha^{-1} (2030), 116 t ha^{-1} (2050) and 199 t ha^{-1}(2119) the predicted sequestration is >1.9 M t C (2030), >3.5 M t C (2050) and > 6.1 M t C (2119) (**Table 26**). Sequestration potential in biomass is estimated at 2.65 M t CO_2 e (2030), 4.96 M t CO_2 e (2050) and 6.34 M t CO_2 e (2119) (**Table 27**).

Table 19. Feasible cumulative sequestration (**t C Biomass and Soil**) from Mixed–species Environmental Plantings across 13,533,700 ha of temperate areas (MEPT) in NSW at a range of industry adoption rates and an assumed 20% on-farm application[1]

a. Future feasible sequestration from MEPT (t carbon) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	27,067	2,300,729	4,033,043	6,333,678
		M t CO_2-e	8.44	14.80	23.22

b. Future feasible sequestration from MEPT (t carbon) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	135,337	11,503,645	20,165,213	31,668,858
		M t CO_2-e	42.21	74.01	116.22

c. Future feasible sequestration from MEPT (t carbon) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	270,674	23,007,290	40,330,426	63,3377.16
		M t CO_2-e	84.44	148.01	232.45

[1] There is overlap (966,300 ha) between temperate area Mixed-species, Environmental Plantings with Mallee plantings and there an over estimation which should be compensated for by the relatively low adoption rates.

Table 20. Feasible cumulative sequestration (**t C Biomass**) from Mixed–species Environmental Plantings across 13,533,700 ha of temperate areas (MEPT) in NSW at a range of industry adoption rates and an assumed 20% on-farm application[1]

d. Future feasible sequestration from MEPT (t carbon) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	27,067	974,412	1,556,352	2,338,589
		M t CO_2-e	3.57	5.71	8.57

e. Future feasible sequestration from MEPT (t carbon) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	135,337	4,872,132	9,135,247	11,693,116
		M t CO_2-e	17.86	33.49	42.87

f. Future feasible sequestration from MEPT (t carbon) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	270,674	9,744,264	18,270,495	23,386,233
		M t CO_2-e	35.73	66.99	85.75

[1] There is overlap (966,300 ha) between temperate area Mixed-species, Environmental Plantings with Mallee plantings and there an over estimation which should be compensated for by the relatively low adoption rates.

Table 21. Feasible cumulative sequestration (**t C Biomass and Soil**) from Mallee (***Eucalyptus kochii***) across 2,194,800 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from Mallee (*Eucalyptus kochii*) (t C) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	4,389.6	232,648	456,518	834,024
		M t CO$_2$-e	0.85	1.68	3.06

b. Future feasible sequestration from Mallee (*Eucalyptus kochii*) (t C) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	21,948	1,163,244	2,282,592	4,170,120
		M t CO$_2$-e	4.27	8.38	15.30

Table 11c. Future feasible sequestration from Mallee (*Eucalyptus kochii*) (t C) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	43,896	2,326,488	4,565,184	8,340,240
		M t CO$_2$-e	8.54	16.75	30.61

Table 22. Feasible cumulative sequestration (**t C Biomass**) from Mallee (***Eucalyptus kochii***) across 2,194,800 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from Mallee (*Eucalyptus kochii*) (t C) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	4,389.6	95,254	178,217	228,259
		M t CO$_2$-e	0.34	0.65	0.84

b. Future feasible sequestration from Mallee (*Eucalyptus kochii*) (t C) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	21,948	476,272	891,088	1,141,296
		M t CO$_2$-e	1.75	3.27	4.18

Table 11c. Future feasible sequestration from Mallee (*Eucalyptus kochii*) (t C) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	43,896	952,543	1,782,178	2,282,592
		M t CO$_2$-e	3.49	6.53	8.37

Table 23. Feasible cumulative sequestration (**t C Biomass and Soil**) from Mallee (***Eucalyptus loxophleba***) across 1,496,300 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from Mallee (*Eucalyptus loxophleba*) (t C) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	2,992.6	182,573	353,174	631,523
		M t CO_2-e	0.67	1.30	2.32

Table b. Future feasible sequestration from Mallee (*Eucalyptus loxophleba*) (t C) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	14,963	912,743	1,765,634	3,157,193
		M t CO_2-e M	3.35	6.48	11.59

Table c. Future feasible sequestration from Mallee (*Eucalyptus loxophleba*) (t C) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	29,926	1,825,486	3,531,268	6,314,386
		M t CO_2-e	6.70	12.96	23.17

Table 24. Feasible cumulative sequestration (**t C Biomass**) from Mallee (***Eucalyptus loxophleba***) across 1,496,300 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from Mallee (*Eucalyptus loxophleba*) (t C) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	2,992.6	73,318	136,462	175,366
		M t CO_2-e	0.27	0.50	0.64

Table b. Future feasible sequestration from Mallee (*Eucalyptus loxophleba*) (t C) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	14,963	366,593	682,312	876,831
		M t CO_2-e	1.34	2.50	3.22

Table c. Future feasible sequestration from Mallee (*Eucalyptus loxophleba*) (t C) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	29,926	733,187	1,364,625	1,753,663
		M t CO_2-e	2.69	5.00	6.43

Table 25. Feasible cumulative sequestration (**t C Biomass and Soil**) from Mallee (***Eucalyptus polybractea***) across 3,079,100 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from Mallee (*Eucalyptus polybractea*) (t C) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	6,158	387,954	714,328	1,225,442
		M t CO_2-e	1.42	2.62	4.50

b. Future feasible sequestration from Mallee (*Eucalyptus polybractea*) (t C) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	30,791	1,939,833	3,571,756	6,127,409
		M t CO_2-e	7.12	13.11	22.49

c. Future feasible sequestration from Mallee (*Eucalyptus polybractea*) (t C) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	61,582	3,879,666	7,143,512	12,254,818
		M t CO_2-e	14.24	26.22	44.98

Table 26. Feasible cumulative sequestration (**t C Biomass**) from Mallee (***Eucalyptus polybractea***) across 3,079,100 ha of suitable areas in NSW at a range of industry adoption rates and an assumed 20% on-farm application

a. Future feasible sequestration from Mallee (*Eucalyptus polybractea*) (t C) based on **1% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
1	20%	6,158	144,595	270,336	346,079
		M t CO_2-e	0.53	0.99	1.27

b. Future feasible sequestration from Mallee (*Eucalyptus polybractea*) (t C) based on **5% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
5	20%	30,791	723,588	1,351,724	1,730,454
		M t CO_2-e	2.65	4.96	6.34

c. Future feasible sequestration from Mallee (*Eucalyptus polybractea*) (t C) based on **10% adoption** across NSW

Adoption (%)	Area of farm applied (%)	Adoption area (ha)	2030	2050	2119
10	20%	61,582	1,447,177	2,703,449	3,460,908
		M t CO_2-e	5.31	9.91	12.69

6.4 Summary of feasible sequestration from vegetation management

We assessed the feasible sequestration potential for NSW based on FullCAM spatial estimates of the quantum of sequestration and realistic expectations for adoption which recognise the barriers for adoption and the current developments to address these barriers. The opportunities for vegetation management (carbon sequestration in biomass) as total potential aggregated for each NSW Local Land Service region are provided in **Appendix V.**

We have assumed that adoption barriers due to a lack of information on carbon market opportunities will be met by ongoing activities by various organisations such as NSW DPI Accessing Carbon Markets Project, the CER or the CMI. However, the ability for land managers to be able to understand how sequestration activities can be incorporated into existing farm enterprises remains problematic.

The literature frequently assumes that the primary barrier to the expansion of carbon markets is economic (Dean et al. 2015; Cockfield et al 2019; CMI 2020). These economic barriers capture complexities within eligibility rules and audit requirements resulting in high transactional costs as well as the trade-offs with existing agricultural production (Cockfield et al. 2019). Some of the administrative complexities have been streamlined in the past 12 months or are currently being addressed by the Commonwealth Department of Industry Science Energy and Resources.

It is likely that the economic barriers to adoption of abatement activities from agriculture will diminish if:

- emerging method modifications described in this report which address issues of scale and provide new opportunities for agriculture to participate in carbon farming are implemented
- streamlining demonstration of compliance and modifying ERF methods to increase the supply of ACCUs are prioritised by the Clean Energy Regulator and DISER
- increasing ambition by state governments, industry sectors and corporates to achieve net zero targets drives increasing demand
- the value of ACCUs increases as demand for carbon credits grow.

The important factor here is that barriers to adoption of ERF methods are recognised and ongoing removal of these barriers will likely open new opportunities for NSW farmers to access carbon markets. The rapid expansion of carbon farming activities in the Australian rangelands has occurred because these areas have relatively low agricultural productivity and carbon farming presents a good value proposition for rangeland pastoralists. Within the last two years the rate of registration of projects has declined rapidly across most of Australia as the 'low-hanging fruit" have been taken up, and there is general recognition that areas of higher agricultural productivity need a higher price on carbon to increase interest from the land sector. However, recent research has identified that non-financial drivers of adoption may be more important (Kragt et al 2017). For example, surveys across the Western Australian wheat belt revealed that farmers were more motivated to adopt carbon farming practices where knowledge and a perception of the co-benefits (e.g. yield and production increases and environmental benefits) could be identified.

- This suggests that if farmers are aware of the value of abatement activities and can identify how these activities can be integrated into existing farm management, there may be potential to increase adoption

Knowing other adopters was also identified as being important in the study of Kragt et al. (2017), which was a similar finding to surveys undertaken in NSW (Cross et al. 2019).

- This suggests that leading innovators, mentoring and demonstrating abatement are important in facilitating greater adoption

Another broad-scale survey undertaken in Western Australia (Castelo and Marcelo, 2017) found that higher levels of knowledge about the ERF were associated with a decreased likelihood of adoption (perhaps deterred by method complexity) and that farmers were more motivated by a moral responsibility (to implement environmental practices) and the availability of technical support rather than economic returns. Where technical support was provided through strong relationships between farmers and carbon project developers, the likelihood of adoption was higher (Castelo and Marcelo, 2017; Cross et al. 2019). In NSW, there is a real opportunity to increase adoption of carbon farming methods as we are uniquely placed in having dedicated extension services through Local Land Services to maintain trusted relationships between farmers and carbon markets.

There are several other considerations around the economic impacts of carbon farming:

- Carbon income is not deemed as "primary production" income by ATO leading to complexities in tax planning
- Continual income from carbon farming can support farm planning, increasing financial resilience
- Carbon farming can provide an income stream in areas of low agricultural productivity (degraded or low productivity areas)
- The income stream from carbon farming can support viability and sustainable agricultural production through investment in farm infrastructure e.g. in rangelands the erection of fencing for management grazing pressure from kangaroos and goats
- Carbon is an enterprise contributing to property diversification, providing income during periods of low commodity returns

Based on consideration of the above, we provide relatively conservative adoption rates for each of the three categories of vegetation and are summarised Table 28.

Opportunities for small scale carbon sequestration

While participation in the ERF is expected to expand with increasing demand for carbon offsets, there are considerable opportunities for sequestration outside the ERF from small-scale activities. A major barrier to ERF participation is the viable scale of a project. Here, a large-scale project is required to successfully bid at auction with a competitive price, making small scale project uncompetitive. The size of an ERF project e.g. area (vegetation or soils) or the size of herds (beef herd management) has locked out smaller landholders from ERF carbon markets.

In parallel to established ERF markets, the NSW government may play a role in supporting the development of small-scale activities through novel project aggregation solutions to enter either the federal government ERF marketplace or the secondary market. Here, the NSW government could play a role in brokering farmer activity with markets much the same way as the CMI does within the Carbon Marketplace (CMI, 2020). The role of local governments in helping to facilitate local sequestration and developing net zero precincts may also provide opportunities to support regional-scale aggregation.

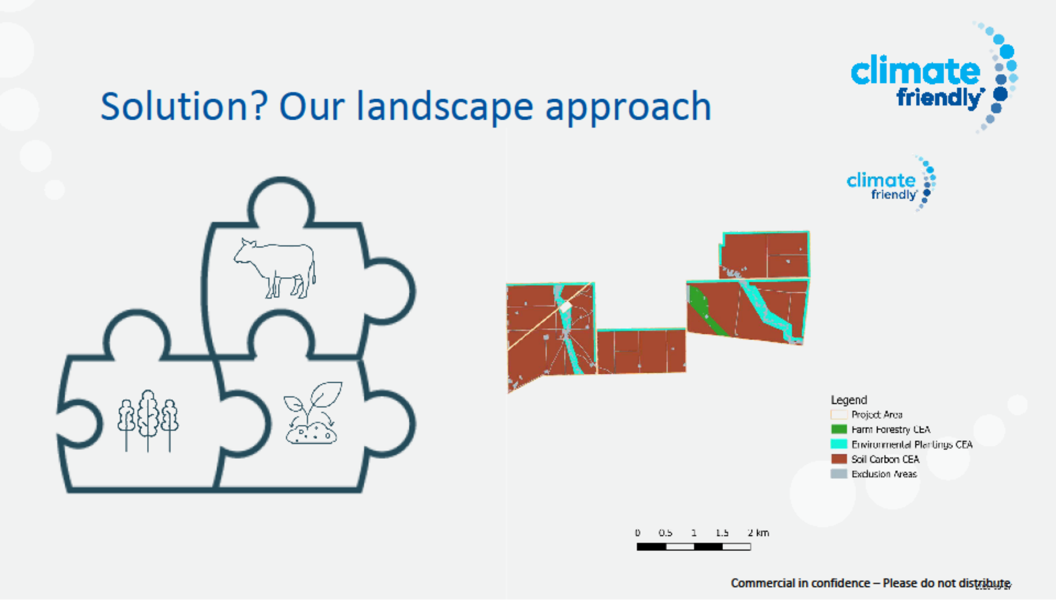
The new model offered by Greening Australia through their Biodiverse Carbon program (**section 6.3.1**) may be another pathway to unlock further adoption.

Another approach which will amplify the amount of abatement delivered from agriculture combines or nests different activities within the one farm. For example, Climate Friendly, a major carbon project developer in NSW, is proposing a new method that adopts a "*Landscape Approach*" where activities such as environmental plantings/plantations and soil carbon methods are combined (**Figure 19**). Extending this idea, additional whole-farm abatement can be further leveraged through inclusion of:

- Herd management
- the use of feed additives/supplements to livestock
- finishing livestock through small-scale feed-lotting, reducing the emissions per head, and therefore lowering emissions intensity of production

- Integration of clean energy production and energy efficiencies
- Reducing GHG emissions from supply chain, off-farm processes (e.g. horticulture, intensive livestock sector)

While the nesting of sequestration activities (ERF methods and non-ERF activities) provides a significant opportunity to amplify the abatement currently being delivered in NSW it also allows activities to be integrated with existing agricultural land management, rather than necessitating a trade-off between production and carbon. This will have the benefit of supporting continued production of food and fibre, increasing farm income streams, supporting greater regional and farm enterprise resilience while also delivering abatement.


Solution? Our landscape approach

Commercial in confidence – Please do not distribute

Figure 19. Climate Friendly are piloting a "Landscape Approach" which combines multiple ERF methods e.g. Plantations, Environmental Plantings, Soil Sequestration on the one farm. *Source:* Climate Friendly

Blockchain technology has been identified as a mechanism to reduce administrative costs, lowering project costs while demonstrating transparency and consistency in carbon crediting and purchasing (Pan *et al* 2019). This technology uses online networks to conduct, validate and record transactions much as a ledger would do. It is possible that this mechanism may also support the labelling with provenance information which can be used to open access into markets for verifiable additional environmental benefits for agricultural production other than abatement.

Limitations of the assessment

For FullCAM modelling we have assumed that vegetation-based activities would commence in 2020. This has allowed us to estimate cumulative carbon sequestration for 10-years (2020 to 2030), 30-years (2020 to 2050) and 100-years (2020 to 2119) to reflect continued delivery of abatement from one regrowth/planting event commencing 2020. Our modelling therefore does not account for a continual pipeline of abatement from multiple regrowth/planting events.

While it was necessary to commence modelling at 2020 in order to align the GIS spatial layers underpinning the land-use suitability mapping to contemporary land-use, it is realistic to expect a ~2-year delay in realising industry adoption from PIPAP commencement (2021). For this reason, we suggest the sequestration rates from 2020 to 2028 will provide indicative 2030 quantum of sequestration which captures a 2-year project start-up period (**Table 28**).

For regrowth and afforestation activities, we used a relatively conservative range of industry adoption rates (1-10%). However, for these activities it is likely that on any one farm, not all land will be used for vegetation-based sequestration. To account for this, we have applied an 'on-farm factor', assuming only a small portion of a farm will be managed for carbon (20%). The blanket application of a generic value for the proportion of on-farm adoption is problematic because farm-scale trade-offs have rarely been examined and there is likely a wide range of values across the agricultural sector. The utility of an on-farm tool to optimise land-use for carbon is currently being evaluated by NSW DPI.

In our analyses, for a number of vegetation-based sequestration activities (clearing of native vegetation, Environmental and Mallee plantings) there were some slight overlaps in suitable areas, as indicated in sections 6.1.1 and 6.3.2 respectively.

The impacts of climate change on achieving sequestration have not been accounted in our estimations. To address this, we provide a case study for one, relatively low cost, ERF method, ***Human-induced regeneration*** to illustrate a modelling approach that accounts for both climate impacts as well as the current economic barriers.

Table 27. Overview of feasible sequestration (accumulated sequestration 2020 to 2030) from NSW agricultural sector. Activities associated with Emissions Reduction Fund methods (carbon markets) and comparable non-market practices.

ERF method	Practice	Area (ha)	% Adoption rate	% of farm (ha)	Assumptions	Cumulative sequestration t C (biomass & soil) 2030	Cumulative sequestration t C (biomass) 2030
Clearing of native vegetation							
Avoided Deforestation	Recognising vegetation < and > 20% cover Ecological thinning and method expansion	(Western NSW) 299,455 (Western NSW) 119,782	5 1	-	Most activities in western NSW; recognised method enhancement and expansion opportunities realised	1,796,730 359,346	1,577,166 311,433
	Reduced clearing rates	(Eastern NSW) 409,500	-	-	Dis-incentivising current rate of clearing in the eastern areas of NSW	6,961,500	6,838,650
M t CO_2-e						**33.43**	**31.99**
Vegetation regrowth management							
Human-induced regeneration	Natural regeneration	33,337	5	20	Uptake of current adoption continues	1,700,537	597,591
M t CO_2-e						**6.24**	**2.19**
Reforestation and Afforestation							
Environmental Plantings	Planting paddock boundaries and remnant enhanced; rehabilitation and restoration, shelter belts, amenity plantings	(Temperate NSW) 135,337	5	20	Cost barriers are removed; adoption targets temperate areas of NSW; co-sharing costs of mixed native species by direct seeding and tube stock planting are in place	11,503,654	4,872,132
Mallee *Eucalyptus kochii*		(Low rainfall NSW) 21,948	5	20	Adoption targets marginal areas of the southern cropping zones where cropping is becoming increasingly more marginal	1,163,244	476,272
Mallee *E. loxophleba*		14,963	5	20		912,743	366,593
Mallee *E. polybractea*		30,791	5	20		1,939,833	723,588
M t CO_2-e						**56.95**	**23.6**
					M t CO_2e	**96.62**	**57.78**

Table 28. Cumulative sequestration in biomass (above ground biomass (AGB), below ground biomass (BGB)) between 2020 and 2028. This provides estimated abatement at 2030 when activities commence in 2022 (allowing for a two-year period of adoption of the PIPAP program).

		Area	**AGB (t biomass)**	**BGB (t biomass)**	**Total (t biomass)**	**Cumulative (M t CO_2-.e)**
Vegetation regrowth management	Human-induced regeneration	3,338,500	68,372,270	28,993,130	97,365,400	178.5
Reforestation and Afforestation	Mixed species-environmental plantings (temperate areas)	13,533,700	556,405,600	235,520,300	791,925,900	1451.9
	Mallee *E. kochii*	2,194,800	43,334,970	34,404,600	77,739,570	142.5
	Mallee *E. loxophleba*	1,496,300	33,216,980	26,394,030	59,611,010	109.28
	Mallee *E. polybractea*	3,076,100	65,576,170	52,091,800	117,667,970	251.71

6.5 Soil carbon

6.5.1 Estimating the potential from FullCAM

FullCAM outputs for soil carbon estimates for 2030 and 2050 for each ERF method are given in the previous section and estimates to 2119 are provided in **Appendix III**. Unlike the biomass estimates, soil carbon associated with Australian tree/shrub species has not been extensively validated in FullCAM and some uncertainty exists over the modelled estimates. For example, the soil carbon parameters set in FullCAM are constant and may mis-align with spatial variation (e.g. initial C-stock or decomposition rates of wood/litter/dead roots). This may result in either over or under-estimates depending on the location (S. Roxburgh *pers. comm*).

Observed soil organic carbon (SOC) stock under different rangeland vegetation communities reflects these site-specific differences. Here, the relationship between increasing SOC stock and increasing woody density may alter with vegetation community. For example, SOC stocks were less under high density Mulga compared with low density Mulga: 23.8 (1.0 se) *vs* 31.7 (1.2 se) t C ha^{-1} (**Figure 20**). Unlike Mulga, increasing stem densities of Pine (up to 10,000 stems ha^{-1}) and Box (up to 500 stems ha^{-1}) incrementally increased SOC stock. SOC stocks were highest under high density Box compared with low density Box: 45.3 (5.6 se) *vs* 29.4 (2.5 se) t C ha^{-1} and high-density Pine compared with low density Pine; 33.4 (2.8) *vs* 28.5 (2.3) t C ha^{-1}. This shows that both the vegetation community type, as well as the density of woody cover will influence the potential sequestration of SOC.

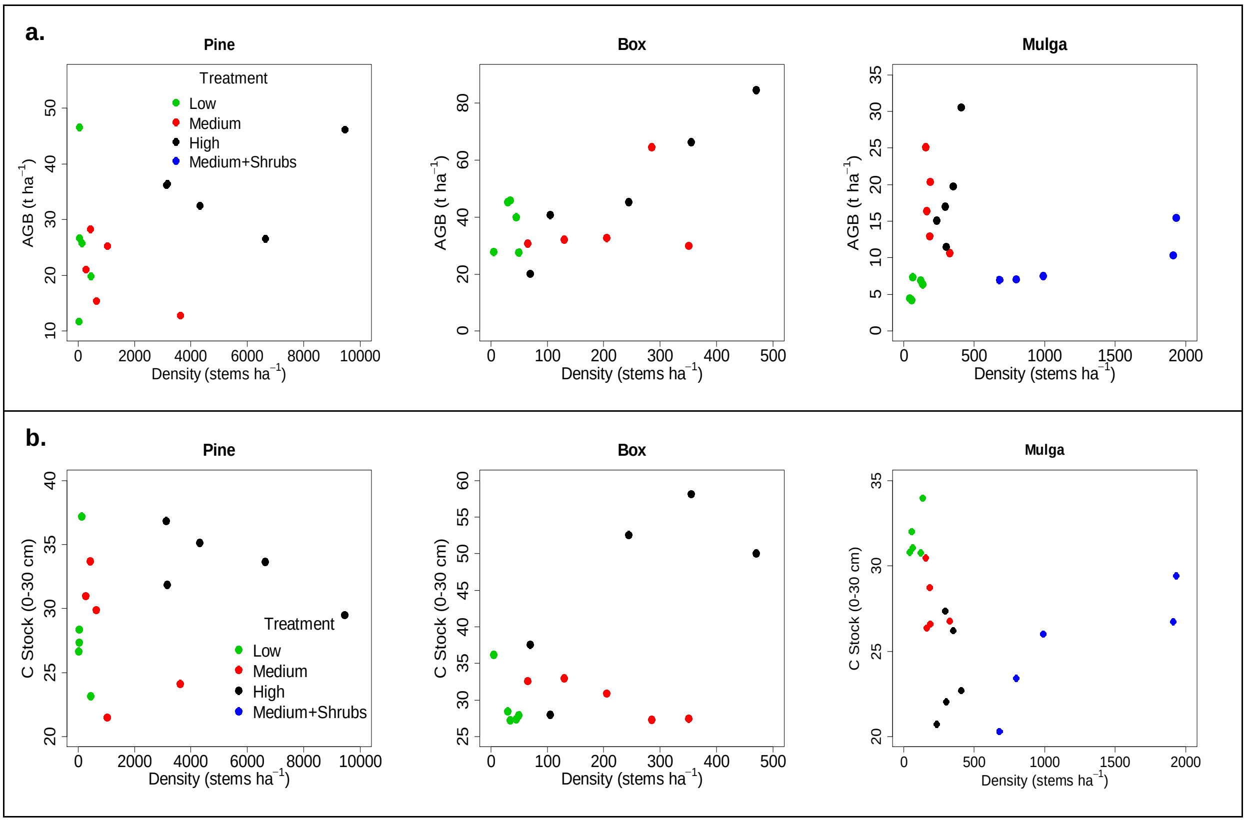


Figure 20. Above ground biomass (AGB, t ha^{-1}) for Pine (*Callitris glaucophylla*), Box (*Eucalyptus populnea*) and Mulga (*Acacia aneura*) species at different densities and **b** mean soil carbon stock, (C-stock, t C ha^{-1},0-30cm) of Pine, Box and Mulga communities at different densities (Low, Medium, High) (stems ha^{-1}). *Source:* Waters et al (2017b)

6.5.2 Estimating the potential from agricultural systems

In the previous section we provided predictions for soil carbon sequestration associated with woody cover and regrowth of native vegetation using FullCAM. To capture the potential soil carbon sequestration from agricultural management practices we examined sequestration within cropping and pastoral systems using two approaches:

- Conservative estimates (default values) based on the DISER (Department of Industry, Science, Energy and Resources) default soil carbon values were compared to the published literature for NSW soils on the rates of sequestration change under agricultural management practices. The upper and lower limits of sequestration were identified
- A mixed modelling approach was used to create a benchmark soil carbon map for NSW from which change in cover was used to estimate the potential sequestration.

6.5.2.1 Default soil carbon values

Within cropping areas, activities such as the conversion of cropland to pasture; land use intensification and stubble retention can be employed with the two ERF soil carbon methods (detailed in **Appendix I**);

- ***Estimating Sequestration of carbon in Soil using Default Values*** (Estimating Soil carbon), and
- ***Measurement of Soil Carbon Sequestration in Agricultural Systems*** (Measuring Soil Carbon)

Default values provided by the DISER show the spatial coverage of sequestration rates for three crop management activities (conversion of crop to pasture; sustainable intensification and stubble retention) (**Figure 21**). We mapped each crop management activity based on the area for different land use categories using the NSW Government Land-use data base for 2017 (**Table 31**).

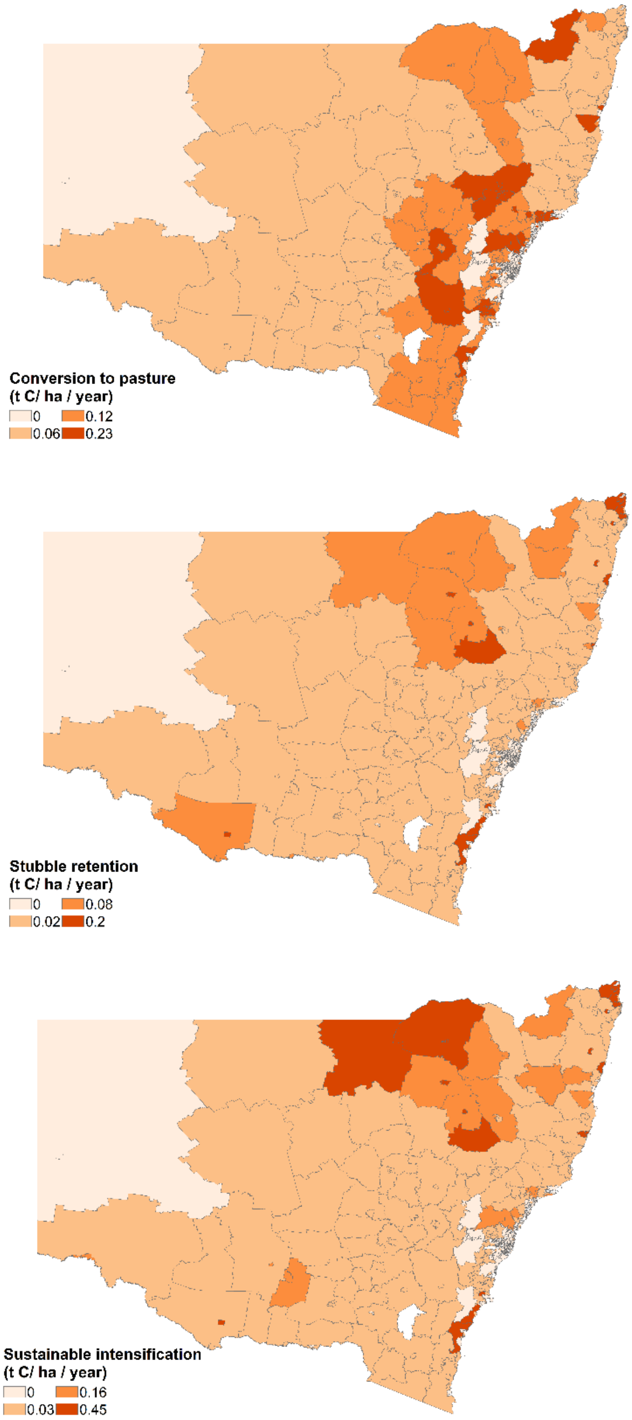


Figure 21. Spatial distribution of conservative soil carbon estimates (default values) based on avoided soil carbon loss and sequestration potential for conversion to pasture (top), stubble retention (middle) and sustainable intensification (bottom). *Source* Department of Environment and Energy https://data.gov.au/data/dataset/emissions-reduction-fund-environmental-data

Table 29. Area suitable for different agricultural management activities and estimated sequestration using recognised default values[1]

				Cumulative Sequestration t C	
Sequestration rate[1] (t C ha $^{-1}$ year $^{-1}$)	Land use category[2]	Area suitable (ha)	Total area (ha)	at 2030 (10 % adoption)	at 2050 (10 % adoption)
		Conversion of croplands to pasture			
0.06	Cropping	9,405,777		6,569,192	
	Irrigated Cropping	1,542,877	10,948,654	(656,919)	19,707,577 (1,970,757)
0.12	Cropping	1,712,628		2,310,602	6,931,807
	Irrigated Cropping	21,2874	1,925,502	(231,060)	(693,180)
0.23	Cropping	68,860		160,770	482,310
	Irrigated Cropping	1,040	69,900	(16,077)	(48,231)
Conversion of croplands to pasture: total sequestration for 10% industry adoption				**904,056**	**2,712.168**
		Stubble retention[3]			
0.02	Cropping	8,264,190		1,837,740	
	Irrigated cropping	924,512	9,188,702	(183,774)	5,513,221 (551,322)
0.08	Cropping	2,779,731		2,860,473	8,581,418
	Irrigated cropping	795,860	3,575,591	(286,047)	(858,141)
0.20	Cropping	142,831		358,576	1,075,728
	Irrigated cropping	36,457	179,288	(35,857)	(107,572)
Stubble retention - total sequestration for 10% industry adoption				**505,678**	**1,517,035**
		Sustainable intensification			
0.03	Grazing native vegetation	24,863,225			
	Grazing modified pasture	5,436,174			
	Cropping	8,263,625			
	Grazing irrigated modified pastures	110,916		11,985,216	35,955,647
	Irrigated cropping	1,276,779	39,950,719	(1,198,521)	(3,595,564)
0.16	Grazing native vegetation	1,920,425			
	Grazing modified pasture	875,617			
	Cropping	1,139056			
	Grazing irrigated modified pastures	4,448		6,617,253	19,851,758
	Irrigated cropping	196,237	4,,135,783	(661,725)	(1,985,175)
0.45	Grazing native vegetation	2,580,511			
	Grazing modified pasture	213,842			
	Cropping	1,784,578			
	Grazing irrigated modified pastures	2,209		21,892,122	65,676,366
	Irrigated cropping	283,776	4,864,916	(2,189,212)	(6,567,636)
Sustainable intensification - total sequestration for 10% industry adoption				**4,049,458**	**12,148,376**
Grand total				**5,459,192**	**16,377,579**

[1] Department of Environment and Energy (2019) maps, see Figure 21 [2] Australian Landuse Map (2017). NSW Land-use dataset https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017 [3] Assumed 10% of all cropping areas rather than 10% of area currently not adopting stubble retention as it was not possible to get accurate values for the latter.

Table 30. Estimates of soil carbon sequestration rates under agricultural management practices from studies undertaken in NSW.

Management description	Sequestration rate (0-30cm) (t C ha -1 yr-1)	Region of study	Source (s)
Pasture management			
Liming	0.46 - 0.55	Eastern Riverina	Chan et al (2011)
Increase length of pasture phase in rotations	0.22 - 0.40	Riverina	Helyar et al (1997) cited in Chan et al 2011;
Include pastures in rotation	0.02 - 0.26	Riverina	Chan et al (2011)
Nutrient management	0.41	SW slopes and CW NSW	Chan et al (2010)
Grazing management			
Management of grazing pressure	1.04 0.08-0.21	Rangelands (ridges only) Rangelands	Orgill et al (2017a) Waters et al (2015)
Conversion of crop to pasture			
Conversion of crop to permanent pasture	0.55-0.70	Liverpool Plains	Young et al (2009);
	0.06-0.23 1.2	NSW excluding Western Region CW NSW	See Figure 21. Badgery et al (2020)
Cropping systems			
Stubble retention	0.02 - 0.2	NSW excluding Western Region	See Figure 21
Reduced tillage	0.28	CW NSW	Badgery et al (2020)
Reduced tillage and biosolids	1.14	CW NSW	Badgery et al (2020)

The uncertain financial return from soil carbon projects is a major barrier to the uptake of these ERF methods because it will depend on not only the price of carbon but also the capacity of the soil to store carbon, which is determined by current land use and location. The relative changes are likely to be greatest for degraded soils but this is only relevant using the **Measurement of Soil Carbon Sequestration in Agricultural Systems** method: the alternative method, **Estimating Sequestration of Carbon in Soil using Default Values,** applies the same values irrespective of level of degradation. The overwhelming barrier to broad-scale adoption of the ERF method **Measurement of Soil Carbon Sequestration in Agricultural Systems** is the high cost of baseline soil carbon measurements. There is considerable scope to consider the role of government in co-funding this one-off cost to unlock wider participation as evidenced by recent interest in soil carbon project registration following forward payments of up to $5,000 to help meet the costs of baseline measurement.

The alternative **Estimating Sequestration of Carbon in Soil using Default Values** described above is generally considered too conservative in carbon estimations to support widespread uptake, but the advantage is that this method has relatively low costs without the need to directly measure soil carbon. Our review of the literature for NSW suggests the conservative estimates provided by DISER underestimate the potential for sequestration through grazing management and the incorporation of biosolids, so the regional potential to deliver soil carbon sequestration may be much greater than indicated by the DISER default values (**Table 32**). In extensive areas such as the rangelands, low rates of soil C sequestration per ha over extensive areas amounts to a large sequestration pool, but increased carbon project costs. Modification of this method would provide significant abatement potential not only for rangelands but also other areas in NSW. There have been several proposed approaches to address the issue of the low default values (which limits the value of a soil carbon project). For example, default values could be determined at finer spatial resolution, such as the100m resolution used in the benchmark soil carbon maps provided in this report (section 6.5.3). Alternatively, Climate Friendly have proposed a hybrid modelled-measured method (see Viscarra-Rossell et al. (2016)).

6.5.3 Estimating the potential from vegetation cover change

A machine learning approach was applied with a dataset of 2160 SOC (0-30 cm) samples across NSW (**Figure 10** and **Appendix IV** for additional detail), together with a suite of key soil forming environmental variables (climate, parent material, topography, biota-land use and age-weathering). The modelling explored random forest decision tree and multiple linear regression techniques, following methods outlined in Wang *et al.* (2018) and Gray *et al.* (2019).

The broad concept involved modelling current SOC stocks under current land use and vegetation cover to create a benchmark map. Re-modelling SOC stocks under changed land use (increasing vegetation cover) to promote carbon sequestration was then undertaken. The difference in SOC stock between the benchmark and changed vegetation cover was indicative of the potential sequestration under the modified management regime.

Increasing vegetation cover by 10% was considered a realistic expectation for agricultural landscapes and may include tree planting, natural regeneration, increased pasture cover, increased crop/stubble cover. The current vegetation cover estimates were derived from MODIS satellite imagery data and included both living and dead vegetation cover (Guerschman and Hill 2018).

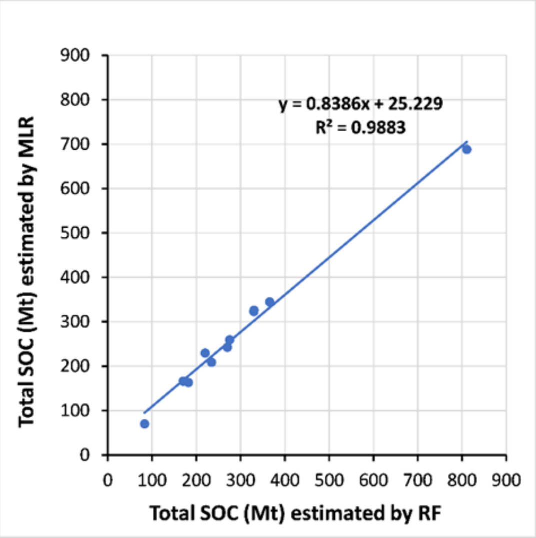
6.5.3.1 Benchmark map

The current SOC stock (t ha^{-1}, 0-30 cm) estimated from the Multiple Linear Regression (MLR) and Random Forest (RF) models for each LLS region is provided in **Table 33**. For NSW the current SOC stock based on the MLR and RF models tended have good overall agreement (R^2 =0.99, between estimated MLR and RF models, **Table 33**) with MLR generally resulting in lower SOC stock estimates compared to RF model predictions. For some regions e.g. Western, there were large differences between predictions from the two models. Additional inconsistencies can also be seen for some regions such as Northern Tablelands where MLR estimates were higher than predictions from RF.

Based on a comparison of the statistics, RF model performed better (R^2=0.70; LCC=0.81; RMSE=0.31) than MLR (R^2=0.55; LCC=0.71; RMSE=0.38) (See **Appendix IV, Table IV b**). A comparison of the predicted current SOC stock from each modelling approach is provided in **Figure 22.**

Table 31. Predicted current SOC stock (t ha^{-1}, 0-30 cm) for NSW Local Land Services (LLS) regions based on multiple linear regression (MLR) and Random Forests (RF) models. The relationship between estimated SOC from each modelling approach is also shown.

LLS region	Area (km^2)	SOC stock (M t) MLR	RF
Central Tablelands	30,265	166.3	170.2
Greater Sydney	11,476	70.2	83.1
Hunter	30,909	208.8	234.1
North Coast	29,555	259.2	275.4
North West	76,807	322.7	329.8
Northern Tablelands	36,821	229.6	219.7
South East	54,433	325.9	330.4
Western	296,828	687.8	811.0
Central West	87,375	344.7	365.4
Riverina	65,657	242.7	269.9
Murray	41,398	163.1	182.2
Total (NSW)	**761,524**	**3,020.7**	**3,271.1**



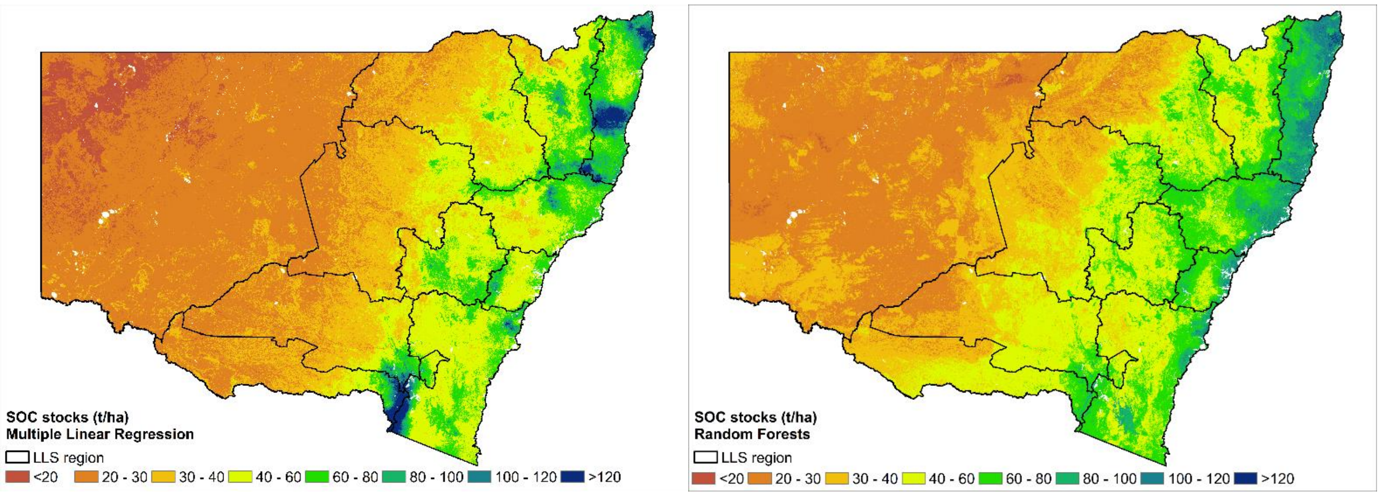


Figure 22. Benchmark map of current SOC stock (t ha^{-1}) estimated using Multiple Linear Regression (left) and Random Forest (right) modelling.

6.5.3.2 Cover change

Using the two benchmark SOC stock maps (**Figure 22**), potential sequestration with an absolute 10% increase in vegetation cover was mapped to develop a potential sequestration map. For a 10% absolute increase in cover, results were irregular for the RF model despite better model performance than MLR for the current SOC stock map. For the RF model, large areas across NSW showed losses in SOC, even with increased cover. With the RF model few areas had sequestration > 6 t ha^{-1}. In contrast, the MLR model results were more consistent with most areas showing positive sequestration, ie an increase in SOC with additional vegetation cover. Many areas under the MLR model output showed significant sequestration (>12 t/ha, **Figure 23**). These results are perhaps unsurprising as RF is a non-linear model so the interaction between cover and SOC is not constant.

Changes in SOC stock based on a 10% absolute change in cover from MLR model are illustrated in **Figure 23**. Here, a mean increase of 7.4 t C ha^{-1}, amounting to potential soil carbon sequestration of 452.8 Mt soil C (1,600 Mt CO$_2$ e) across NSW, can be achieved (omitting the Greater Sydney area). Detailed maps of potential soil carbon sequestration for each Land Service region are provided in **Appendix V**.

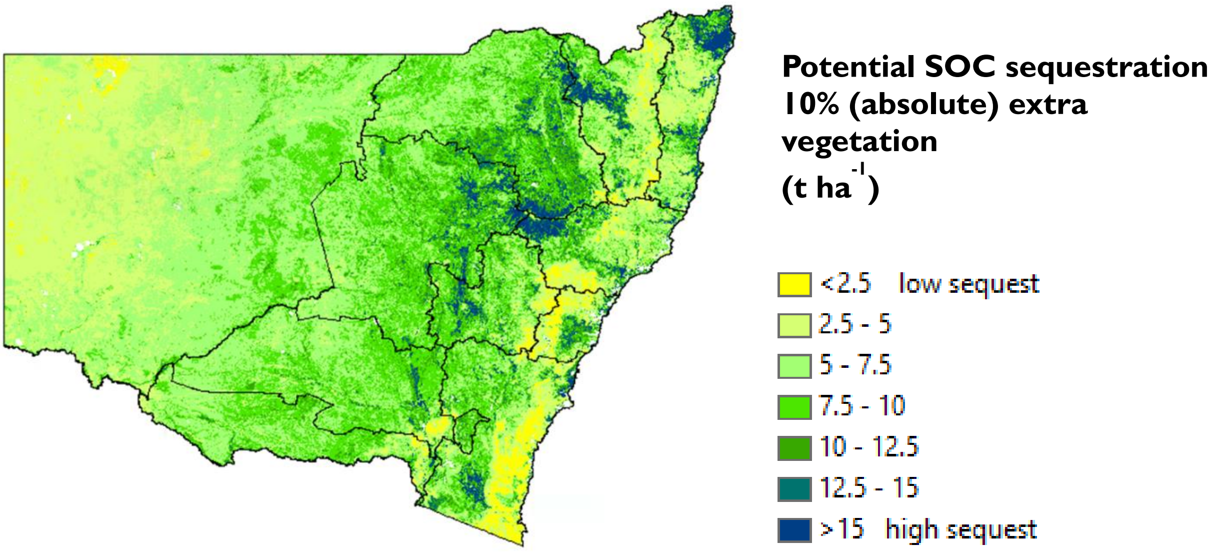


Figure 23. Potential SOC sequestration from a 10% absolute increase in vegetation cover

The extent of C sequestration with the 10% (absolute) increase in vegetation cover was shown to follow consistent broad trends over the State (**Figure 24**): sequestration levels increase with wetter climate, clay-rich fertile soils and higher vegetation cover. For example, under dry—sandy infertile soils—low vegetation cover conditions only approximately 3.2 t C ha^{-1} would be expected to be sequestered, compared with approximately 17.5 t C ha^{-1} under wet—clay rich, fertile soils—high vegetation cover conditions. These reflect similar trends revealed in Gray et al. (2015).

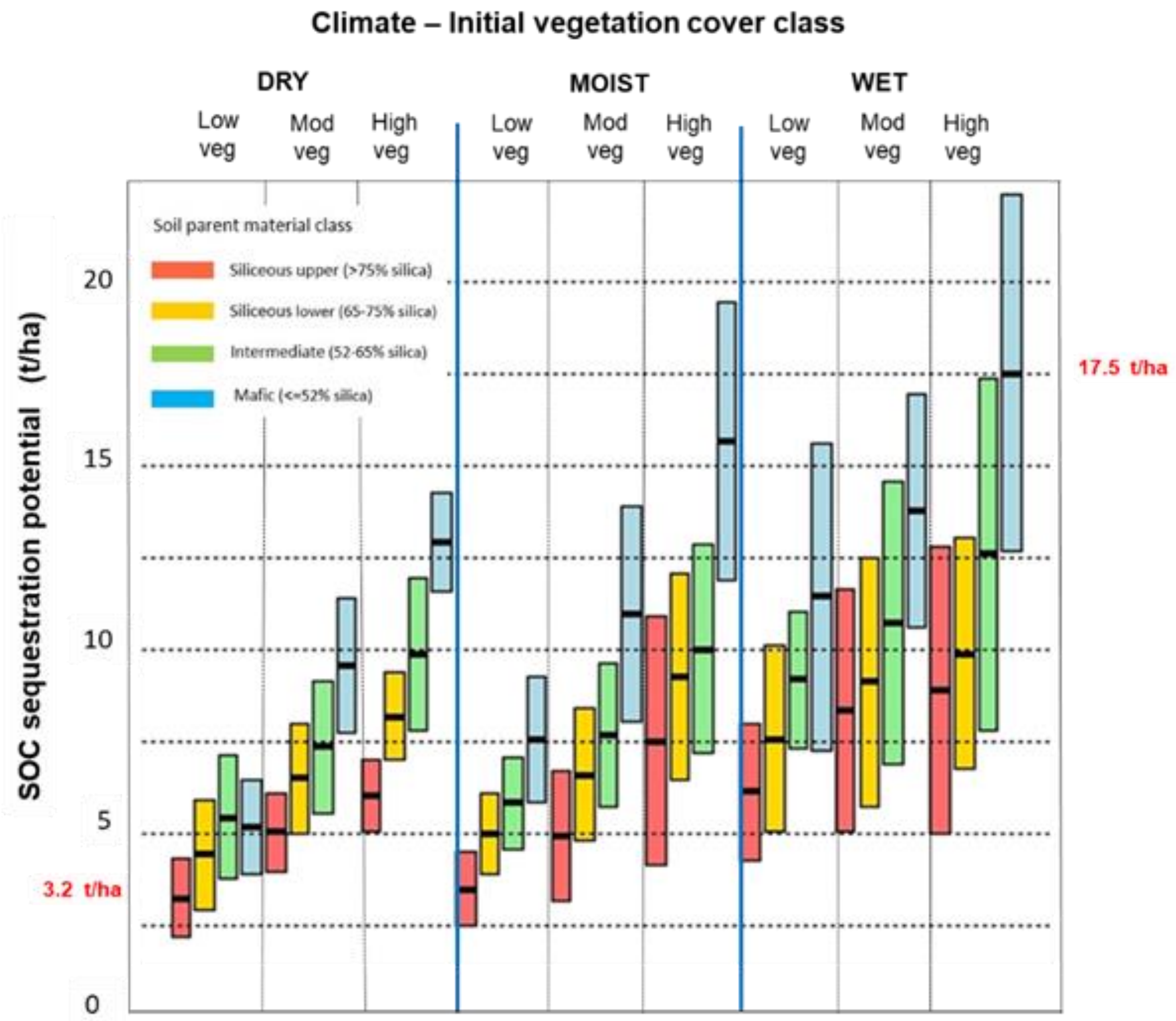
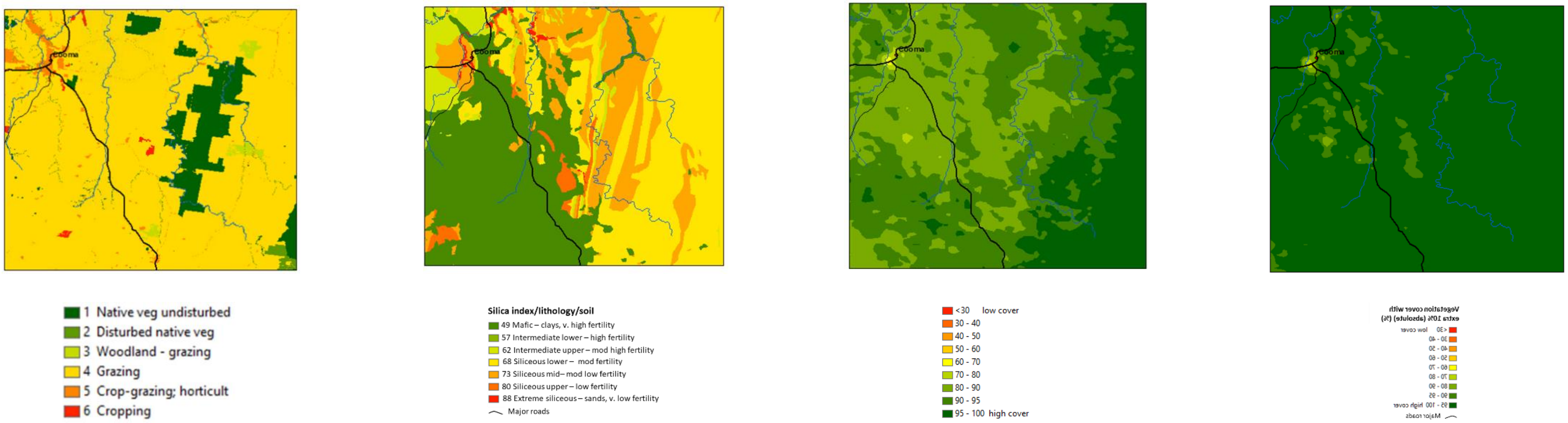


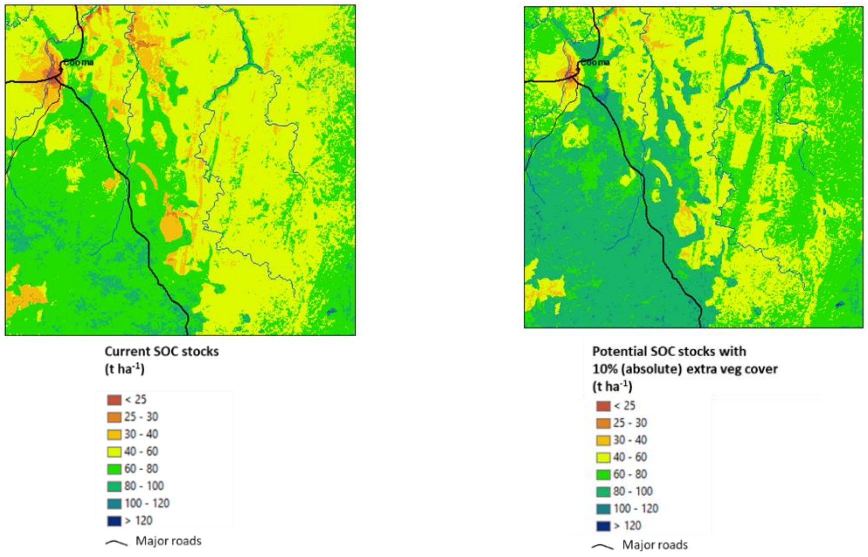
Figure 24: SOC sequestration potential (with 10% absolute vegetation cover increase) by climate-soil type-vegetation cover class over NSW (0-30 cm depth, t/ha)

The results of the MLR model outputs were examined using a number of 'case studies' which confirmed that regional scale increase related to soil type and vegetation. Two 'case studies' from contrasting environments (southern native grassland community dominated by grazing (Monaro district); A northern cropping system (Narrabri district)) illustrate these relationships **Figures 25-26,** respectively.

Current Land-use and LDI (2017) **Silica index (lithology/soil type)** **Current vegetation cover (%)** **Current vegetation cover + 10% (absolute)**



Current SOC stocks (t ha^{-1}) **Potential SOC stocks with + 10% absolute cover** **Potential sequestration with a + 10% absolute cover**



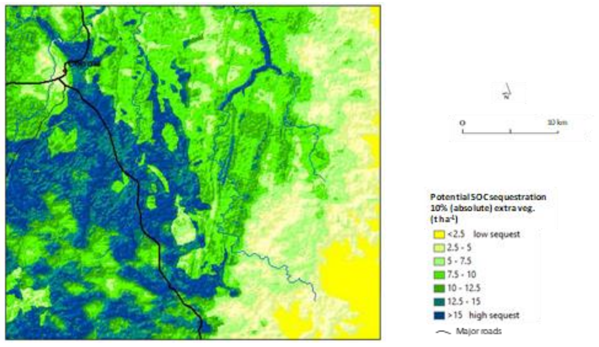
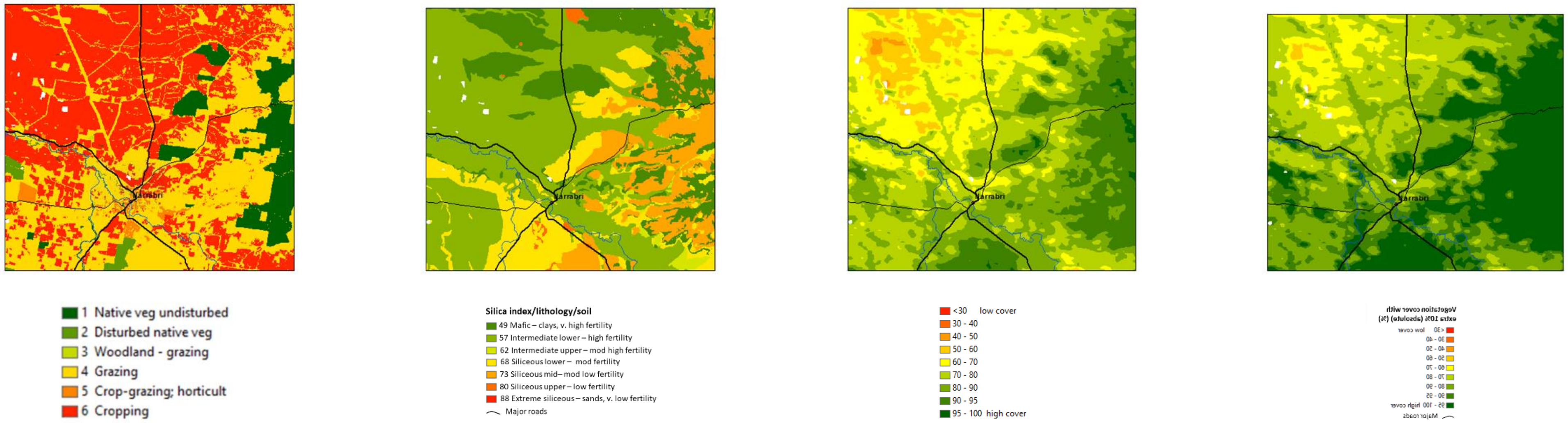


Figure 25. An example of native grasslands managed for grazing (Monaro grassland). Here, most of this grassland area has high vegetation cover (90 % +). A 10% increase in vegetation cover is predicted to result in potentially high levels of sequestration ranging from 2.5 to >15 Mg ha^{-1}.

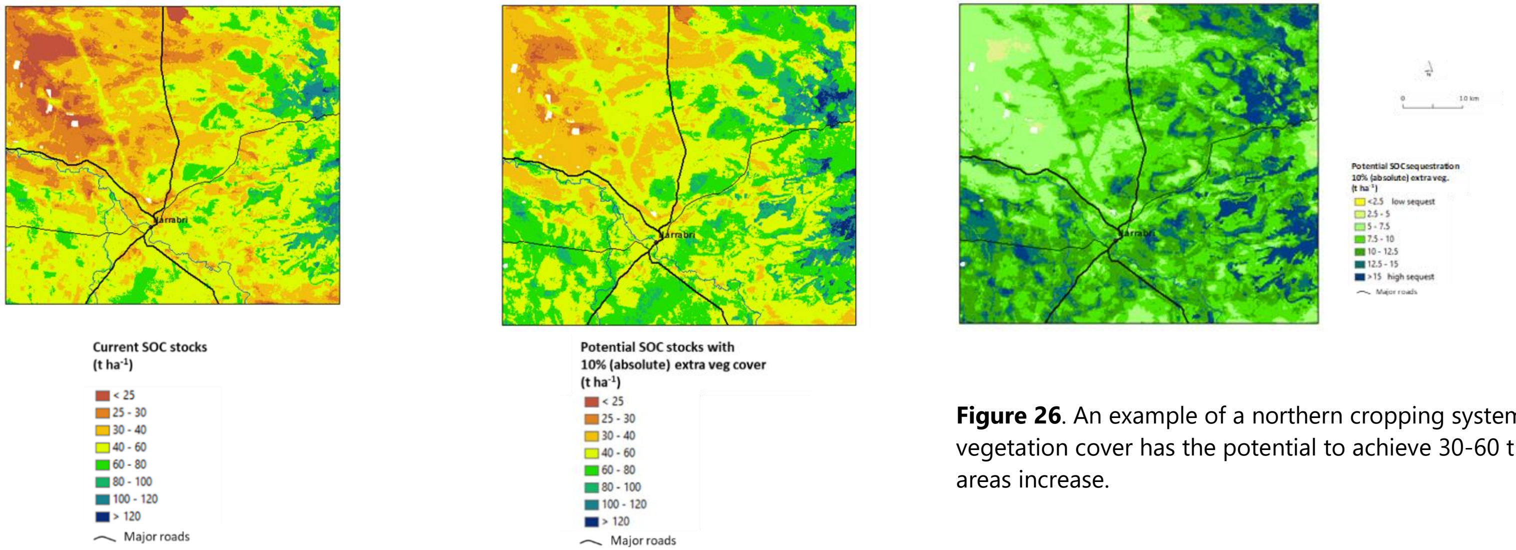


Current Land-use and LDI (2017)

Silica index (lithology/soil type)

Current vegetation cover (%)

Current vegetation cover + 10% (absolute)



Current SOC stocks (t ha^{-1})

Potential SOC stocks with + 10% absolute cover

Potential sequestration with a + 10% absolute cover

Figure 26. An example of a northern cropping system (near Narrabri) where a 10% increase in vegetation cover has the potential to achieve 30-60 t ha^{-1} soil sequestration within cropping areas increase.

6.5.3 Production trade-offs

- A shift in practice from crops to perennial pastures may offer substantial increases in soil carbon but the value of the carbon will depend on multiple factors and be site specific. For example, the historical land use, or the starting condition of soils will determine the amount of carbon that can be sequestered and the value of soil carbon. The greatest gains, both in terms of carbon accumulation and production will be from degraded soils.
- The overall long-term carbon benefits of conversion from cropping to pasture will need to be balanced against any increased emissions from livestock.
- Opportunities for abatement from the conversion of croplands to pasture occur over extensive areas of northern NSW. Here, the use of tropical perennial grasses and legumes represent an opportunity to increase levels of soil carbon and maintain productive pastures. The incorporation of legumes in pastures can increase soil fertility through increased nitrogen and may prove cost-effective compared to the costs of fertiliser inputs. With shifts southward of suitable areas for some tropical pasture species, there is opportunity to extend these practices into central NSW.

6.5.4 Adoption

The value of soil carbon and the desire to manage for increased soil carbon has long been recognised by farmers, forming the primary focus of organisations such as Farmers for Climate Action, Carbon Farmers of Australia as well are large farmer networks such as the Farming Together and Regenerative Farmers. These established networks will provide relatively high rates of adoption.

6.6 Summary of feasible sequestration from soil management

There is a concerted effort by DISER to modify soil carbon methods to overcome recognised barriers to adoption. DISER is working with the CER to improve the usability of the current measured soils method. Improvements will address concerns raised by industry and include revisions to sampling requirements and guidance and improvements to equations in the method. For example, the CER has recently provided forward payments of up to $5,000 to contribute to the costs of baseline measurement of soil carbon (CER, 2020c) which has led to increased interest in soil carbon projects (M. Warnken *pers. comm*).

We focused on conversion of cropping to pasture (permanent or as part of a rotation). There are also opportunities for land use intensification as well as stubble retention. While stubble retention is now considered best practice there are issues around chemical resistance (to glyphosate), and in high rainfall years large volumes of stubble may necessitate burning. As there may be limited opportunities for wide-scale adoption of stubble retention, there will be limited further uptake of abatement opportunities under this management practice.

There is significant potential in NSW to increase the current area of sown perennial pastures and achieve production and abatement outcomes (particularly where legumes and superphosphate are incorporated). Indicative benefit cost analysis suggests incorporation of legumes may increase pasture quality and quantity amounting to $287/ha benefit to livestock production (S Boschma *pers. comm*).

As a result of climate change, the suitable areas for tropical perennial pasture species may be expanding from northern NSW to include areas south of the current distribution (**Figure 27**). These changes in distribution patterns are the focus of ongoing DPI research but preliminary results suggest several traditional and new (*Megathyrsus* sp.; *Brachiaria*) perennial grasses and tropical legumes (*Desmanthus* sp) may expand opportunities for farmers across NSW (Boschma and Badgery 2018). Leucaena is woody legume, which is currently not recommended by NSW DPI due to its weed potential. However, sterile lines are being developed which could provide a species with a greater C storage potential compared to herbaceous legumes.

While recent drought conditions have led to difficulties in pasture establishment, based on seed sales, around 25,500 ha of tropical perennial pastures are being sown annually in northern NSW (S. Boschman *pers. comm*) suggesting an appetite to adopt perennial pastures and/or improve existing degraded pastures with newer varieties of persistent tropical perennial grasses. Further expansion may be limited by seed supply e.g in the recent drought, seed sources from Queensland were in limited supply.

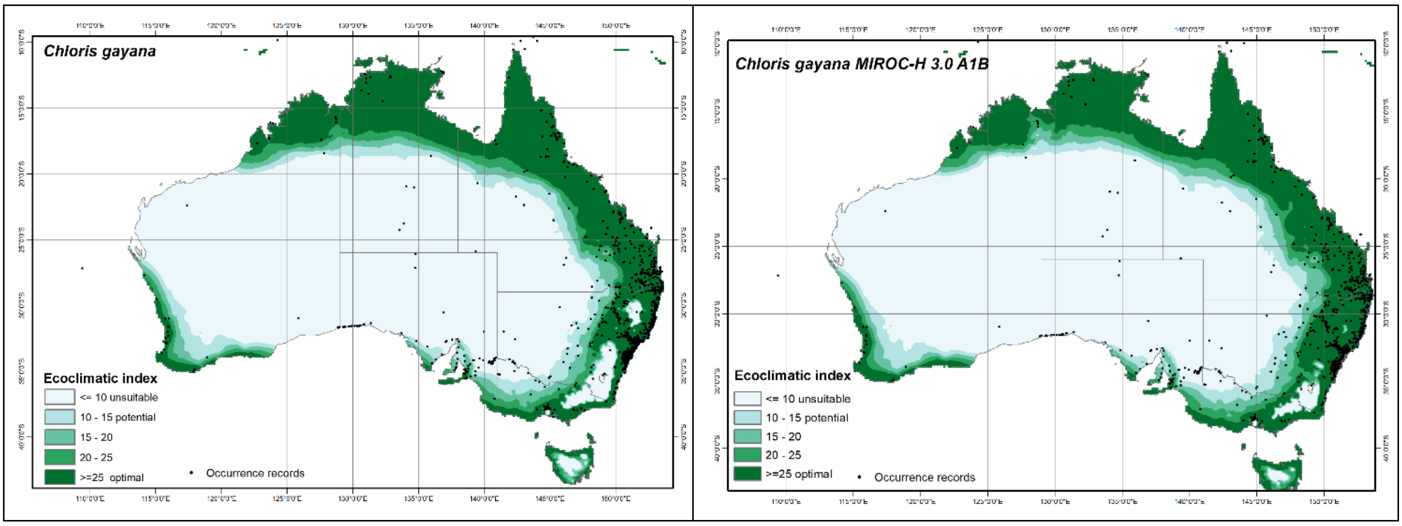


Figure 27. The current (left) and potential future distribution range (right) for tropical perennial pasture (Rhodes grass, *Chloris gayana*) under future climate. Dots represent occurrence records from the Atlas of Living Australia (*Source:* Simpson et al. 2019)

Table 32. Overview of feasible sequestration from soil in agricultural landscapes. Activities associated with Emissions Reduction Fund method- Estimating sequestration of carbon in soil using default values method (model-based soil carbon)

ERF method	Practice	Area (ha)	% Adoption rate	% of farm (ha)	Assumptions	Cumulative sequestration T C 2030
Soil carbon						
Default values	Conversion of cropland to pasture	1,373,406	10	-	Based on the current rates of conversion to pastures	904,056
	Stubble retention	1,294,358	10	-	Based on current potential for area for adoption of retention of stubble in croplands	505,678
	Sustainable intensification	10,740,034	10	-	Industry uptake across a broad range of activities including grazing management, pasture enhancement, nutrient management; soil acidity management; new irrigation; pasture renovation	4,049,458
					Total	**5,459,192**
					M t CO_2e	**20.0**

7. Integrated modelling assessment

Ongoing NSW DPI research as part of the NSW DPI Climate Change Research Strategy is examining the climate change impacts on sequestration rates across NSW as well as the land-use trade-offs between carbon sequestration and agricultural production.

Here we present a case study to illustrate an approach which identifies feasible abatement potential accounting for both future climate impacts and the cost of switching land use. This is illustrated for one ERF method – Human-induced regeneration. This study involved three steps:

- 3-PG model parameterisation and validation
- Output from 3-PG modelling used to estimate carbon sequestration (each year, for 100 years) accounting for climate change impacts
- LUTO (Land-use Trade-offs Model) modelling

7.1 3-PG model parameterisation and validation

The FullCAM model does not allow for changes in climate variables (or changes in atmospheric CO_2 level) and therefore cannot model the impacts of climate change. The 3-PG model is a physiological process-based model that predicts tree growth, developed by Landsberg and Waring (1997). This model is responsive to climate variables and therefore can be used to estimate changes in sequestration under future climates.

We first evaluated the performance of 3-PG model in predicting AGB for mixed-species environmental plantings against 362 observations provided by K Paul (CSIRO) (**Figure 28**) and found good agreement between 3-PG predicted and observed values (**Figure 29**).

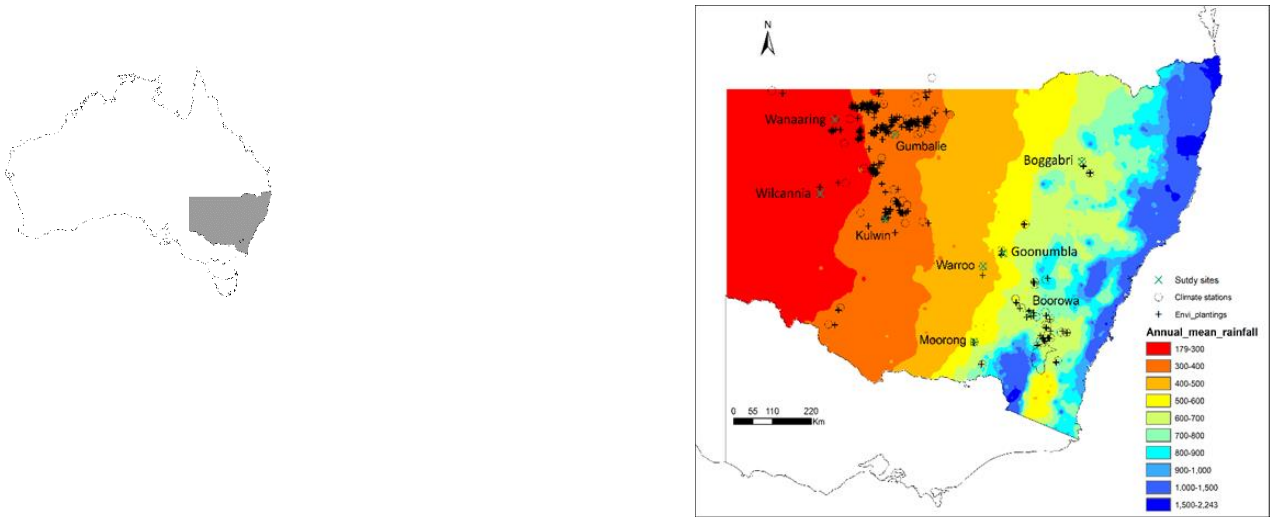


Figure 28. Location of 362 observation sites of Mixed-Species Environmental plantings (MEP, black cross), 59 climate stations (circles), and 9 sample study sites (green cross). The spatial distribution of the 9 test sites covers a range of rainfall regimes. After Wang et al *(in preparation)*

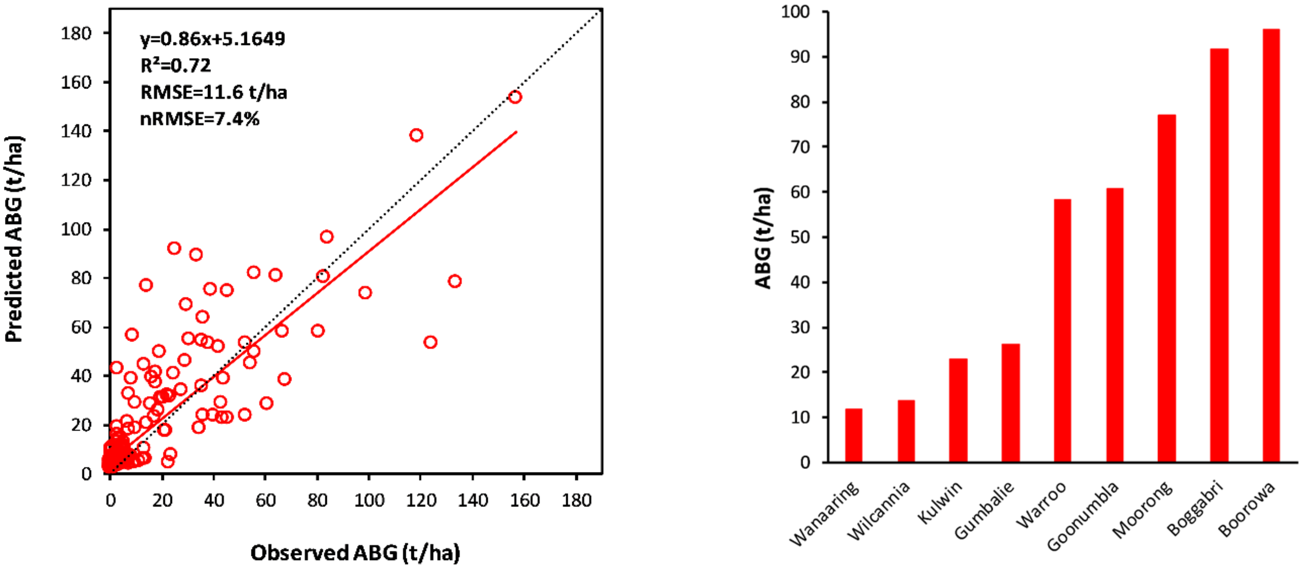


Figure 29 A strong relationship between observed and 3PG-predicted AGB was found ($R^2=0.72$, RMSE 11.6 t ha^{-1}) across the wide geographic range (left). The observed range of biomass estimates followed the rainfall gradient from <250 mm annual mean rainfall (Wanaaring) to >550 mm annual mean rainfall (Boorowa). After Wang et al. *(in preparation)*

We then assessed the impacts of climate change on AGB under different future emission scenarios based on the latest climate data from CMIP6 for nine representative 'test sites' which covered a range of rainfall (Annual average rainfall- 238 mm, (Wanaaring) to 578 mm (Boorowa)) **(Figure 28)**.

SSP2-4.5 & SSP5-8.5

*Shared socio-economic pathways (**SSPs**) link socioeconomic development, mitigation responses and land management to the amount of land used for crops, pastures, forest, bioenergy and conservation.*
***SSP2-4.5 (herein referred to as SSP245):** Shared socio-economic pathway 2 (**SSP2**) is considered the 'middle road' where societal as well as technological development follow historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre. **4.5** refers to the Representative Concentration Pathway RCP 4.5 GHG emissions trajectory.*
***SSP5-8.5 (herein referred to as SSP585):** Shared socio-economic pathway 5 (**SSP5**) is considered the resource intensive pathway with resource-intensive production and consumption patterns resulting in high emissions from ongoing fossil fuel use. Mitigation focuses on technological solutions including substantial bioenergy and BECCS. Intensification and competing land uses contribute to declines in agricultural land. **8.5** refers to the Representative Concentration Pathway RCP 8.5 GHG emissions trajectory.*

Spatial downscaling was undertaken for monthly gridded climate projections from 19 GCMs (to capture the variation of future climate projections), spatially interpolated for each of the 9 test sites, using an inverse distance-weighted (IDW) interpolation method. This was followed by a bias correction procedure to correct site-based monthly GCM simulations. Temporal downscaling was then undertaken, where daily climatic variables (e.g. radiation, maximum and minimum temperatures and rainfall) were then generated for each of the 9 test sites from the spatially downscaled projections by using a modified version of the WGEN stochastic weather generator (Richardson and Wright, 1984) with parameters derived from the bias-corrected monthly data.

Monthly future projections of solar radiation, maximum temperature, minimum temperature and rainfall generated by 19 GCMs were downloaded from CMIP6 (https://pcmdi.llnl.gov/CMIP6/). These monthly gridded future climate data were then statistically downscaled to each test site at a daily resolution using the method developed by Liu and Zuo (2012). There were 19 GCMs (https://esgf-node.llnl.gov/search/cmip6/) available for our statistical downscaling under SSP245 and SSP585 **(Table 35)**. Two future climate scenarios were used, that is, a low scenario **(SSP245)** and high scenario **(SSP585)** for two future time periods of 2021-2060 (**2040**s) and 2061-2100 (**2080**s). The CO_2 concentration applied in 3-PG for each scenario was set as SSP245_2040s: 463 ppm; SSP245_2080s: 543 ppm; SSP585_2040s: 512 ppm; SSP585_2080s: 849 ppm.

Table 33. The 19 global climate models (GCMs) under SSP245 and SSP585 climate scenarios used to assess climate impacts at 9 test sites.

Model ID	Name of GCM	Institute ID	Country
01	ACCESS-CM2	BoM	Australia
02	ACCESS-ESM1-5	BoM	Australia
03	BCC-CSM2-MR	BCC	China
04	CanESM5	CCCMA	Canada
05	CanESM5-CanOE	CCCMA	Canada
06	CNRM-CM	CNRM	France
07	CNRM-ESM	CNRM	France
08	EC-Earth3	EC-EARTH	Europe
09	EC-Earth3-Veg	EC-EARTH	Europe
10	FGOALS-g3	FGOALS	China
11	GFDL-ESM4	NOAA GFDL	USA
12	GISS-E2-1-G	NASA GISS	USA
13	INM-CM4-8	INM	Russia
14	INM-CM5-0	INM	Russia
15	IPSL-CM	IPSL	France
16	MIROC6	MIROC	Japan
17	MIROC-ES2L	MIROC	Japan
18	MPI-ESM1-2-HR	MPI-M	Germany

Where a CO_2 fertilisation effect was included in the modelling, a large positive change in predicted AGB under future climates for dry sites (Wanaaring, Wilcannia and Kulwin) was evident (**Figure 30).** Where the CO_2 fertilisation effect was omitted from the modelling, this resulted in a large negative impact on AGB which was most pronounced for low rainfall areas. These inconsistencies are not surprising.

There is a large body of literature that supports the notion of increased woody growth associated with increased photosynthesis from elevated CO_2 concentrations, the ''CO_2 fertilization effect", and which has been widely reported for boreal, temperate forests (e.g. Norby and Zak 2011). A review of results from four **F**ree-**A**ir **C**O_2 **E**nrichment (FACE) experiments in USA and Europe showed a consistent growth stimulation of 23 +/- 2% at elevated CO_2 (~550ppm) (Norby et al. 2005). However, in the Australian environment, where water and nutrients are limiting, these fertilisation effects may not be realised. A recent FACE study on mature Eucalyptus forest ecosystem (EucFACE) showed that where P was limiting, AGB was constrained under elevated CO_2 and moderated by available water (Ellsworth et al. 2017). It would therefore appear that any CO_2 fertilisation may not be manifest in most Australian climates. The effects of CO_2 fertilisation on young growing trees in Australian environments is also uncertain. There is evidence that a positive impact on growth of immature trees (~30% increase over a 10-year period) will occur under elevated CO_2 in temperate environments (Walker at al 2019).

Increasing concentrations of atmospheric CO_2 will modify rainfall and temperature patterns which are also likely to have a direct effect on tree growth. Across all our test sites, there was an increase in temperature under each future climate scenario (~ +1 to 4°C) (**Figure 31**). There were less consistent changes for rainfall and radiation. A relatively small increase in rainfall for the Boggabri location in northern NSW was apparent but elsewhere there was a general trend of increased rainfall variability which was particularly evident for low rainfall sites. Radiation tended to increase at higher rainfall sites (>450 mm, MAR).

While these results are preliminary, the 'winners' and 'losers' in terms of climate change impacts on sequestration appear to be regionally specific. For locations <350 mm MAR, the risks to sequestration are likely to be greatest, and it is these locations that are currently accommodates most of the ERF activity in NSW.

7.2 Carbon accumulation (adjusted for climate)

Across the areas mapped as suitable for HIR (3,338,500 ha) we report changes in annual biomass accumulation for future periods (2030, 2050 and 2100) using the 3-PG modelling described above.

We firstly used an inverse distance weighted (IDW) interpolation method (as above) to interpolate future climate data from 2096 SILO sites across NSW at a 1km resolution. This provided a spatial map of each monthly climate variable (rainfall, temperature and radiation). Then we ran 3-PG for 33385 grid cells (1km^2) to determine the area suitable for HIR. This meant that 3-PG predicted a value for carbon for each independent grid cell.

Changes in 3-PG results for AGB and BGB for one GCM model (ACCESS-CM2, AC2, see **Table 35**) for the 100 years (2001-2100) for a low emissions scenario, SSP245 (CO_2=480ppm) and a high emissions scenario, SSP585 (CO_2=621 ppm) were determined (**Figure 32**). Changes in AGB over 30 years show ~ 30-40 t ha^{-1} increase in central NSW compared with 40-80 t ha^{-1} predicted with FullCAM modelling. This suggest that future climate impacts will result in some increases and some decreases in sequestration in different locations. However, the role of the CO_2 fertilisation effect requires further examination, and forms part of ongoing NSW DPI research.

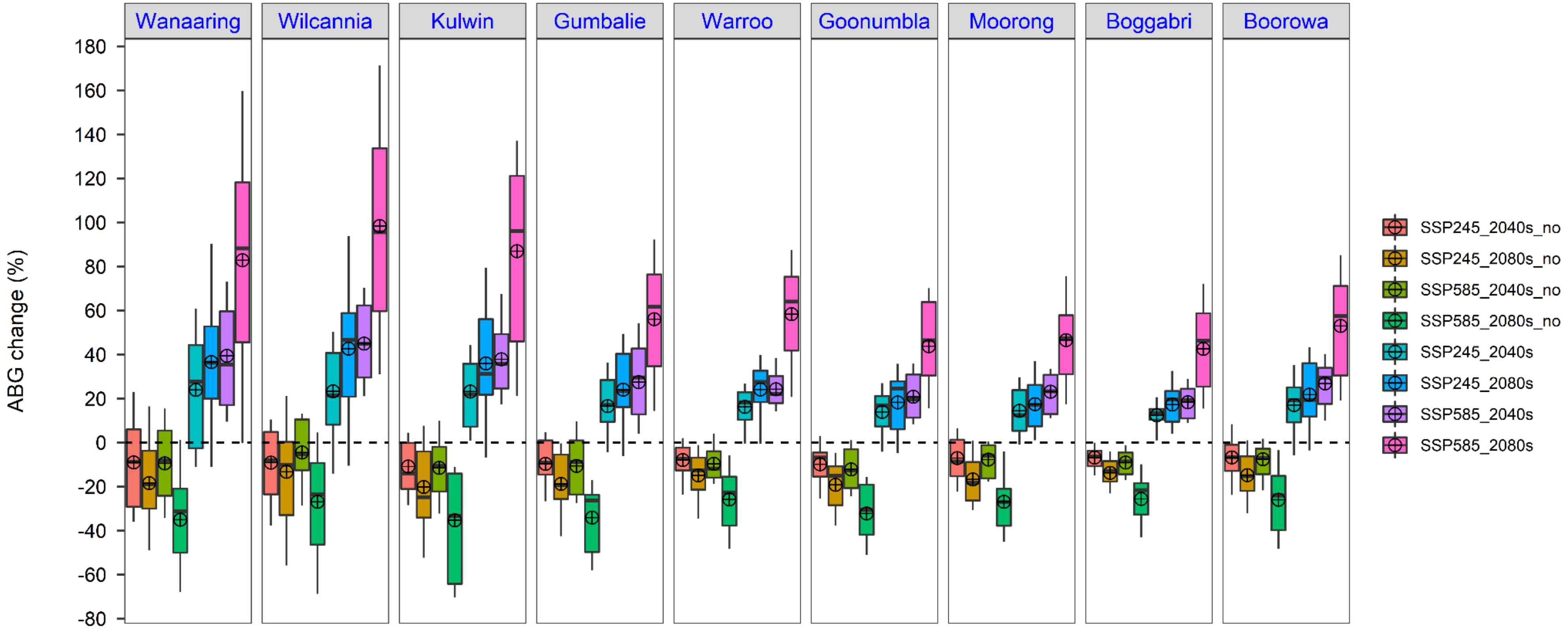


Figure 30. Projected changes in 3PG-simulated AGB from 19 CMIP6 GCMs at 9 test sites. Data presented are changes in 40 yr accumulated AGB under SSP245 and SSP585 for 2040s (2021-2060) and 2080s (2061-2100) compared to 1979-2018. For each scenario, we also included non-CO_2 fertilization effects (SSP245_2040s_no, SSP245_2080s_no, SSP585_2040s_no and SSP585_2080s_no). Box boundaries indicate the 25th and 75th percentiles across GCMs, whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the multi-model median and mean, respectively. After Wang et al *(in preparation)*

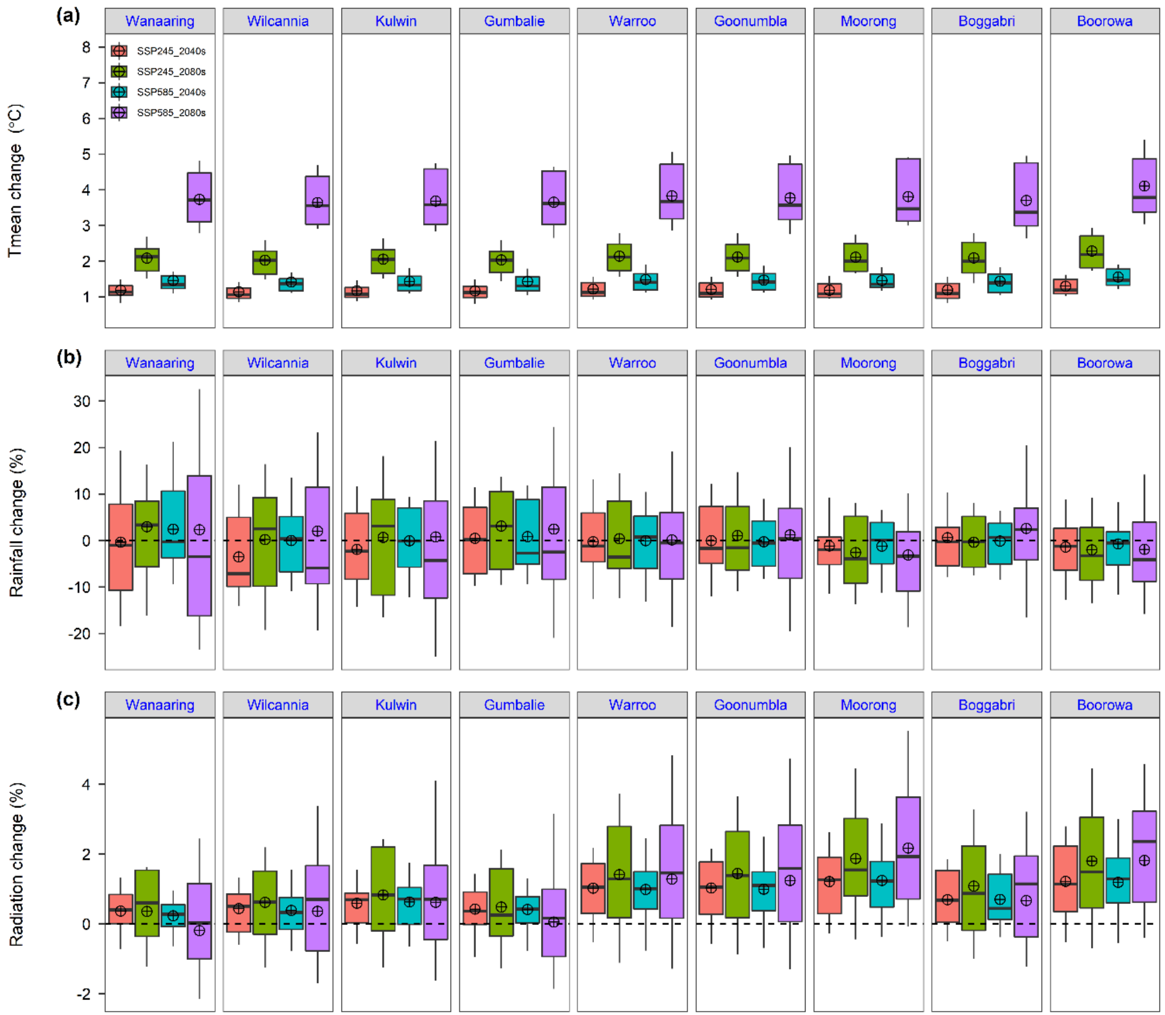


Figure 31. Projected changes in annual mean temperature (Tmean, a), rainfall (b) and radiation (c) from 19 CMIP6 GCMs at 9 test sites across NSW for SSP245 and SSP585 by 2040s (2021-2060) and 2080s (2061-2100) compared to 1979-2018. Box boundaries indicate the 25th and 75th percentiles across GCMs, whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the multi-model median and mean, respectively. After Wang et al. *(in preparation)*

7.3 Land-use Trade-off modelling

The Land-use Trade-offs Model (LUTO) is a high resolution, integrated environmental-economic model used to examine future spatiotemporal dynamics of land-use change. It has been used in Australia to examine the implications of policy changes (Bryan et al. (2016), the settings for economic trade-offs (Connor et al. 2015) and prioritisation of land-use (Crossman and Bryan, 2009). The model has spatial layers for Australia; however we have developed a finer-scale resolution of economic and land-use spatial layers for NSW.

Livestock carrying capacity (DSE, dry sheep equivalent) derived from LLS was used to create a spatial map of DSE which was validated using technical expert review. This allowed us to more realistically quantify the potential economic returns in changing land-use from a livestock enterprise to vegetation regrowth for carbon sequestration (***Human-induced Regeneration***). We then used 'climate adjusted' 3-PG derived carbon sequestration layers (described above, including CO_2 fertilisation effect) to feed into the LUTO model and assess the economic trade-offs over time, accounting for the impacts of climate change. Cost scenarios included:

- The costs of lost pasture production with increasing woody cover (limiting livestock carrying capacity)
- The cost of total grazing pressure fencing, that allows the management of all grazing animals (domestic, native and feral herbivores)

Under current climate carbon offset supply would be exhausted for a carbon price of \$30 to \$40 tCO_2-e. That is, at this price range all areas suitable for HIR will be utilised (**Figure 34**). Under future climate SSP245, 'middle of the road' carbon supply would be exhausted for a carbon price of around \$25 tCO_2-e under all scenarios (**Figure 35**). Under future climate SSP585, 'fossil fuel, high emissions' carbon supply would be exhausted for a carbon price of around \$20 tCO_2-e under all scenarios (**Figure 36**).

An overview of these interim results is provided in **Table 34.** These are interim results, and our current carbon offset supply estimates are based on a single mean value for carbon fertilisation over the entire 100 years 3-PG modelling period. The influence of the CO_2 fertilisation effect on 3-PG model output is described above and we intend to examine the incremental increase the CO2 (annually) which will likely decrease carbon sequestration estimates and therefore decrease levels of supply.

Table 34. Summary of the price of carbon (t CO_2-e) ERF method, Human induced regeneration which would provide economic justification to switch landuse from current agricultural production to carbon farming

	Low cost scenario	**Medium cost scenario**
Current climate	low impact of trees on pasture and no fencing costs **77%** of the carbon is available at **$12** (current price of carbon) **100%** of carbon available at **$40**	medium impact of trees and $24 ha fencing cos, **38%** of carbon is available at **$12** (current price of carbon) **99%** of carbon available at **$40**
Future climate (SSP245)	low impact of trees on pasture and no fencing costs **94%** of the carbon is available at **$12** (current price of carbon) **100%** of carbon available at **$40**	medium impact of trees and $24 fencing costs, **75%** of carbon is available at **$12** (current price of carbon) **100%** of carbon available at **$40**
Future climate (SSP585)	low impact of trees on pasture and no fencing costs **99%** of the carbon is available at $12 (current price of carbon) **100%** of carbon available at **$40**	medium impact of trees and $24 fencing costs **90%** of carbon is available at **$12** (current price of carbon) **100%** of carbon available at **$40**

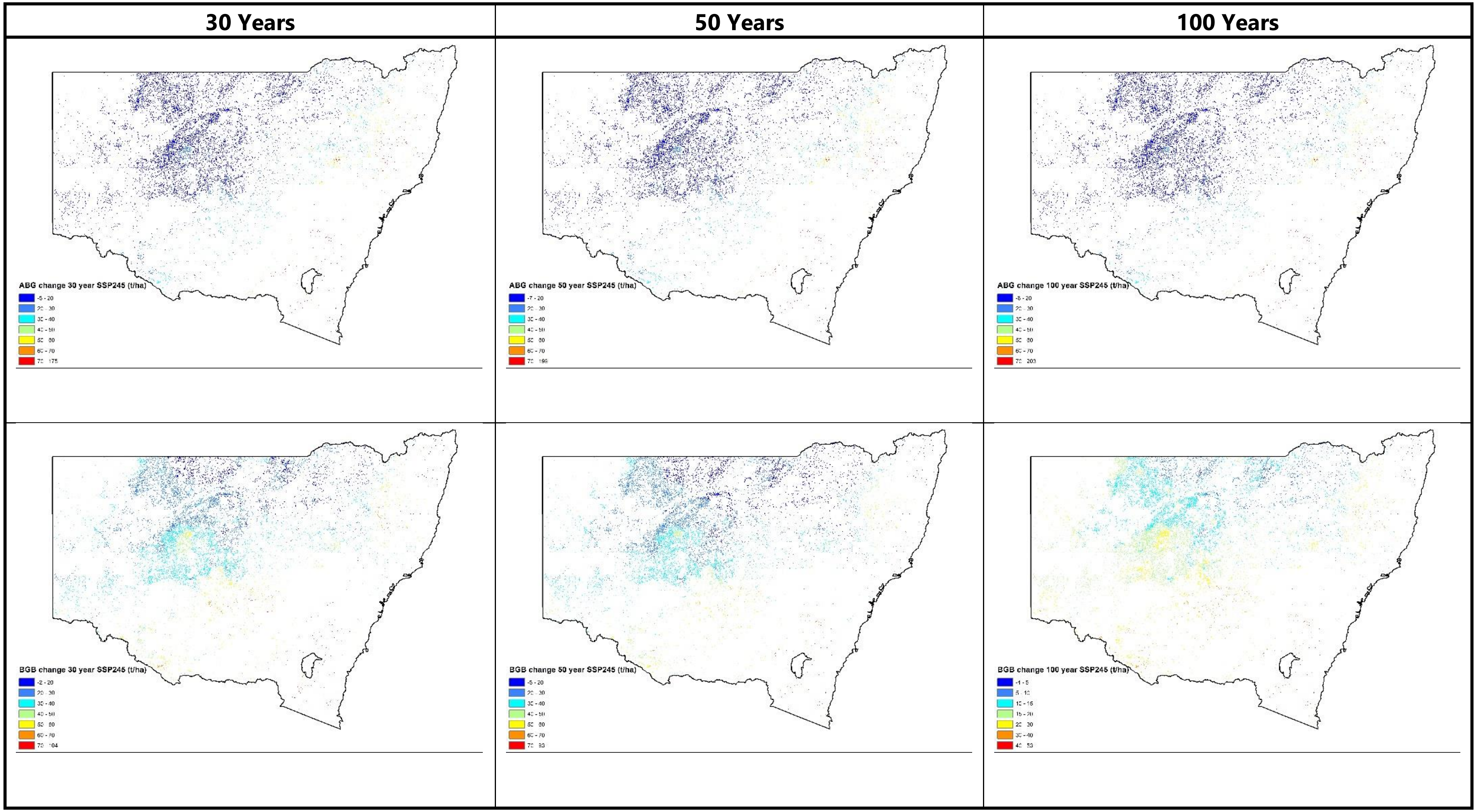


Figure 32. Predicted changes in above ground (AGB, t ha^{-1}) and below ground (BGB, t ha^{-1}) biomass at 2030, 2050 and 2100 under ERF method – Human-induced revegetation for a low emissions scenario (SSP245) based on the 3-PG model.

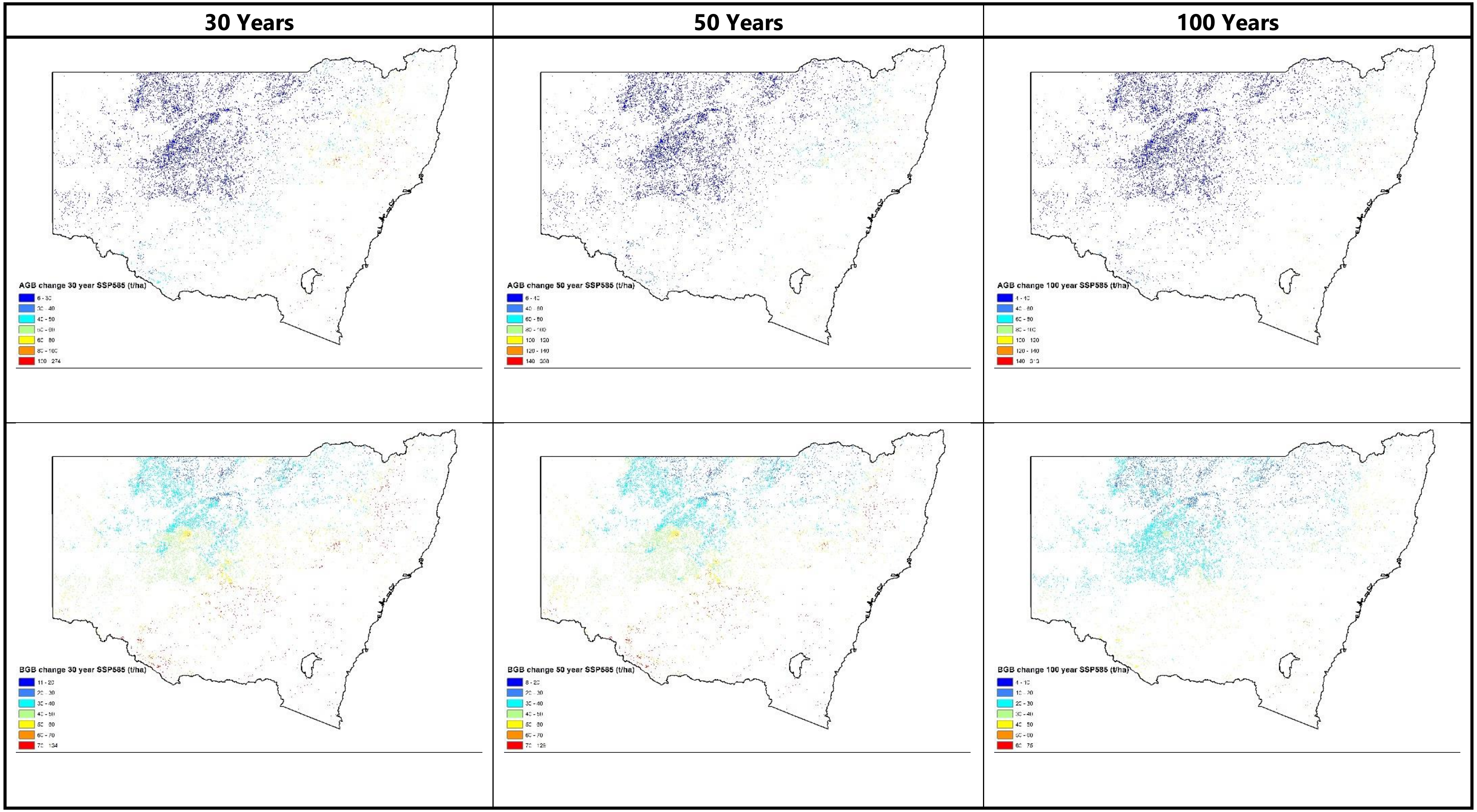


Figure 33. Predicted changes in above ground (AGB, t ha^{-1}) and below ground (BGB, t ha^{-1}) biomass at 2030, 2050 and 200 under ERF method – Human-induced revegetation for a high emissions scenario (SSP585) based on the 3-PG model.

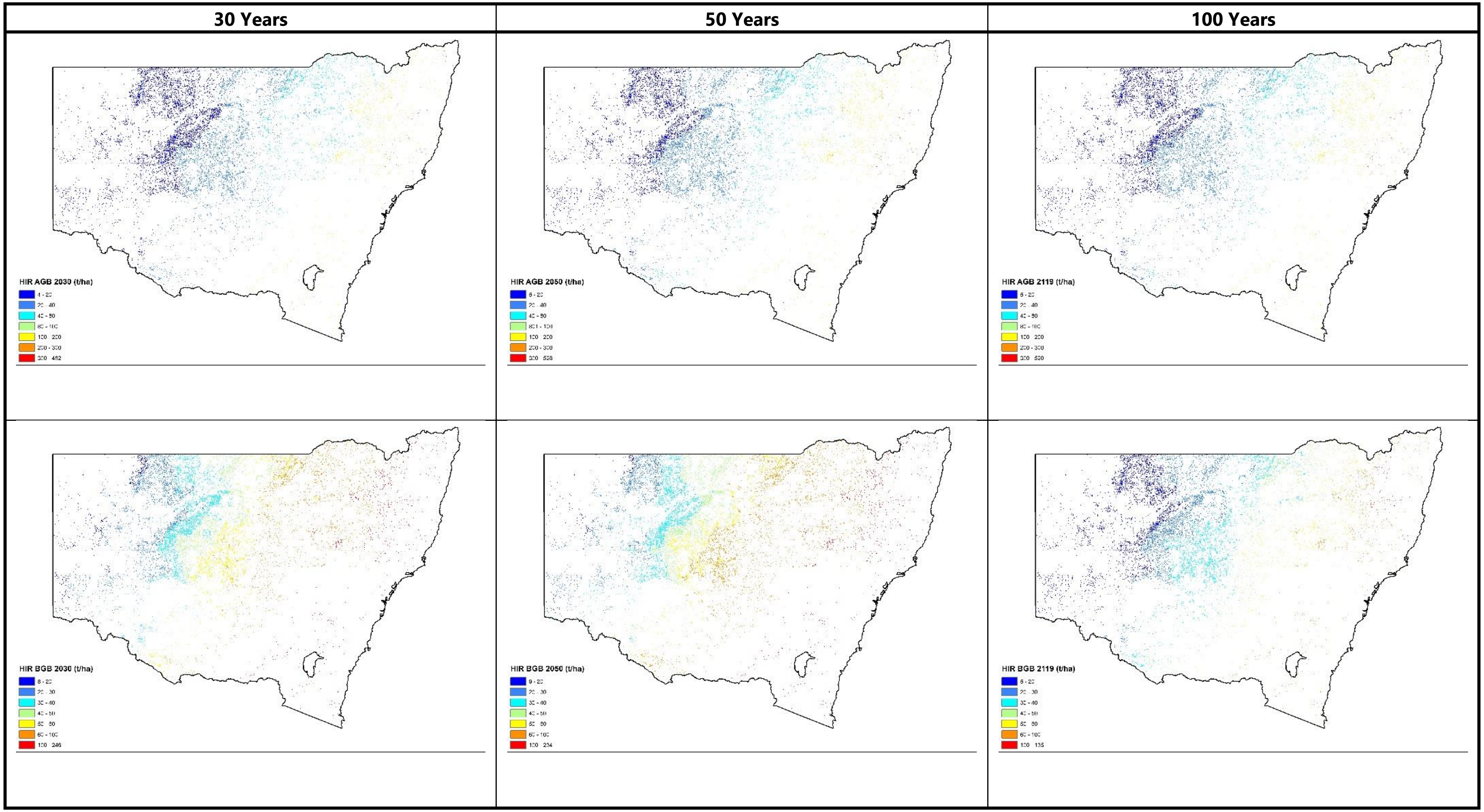


Figure 34. Predicted above ground (AGB, t ha^{-1}) and below ground (BGB, t ha^{-1}) biomass at 2030, 2050 and 2119 under ERF method – Human-induced revegetation based on FullCAM model

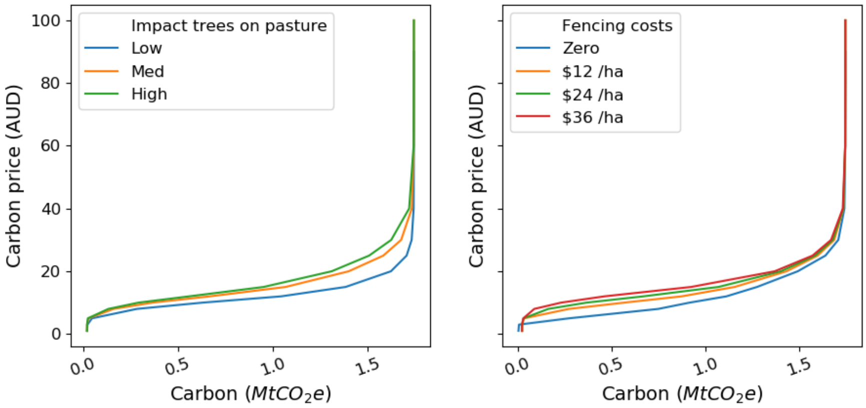


Figure 34. Carbon supply against alternative carbon prices (3-PG modelled) for current climate

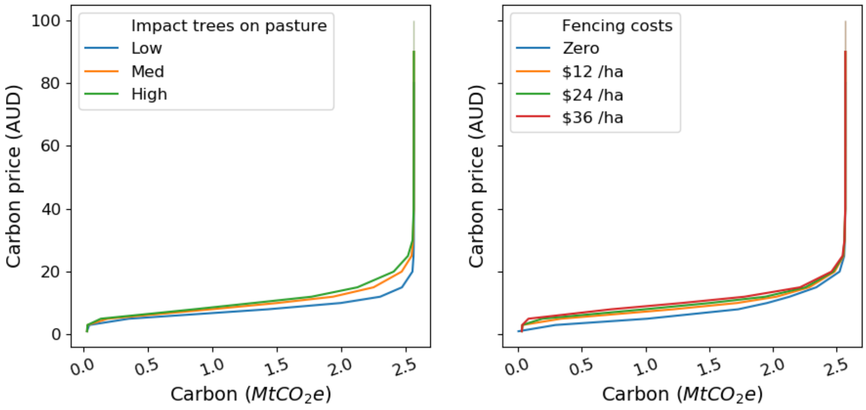


Figure 35. Carbon supply against alternative carbon prices (3-PG modelled) for SSP245

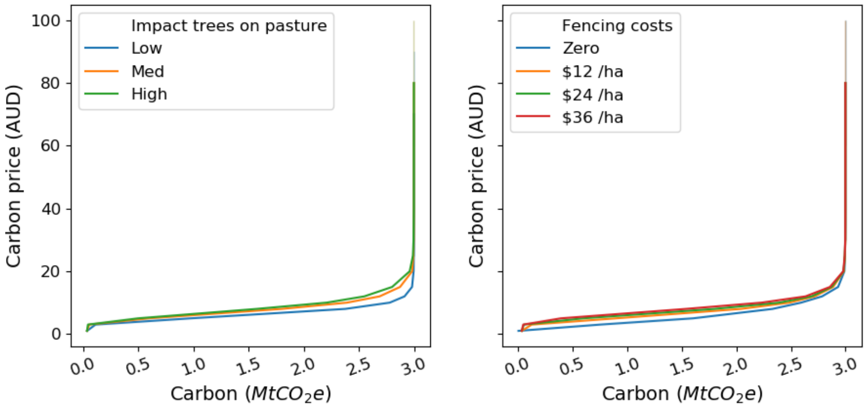


Figure 36. Carbon supply against alternative carbon prices (3-PG modelled) for SSP585

PART B: Emissions Reduction

8. Emissions reduction potential

8.1 Enteric methane

Enteric methane, released through the digestion processes of ruminant livestock, is the major source of GHG emissions from agriculture in NSW, contributing around 75% of agriculture sector emissions. While methane is a natural product of rumen fermentation, it represents a waste of energy from the food consumed. Thus, some strategies to reduce enteric methane emissions can simultaneously improve productivity as well provide climate change mitigation.

Efforts to mitigate enteric methane have been under research for decades. Strategies fall into two broad categories:

- dietary manipulation; and
- system-level approaches including herd management, breeding and vaccines.

8.1.1 Analysis

The effectiveness of each of these strategies is considered below, with respect to theoretical (technical) potential, technology readiness, barriers to adoption, trade-offs and co-benefits. Finally, an estimate of feasible potential abatement in 2030 is provided.

Estimated abatement is quantified with respect to a baseline representing the projected emissions in 2030 without intervention. The major drivers of enteric methane emissions are livestock numbers followed by the methane yield (methane emissions per unit feed intake) and the productivity of livestock systems (meat and milk produced per animal unit).

8.1.2 Projected livestock numbers

Livestock numbers are influenced by commodity prices and seasonal conditions but fluctuate further due to stock movements between states. Numbers of stock declined substantially during the drought and are expected to recover as drought conditions ease.

Projections are based on livestock numbers provided in the national greenhouse gas inventory (AEGIS, 2018 inventory https://ageis.climatechange.gov.au/QueryAppendixTable.aspx), the MLA Market Information statistics database http://statistics.mla.com.au/Report/List, information provided by NSW DPI Data Analytics group and personal communication with Hutton Oddy, NSW DPI.

Cattle

Historically, cattle numbers were highest in the mid-1970’s, exceeding 9 million (including dairy cattle). In the period 1990-2012 total cattle numbers were stable but recently have declined due to drought (**Figure 37**). However, the total beef herd has been roughly stable since 1990, apart from the recent decline, and it is projected that the NSW cattle herd will be at 5.0-6.5 million head in 2030.

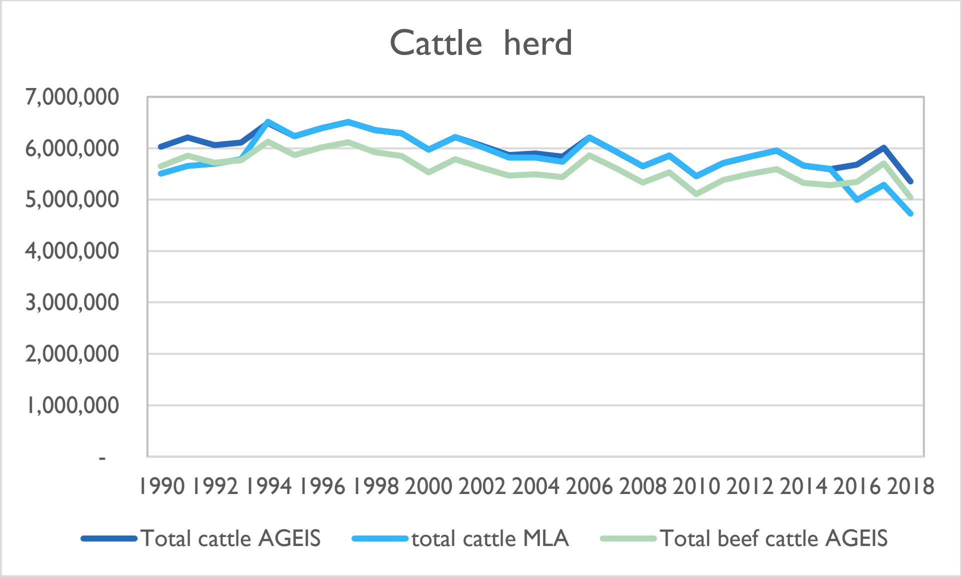


Figure 37. Total cattle herd and total beef cattle, NSW [Sources AGEIS, DISER 2020e; ABS, from MLA 2020]

The number of beef cattle finished in feedlots has increased dramatically, tripling over the last three decades (**Figure 38**). Based on the increasing trend, the projected number of cattle in feedlots in 2030 is 7-10% of the beef herd, assumed to comprise steers >1 year old. Therefore, the number in feedlots is estimated at 350-650 thousand head in 2030.

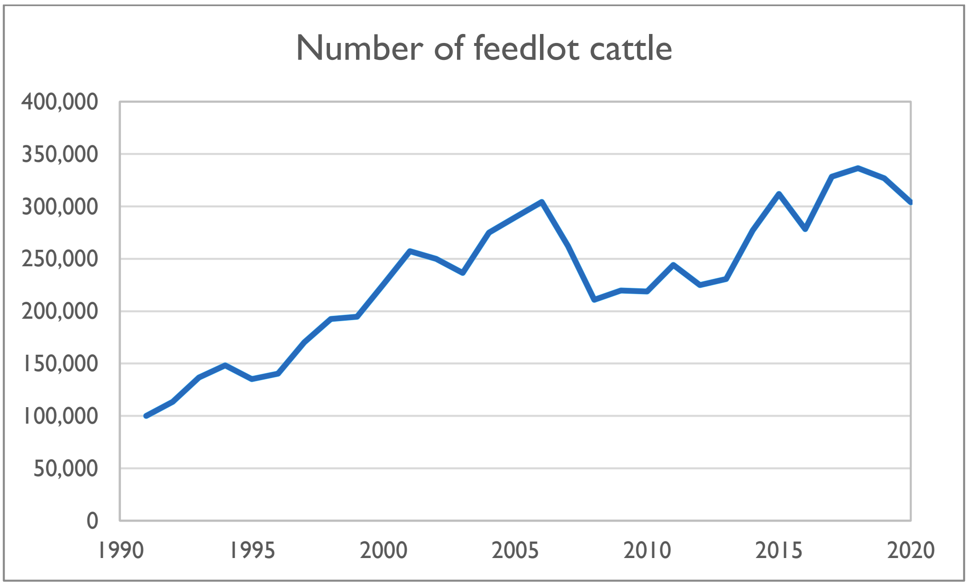


Figure 38. Number of cattle in feedlots (annual equivalent) [Source: ALFA, MLA feedlot survey]

The number of dairy cattle has decreased steadily since 2000 (**Figure 39**). Based on this downward trend, the size of the dairy herd in 2030 is estimated at 250-350 thousand head.

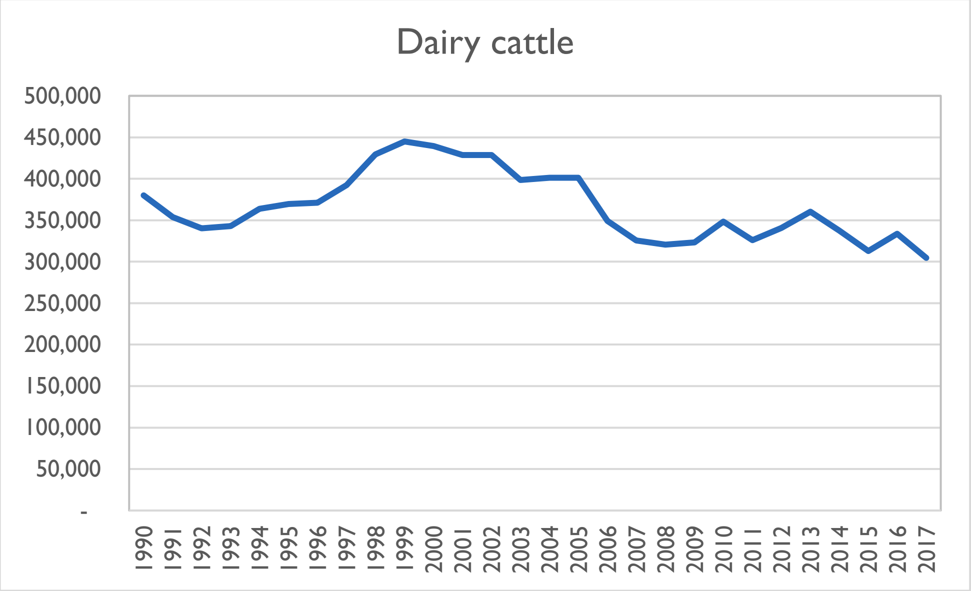


Figure 39. Dairy herd, NSW, number of head. [Source: AGEIS, DISER 2020e]

Sheep

Historical sheep numbers vary widely, ranging from 25 to 70 million, influenced by the relative prices for wool and cereals. Numbers fell steadily from 1990 to 2010, then stabilised around 27 million (**Figure 40**). The sharp drop from 1991-1996 was associated with the discontinuation of the Minimum Reserve Price Scheme that had supported wool prices (Pattinson et al. 2015). The breed composition of the NSW flock has shifted from a dominance of Merinos towards dual-purpose (wool and meat) breeds, and meat breeds such as the fleece-shedding Dorper. Reflecting this trend, the demographics of the flock have shifted over time, with increased proportion of breeding ewes and lambs, and fewer wethers, a trend further exacerbated during drought (Pattinson et al., 2015). Numbers are expected to recover after the current drought and estimated at 25-35 million in 2030. Sheep feedlotting has historically been a relatively minor activity but anecdotal evidence suggests some recent expansion of on-farm dedicated feedlot enterprises during the drought. Supplementary feeding on-farm has increased during the current drought, to maintain a breeding flock to enable recovery after drought, and lambs have been finished on total rations. Supplementary feeding and feedlotting offers potential to mitigate emissions through enhanced productivity and the application of dietary manipulation strategies. Expansion of mixed farming, through re-introduction of wool sheep into cropping properties, is anticipated on the slopes and plains, as a response to increasing incidence of herbicide resistant weeds, and to build economic resilience to increasing climate variability (Pattinson et al. 2015).

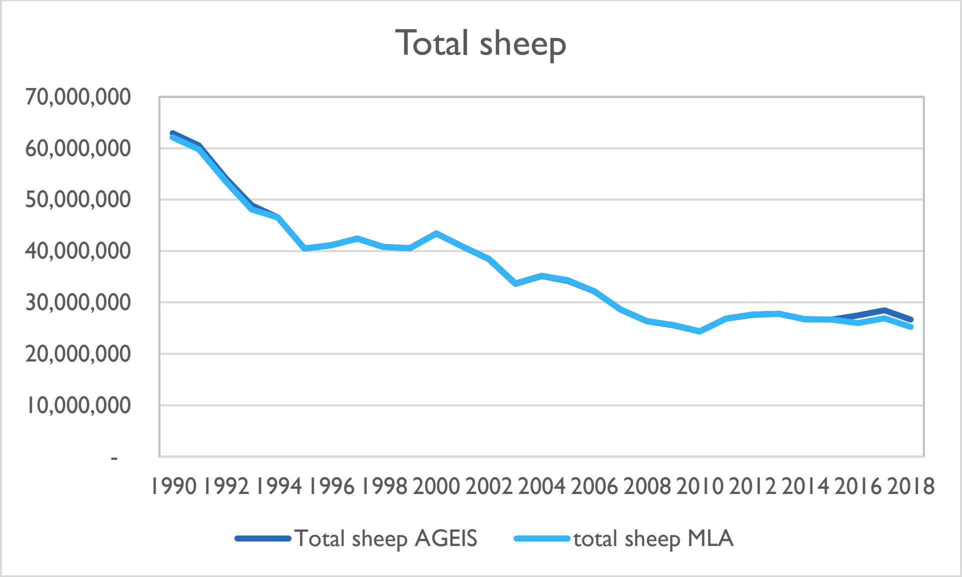


Figure 40. Number of head of sheep [Sources: AGEIS (DISER); ABS, from MLA Market Information]

Uncertainties and limitations in the data and methods: Particularly in recent years, there are some discrepancies in the numbers of livestock between AGEIS (DISER, 2020) and ABS data (from MLA, 2020) due to changes to the ABS reporting. The MLA database does not disaggregate beef and dairy cattle, which makes it difficult to use these figures for emissions calculations, thus there has been strong reliance on the AGEIS database and its disaggregation to livestock classes that align with the quantification algorithms.

ABS data also have other limitations; in particular, the data do not capture livestock agistment. As the widespread nature of the drought has resulted in large numbers of livestock moving between states the number of livestock in NSW may be inaccurate. In addition, the livestock industry is tending towards trading livestock compared to the more traditional practice of retaining breeding flocks and herds, which will further compound issues around livestock movement and gaining an accurate estimate of livestock numbers. There is potential for DPI Data Analytics to provide more accurate estimates of current and future livestock numbers.

This analysis has considered only beef and dairy cattle and sheep. While it is recognised that other livestock including goats, pigs and horses also contribute to enteric methane, their combined contribution is less than 1% of NSW enteric methane, and opportunities to manage this source are limited.

8.1.3 Quantification of technical and feasible potential abatement

Baseline estimates of enteric methane emissions for 2030, with no abatement measures, were derived using the algorithms applied in Australia's national greenhouse gas inventory, as described in the National Inventory report (DISER, 2020c), and the livestock numbers obtained as described in section **8.1.2**.

The effectiveness of dietary strategies to reduce enteric methane was derived from a meta-analysis of in vivo studies published between 2000 and 2020 (Almeida et al., 2020). A total of 108 papers were included in the analysis. These results provided the estimate of technical (theoretical) potential reduction in enteric methane emissions, per unit dry matter intake.

Feasible potential was defined as the abatement likely to be delivered in 2030 assuming regulatory and cost barriers are overcome. Feasible potential was quantified as the product of technical potential and adoption rate. Estimates of adoption rate in 2030 were based on expert judgement (personal communication with Roger Hegarty UNE, Hutton Oddy DPI and Paul Greenwood DPI/CSIRO) taking into consideration risks, trade-offs and co-benefits especially for production, practicality of each measure, and alignment with current management practices and objectives. The effectiveness and adoption rates of non-dietary strategies were assessed through review of scientific literature and industry reports, and personal communication with the experts named above. The barriers identified and the justification for the adoption rates assumed for each strategy are also provided.

8.1.4 Dietary manipulation

Various feed additives have been identified that can inhibit enteric methane production. There are three mechanisms by which methane production in the rumen can be reduced: shifting the end-product of microbial fermentation in favour of the volatile fatty acid propionate, providing an alternate hydrogen sink and inactivating rumen methanogens (methane-producing bacteria). Three additives have been found to be particularly effective, namely nitrate, 3-NOP and Asparagopsis. Their efficacy in reducing methane yield is illustrated in Error! Reference source not found. and described below. Methane inhibitors can impact feed intake and animal production, by affecting the efficiency of digestive processes, so the impact on methane emissions intensity (g CH_4/kg milk or liveweight gain) is also considered.

Rumen fermentation:
Rumen fermentation enables ruminant livestock (cattle, sheep, goats) to digest forage. Bacteria and protozoa in the rumen ferment cellulose, hemicellulose, starch and sugars to produce volatile fatty acids, mainly acetate, propionate and butyrate, which provide energy to the animal. Methane is produced by archaea, from carbon dioxide and hydrogen, and is lost by eructation (belching).

Nitrate

Nitrate decreases methane production by competing for hydrogen (H_2) in the rumen, decreasing the availability of H_2 for methanogens. Dietary inclusion at 17 to 22 g/kg DM was found to decrease methane yield by 10- 22% (95% CI; mean reduction of 16%), with no adverse effect on fibre digestibility or dry matter intake (Almeida et al. 2020). Furthermore, nitrate supplies non-protein nitrogen to rumen biota, to support microbial protein synthesis. Nitrate supplementation poses a risk of methaemoglobinaemia (caused by nitrate and nitrite poisoning), but this risk is minimal when supplied as a lick-block. Nevertheless, concern over potential for poisoning and possibility of milk contamination is expected to limit adoption especially in dairy cattle. Nitrate can be provided to grazing as well as confined animals, so has wider applicability than 3-NOP and Asparagopsis. Nitrate as a lick-block is available commercially, and there is an existing ERF method for feeding nitrates to beef cattle, although no projects have been registered. Producers who have fed urea supplements at least once in the previous five years will meet the eligibility criteria for this method. Lack of awareness, concerns over safety of nitrate, and perception of onerous MRV requirements are considered major barriers to adoption of the method.

3-NOP

3-nitrooxypropanol (3-NOP) is an effective inhibitor of methane production by methanogenic archaea. It does not diminish feed digestibility but may have a small negative impact on feed intake. Studies have concluded that it poses no food security threat nor risk to animal health. The efficacy appears to vary between dairy and beef cattle, and between diet types (high forage vs high grain), although results are inconsistent between studies. Almeida et al. (2020) found 18-39% reduction in methane yield across 14 studies (95% CI; mean reduction of 23%). The effectiveness is dose-related, with doses ranging from 40 to 340 mg 3-NOP/kg DM between the studies reviewed. Some studies have shown enhanced livestock productivity (milk or meat production), up to 3%.

Methanogenic archaea:
A diverse group of microorganisms which are similar to bacteria in size, and simplicity of structure but radically different in molecular organisation. Approximately I billion tonnes of methane is formed globally each year by methanogenic archaea in freshwaters sediments, swamps, rice fields, land fill as well as inside the intestinal tracts of ruminants.

3-NOP is commercially produced by Dutch company DSM, but not yet approved for use in Australia. It is currently being considered for approval in Europe. It is expected to be available in Australia within 2-3 years. 3-NOP needs to be ingested regularly, so is only suitable for use in feedlots and dairy cattle. However, testing of slow-release forms that could be used in grazing animals is underway. As a novel chemical product there may be some resistance from consumers, though the possible co-benefit of enhanced productivity will likely encourage adoption. The Federal Department of Industry, Science Energy & Resources is developing a technology investment roadmap. The discussion paper (DISER, 2020d) foreshadows measures to encourage the use of supplements and forage feeds in beef cattle production, including the development of an ERF method for 3-NOP.

Asparagopsis (seaweed)

Some species of seaweed (macroalgae), notably *Asparagopsis taxiformis* (also referred to as red algae), have recently been found to be highly effective in reducing enteric methane, due to their high content of bromoform. After promising in vitro studies, showing abatement of up to 90%, in vivo trials have recently commenced. From only three studies published to date, Asparagopsis was found to reduce methane by 30.0% to 69.0% (95% CI; mean reduction of 49.0%) when provided at 0.5-3.0% of the diet (Almeida et al., 2020). Some studies found a small reduction in feed intake and milk yield, but the most recent study (Kinley et al. 2020) reported a weight gain improvement of 42% over 90 days, in steers receiving 0.20% Asparagopsis, and a reduction in methane of up to 98%. Application of this strategy is limited to feedlots and dairy cattle, because it needs to be consumed frequently. The dried seaweed is included as a component of the ration.

As bromoform is a volatile halogenated substance, environmental concerns have been raised over the potential for ozone depletion. Other concerns relate to possible risks to animal health, as it may be carcinogenic. Due to the small number of in vivo trials to date, and unknown long-term effects on productivity, there is only moderate confidence in estimates of potential emissions reduction through use of Asparagopsis. Nevertheless, due to its apparently very high efficacy, there is strong research interest, and growing commercial interest. CSIRO, with partners MLA and James Cook University, has patented FutureFeed, a livestock feed supplement based on Asparagopsis, and established a company of the same name, that is currently seeking investors. The economics and sustainability of large-scale production of Asparagopsis are another challenge being taken by several new companies, including CH4 Global and SeaForest, that aim to scale up production in Australia. A National Seaweed Industry Blueprint is under development, with support from AgriFutures. CSIRO estimates that to supply 30% of the Australian feedlot and dairy industry will require approximately 2,000 hectares of seaweed farms, producing 25,000 dry tonnes of seaweed annually (CSIRO, 2020). A commercial product is anticipated within 5 years. The potential to produce the active compound via synthetic biology is being investigated; if successful this could reduce costs and avoid environmental impacts of seaweed production. The Federal Department of Industry, Science Energy & Resources' discussion paper on the technology investment roadmap (DISER, 2020d) indicates support for the use of dietary supplements in beef cattle production, including the development of an ERF method for Asparagopsis.

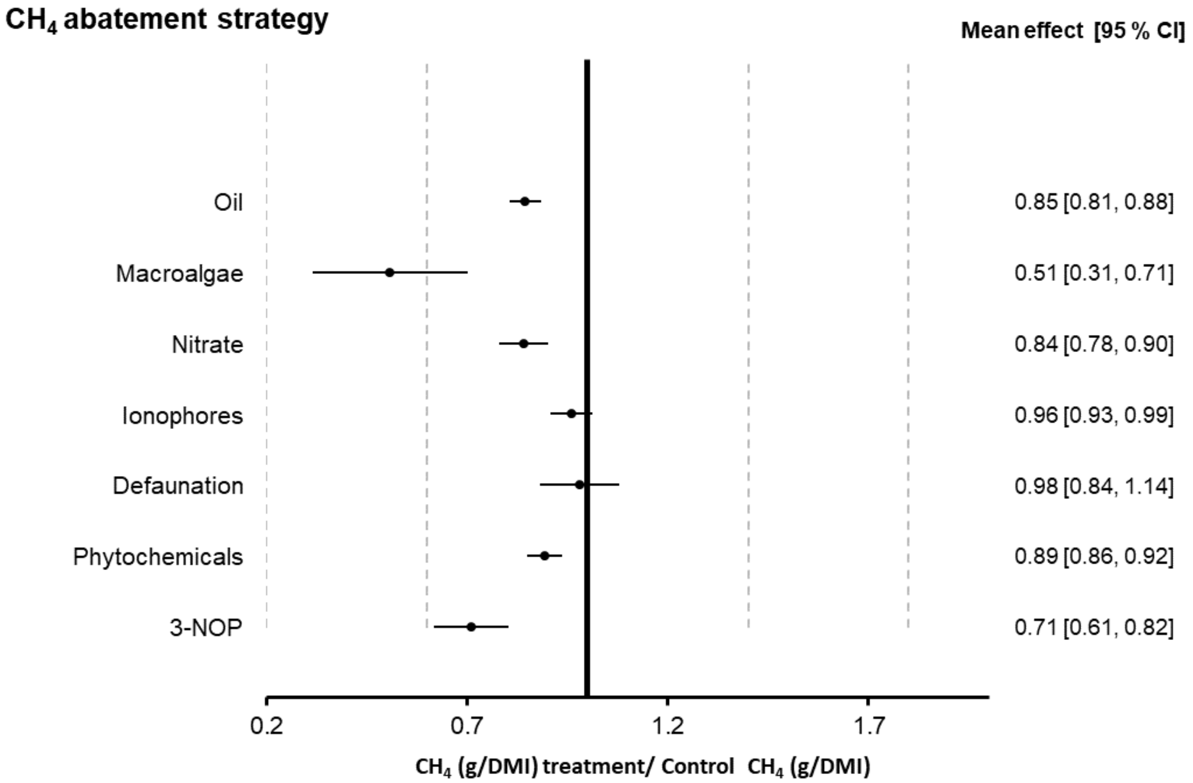


Figure 41. Forest plot depicting the standardized mean effect of the estimated ratio of methane yields for mitigation strategy vs control emissions (mean methane emission in treatment with mitigation strategy divided by mean methane emission in control) and the 95% confidence interval (95% CI). Values below 1.0 indicate that the mitigation strategy yields a reduction in methane emissions. *Source: Almeida et al. 2020.*

Other dietary approaches

Various other feed additives have been found effective to a lesser extent than the three discussed above. Several oils and phytochemicals including tannins, such as found in grape marc, have been shown to reduce methane yield by 15% on average (12-20%; 95% CI) (Almeida et al. 2020). Ionophores, that inhibit ciliate protozoa, enhance productivity but reduce methane yield by less than 5% on average (Almeida et al. 2020) (**Figure 41**).

8.1.5 Whole system modification

Herd management

Measures that enhance productivity of livestock production systems simultaneously reduce methane intensity, through producing more product (meat, milk or wool) per unit of feed consumed by the whole herd/flock. This basket of measures is collectively termed herd management. Culling unproductive animals, selecting for higher fecundity, introducing improved genetics (faster growth, higher milk yield) are consistent with reduced methane intensity. Providing additional watering points can reduce the distance walked, and therefore reduce the maintenance energy requirement of grazed livestock.

Methane yield is affected by feed quality: methane production is reduced on low-fibre feed such as grain and legume-dominant pasture, so pasture improvement, introduction of forage legumes, grazing management that enhances pasture quality, supplementary feeding and feedlot finishing are all effective measures. Incorporating a higher proportion of starch in the diet, through feeding grain and cereal forages, favours propionate as an end product of fermentation, while feed with high digestibility, such as legume-dominated pasture, passes more quickly through the rumen and this reduces methane yield per unit of feed intake (Grainger and Beauchemin, 2011). A combination of factors improving feed quality will likely result in reduced methane generation in ruminant animals.

A number of forage legumes have been identified as having significant potential to reduce enteric methane, due to presence of tannins and saponins. These include the perennial forage legumes *Leucaena* and *Desmanthus*, both of which have been shown to be productive and persistent in northern and central NSW. Other legumes are being evaluated for capacity to reduce methane. Biserrula, a particularly drought-tolerant annual legume, also shows promise. Furthermore, enhancing the productivity and quality of pastures, through introduction of pasture legumes, pasture renovation and grazing management to maintain groundcover, also has potential to contribute to abatement through sequestration of carbon in soils (see **section 6.5**), Additionally, shrub legumes can enhance carbon stocks in shoot and root biomass. However, *Leucaena* is considered an environmental weed, so should be actively managed to reduce seed set. Research is underway to develop a sterile line to reduce weed risk (Harris et al. 2019).

Herd management approaches are estimated to have a technical potential abatement of 5-25% and are most applicable in grazing systems. These practices are all consistent with good management and increased profitability, so should be readily adopted. Barriers to adoption are up-front costs and possible trade-offs with other desirable traits. High rates of adoption are anticipated if there is adequate financial incentive, such as though the ERF or carbon neutral product schemes.

There is an existing ERF method for herd management, but it has had limited uptake nationally, and there is only one project in NSW. Eligible activities under this method include feeding supplements, installing fences, planting improved pastures, improving herd genetics, and increasing density of water points. Low adoption is considered to have resulted from a lack of awareness and a perception of onerous MRV requirements, but the primary factor is considered to be the size of a herd required to develop a viable project. These barriers could be overcome if carbon project developer's direct attention to devising effective and efficient strategies for participation, and if bundling or whole-farm ERF methods are introduced (See **6.4** for further detail). The discussion paper for the Technology Roadmap mentioned above (DISER, 2020d) indicates support for measures to encourage introduction of forage legumes, specifically *Leucaena* and *Desmanthus*.

Breeding

Research has identified a genetic basis for variation in methane emissions between animals. Selecting for lower residual feed intake (lower feed intake for same growth) and/or lower residual methane production (lower methane production for same feed intake) has potential to deliver slow but ongoing gains in methane reduction of 0.2% to 0.4% per year that could amount to abatement of 4-8% over 20 years (Black et al. 2015).

These estimated potential gains apply to Angus cattle, the breed that has been the focus of Australian research to date. Progress for other beef breeds and sheep will take longer. Rapid gains in dairy cattle are possible, as genomic selection is well established and rapid dissemination can be achieved through artificial insemination (Black et al. 2015).

Vaccine

Research to develop a vaccine that induces a serum antibody response against methanogenic microbes has been ongoing for several decades. For example, the Australian National Livestock Methane Program (NLMP) investigated potential peptide sequences that could be used as antigens (Black et al. 2015). Recent research into the development of a vaccine has focussed in New Zealand. A successful vaccine would have a major impact, providing a practical approach to mitigate methane production from extensive as well as intensive livestock production systems. No evidence of consistent mitigation in *in vivo* studies has yet been published, so an effective vaccine is not anticipated by 2030.

8.1.6 Feasible abatement of enteric methane

Feasible abatement was calculated as the product of technical abatement (described above) and adoption rate. Adoption rate for each strategy (**Table 36**) was estimated based on consideration of the suitability of the measures for each segment of the industry (beef, dairy, feedlot cattle and sheep), synergies or trade-offs with production, and alignment with conventional practices. Regulatory and cost barriers were assumed to be overcome by 2030. Dietary additives were predicted to achieve widespread adoption in the feedlot and dairy sectors, supported by new ERF methods. These assumptions are consistent with the strong support for these measures expressed in the Department of Industry, Science, Energy and Resources' discussion paper on the Technology Investment Roadmap (DISER, 2020d), and the MLA's CN30 initiative (MLA, 2020; Mayberry et al. 2019).

Herd and flock management practices were considered to have broad adoption due to their consistency with good practice for productive and profitable livestock systems. In beef cattle and sheep, herd/flock management was assumed to emphasise pasture management and breeding, whereas in dairy the key strategy was assumed to be supplementary feed.

Novel dietary additives and conventional herd management approaches were considered complementary (Oddy, Hegarty, pers. comm.), therefore their effects were assumed to be additive.

Table 36. Summary of technical and feasible abatement of enteric methane through dietary additives and herd/flock management

Livestock system	**Mitigation strategy**	**Technical abatement potential % (1)**			**Adoption % 2030**			**Feasible abatement (2) % in 2030**			**Best dietary strategy**			**Combined strategies (3) feasible abatement %**		
		likely	min	max	likely (3)	min (4)	max (4)	likely	min	max	likely	min	max	likely	min	max
Beef - grazed																
	asparagopsis	50	30	69	5	0	10	2.5	0.0	6.9	4.8	1.0	11.7	4.8	1.0	11.7
	3-NOP (5)	29	18	39	2	0	30	0.6	0.0	11.7						
	nitrate	16	10	22	30	10	50	4.8	1.0	11.0						
	herd mgt (6)	15	10	20	80	30	90	12.0	3.0	18.0				12.0	3.0	18.0
Overall														**16.8**	**4.0**	**29.7**
Sheep																
	asparagopsis	50	30	69	5	0	10	2.5	0.0	6.9	3.2	0.5	8.8	3.2	0.5	8.8
	3-NOP	29	18	39	0	0	10	0.0	0.0	3.9						
	nitrate	16	10	22	20	5	40	3.2	0.5	8.8						
	herd mgt (6)	10	5	20	50	50	80	5.0	2.5	16.0				5.0	2.5	16.0
Overall														**8.2**	**3.0**	**24.8**
Beef - feedlot																
	asparagopsis	50	30	69	60	0	70	30.0	0.0	48.3	30.0	5.4	48.3	30.0	5.4	48.3
	3-NOP	29	18	39	60	30	70	17.4	5.4	27.3						
	nitrate	16	10	22	80	20	90	12.8	2.0	19.8						
	herd mgt (6)	5	5	10	80	30	90	4.0	1.5	9.0				4.0	1.5	9.0
Overall														**34.0**	**6.9**	**57.3**
Dairy																
	asparagopsis	50	30	69	60	0	70	30.0	0.0	48.3	30.0	1.8	48.3	30.0	1.8	48.3
	3-NOP	29	18	39	60	10	70	17.4	1.8	27.3						
	nitrate	16	10	22	40	10	50	6.4	1.0	11.0						
	herd mgt (6)	20	15	25	80	50	80	16.0	7.5	20.0				16.0	7.5	20.0

Overall	**46.0**	**9.3**	**68.3**

[1] Technical potential is the theoretical maximum abatement (with 100% adoption). For dietary strategies, this is based on the mean and 95% CI from Almeida et al. (2020). For herd management it is based on expert judgement, industry reports and Black et al., (2015).

[2] Feasible abatement is the plausible level of abatement if price and regulatory barriers are overcome.

[3] Novel dietary additives and conventional herd management approaches are considered complementary, therefore effects are assumed to be additive.

[4] "most likely" adoption rate is based on Hegarty and Almeida (2020).

[5] Maximum and minimum adoption rates were based on consultation with experts.

[6] Maximum adoption of 3-NOP assumes that a slow-release formulation becomes available for use in grazing stock (currently being tested)

[7] Herd management refers to conventional management strategies to enhance productivity including culling unproductive animals, supplementary feeding, feed formulation e.g. oils, grazing management and improved genetics. It excludes novel dietary additives developed specifically for methane abatement.

8.2 Nitrous oxide from soil

Nitrous oxide (N_2O) contributes around 20% of the NSW agriculture sector emissions. N_2O, (a GHG about 300 times more powerful as a climate forcer than CO_2), is released from soil through the natural processes of nitrification and denitrification, particularly in waterlogged (low oxygen) conditions. N_2O is derived from nitrogen applied as inorganic and organic fertilisers, from manure and urine of grazing livestock, through nitrogen fixation by crop and pasture legumes, and through decomposition of crop residues. Some nitrogen applied in fertilisers or deposited by livestock is volatilised as ammonia and redeposited elsewhere in the landscape through rainfall or dust, constituting a source of indirect N_2O emissions. Indirect N_2O also arises from N translocated through leaching and runoff. The major sources of N_2O are crop residue decomposition, livestock excreta, inorganic fertiliser and leaching (**Figure 42**).

8.2.1 Analysis

The technical potential for abatement of nitrous oxide (N_2O) emissions from soil was determined through literature review and consultation with Prof Peter Grace, who led the NORP and NANORP research programs (Nitrous Oxide Research Program, 2009–2012, and the National Agricultural Nitrous Oxide Research Program, 2013–2016). N_2O emissions from inorganic fertiliser can be reduced by enhanced efficiency fertilisers, including formulations with slow-release coatings or treatment with nitrification inhibitors, and through modification of fertiliser rates, timing and placement. We assumed that nitrification inhibitors can reduce N_2O by 50%, and would be adopted on 66% of cropland, assuming an ERF method for DMPP (see below) is introduced, We further assumed that fertiliser management practices could reduce N_2O emissions by 20%, with a conservative adoption rate of 10% of N applied to crops. We based fertiliser use in 2030 on AGEIS activity data for 2017 (DISER, 2020e), close to the highest production in the period 1990-2018.

Abatement of N_2O through removal of crop residues was also assessed. N_2O from residue decomposition constitutes the largest fraction of the N_2O emissions from soil. The quantity of residues available for removal was derived from the Australian Biomass for Bioenergy Assessment (ABBA, 2020), which assumes 1.5t is retained per hectare, for soil protection. The quantity of residues projected for 2030 was based on the average for 2013-2018 (ABBA, 2020). The algorithms and emissions factors used in the NIR were used to calculate baseline emissions in 2030. We assumed that 10% of the available cereal crop residues could be used for biochar production, and that the emissions factor would therefore be reduced from 0.01 Gg N_2O-N/Gg N (for residues) to 0.002 Gg N_2O-N/Gg N (see below).

Management of soil nitrous oxide emissions was investigated in Australia through the NORP and NANORP research programs. N_2O emissions from inorganic fertiliser can be reduced through the use of enhanced efficiency fertilisers, including formulations with slow-release coatings or treatment with nitrification inhibitors. Nitrification inhibitors such as 3, 4-dimethylpyrazole phosphate (DMPP) and Dicyandiamide (DCD), block ammonia monooxygenase (the enzyme that catalyses the first step of nitrification). DMPP has been shown to be highly effective in cropping soils in Australia, reducing N2O by 60-80% (e.g., Riches et al., 2016; Scheer et al., 2016; Schwenke et al., 2016). While high efficacy has been found in some pasture situations (e.g. Suter et al., 2016), nil responses have also been observed (e.g. Dougherty et al., 2016). Because nitrification inhibitors reduce the loss of nitrogen (as N_2O and N_2), they can enhance nitrogen retention, and thus plant growth, though growth responses are not consistently observed. There has been limited application of the commercially-available DMPP product “ENTEC”, due to its higher cost compared with conventional fertiliser. Development of an ERF method for DMPP is expected to overcome this economic barrier and stimulate adoption. In this assessment, efficacy of 50% and adoption rate of 70% in 2030 was assumed, in cropping applications only. The baseline N_2O emissions from inorganic fertilizer was assumed to equal the emissions in 2017, which was close to the maximum value in the period 1990-2017.

N_2O emissions are highly episodic, spiking rapidly after rainfall and irrigation events, when oxygen availability is low. Emissions can be reduced by over 40% through strategic timing of fertiliser applications with respect to irrigation schedules, and by splitting N applications (e.g. Schwenke et al. 2016). Supplying nitrogen through inclusion of legumes in the crop rotation is also effective (e.g. Mielenz et al. 2016). An ERF method for management of N fertiliser in cotton has been available since 2015 but no projects have been registered. A non-market approach may be most effective for encouraging adoption of improved N management. A conservative adoption rate of 10%, and efficacy of 20% was assumed for emissions reduction through improved N management.

Residue emissions constitute the largest fraction of the N_2O emissions from soil, but this is partly due to the emission factors used in the NIR: the EFs for inorganic and organic amendments, including animal manure are lower than the IPCC default value, because experimental data show lower emissions in Australian conditions (DISER, 2020c). However, the default of 0.01 Gg N_2O-N/Gg N is used for crop residues. Removal of residues for bioenergy or biochar production would reduce the soil N_2O emissions, but could raise sustainability concerns, as crop residues reduce erosion risk, control weeds, conserve moisture and contribute to soil organic matter. Based on Farine et al. (2012), 1.5 t/ha was assumed to be retained to provide soil protection. This assumption reduces the total residue available for removal by about 50% (ABBA, 2020). The quantity of residues projected for 2030 was based on the average for 2013-2018 (ABBA, 2020). The algorithms and emissions factors used in the NIR (DISER, 2020c) were used to calculate baseline emissions in 2030. It was assumed that 10% of the available cereal crop residues was used for biochar production. A fraction of the N removed in residues, if used for biochar, would be returned to the soil. Therefore, it was assumed that the EF of the removed residues is reduced to 0.002 Gg N_2O-N/Gg N, the value used for inorganic fertilisers, to reflect the low availability of N in biochar (Kammann et al. 2015).

Soil N_2O emissions are highly variable spatially and temporally, strongly influenced by aeration at micro-scale, temperature, and availability of labile carbon. Therefore, there is similarly large uncertainty in the estimates of baseline emissions and quantum of abatement through nitrification inhibitors and fertiliser management. Nearly 30% of soil N_2O is derived from dung and urine deposited by grazing animals. While manures from feedlots, dairies and piggeries can be managed to minimise N_2O losses (e.g. through soil incorporation rather than surface spreading), N_2O from grazing animals can't be readily managed. One possible option is introducing dung beetles, to hasten the incorporation of dung and minimise ammonia volatilisation. Feeding biochar may further reduce N volatilisation and increase N adsorption, reducing risk of N loss through leaching and runoff. Neither of these possible abatement options is included in this assessment.

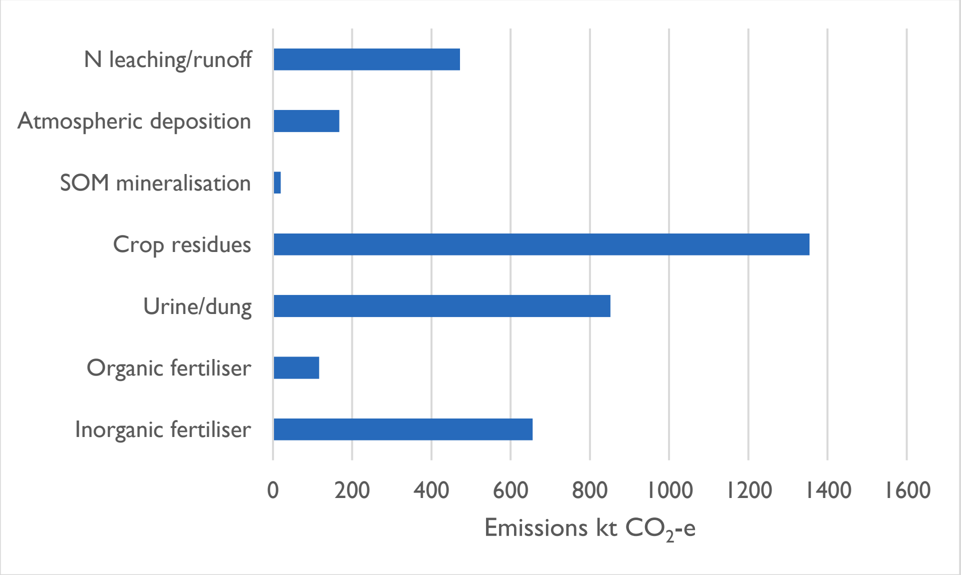


Figure 42. Sources of nitrous oxide emissions from soil in NSW, 2017 inventory [Source: AGEIS]

8.3 Avoided emissions from decomposition (carbon stabilisation in biochar)

8.3.1 Analysis

Estimation of the technical potential for abatement through the production of biochar was based on the IPCC method for quantification of carbon stabilisation through pyrolysis (IPCC, 2019). Pyrolysis of biomass to produce biochar stabilises the carbon in a recalcitrant form, and when applied to soil, biochar carbon is estimated to persist for hundreds to thousands of years, depending on the feedstock and production temperature.

The IPCC's 2019 refinement of guidelines for national greenhouse gas inventories (IPCC, 2019) provides a method for the calculation of carbon stabilised in biochar. The calculation of technical potential abatement through biochar production in NSW utilised the IPCC method combined with biomass data from the Australian Biomass for Bioenergy Assessment (ABBA, 2020) and biochar production data from Anaya de la Rosa (2020). The biochar production data, including recovery rate, co-product yield, carbon content of biochar and fossil energy inputs at each stage of the supply chain, draw on a comprehensive review of literature (Anaya de la Rosa, 2020), DPI's experience in biochar LCA (e.g. Krull et al. 2012; Cowie et al, 2015; Brandão et al, 2013; Mohammadi et al. 2016; Simmons et al. *in Review*), and production data supplied by collaborators in the biochar industry. The biomass feedstocks assumed to be utilised were poultry litter, feedlot manure, agri-processing residues (nut shells, gin trash, rice hulls) and urban greenwaste. For most feedstocks, the ABBA figures for average 2013-2018 production were used. For almonds, a new crop in NSW, the baseline for 2030 assumed all trees had reached production. The proportions of each feedstock assumed to be utilised for biochar are: 90% of agri-processing residues, as these are already collected and have no current alternative use; 50% of poultry litter and greenwaste, acknowledging that these materials are utilised for compost, organic amendments, and mulch, and 10% of cereal straw, as described in **Section 8.2.1**.

Besides stabilising carbon in organic matter, the production of biochar and its use as a soil amendment has the potential to reduce N_2O and methane emissions from decomposition of organic residues (e.g. Agyarko-Mintah et al. 2017) reduce N_2O emissions from soil (Cayuela et al. 2015; Borchard et al. 2019), stabilise carbon in organic matter (Weng et al. 2017) and provide emissions reduction in the energy sector, through production of renewable heat and electricity.

Feasible abatement in 2030 through biochar, considering only the carbon stabilisation component is estimated at 1.56 Mt CO_2-e. Supply chain emissions were estimated at 0.2 Mt CO_2-e. These were excluded from the calculation, as were avoided emissions from reduced fertiliser requirement and displaced grid electricity, estimated at 0.9 Mt CO_2-e.

8.4 Avoided emissions through management of manure

Emissions of methane and nitrous oxide from manure contribute around 4% to the agriculture sector inventory, with the largest share from piggeries and cattle feedlots. Emissions vary markedly depending on the manure management system, so there is potential for abatement through adoption of low-emissions manure management approaches. Around 50% of NSW piggeries use uncovered effluent ponds (DISER, 2020c). Covering ponds to capture and flare the methane reduces emissions by 90% (DISER, 2020c). Furthermore, biogas can be utilised for heat or to generate electricity, offering additional abatement and reducing operating costs. An ERF method for management of manure in piggeries (and dairies) is available, and seven projects are registered in NSW. The "animal effluent management" method allows for two different approaches to manure management:

- process manure in an anaerobic digester or covered pond, to capture the methane for flaring or generation of electricity
- separate solids for processing by an aerobic method such as composting.

Around 35% of NSW piggeries use a deep litter manure management system, which produces over 90% less methane than uncovered ponds (DISER, 2020c). Nevertheless, there is potential to reduce emissions from these systems by incorporating biochar into the litter. Due to its strong adsorptive properties, biochar can reduce methane, nitrous oxide and ammonia emissions, with the additional benefit of reduced odour (Schmidt and Shackley, 2016). Pyrolysis of the spent litter to produce biochar could avoid methane and nitrous oxide emissions from manure storage.

8.4.1 Analysis

The technical potential for abatement from piggery manure was calculated by assuming that all uncovered ponds would be covered, and manure from deep litter systems would by pyrolyzed to produce biochar, avoiding manure stockpiling. The number of pigs was projected at 400,000- 600,000 based on the range in the period 2010 – 2017. The calculation of feasible abatement assumed 20% adoption of biochar use by piggeries using deep litter systems, and 50% conversion from uncovered to covered ponds. The algorithms provided in the National Inventory Report (NIR) (DISER, 2020c), and the emissions factors for alternative management provided in the IPCC's 2019 Refinement (IPCC, 2019) were used. The technical and potential abatement in 2030 through these practices were estimated at 0.14-0.20 and 0.06-0.08 Mt CO2-e, respectively.

Cattle feedlots are the next largest source of emissions from manure management in NSW. Over half the feedlots use drylot (feedpad) systems, with manure stockpiling, while the others use composting or direct application to land. The use of biochar in feedlots could provide abatement in the same ways as described for deep litter piggery systems: addition of biochar to the feedpad would adsorb nitrate and ammonia, and reduce emissions of methane and nitrous oxide through greater aeration. Pyrolysis of feedlot manure would avoid emissions from stockpiling manure. The calculation of abatement potential was based on the livestock numbers described in section **8.1.2** and used the NIR algorithms and IPCC 2019 Refinement emissions factors as described for piggeries. Technical potential abatement is estimated at 0.12-0.23 Mt CO2-e, and feasible abatement is assumed to be half these values.

8.5 Avoided emissions from rice cultivation

The production of irrigated rice releases significant quantities of methane, due to decomposition of organic matter in flooded (anaerobic) conditions. In some years, rice cultivation contributes over 3% of agriculture sector emissions (AGEIS, DISERe). GHG emissions (CO_2-e) from methane emitted by flooded soils in rice production systems were calculated using the equations in the NIR (DISER, 2020c). Australian research has found that modification of stubble and water management (drill sowing and delaying flooding) reduce methane emissions by over 50% (Bull and Rose, 2018). Reduced flooding can also increase N_2O emissions but only in soils with high organic matter levels or where organic amendments such as manure are applied (Jiang et al., 2019) and it was assumed that the soils used to grow rice did not have manure applied, consistent with NIR. Methane emissions from rice production with reduced flooding were calculated by adjusting the scaling factor used to account for differences in water regime from 1 to 0.5 (assuming 50% reduction) and multiplying by the area of rice, using the average area planted in the period 1990-2018 as an estimate for the area planted in 2030. This gave a technical potential estimate of 0.2Mt CO2-e, and half this value is considered feasible, as the practice does not reduce yields (Bull and Rose, 2018), and there are no logistical barriers to adoption.

8.6 Summary of feasible abatement through emissions reduction

Barriers to adoption of the emissions reduction strategies are summarised in **Table 37** and **Table 38** provides an overview of feasible abatement through each strategy. The major source of emissions in the agriculture sector is enteric methane from sheep and cattle, contributing 70% of NSW Agriculture sector emissions. Strategies to reduce enteric methane include dietary additives and herd management to enhance productivity. Three dietary additives, nitrate, 3-NOP and Asparagopsis have been found particularly effective, reducing methane yield by 16, 29 and 49% on average, respectively (Almeida et al, 2020). Dietary strategies are suited to feedlot and dairy systems. Herd management approaches are estimated to reduce methane emissions by 5-25% and are most applicable in grazing systems.

Based on the projected size of the cattle herd in 2030, and realistic rates of adoption, the feasible abatement through a combination of dietary additives and herd management is estimated at 1.5-2.0 Mt CO_2-e. The estimated feasible abatement for enteric methane from sheep is estimated at 0.4-0.5 Mt CO_2-e.

Nitrous oxide emissions from soil contribute 15% of agriculture sector emissions. Nitrification inhibitors, especially DMPP, have been found effective in Australian cropping systems, reducing the N_2O emissions factor by over 70%. Feasible abatement in 2030 through nitrification inhibitors, fertiliser management and removal of crop residues is estimated at 0.267 Mt CO_2-e.

Pyrolysis of biomass to produce biochar stabilises the carbon in a recalcitrant form. Feasible abatement in 2030 through biochar, considering only the carbon stabilisation component, with no credit for avoided emissions, is estimated at 1.56 Mt CO_2-e.

Modified management of manure in piggeries and feedlots could contribute a further 0.12-0.20 Mt CO_2-e feasible abatement in 2030.

Table 37. Factors influencing feasibility of adoption of emissions reduction strategies in the agriculture sector

Emissions source	Abatement strategy	ERF method available[1]	Co-impacts on production[2]	Barriers to adoption	Adoption[3] (%)	Confidence [4]
Enteric methane						
Beef, feedlot	Feed additive	N (P)	🟨	Not yet approved or commercially available; limited evidence of impacts on production; large-scale seaweed production required; ERF method required	60-80	🟢
	Herd management	N	🟩	Limited potential for improvement	80	🟩
Beef, grazing	Feed additive	Y (nitrate only)	🟨	Toxicity concerns for nitrate; availability of slow release 3-NOP and Asparagopsis	2-30	🟢
	Herd management	Y	🟩	Cost of fencing, pasture improvement	80	🟩
Dairy	Feed additive	Y	🟢	As for feedlot	40-60	🟢
	Herd management	N (P)	🟩	Cost of supplementary feed	80	🟩
Sheep	Feed additive	N	🟢	Toxicity concerns for nitrate; availability of slow release 3-NOP and Asparagopsis	0-20	🟢
	Herd management	N (P)	🟩	Cost of fencing, pasture improvement	50	🟩
Nitrous oxide						
	Denitrification inhibitors (DMPP)	N (P)	🟢	Lack of awareness, cost, lack of ERF method	66	🟩
	Fertiliser management	Y (cotton only)	🟢	Lack of awareness, MRV requirements, cost	10	🟩
	Residue removal (for biochar/bioenergy)	N	🟧	Sustainability concerns; cost of residue removal	10, cereal straw only	🟢

Biochar	Carbon stabilisation through use of biochar as a soil amendment	N (P)	🟩	Regulatory approvals for production and application of biochar; Cost and availability of pyrolysis facilities and biochar;	90% process residues 50% greenwaste, poultry litter 10% cereal straw	🟩

[1] Y: ERF method available; N: no ERF method available; P: ERF method foreshadowed or readily developed based on current methods

[2] Co-impacts: dark green: significant benefits to production; light green: small benefits to production; yellow: no impact on production; orange: potential for small negative effect on production; red: significant negative impact on production

[3] Assumes cost and regulatory barriers removed. See section 8.1.6 for additional discussion on assumptions related to adoption.

[4] Confidence in estimated feasible abatement, considering evidence base for effectiveness and barriers to adoption: dark green: high; light green: moderate; yellow: low.

Table 38. Overview of feasible emissions reduction (in 2030) from NSW agriculture.

Emissions source	Practice	Scale of sector in 2030	Technical potential (% reduction)	% Adoption rate	Assumptions	2030
Enteric methane reduction						
Beef, feedlot	Feed additive	350,000-650,000 head	50	60-80	Feedlot numbers continue current upward trend. Most promising feed additive (*Asparagopsis*) approved for use, affordable and accepted by the beef industry. Limited additional mitigation through herd management in this already intensive system	0.18 to 0.33
	Herd management		5	80		
Beef grazing	Feed additive	4.65-5.85 million head	50	2-30	Herd based on range 1990-2015. Moderate uptake of nitrate feed additive (ERF method already available). Widespread adoption of "best practice" herd management (culling unproductive animals, improved genetics, supplementary feeding, improved pasture and grazing management)	1.05 to 1.31
	Herd management		15	80		
Dairy	Feed additive	250,000-350,000 head	50	40-60	Dairy herd continues current downward trend. Most promising feed additives (*Asparagopsis* and 3-NOP) approved for use, affordable and accepted by the dairy industry. Additional mitigation through herd management particularly supplementary feeding	0.28 to 0.39
	Herd management		20	80		
Sheep	Feed additive	25-35 million head	50	20	Flock based on range 2000-2015. Moderate uptake of nitrate feed additive (ERF method already available). Widespread adoption of "best practice" flock management (culling unproductive animals, improved genetics, supplementary feeding, improved pasture and grazing management)	0.37 to 0.52

	Flock management		10	50		
Total enteric methane						**1.87 to 2.55**
Soil emissions of nitrous oxide						
Inorganic fertilisers	Nitrification inhibitors, Fertiliser management	345 Gg N fertiliser, applied to 5.6 m ha crops	50 20	70 10	ERF method available that provides incentive for widespread adoption in cropping systems of the DMPP product that is already commercially available	**0.22**
Crop residues	Remove for biochar/bioenergy	8.4 Mt cereal residues	40	10	Residues in excess of 1.5 t/ha can be removed from cereal crops without impacting productivity. Bioenergy and biochar industries become established, such as though regional biohubs.	**0.05**
Total soil N_2O						**0.27**
Biochar						
Avoided decomposition	Pyrolysis of biomass to produce biochar for soil amendment	11 Mt feedstock	6 Mt CO_2-e	10 straw, 50 manure 90 processing residues	Regulatory barriers to production and use of biochar are overcome.	**1.56**
Other						
Methane, Nitrous oxide from manure	Covered ponds, biogas flared or used; Pyrolysis of litter	400,000-600.000 pigs	70 (covered ponds) 50 (pyrolysis of feedlot manure)	50% uncovered ponds and drylot feedlots	Numbers of pigs remain stable at the range seen 2010-2017; feedlot numbers continue to increase. Available technology for anaerobic digestion and covered ponds adopted more widely. Regulatory barriers to production and use of biochar overcome.	**0.12-0.20**

Methane from rice production	Delayed flooding	94,000 ha	50	50	Modified stubble management and delayed flooding reduce emissions by 50% and will be adopted by 50% of growers	0.10
					M t CO_2e at 2030	**3.92 to 4.68**

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Appendix I. Estimation of technically suitable areas for sequestration activities for broad vegetation and soil management categories (Modified from Baumer et al. 2020)

1: Methods for estimating the technical potential for carbon supply from ERF methods for New South Wales

The Emissions Reduction Fund (ERF) supports land managers to earn carbon credits by changing land use or management practices to store carbon or reduce greenhouse gas emissions.

Table S1 provides a summary of current land sector methods for the ERF and recognised management activities. For each method the key eligibility rules is provided. These requirements were used to produce maps of technically suitable areas in NSW (Figures S1 to S5); this cartography includes areas that are technically suitable under the ERF eligibility rules but do not take into account the price of carbon, costs associated with method compliance/project development, or the current income from existing land use. A combination of all these factors will determine the area feasible for sequestration activities.

Table S1. Major Emissions Reduction Fund (ERF) methods, management and eligibility requirements.

General description	ERF method name	Label	Recognised management activities	Key eligibility requirements
1.1 Clearing of native vegetation	Avoided Deforestation	AD	Cease clearing vegetation	Have a clearing consent issued before 01 July 2010
	Avoided Clearing	AC	Cease clearing vegetation	Unrestricted clearing is permitted on the land The land has been cleared in the last 7 years (5 years if recently changed hands) Land has been cleared at least twice (and used for cropping or grazing afterwards) Land uniformly covered in native forest and evidence of regrowth following clearing events

1.2 Vegetation regrowth management	Human-induced regeneration of a permanent even-aged Native Forest	**HIR**	Management that assists recruitment (seed) of re-sprouting (rootstock). Grazing management: Excluding livestock and the taking of reasonable steps to keep livestock excluded; management can include the timing and extent of grazing Exotic vertebrate pest management: the humane management of feral animals Weed management: Managing non endemic plants Mechanical vegetation management: stop mechanical or chemical destruction, or suppression, of regrowth.	Regrowth on cleared land in the past must have been supressed (e.g. by ongoing livestock grazing, feral animals, plants not native to the area, or mechanical or chemical destruction/suppression) Regrowth is expected
	Reforestation by environmental plantings	**EP**	Mixed environmental planting: Planting of trees endemic to the area	Land cannot contain woody biomass needing to be cleared prior to revegetation unless the species is a ‘prescribed weed species’ Land must be clear of forest cover for at least the past 5 years Trees must have the potential to attain a height of 2m and a

1.3 Reforestation and afforestation				crown cover of at least 20% (forest cover)
	Mallee Plantings	**MP**	Mallee revegetation: Planting of *Eucalyptus kochii*, *E. loxopheba* and *E. polybractea*	All of the above, but Mallee Plantings can only be established in areas where the long-term average rainfall is ≤600mm/year
Establishment of permanent tree plantings	Plantation Forestry	PF	New commercial plantation forestry	Land has been used for grazing, cropping or fallow in the last 5 years Land within a National Plantation Inventory Region
			Conversion of short-rotation plantations to long-rotation	Land must not be part of another forestry offsets project If a rotation of plantation forest is underway, it must be a short rotation and no thinning or pruning must have occurred Where a rotation has occurred in the past 7 years, it must have been a short-term rotation Land has been used for plantation forestry for at least the past 7 years Land within a National Plantation Inventory Region
	Estimating Sequestration of Carbon in Soils Using Default Values	SOIL	Sustainable intensification: new or different management practices that result in increased soil carbon (e.g. application of nutrients, lime or gypsum to improve soil	Land has been used for agriculture for at least 1 out of the last 5 years

1.5 Increasing soil carbon			health); installation of new irrigation with water sourced from privately-funded farm water efficiency savings; re-establishing or rejuvenating a pasture by seeding; changing livestock stocking rate, duration or intensity of grazing; converting from intensive tilling to reduced or no-tilling practices; modifying landscape features to remediate soils; using mechanical means to add or redistribute soil through the soil profile.[1] Converting land under crops to pasture: establishing and maintaining a pasture where there was previously no pasture (cropland or bare fallow).[1] Stubble retention: Retaining crop stubble (residue) after crop harvest in the paddock rather than burning or bailing.[1]	
	Estimating Sequestration of Carbon in Soils Using Measured Method		New management actions —including the above— that result in an increase in soil carbon.	Land has been used for agriculture for at least the last 10 years

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[1] CER (2020). Climate solutions Fund. Soil Carbon projects http://www.cleanenergyregulator.gov.au/csf/Pages/method-soil-carbon.html

1.1 Clearing of native vegetation - Avoided Deforestation

Overview of method:

Avoided deforestation (AD) project requirements: the area selected for AD must have native forest cover at the time of the project application, and clearing consent needs to have been issued prior to 1 July 2010. This consent allows the forest to be converted to crop or grassland. Forest cover is defined as land with trees at least 2m in height, with at least 20% crown cover, and a land area of at least 0.2haForest cover follows the definition (https://www.legislation.gov.au/Details/F2016C00281/Html/Text#_Toc446325225).

Spatial analysis:

Figure S1 illustrates the workflow and data layers (native forest cover, land use, woody vegetation cover) used to identify areas suitable for AD in NSW. The National Forest and Sparse Woody Vegetation Data V3 (2018) (https://data.gov.au/data/dataset/d734c65e-0e7b-4190-9aa5-ddbb5844e86d/resource/bf7420cc-2ec7-470d-87ba-f0a2c0ea1b60/download/woody-vegetation-extent-v3_0-metadata_2018.pdf) was used to identify areas that fulfill the native forest cover criterion. This dataset comprises three classes —forest, sparse woody, non-woody — and it is derived from satellite imagery (Department of the Environment and Energy 2018). The latest imagery dataset (2018) was used, and only the forest class was included, as it shows vegetation that fits with the AD forest cover requirement. The 2017 NSW Land-use dataset (https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017) that uses the ALUM classification to identify agricultural land-use was used to extract three classes —grazing native vegetation, grazing modified pastures and cropping. These two rasters were combined to identify *forest cover on the selected land-use types*.

Major vegetation groups: To further fit with the native forest cover the National Vegetation Information System data – Major vegetation groups V5.1 (Department of the Environment and Energy) http://environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products) were included in the analysis, and only those classes that fit the native forest classification were included.

Given the criterion of *date of clearing consent* is not spatial data, it was not included in the assessment. All but one clearing consent issued by 01 July 2010 have AD projects, and there are no further areas suitable for this method (*P. Theakston pers. comm).*

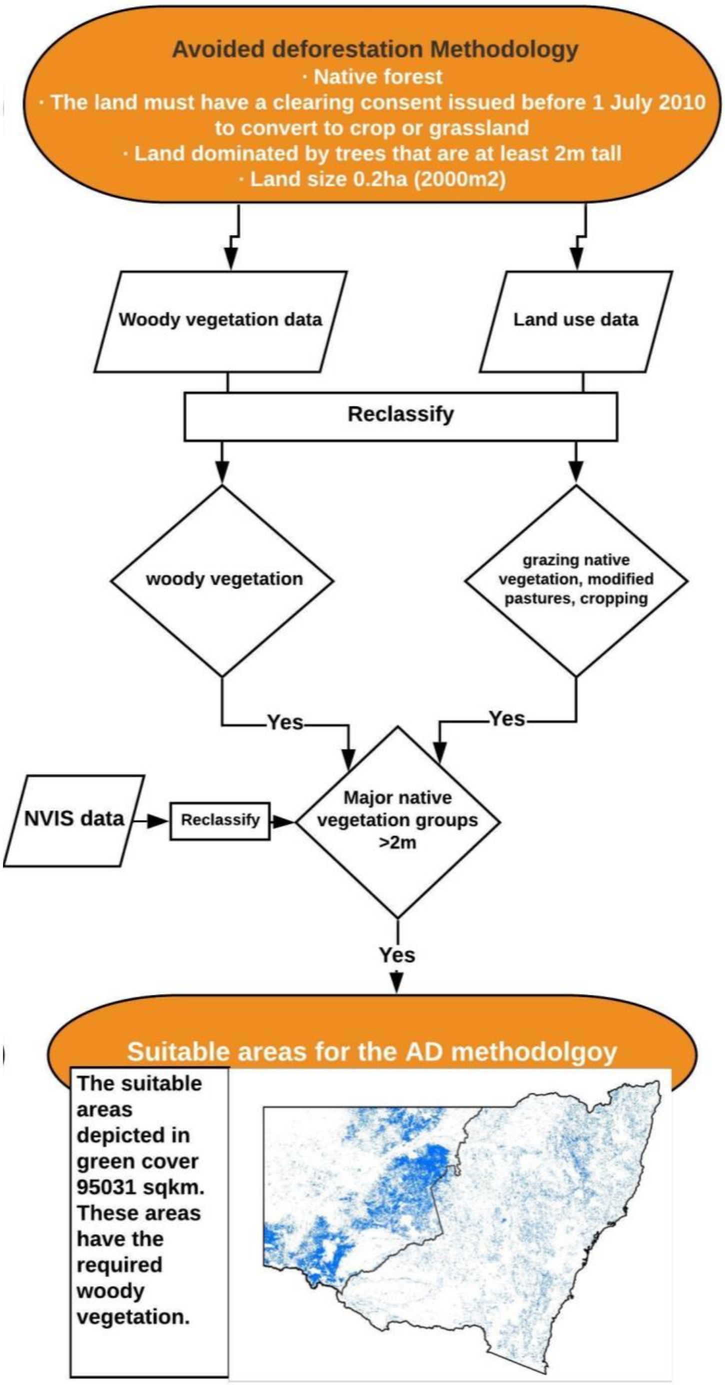


Figure S1. Flow diagram indicating the spatial analysis process and data sources used to identify areas theoretically suitable for AD in NSW. The output map shows 95,031km^2 are suitable for AD, mainly in in the western NSW. However, the requirement of having a clearing consent issued by 01 July 2010 precludes further expansion of this method.

1.2 Vegetation regrowth management - Human-induced regeneration of a permanent even-aged native forest

Overview of the method:

Requirements for a Human-induced regeneration of a permanent even-aged native forest (HIR) project: it must occur on land where regrowth of native forest has been suppressed for at least 10 years. Eligible land includes areas where forest cover has been suppressed through livestock, feral animals, plants not native to the area, mechanical or chemical destruction of regrowth. Eligible land can also include land under conservation where native forest cover has been suppressed through other non-native vegetation, and where there has been no mechanical or chemical destruction of this vegetation. The eligible area must be at least 0.2 hectares in land size, and the HIR project activities must result in the area becoming native forest or attaining native forest cover through regeneration. (https://www.legislation.gov.au/Details/F2016C00281/Html/Text#_Toc446325225).

Spatial analysis:

Figure S2 indicates the workflow adopted to identify areas suitable for HIR in NSW. The National Forest and Sparse Woody Vegetation Data V3 (2018) (https://data.gov.au/data/dataset/d734c65e-0e7b-4190-9aa5-ddbb5844e86d/resource/bf7420cc-2ec7-470d-87ba-f0a2c0ea1b60/download/woody-vegetation-extent-v3_0-metadata_2018.pdf) was used to identify eligible land with a potential to attain native forest cover through regrowth. This dataset includes three classifications, forest, sparse woody, non-woody derived from interpretation of satellite imagery. The latest available imagery (i.e. 2018), was used, and only areas classified as sparse woody were included this analysis. The sparse woody class shows vegetation with canopy cover between 5–19 per cent. Land with this type of woody cover has the potential to regenerate as native forest cover, and it is therefore aligned to the requirements of the HIR method. The 2017 NSW Land-use dataset (https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017) which adopts the ALUM classification to identify agricultural land-use was used to select areas classified as grazing native vegetation, grazing modified pastures, cropping and nature conservation. All other land-use types were excluded.

The above two raster layers were combined to identify sparse woody cover on the selected land-use types. To further identify native forest cover, the National Vegetation Information System data – Major vegetation groups V5.1 (Department of the Environment and Energy) http://environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products) was included in the analysis. Only classes meeting the native forest classification were included.

The output map of Figure S2 shows areas of NSW where native woody cover on agricultural and conservation land-use exists - these areas are eligible for a potential HIR project.

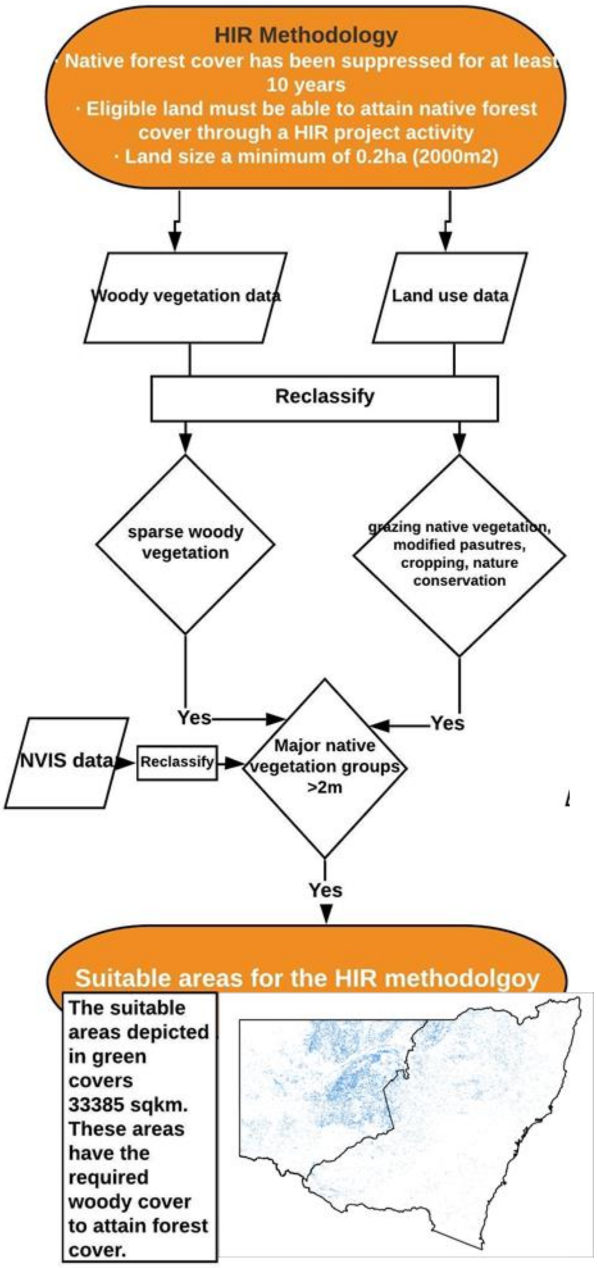


Figure S2. Flow diagram indicating the process and data sources used to identify areas theoretically suitable for HIR in NSW. The output map shows 33385 km^2 concentrated in western NSW are suitable for HIR.

1.3 Afforestation and Reforestation -Afforestation by Environmental or Mallee Plantings

Overview of method:

This method establishes and maintains plants of either a mixed native tree (Mixed Environmental Planting) or Mallee Eucalypt species (Mallee plantings) on land that has been grazed, cropped or fallowed for at least five years before project commencement. The plantings need to achieve forest cover status, and can be planted in belts or blocks or a combination thereof.

Spatial analysis:

Figure S3 shows the process followed to identify areas suitable for EP and MP in NSW. To this end, the 2017 NSW Land-use dataset (https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017) that adopts the ALUM classification was used to identify land-use types that fulfil the requirements of this method. Secondary ALUM classes were selected —grazing native vegetation, grazing modified pastures and cropping. The 2018 National Forest and Sparse Woody Vegetation Data V3 (https://data.gov.au/data/dataset/d734c65e-0e7b-4190-9aa5-ddbb5844e86d/resource/bf7420cc-2ec7-470d-87ba-f0a2c0ea1b60/download/woody-vegetation-extent-v3_0-metadata_2018.pdf) was used to identify the non-woody areas (canopy cover of less than 5 percent). The two raster layers were combined to identify non-woody areas on the eligible land-use types.

The approach is similar to the one used by Evans et al. (2015) to delineate land feasible for assisted natural regeneration or environmental plantings for assessing economics of carbon farming in Queensland's deforested agricultural areas. The economic modelling will further refine this layer showing the economic feasibility for ERF projects under this method. However, activities that increase carbon sequestration through replanting have co-benefits, e.g. for stock shelter, biodiversity, erosion control, increased aesthetics.

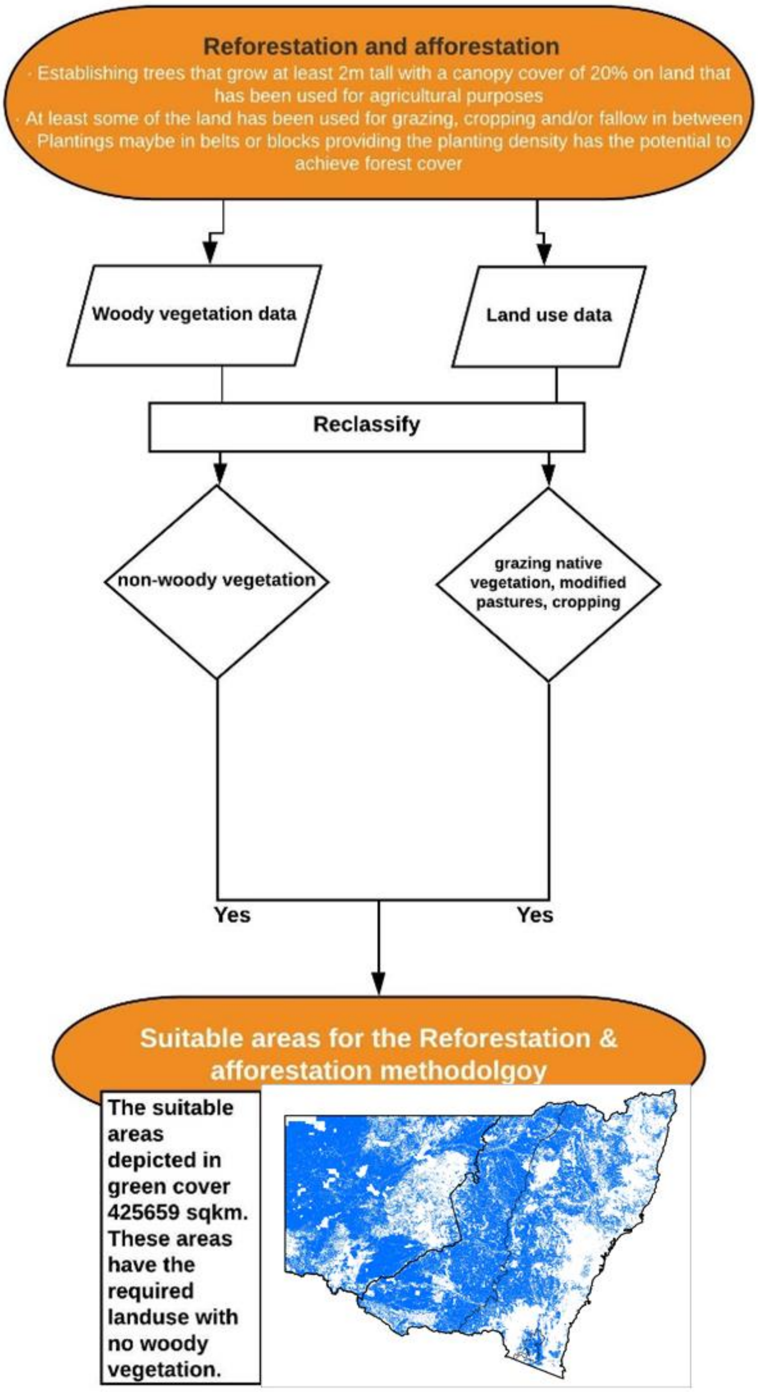


Figure S3. Flow diagram indicating the spatial analysis process and data sources used to identify areas theoretically suitable for Reforestation and afforestation methods in NSW. The output map shows 425,659 km^2 theoretically suitable (see Figure S4).

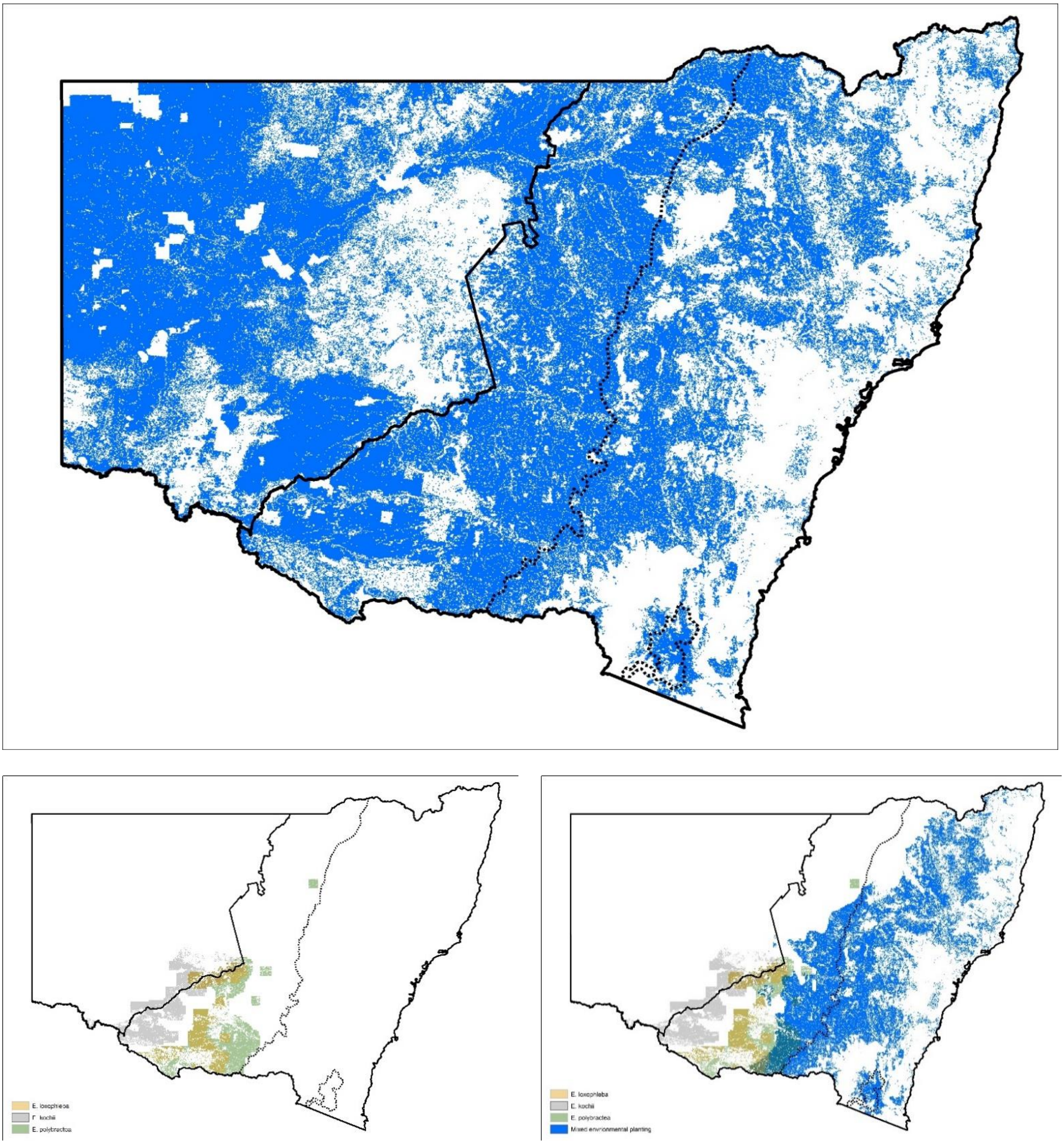


Figure S4. The top map shows areas of NSW theoretically suitable for Reforestation and afforestation by Environmental and Mallee Plantings; the bottom left shows the spatial distribution of the three Mallee species for the <600 mm rainfall zone. The lower right map overlays the three Mallee species distribution with the areas mapped as theoretical suitable within the temperate rainfall zone. Areas outside the temperate zone are unlikely to obtain sufficient rainfall for successful tree planting.

1.4 Increasing soil carbon - Estimating Sequestration of Carbon in Soils Using Default Values or Estimating Sequestration of Carbon in Soils Using Measured Method

Overview of method:

Soil carbon sequestration in agricultural systems involves storing carbon on grazing, cropping and perennial horticultural land by introducing activities that either increase inputs of carbon to the soil, reduce losses of carbon from the soil, or both. Proposed activities have to be new and can include: applying nutrients to the land, applying lime to remediate acid soils, applying gypsum to remediate sodic or magnesic soils, undertaking irrigation activities from new efficiency savings, re-establishing or rejuvenating pastures, altering stocking rate or grazing intensity, retaining crop stubble, converting areas under tillage to reduced or no tillage, modifying landscape or landform features to remediate land, or using mechanical methods to add or redistribute soil http://www.cleanenergyregulator.gov.au/ERF/Pages/Choosing%20a%20project%20type/Opportunities%20for%20the%20land%20sector/Agricultural%20methods/The-measurement-of-soil-carbon-sequestration-in-agricultural-systems-method.aspx.

Spatial analysis:

Figure S5 shows the workflow adopted to identify areas suitable for SOIL in NSW. The 2017 NSW Land-use 2dataset that adopts the ALUM classification was used to identify the eligible land-use types that fulfil the method requirements. From this dataset, the secondary ALUM classes grazing native vegetation, grazing modified pastures, grazing irrigated modified pastures, dryland cropping, irrigated cropping, perennial horticulture, and irrigated perennial horticulture were selected. The output map shows areas across NSW that are suitable for this method.

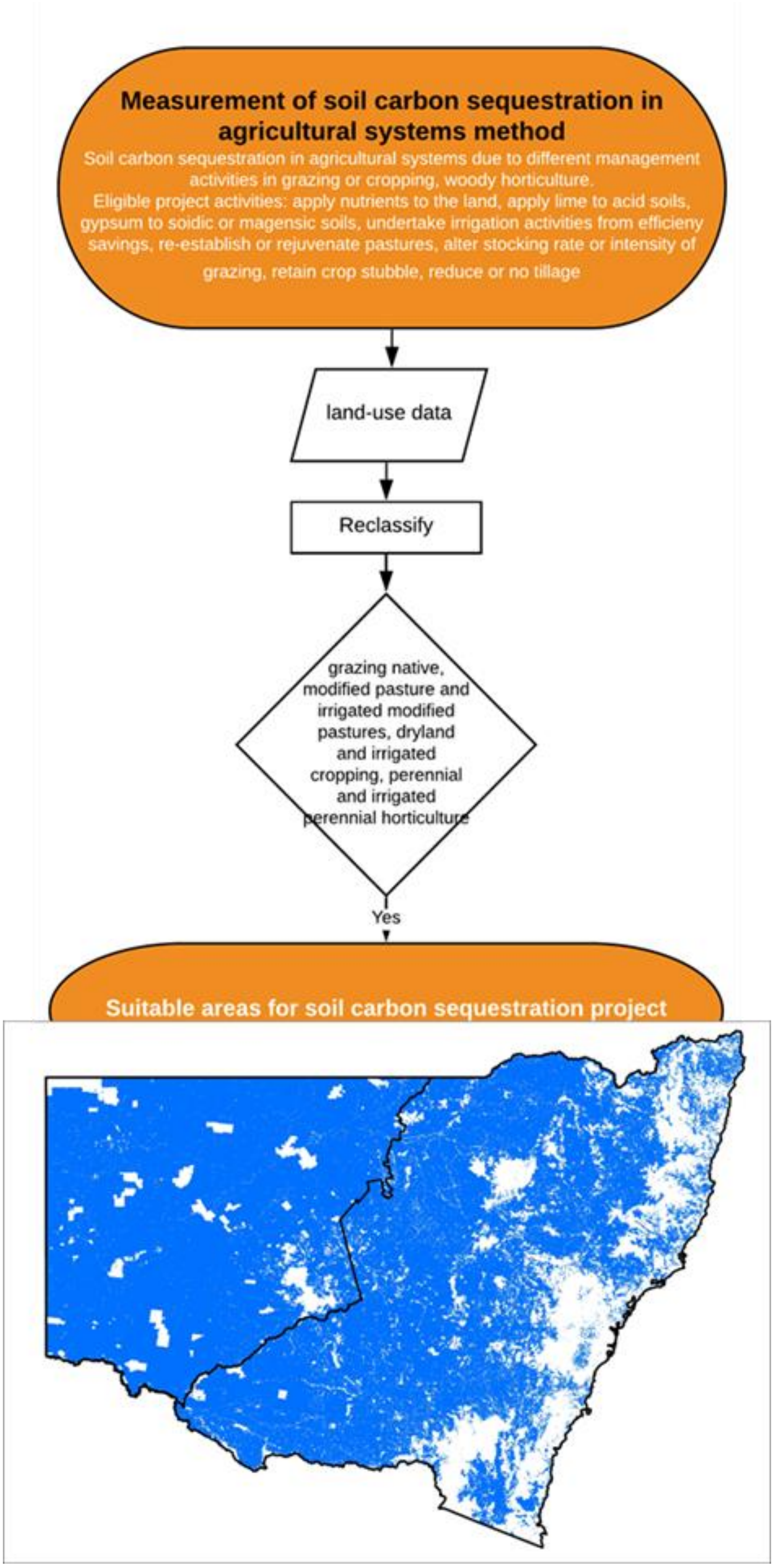
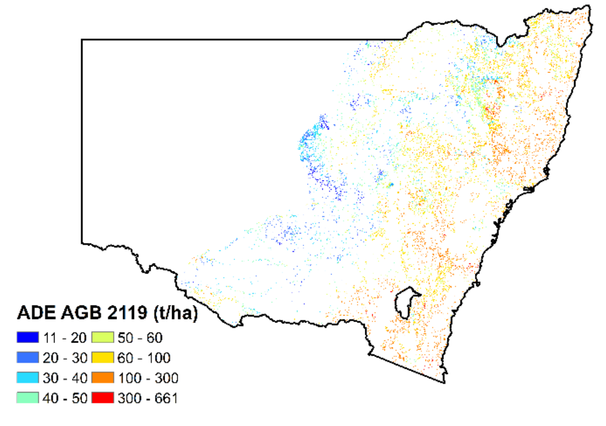
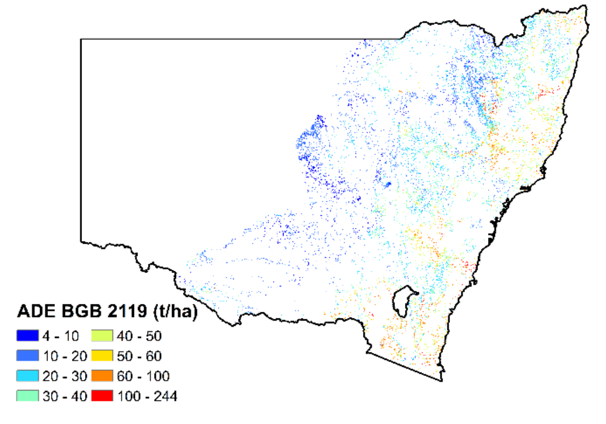
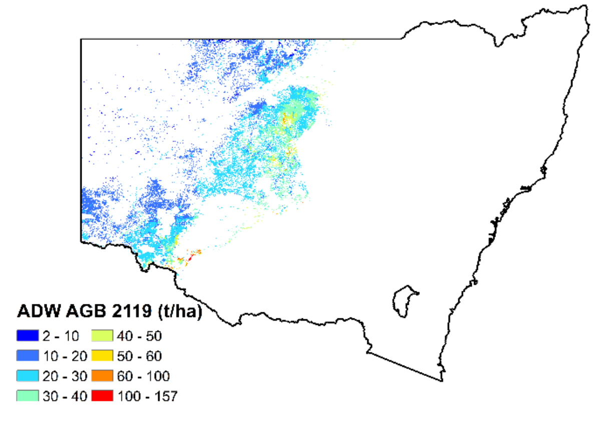
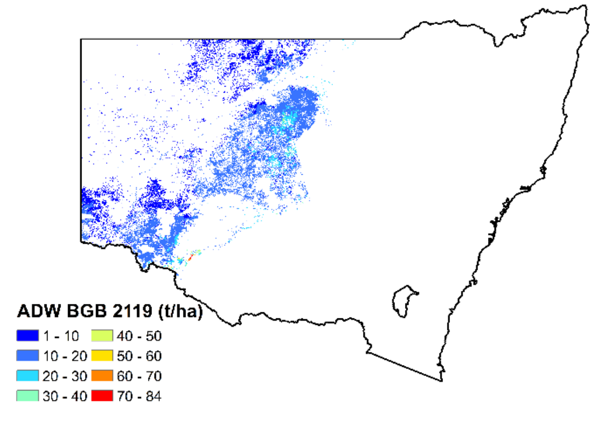
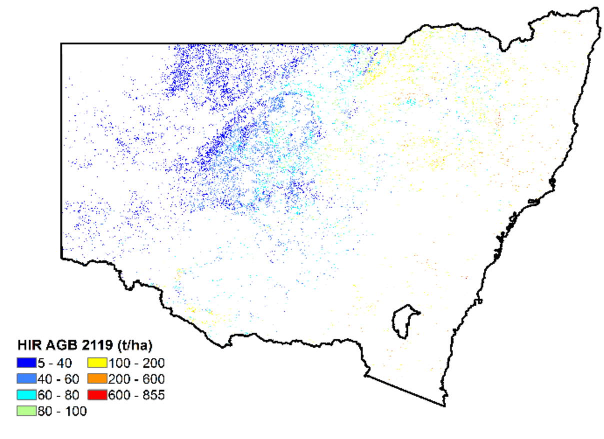
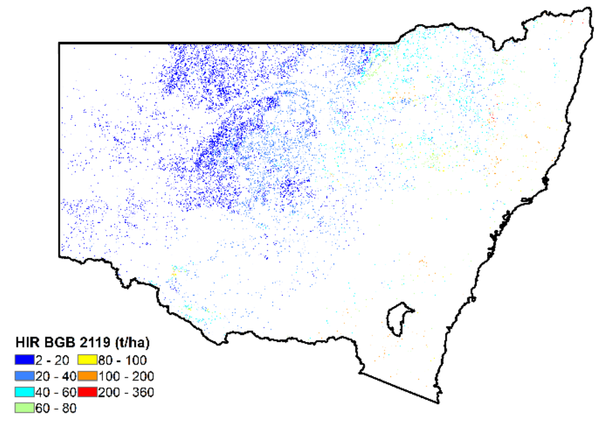
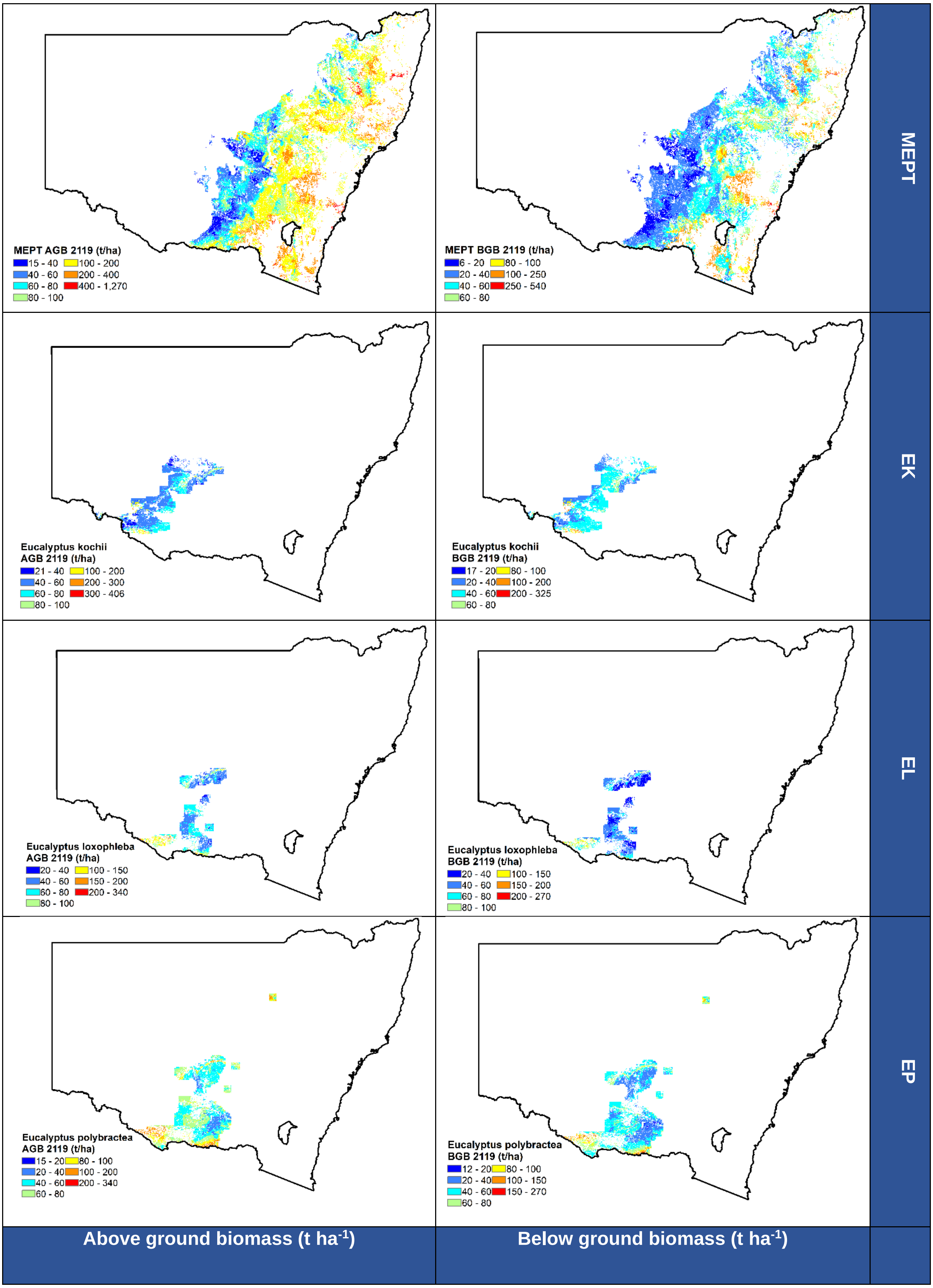
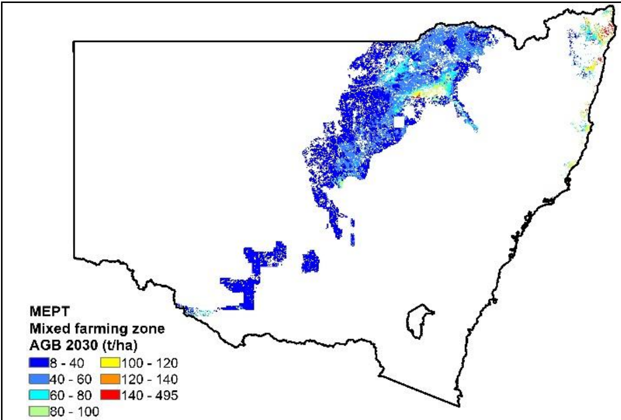
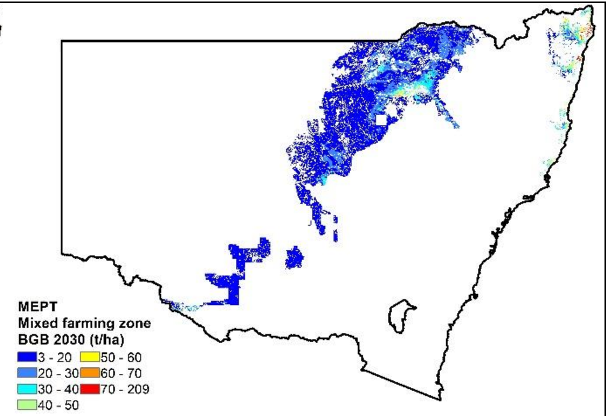
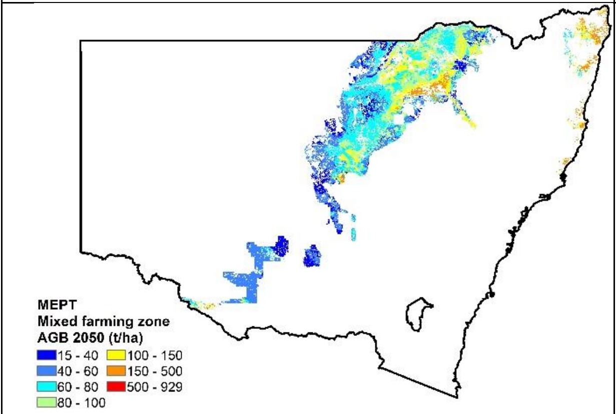
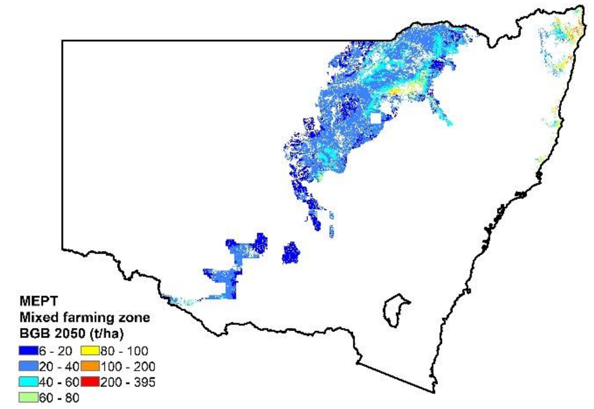
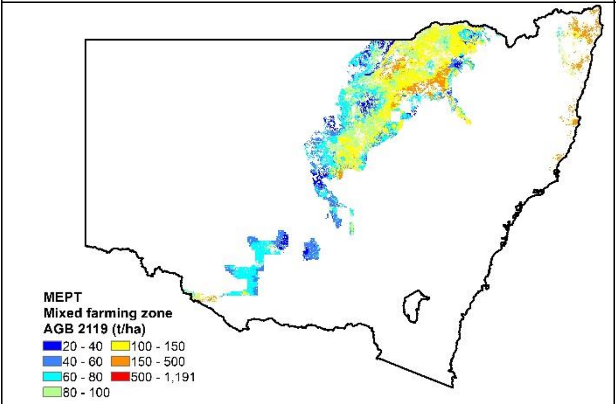
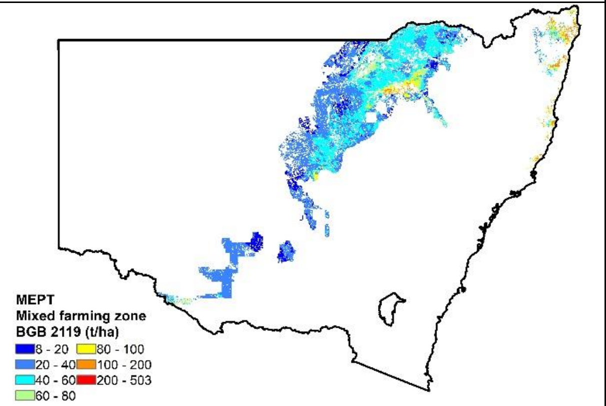


Figure S5. Flow diagram indicating the spatial analysis process used to identify areas theoretically suitable areas for soil carbon projects in NSW. The output map shows a total of 599,515km^2 theoretically suitable.

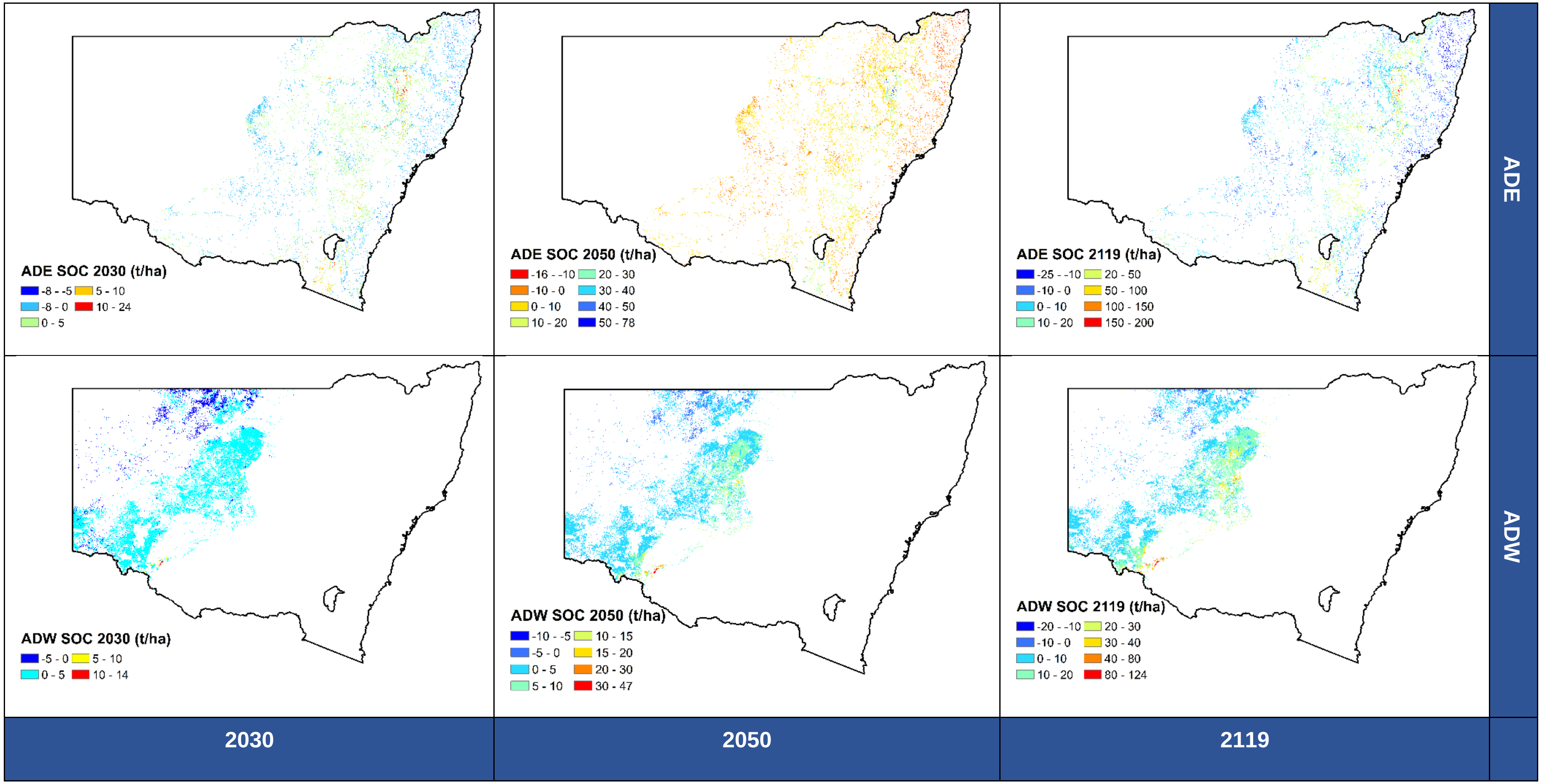
Appendix II. FullCAM modelled cumulatative above ground biomass (BGB, t ha^{-1}) for 2119

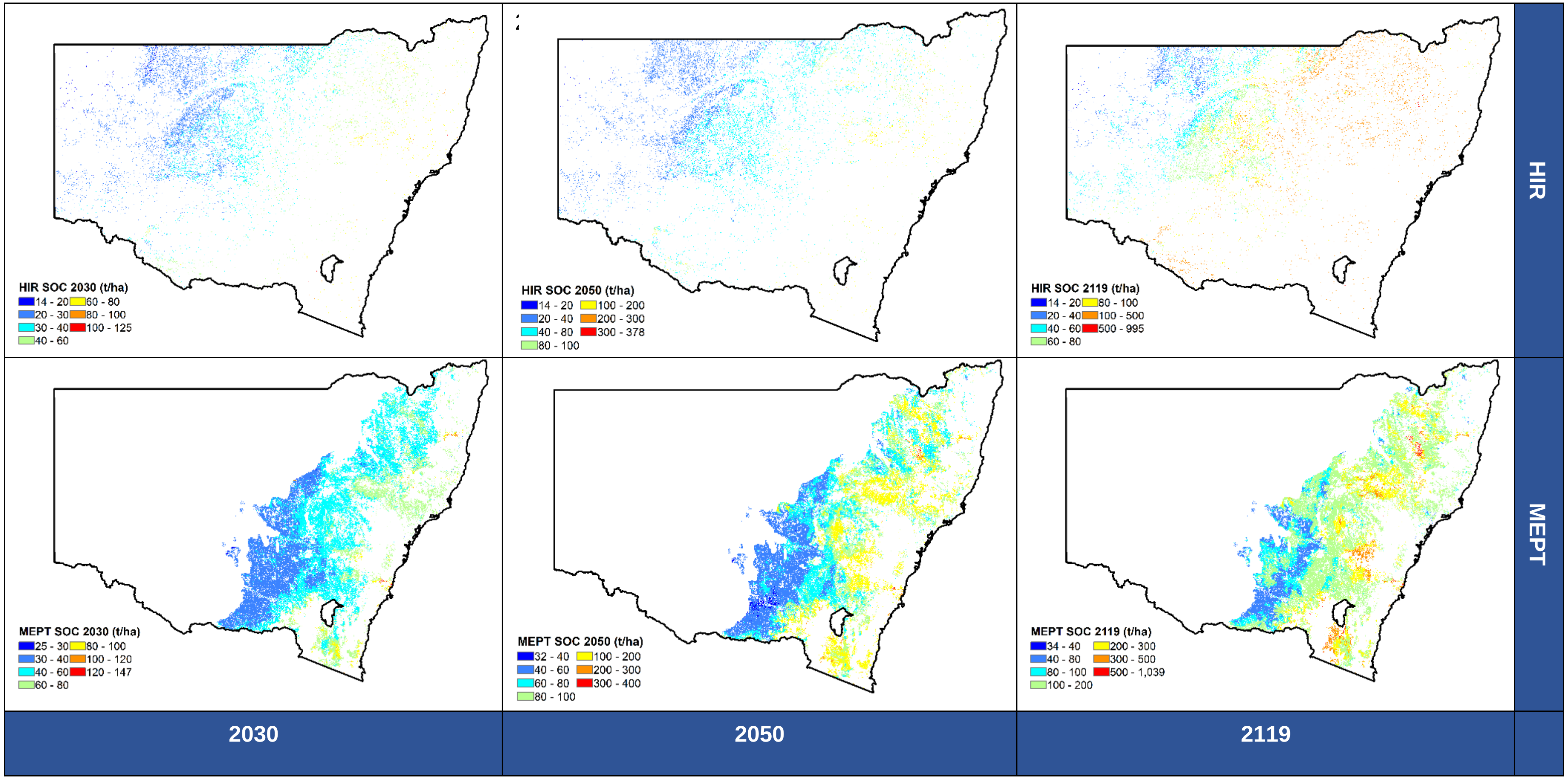
		ADE
		ADW
		HIR
Above ground biomass (t ha^{-1})	**Below ground biomass (t ha^{-1})**	

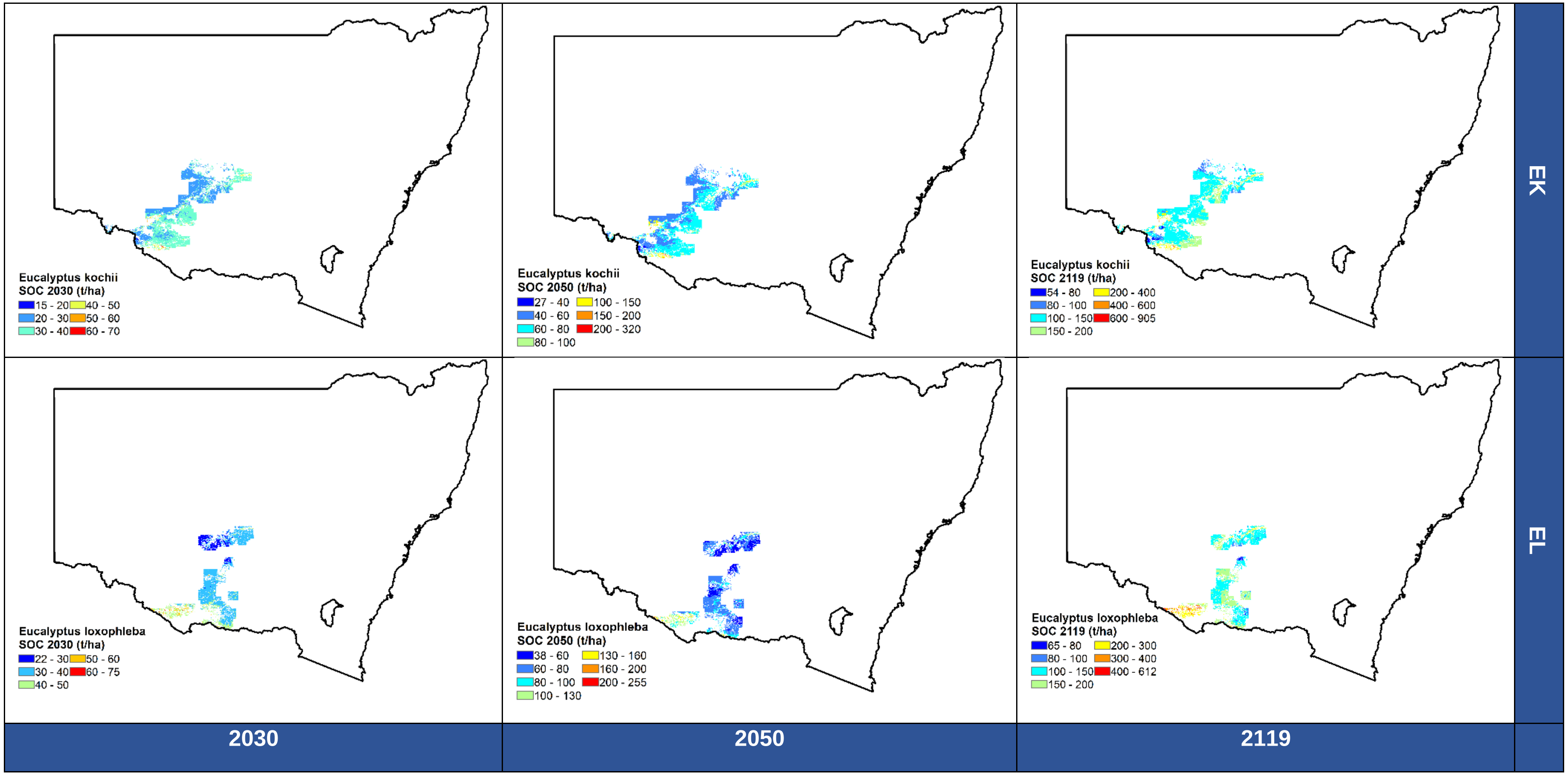

MEPT AGB 2119 (t/ha)
15 - 40
40 - 60
60 - 80
80 - 100
100 - 200
200 - 400
400 - 1,270
MEPT BGB 2119 (t/ha)
6 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 250
250 - 540
MEPT
Eucalyptus kochii
AGB 2119 (t/ha)
21 - 40
40 - 60
60 - 80
80 - 100
100 - 200
200 - 300
300 - 406
Eucalyptus kochii
BGB 2119 (t/ha)
17 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 200
200 - 325
EK
Eucalyptus loxophleba
AGB 2119 (t/ha)
20 - 40
40 - 60
60 - 80
80 - 100
100 - 150
150 - 200
200 - 340
Eucalyptus loxophleba
BGB 2119 (t/ha)
20 - 40
40 - 60
60 - 80
80 - 100
100 - 150
150 - 200
200 - 270
EL
Eucalyptus polybractea
AGB 2119 (t/ha)
15 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 200
200 - 340
Eucalyptus polybractea
BGB 2119 (t/ha)
12 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 150
150 - 270
EP
Above ground biomass (t ha-1)
Below ground biomass (t ha-1)

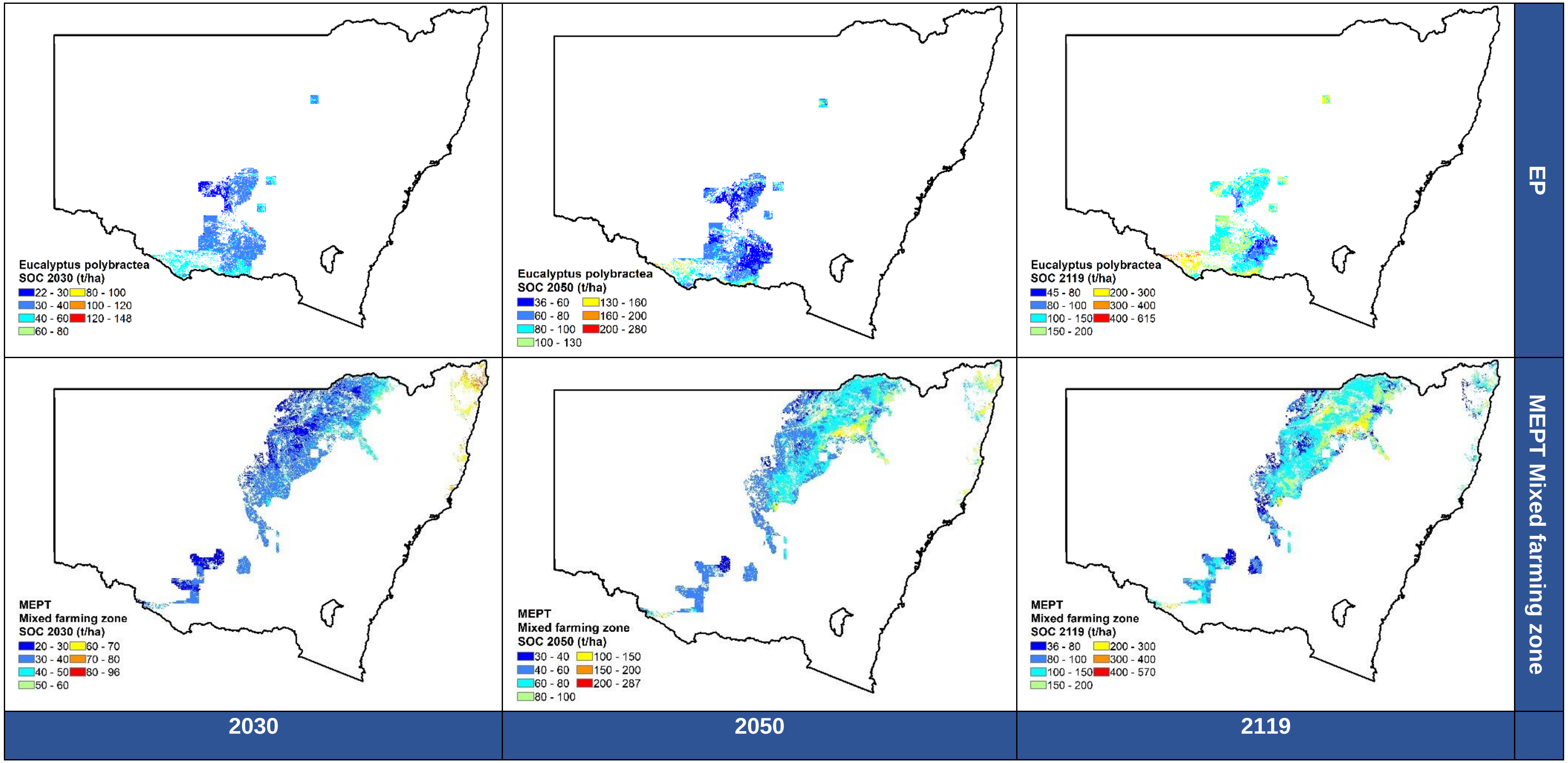
		MEPT Mixed farming zone 2030
		MEPT Mixed farming zone 2050
		MEPT Mixed farming zone 2119
Above ground biomass (t ha^{-1})	**Below ground biomass (t ha^{-1})**	

Appendix III – FullCAM modelled cumulative soil organic carbon t ha^{-1} for 2030, 2050, 2119




HIR SOC 2030 (t/ha)
14 - 20
20 - 30
30 - 40
40 - 60
60 - 80
80 - 100
100 - 125
HIR SOC 2050 (t/ha)
14 - 20
20 - 40
40 - 80
80 - 100
100 - 200
200 - 300
300 - 378
HIR SOC 2119 (t/ha)
14 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 500
500 - 995
HIR
MEPT SOC 2030 (t/ha)
25 - 30
30 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 147
MEPT SOC 2050 (t/ha)
32 - 40
40 - 60
60 - 80
80 - 100
100 - 200
200 - 300
300 - 400
MEPT SOC 2119 (t/ha)
34 - 40
40 - 80
80 - 100
100 - 200
200 - 300
300 - 500
500 - 1,039
MEPT
2030
2050
2119


Eucalyptus kochii
SOC 2030 (t/ha)
15 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
Eucalyptus kochii
SOC 2050 (t/ha)
27 - 40
40 - 60
60 - 80
80 - 100
100 - 150
150 - 200
200 - 320
Eucalyptus kochii
SOC 2119 (t/ha)
54 - 80
80 - 100
100 - 150
150 - 200
200 - 400
400 - 600
600 - 905
EK
Eucalyptus loxophleba
SOC 2030 (t/ha)
22 - 30
30 - 40
40 - 50
50 - 60
60 - 75
Eucalyptus loxophleba
SOC 2050 (t/ha)
38 - 60
60 - 80
80 - 100
100 - 130
130 - 160
160 - 200
200 - 255
Eucalyptus loxophleba
SOC 2119 (t/ha)
65 - 80
80 - 100
100 - 150
150 - 200
200 - 300
300 - 400
400 - 612
EL
2030
2050
2119


Eucalyptus polybractea
SOC 2030 (t/ha)
22 - 30
30 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 148
Eucalyptus polybractea
SOC 2050 (t/ha)
36 - 60
60 - 80
80 - 100
100 - 130
130 - 160
160 - 200
200 - 280
Eucalyptus polybractea
SOC 2119 (t/ha)
45 - 80
80 - 100
100 - 150
150 - 200
200 - 300
300 - 400
400 - 615
EP
MEPT
Mixed farming zone
SOC 2030 (t/ha)
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 96
MEPT
Mixed farming zone
SOC 2050 (t/ha)
30 - 40
40 - 60
60 - 80
80 - 100
100 - 150
150 - 200
200 - 287
MEPT
Mixed farming zone
SOC 2119 (t/ha)
36 - 80
80 - 100
100 - 150
150 - 200
200 - 300
300 - 400
400 - 570
MEPT Mixed farming zone
2030
2050
2119

Appendix IV. Methods used to model soil carbon sequestration potential from vegetation cover change

Responses of soil carbon to changes in woody cover followed a modification of Gray et al. (2019) which uses a mixed modelling approach combining Random Forest and multiple linear regression (MLR) and a Random Forests (RF) method following Wang et al. (2018).

Data Sources:

A soil organic carbon (SOC, t ha-1, 30 cm) dataset was prepared using 2160 points sourced from the following

- NSW Monitoring, Evaluation and Reporting (MER) program of the NSW Government during 2008-09 (OEH, 2014).
- National Soil Carbon Research Program (SCaRP) 2009-2012 https://csiropedia.csiro.au/soil-carbon-research-program/) (Sanderman et al 2011)
- Filling the Research Gap - National Soil Carbon Research Program (2014-2017); Waters et al. 2015; Waters et al 2016; Orgill et al 2017)
- Catchment Action Market Based Instrument (CAMBI) pilot (2009-2019) (Badgery et al 2019)

The initial dataset was reduced to 2153 with the exclusion of sites with SOC greater than 200 t/ha, indicative of organic soils, which were not included in this modelling program. The reduced dataset was divided into training data (1724 data points) and test data (429 data points).

Current SOC stocks under existing land use and vegetation cover conditions, then repeated for a 10% change in vegetation cover relative to existing cover levels (e.g. a current 70% cover increased to 77%).

Input variables:

A total of 16 variables were initially selected was used to predict SOC stock based on topography, land use, Age of parent material, Climate and Parent material (**Table III a**.). From an initial selection of 16 environmental variables the final selection was restricted to eight (statistically strongest variables) for the MLR model, whereas all 16 variables were used for the RF model. The relative importance of each variable from the RF model is shown in Figure (right).

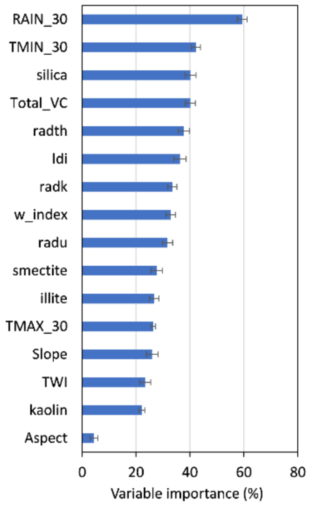


Table IV a. Initial sixteen variables selected for prediction of SOC stock in NSW.

	Variable	Definition
Topography	Slope	Slope gradient in percentage as derived from a DEM
	Aspect	The amount of solar radiation received by site
	Topographic Wetness Index (TWI)	The relative wetness within moist catchments; used as a measure of position on the slope with larger values indicating a lower slope position
Biota/Land use	Land disturbance index (LDI)	The intensity of disturbance associated with the land use following (Gray et al., 2015b); sourced from 1:25 000-scale land-use mapping (DPIE 2020)
	Total vegetation fractional cover (Total_VC)	Total vegetation cover % (photosynthetic and non-photo-synthetic) being average (mean) cover from year 2000 to date of sampling, sourced from CSIRO MODIS data (Guerschman and Hill, 2018)
Age	Weathering Index (WI)	The degree of weathering of parent materials, regolith and soil, based on gamma radiometric data (Wilford 2012); sourced from Geoscience Australia
Climate	Rainfall (Rain)	Mean annual rainfall
	Maximum temperature (Tmax)	Mean annual maximum temperature
	Minimum temperature (Tmin)	Mean annual minimum temperature
Parent material	Silica index	The approximate silica content (%) of the parent material, which relates to its lithology and the resulting soil type (Gray et al 2016)
	Radiometric potassium (Rad_k)	Concentration of the radioelements potassium
	Radiometric uranium (Rad_u)	Concentration of radioelements uranium
	Radiometric thorium (Rad_th)	Concentration of radiometric thorium sourced from Geoscience Australia (Minty et al 2009)
	Kaolin	Relative proportion of Kaolin

Illite	Relative proportions of illitic clay derived from near infra-red (NIR) spectroscopy (Viscarra Rossel 2011); sourced through the CSIRO Data Access Portal https://data.csiro.au/dap/search?q=TERN+Soil
Smectite	Relative proportions of smectite, sourced as above for Illite

Comparison of model results:

Table IV b. Model validation and testing results based on 100 runs for multiple linear regression (MLR) and random forest (RF) respectively

Multiple Linear Regression (MLR)	**Random Forests (RF)**
R^2 = 0.55 (Validation); 0.56 (Test)	R^2 = 0.70 (Validation); 0.68 (Test)
LCCC = 0.71 (Validation); 0.72 (Test)	LCCC = 0.81 (Validation); 0.80 (Test)
RMSE (log unit) = 0.38 (Validation); 0.39 (Test)	RMSE (log unit) = 0.31 (Validation); 0.33 (Test)
MAE = 0.30 (Validation); 0.30 (Test)	MAE = 0.24 (Validation); 0.25 (Test)

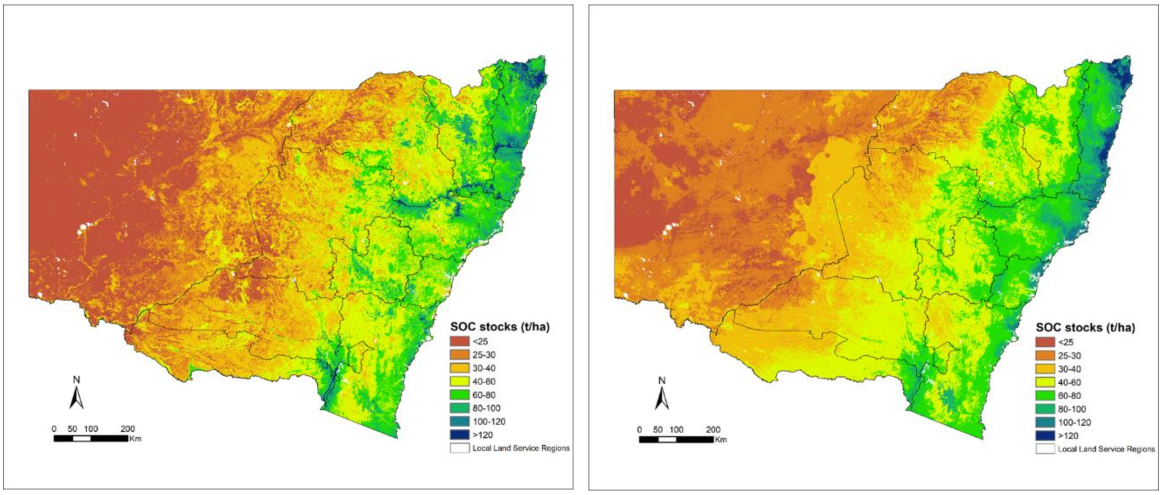


Figure IV a. Current SOC stock (t ha^{-1}, 0-30 cm) for MLR (left) and RF (right) at 100 m resolution

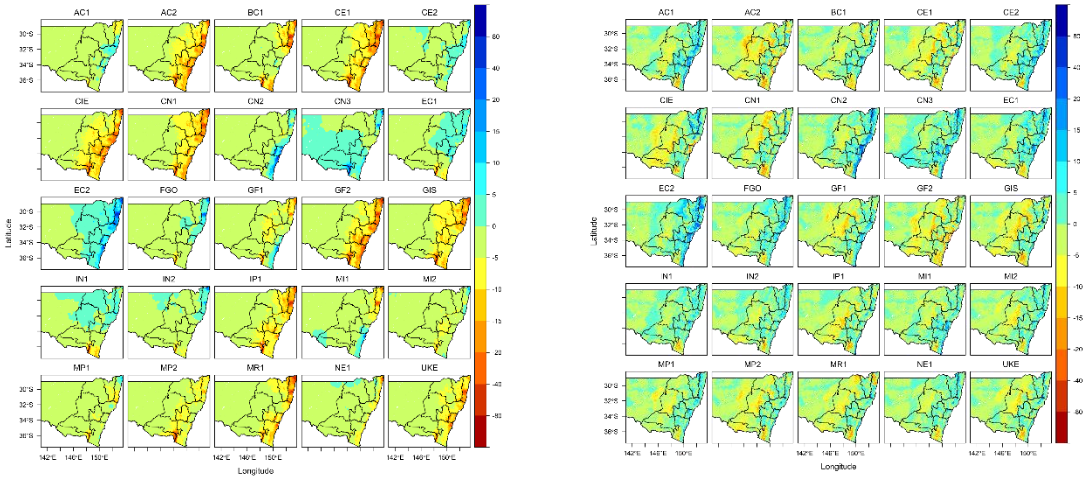
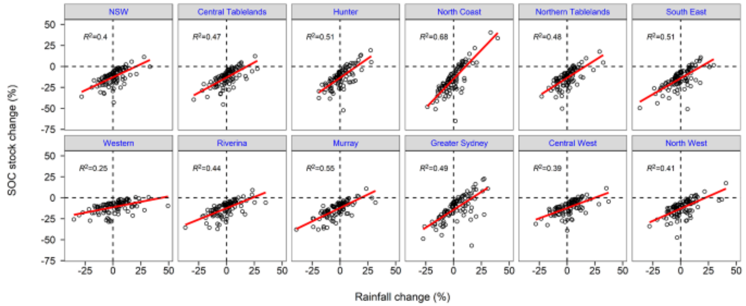
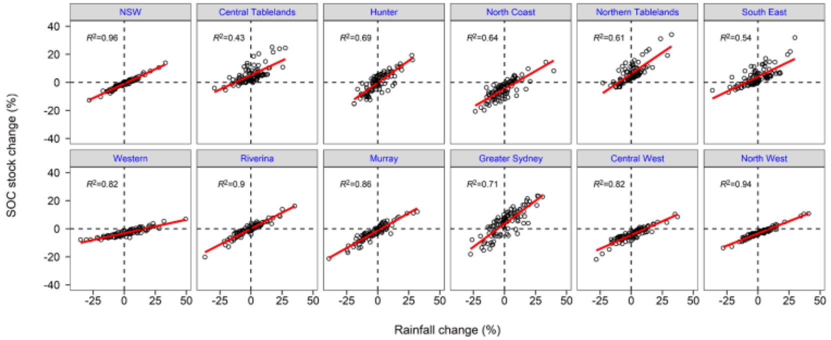


Figure IV b. SOC stock change (t ha^{-1}, 0-30 cm) in 2030-2059 (2050s) under SSP245 compared to the baseline (1990-2019) based on MLR (left) and RF (right) for each of 25 GCMs

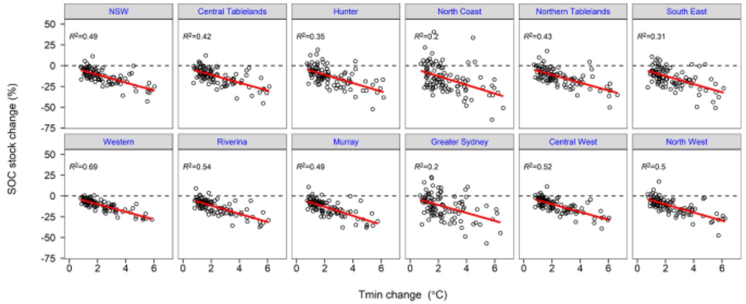
The relationship between SOC stock change (MLR) and rainfall change for different regions



The relationship between SOC stock change (RF) and rainfall change for different regions



The relationship between SOC stock change (MLR) and minimum temperature change for different regions



The relationship between SOC stock change (RF) and minimum temperature change for different regions

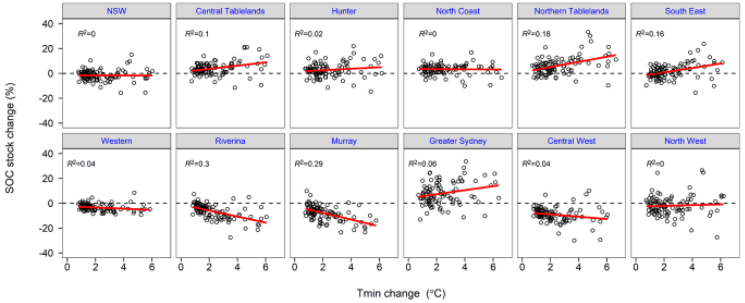


Figure IV c. Relationships between SOC stock change (%) and two important variables (rainfall and minimum temperature) across LLS regions in NSW. Generally, relationships between SOC stock change and rainfall and were consistent between the two modelling approaches, Multiple Linear Regression (MLR) and Random Forests (RF). However, there were large inconsistencies between regions for the relationship between minimum temperature and SOC stock change.

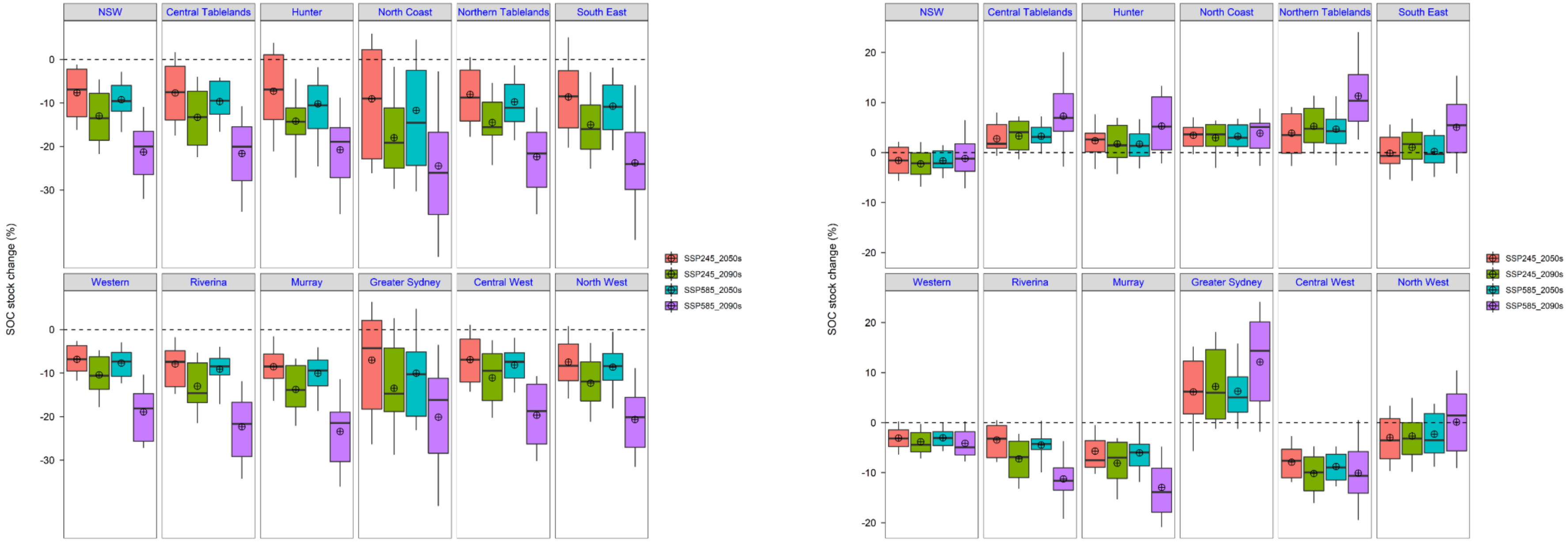


Figure IV d. SOC stock change (%) for different LLS regions under different scenarios compared to the baseline (1990-2019) for Multiple Linear Regression (left) and Random Forests (right).

References (Appendix IV)

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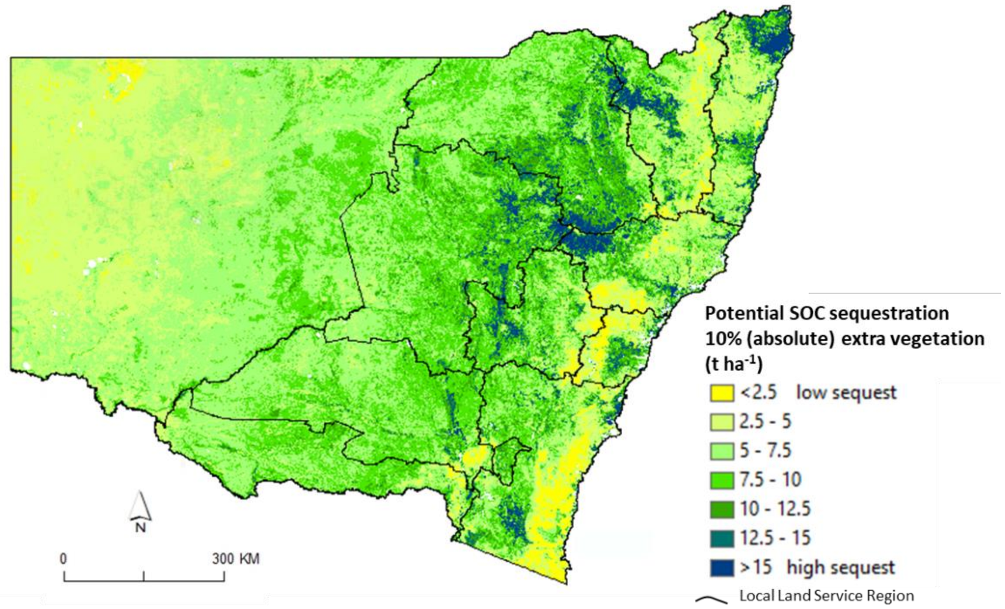
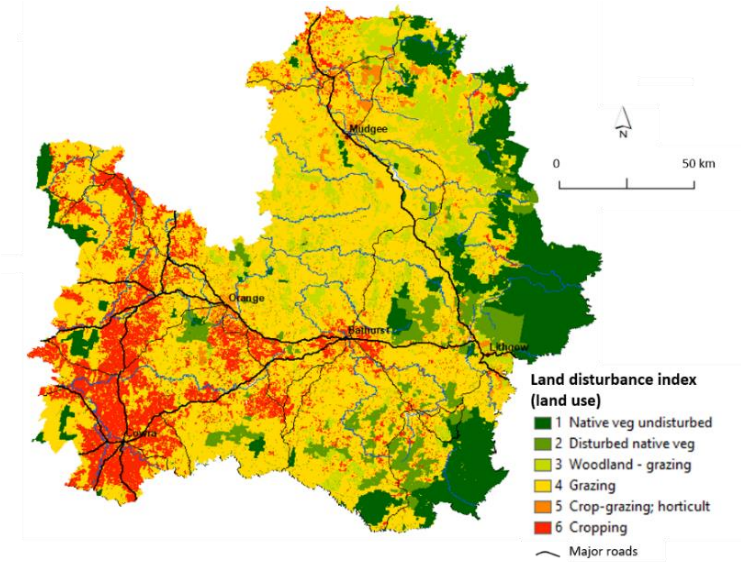
Appendix V. Soil carbon sequestration potential across NSW Local Land Services regions (with 10% absolute increase in vegetation cover)

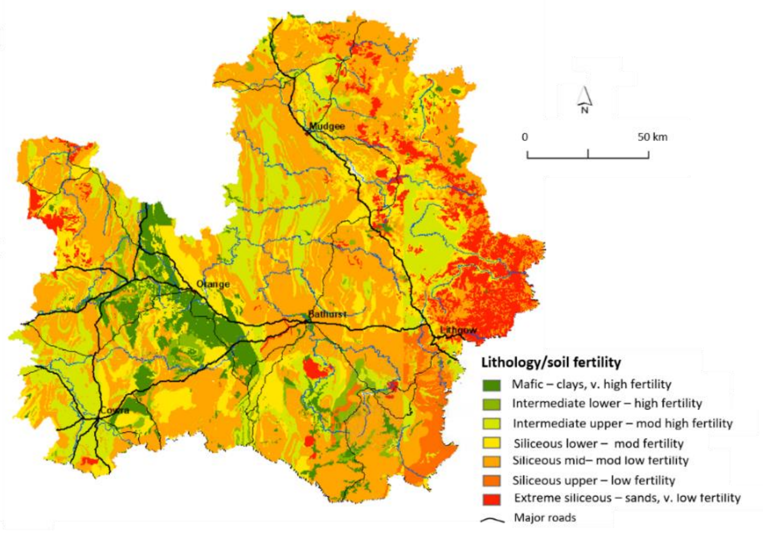


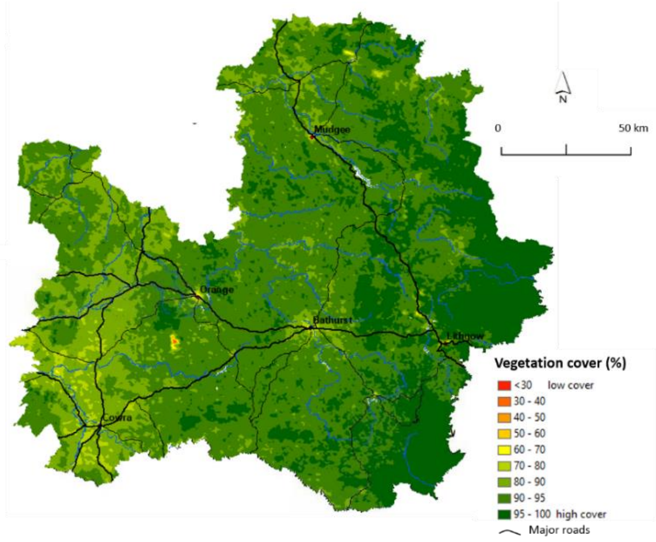
Potential SOC sequestration with 10% absolute extra vegetation cover over NSW.

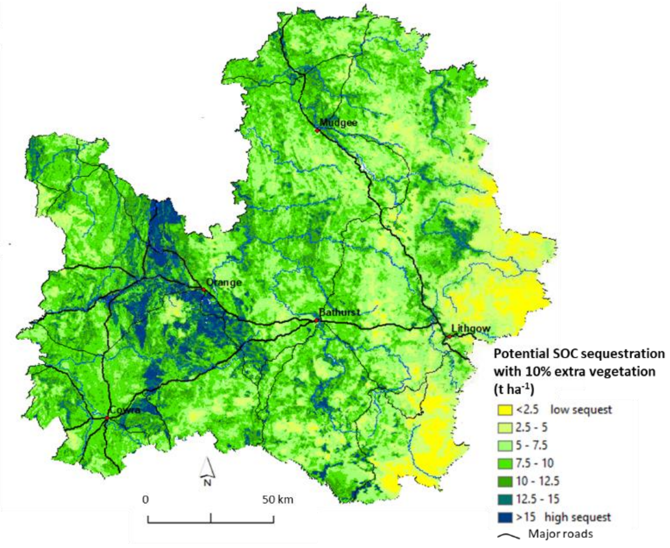
For each LLS region, the current land use (2017), vegetation cover 2000-2017 (total fractional cover – living and dead – MODIS, Geology and soils, and the potential SOC sequestration with a 10% change in absolute cover is given.

Central Tablelands LLS

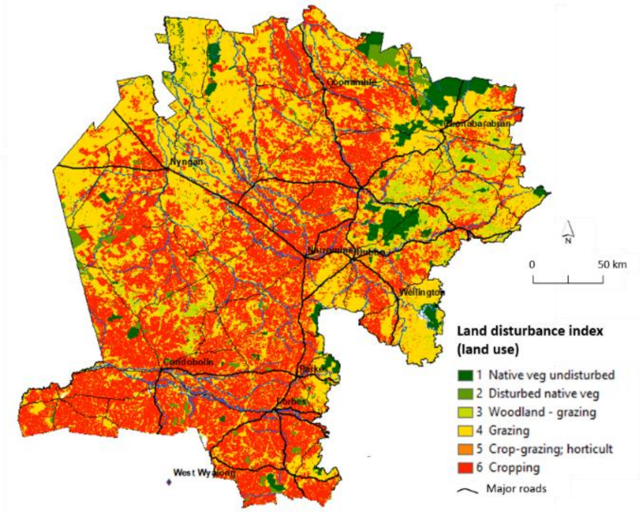








Central West LLS



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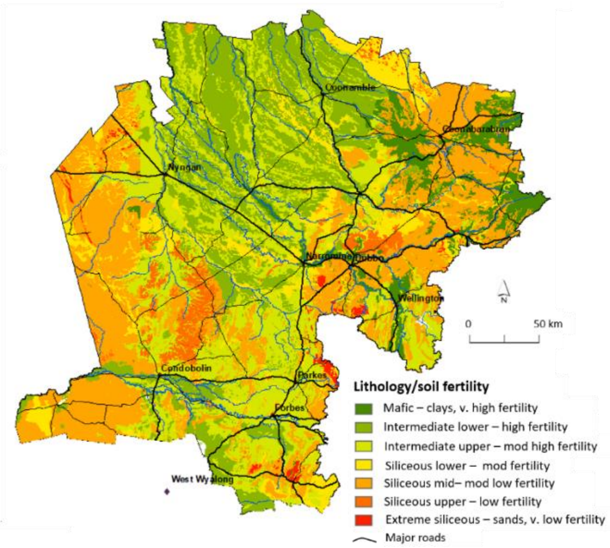
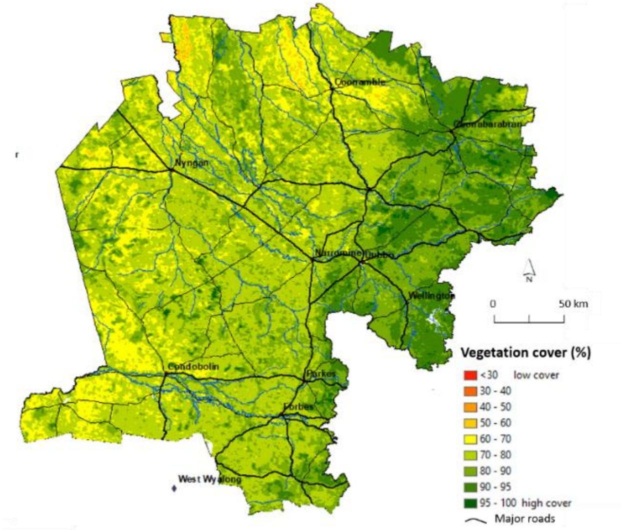
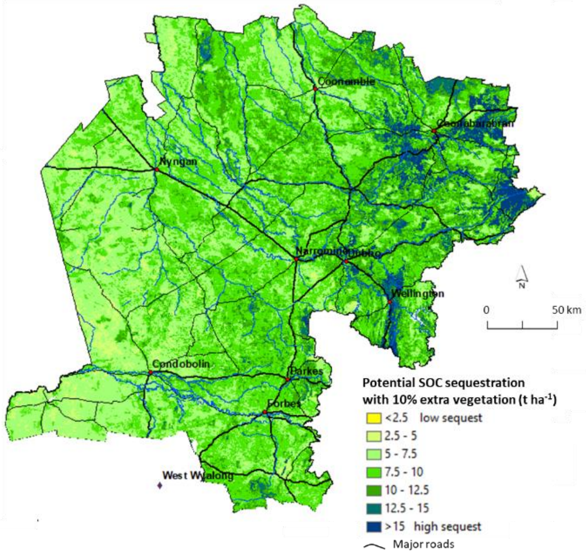
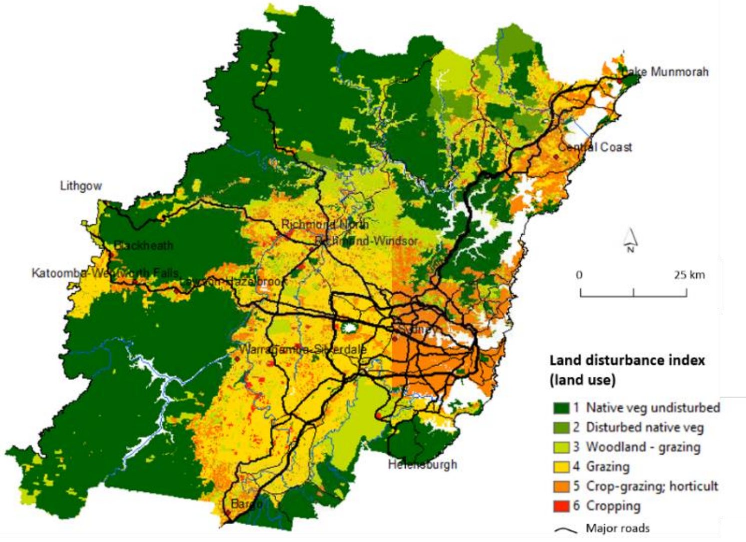
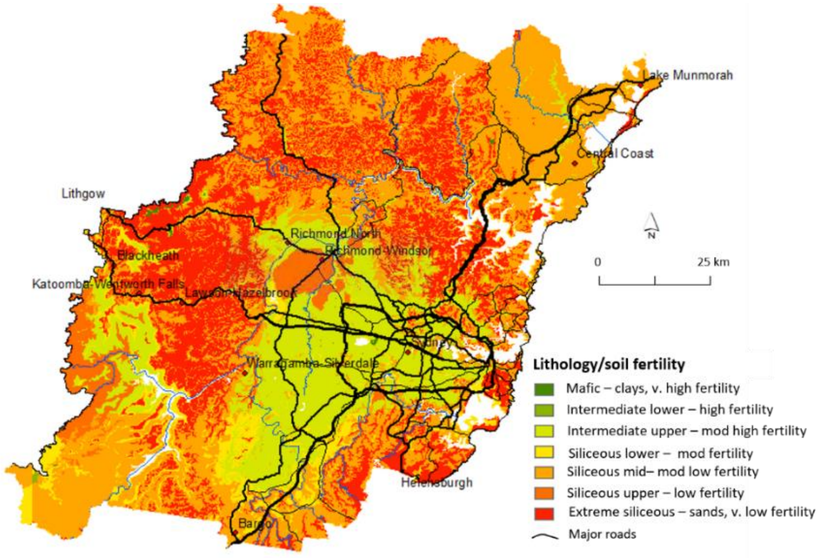


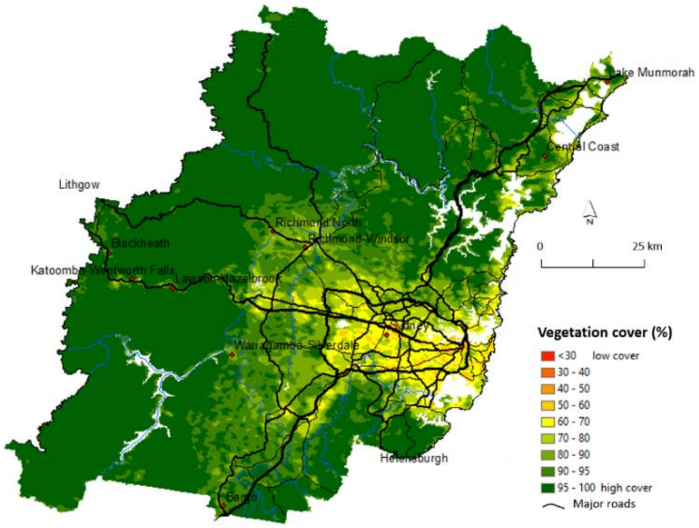


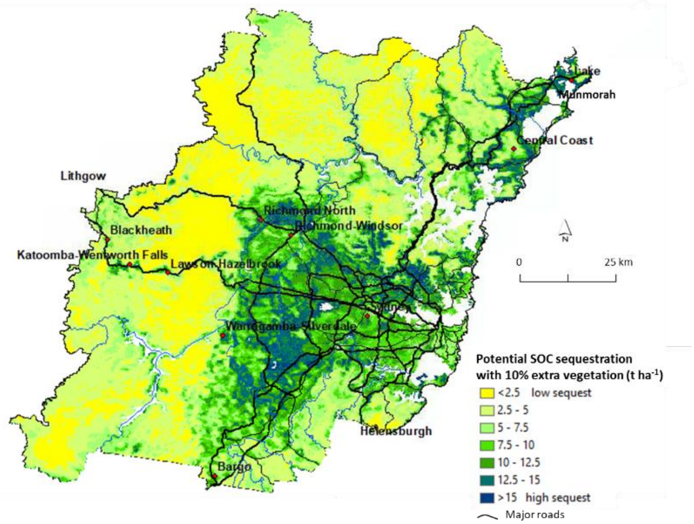


Greater Sydney LLS

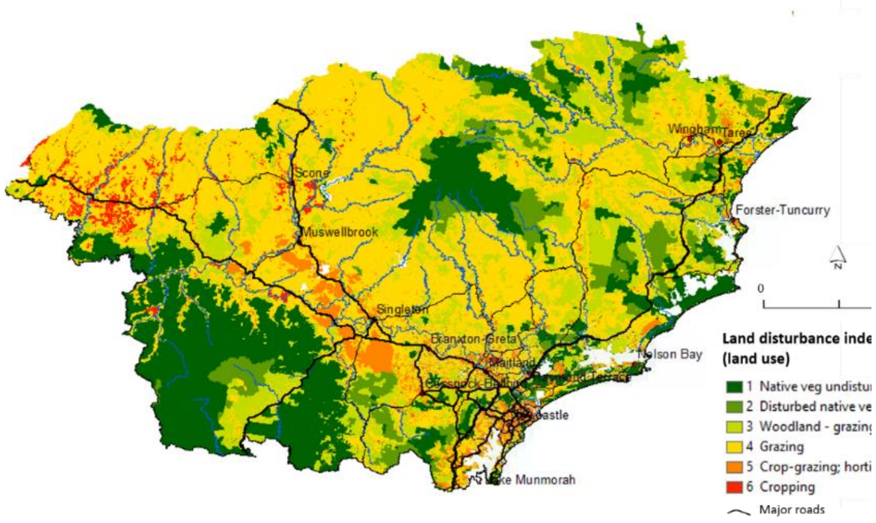


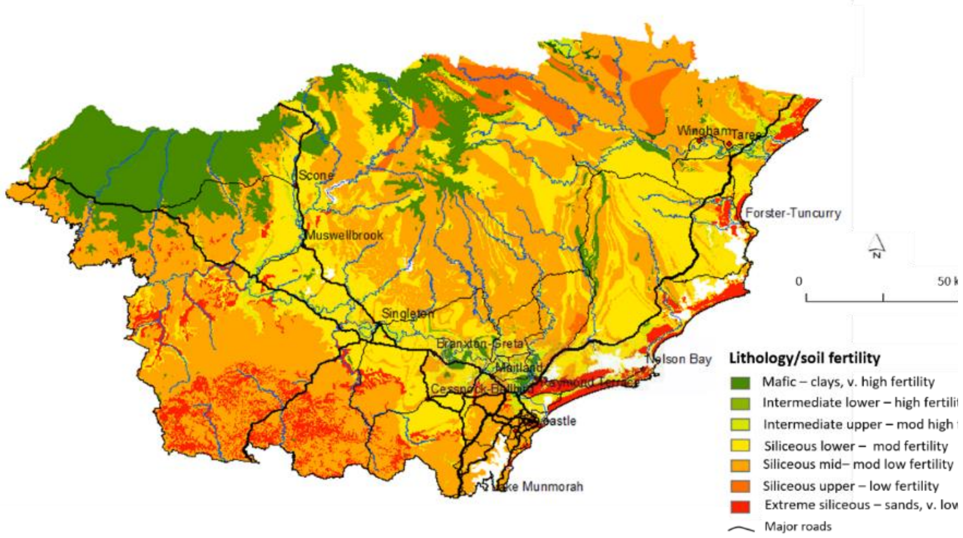


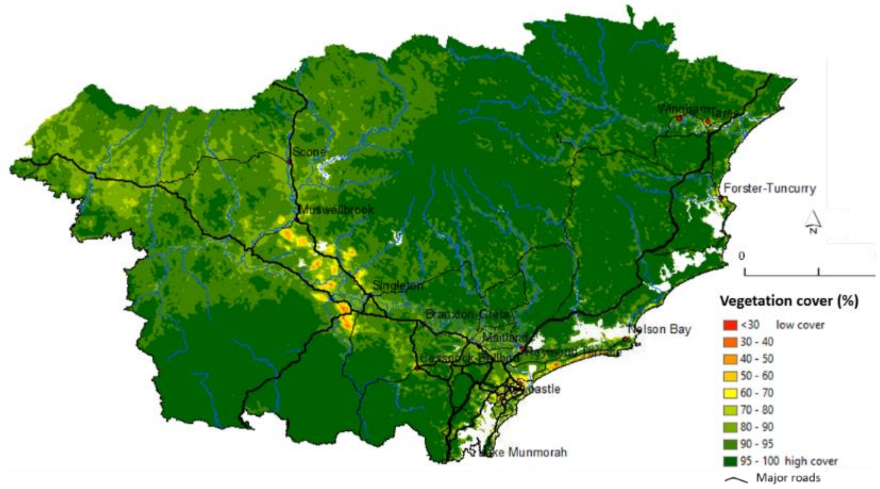


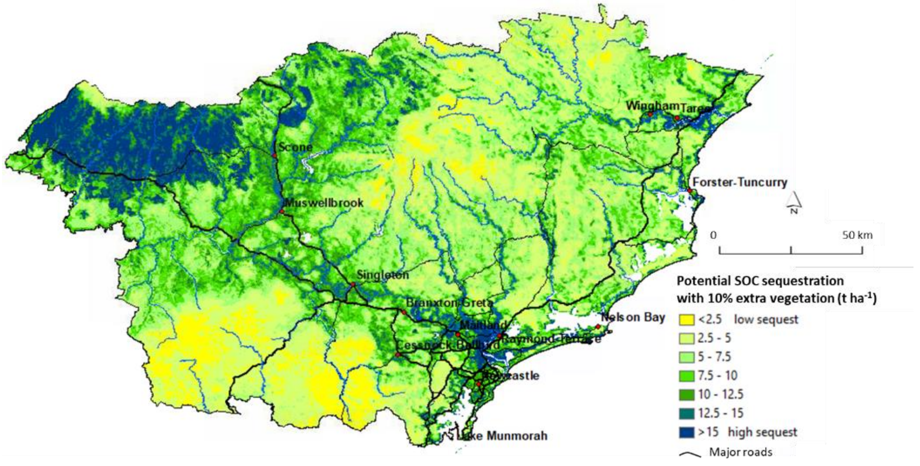


Hunter LLS

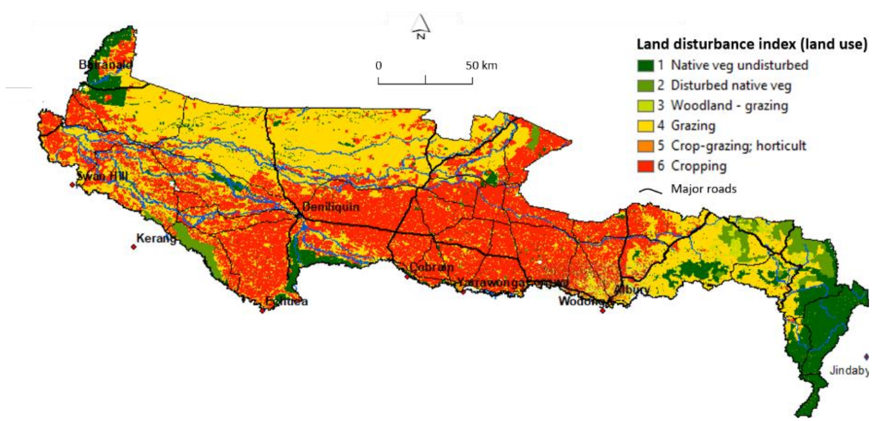

Wingham Taree
Scone
Forster-Tuncurry
Muswellbrook
Singleton
Branxton-Greta
Maitland
Cessnock-Bellbird
Nelson Bay
Newcastle
Lake Munmorah
0
Land disturbance inde
(land use)
🟩 1 Native veg undistu
🟩 2 Disturbed native ve
🟩 3 Woodland - grazin
🟨 4 Grazing
🟧 5 Crop-grazing; horti
🟥 6 Cropping
Major roads

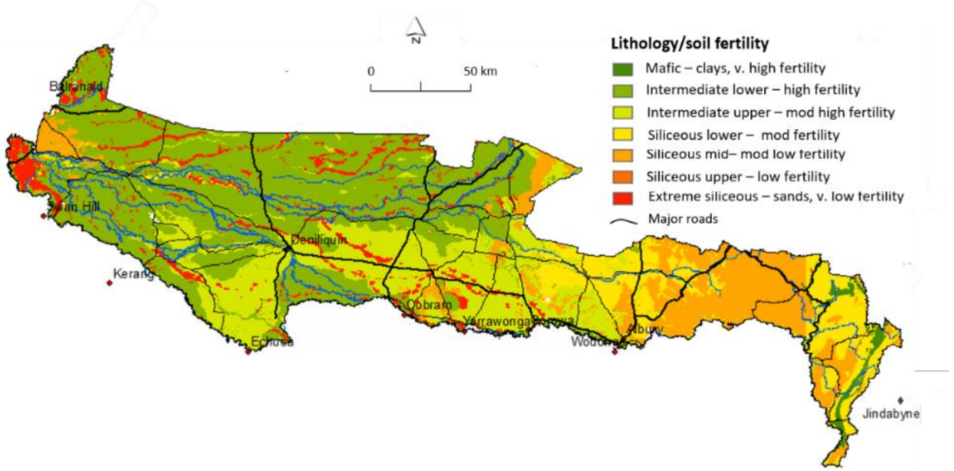

Wingham Taree
Scone
Forster-Tuncurry
Muswellbrook
Singleton
Branxton-Greta
Maitland
Cessnock-Bellbird
Raymond Terrace
Nelson Bay
Newcastle
Lake Munmorah
0
50 k
Lithology/soil fertility
🟩 Mafic – clays, v. high fertility
🟩 Intermediate lower – high fertili
🟨 Intermediate upper – mod high
🟨 Siliceous lower – mod fertility
🟧 Siliceous mid– mod low fertility
🟧 Siliceous upper – low fertility
🟥 Extreme siliceous – sands, v. low
Major roads


Wingham Taree
Scone
Forster-Tuncurry
Muswellbrook
Singleton
Branxton-Greta
Maitland
Cessnock-Bellbird
Nelson Bay
Newcastle
Lake Munmorah
0
Vegetation cover (%)
🟥 <30 low cover
🟧 30 - 40
🟧 40 - 50
🟨 50 - 60
🟨 60 - 70
🟩 70 - 80
🟩 80 - 90
🟩 90 - 95
🟩 95 - 100 high cover
Major roads


Wingham Taree
Scone
Forster-Tuncurry
Muswellbrook
Singleton
Branxton-Greta
Maitland
Cessnock-Bellbird
Raymond Terrace
Nelson Bay
Newcastle
Lake Munmorah
0
50 km
Potential SOC sequestration
with 10% extra vegetation (t ha^{-1})
🟨 <2.5 low sequest
🟩 2.5 - 5
🟩 5 - 7.5
🟩 7.5 - 10
🟩 10 - 12.5
🟦 12.5 - 15
🟦 >15 high sequest
Major roads

Murray LLS


N
0
50 km
Land disturbance index (land use)
1 Native veg undisturbed
2 Disturbed native veg
3 Woodland - grazing
4 Grazing
5 Crop-grazing; horticult
6 Cropping
Major roads
Balranald
Swan Hill
Deniliquin
Kerang
Echuca
Cobram
Yarrawonga
Wodonga
Albury
Jindaby


N
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Lithology/soil fertility
Mafic – clays, v. high fertility
Intermediate lower – high fertility
Intermediate upper – mod high fertility
Siliceous lower – mod fertility
Siliceous mid– mod low fertility
Siliceous upper – low fertility
Extreme siliceous – sands, v. low fertility
Major roads
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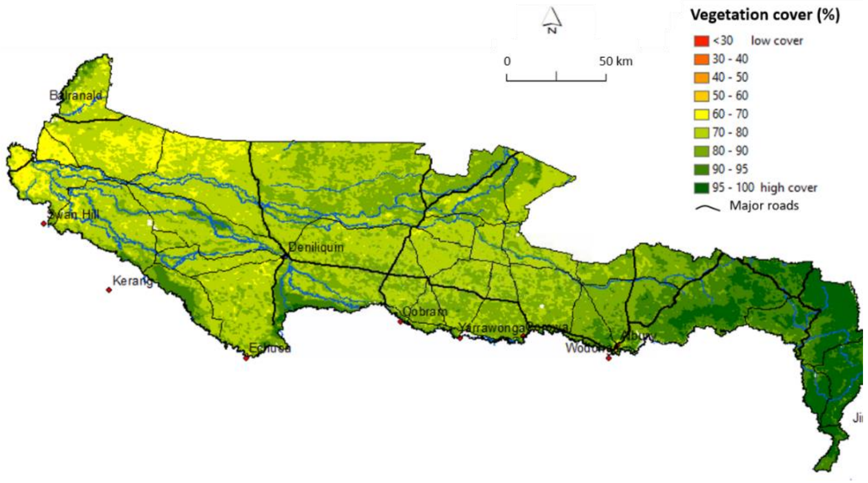
Swan Hill
Deniliquin
Kerang
Echuca
Cobram
Yarrawonga
Wodonga
Albury
Jindabyne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Vegetation cover (%)
<30 low cover
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 95
95 - 100 high cover
Major roads
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Kerang
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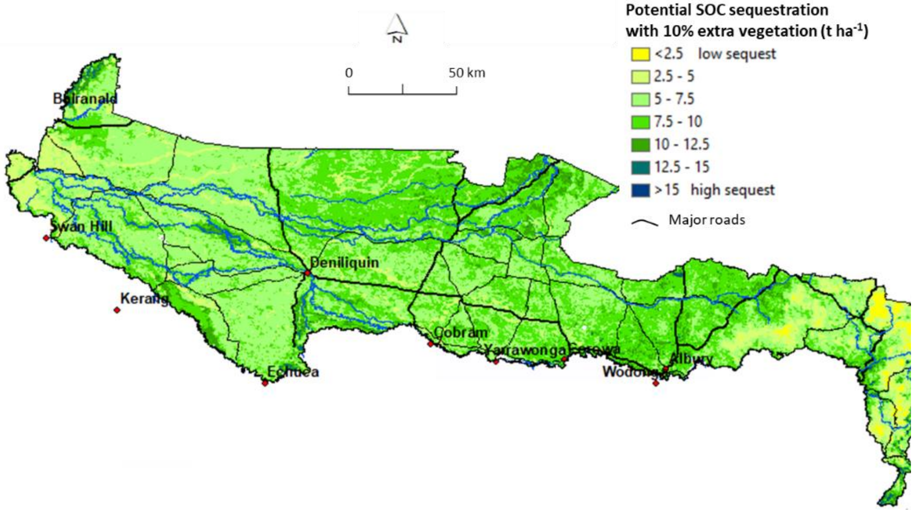
Cobram
Yarrawonga
Wodonga
Albury
Ji


N
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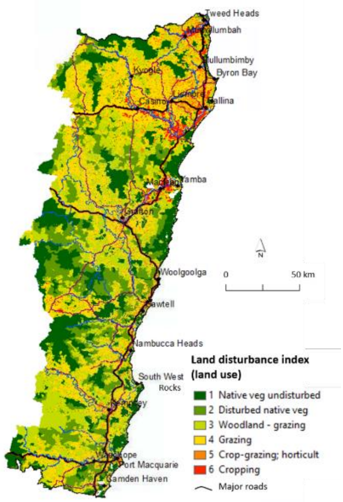
50 km
Potential SOC sequestration with 10% extra vegetation (t ha-1)
<2.5 low sequest
2.5 - 5
5 - 7.5
7.5 - 10
10 - 12.5
12.5 - 15
>15 high sequest
Major roads
Balranald
Swan Hill
Deniliquin
Kerang
Echuca
Cobram
Yarrawonga
Wodonga
Albury

North Coast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Grafton
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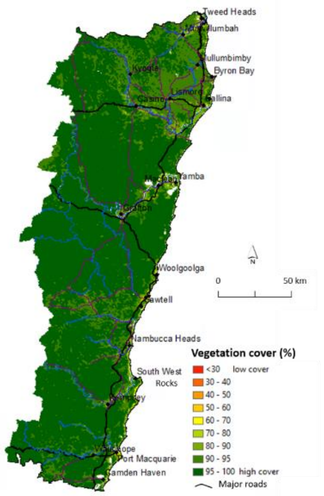
Sawtell
Nambucca Heads
South West Rocks
Kempsey
Wauchope
Port Macquarie
Camden Haven
N
0
50 km
Land disturbance index (land use)
1 Native veg undisturbed
2 Disturbed native veg
3 Woodland - grazing
4 Grazing
5 Crop-grazing; horticult
6 Cropping
Major roads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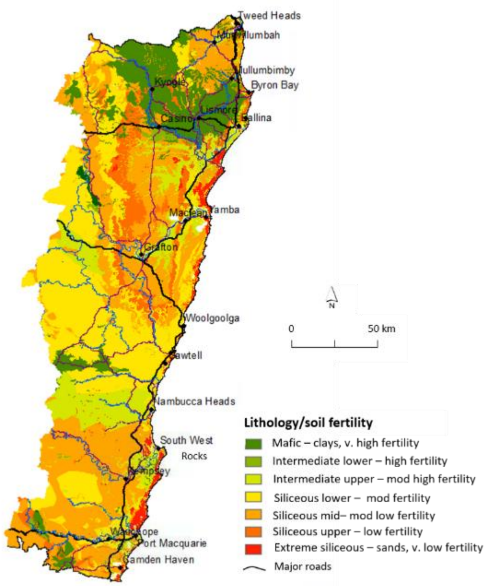
Sawtell
Nambucca Heads
South West Rocks
Kempsey
Wauchope
Port Macquarie
Camden Haven
N
0
50 km
Vegetation cover (%)
<30 low cover
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 95
95 - 100 high cover
Major roads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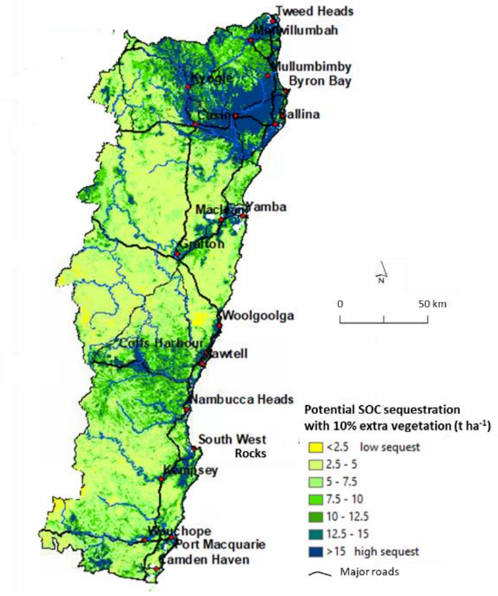
Sawtell
Nambucca Heads
South West Rocks
Kempsey
Wauchope
Port Macquarie
Camden Haven
N
0
50 km
Lithology/soil fertility
Mafic – clays, v. high fertility
Intermediate lower – high fertility
Intermediate upper – mod high fertility
Siliceous lower – mod fertility
Siliceous mid– mod low fertility
Siliceous upper – low fertility
Extreme siliceous – sands, v. low fertility
Major roads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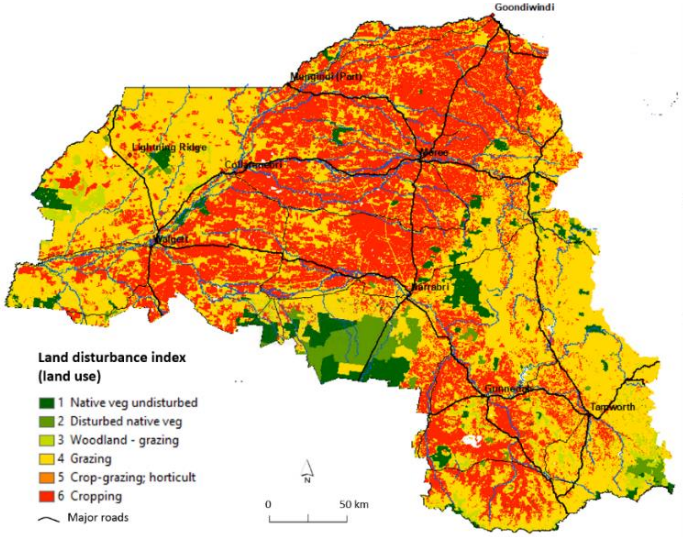
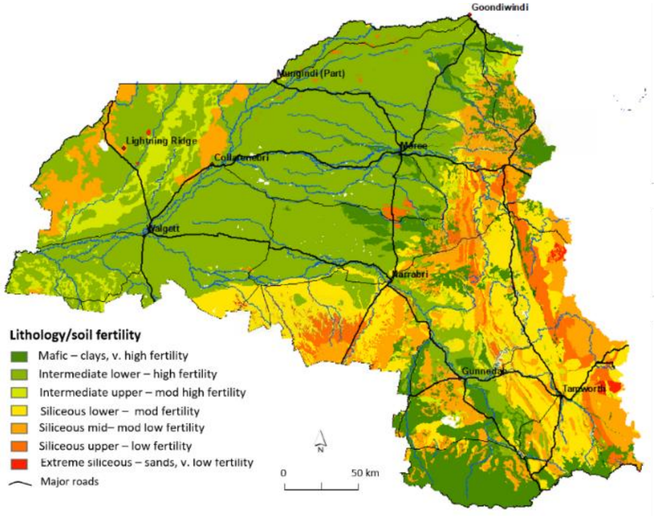
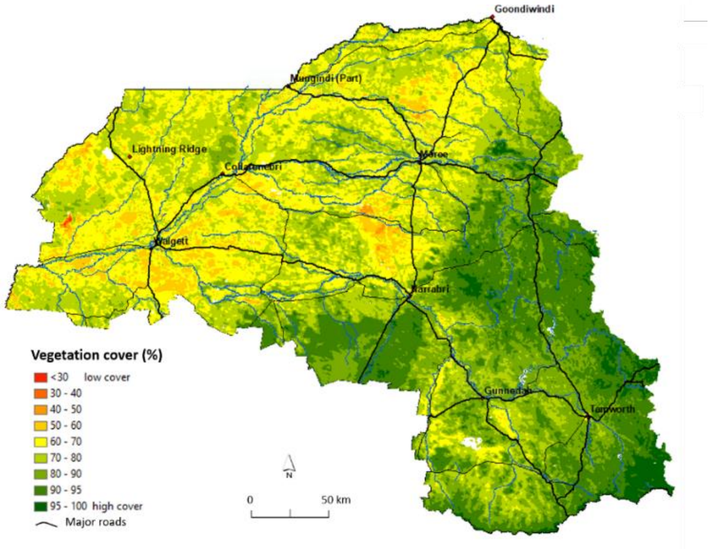
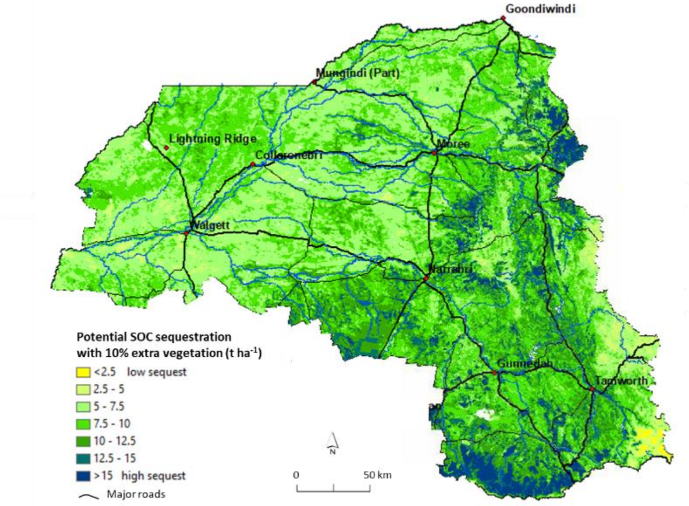
Maclean
Yamba
Grafton
Woolgoolga
Coffs Harbour
Sawtell
Nambucca Heads
South West Rocks
Kempsey
Wauchope
Port Macquarie
Camden Haven
N
0
50 km
Potential SOC sequestration with 10% extra vegetation (t ha^{-1})
<2.5 low sequest
2.5 - 5
5 - 7.5
7.5 - 10
10 - 12.5
12.5 - 15
>15 high sequest
Major roads

North West LLS









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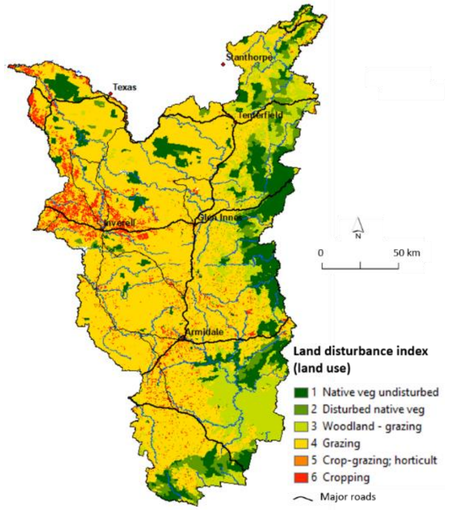
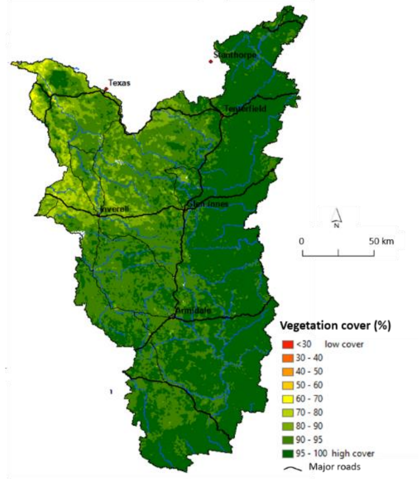
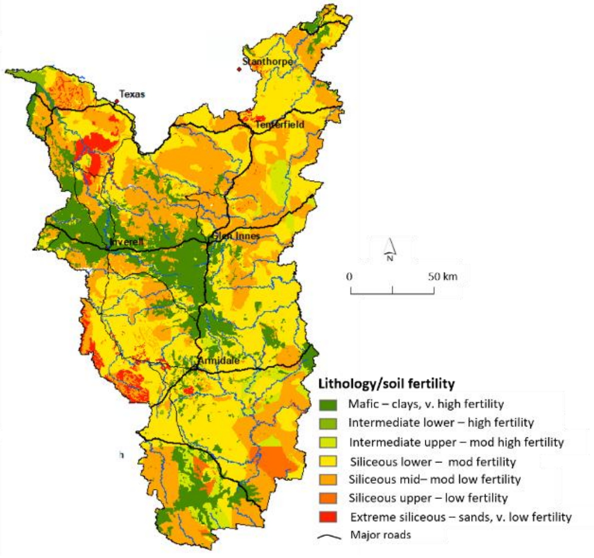
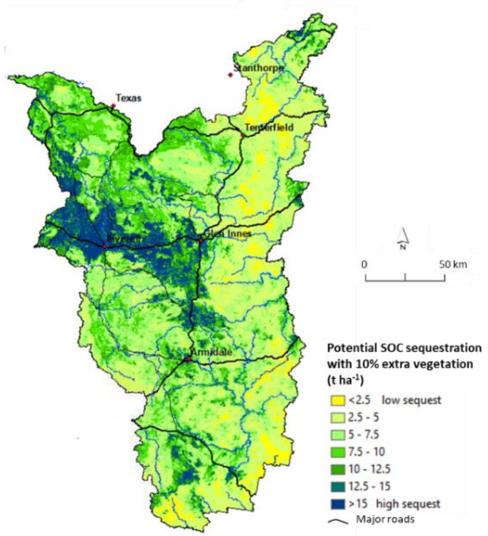
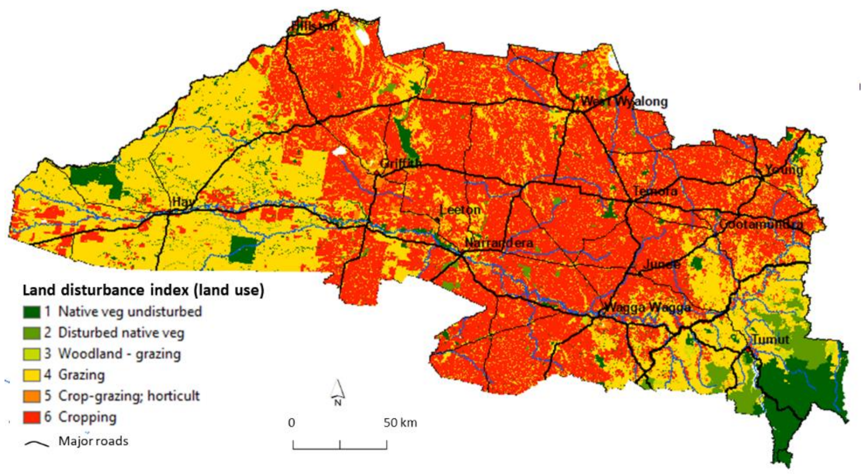


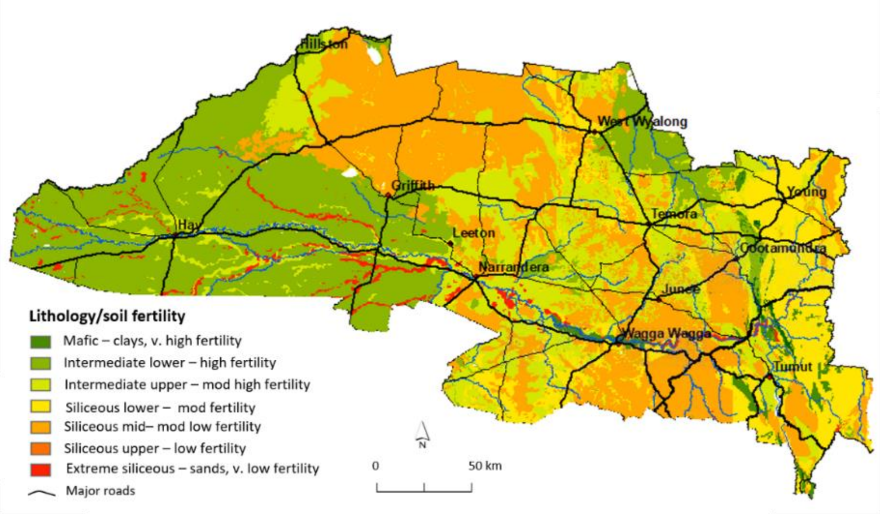


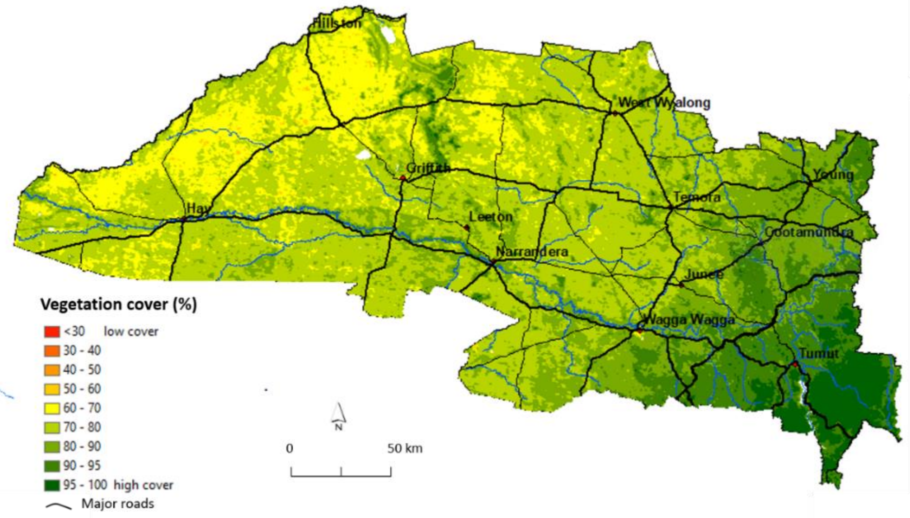


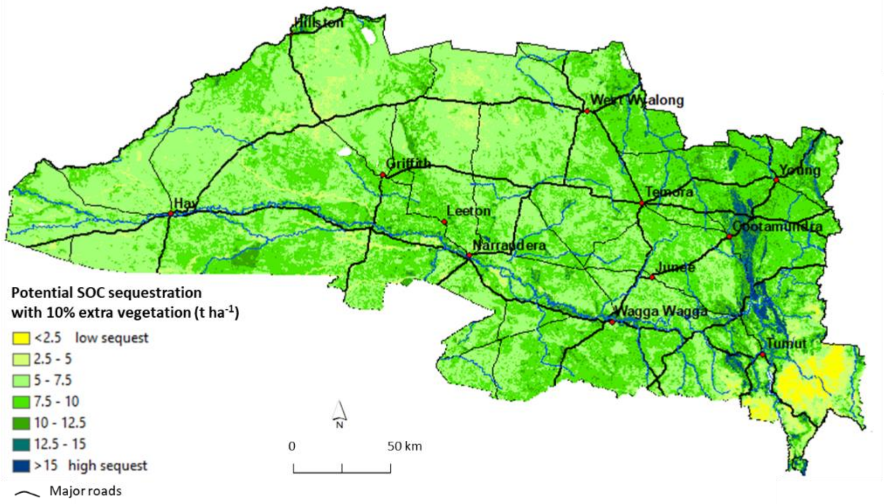


Riverina LLS









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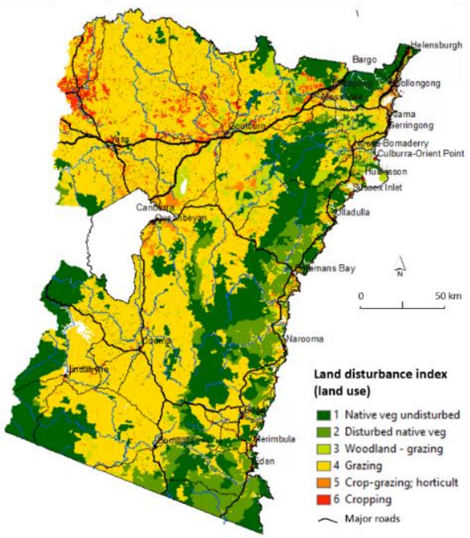
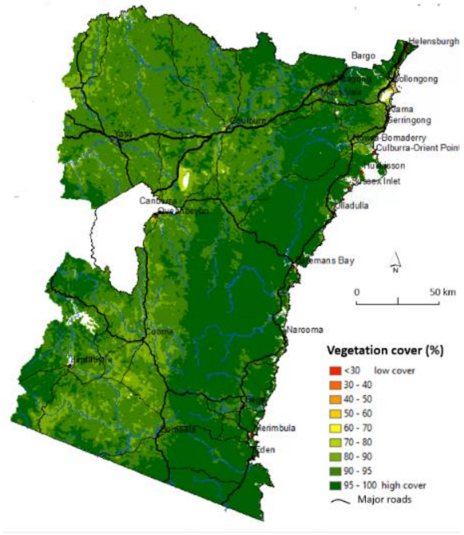
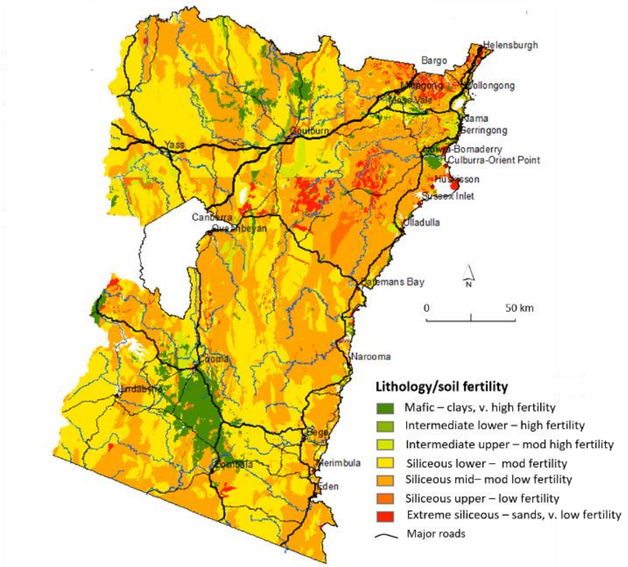
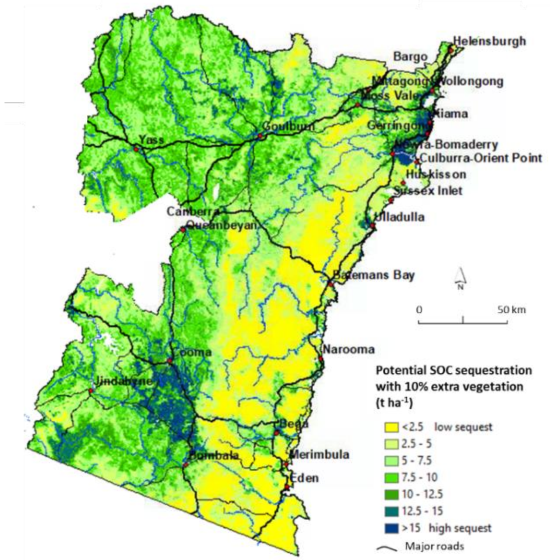
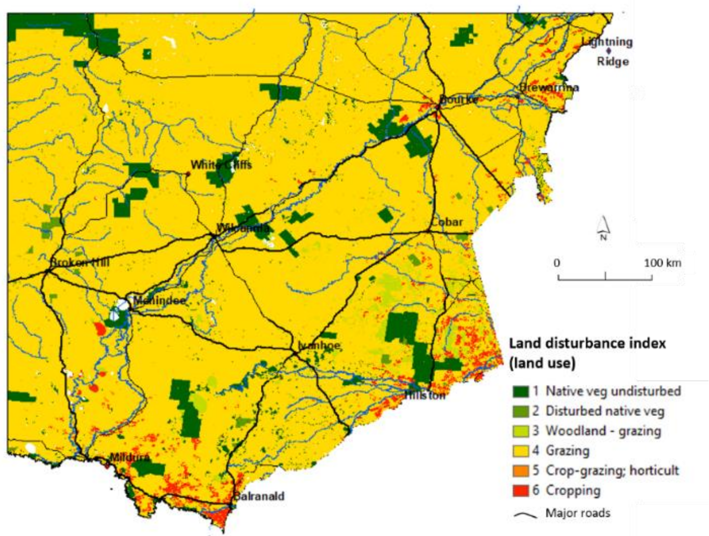








Western LLS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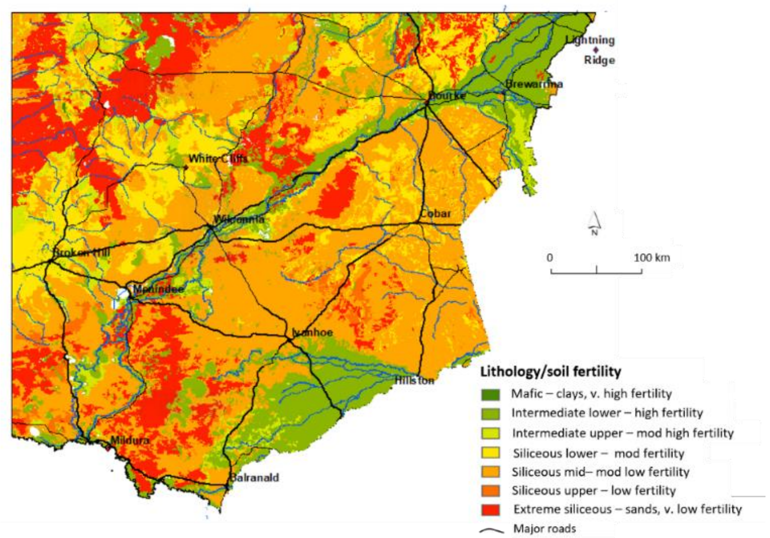
Brewarrina
Bourke
White Cliffs
Wilcannia
Cobar
Broken Hill
Menindee
Ivanhoe
Hillston
Mildura
Balranald
N
0
100 km
Land disturbance index (land use)
1 Native veg undisturbed
2 Disturbed native veg
3 Woodland - grazing
4 Grazing
5 Crop-grazing; horticult
6 Cropping
Major roads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Extreme siliceous – sands, v. low fertility
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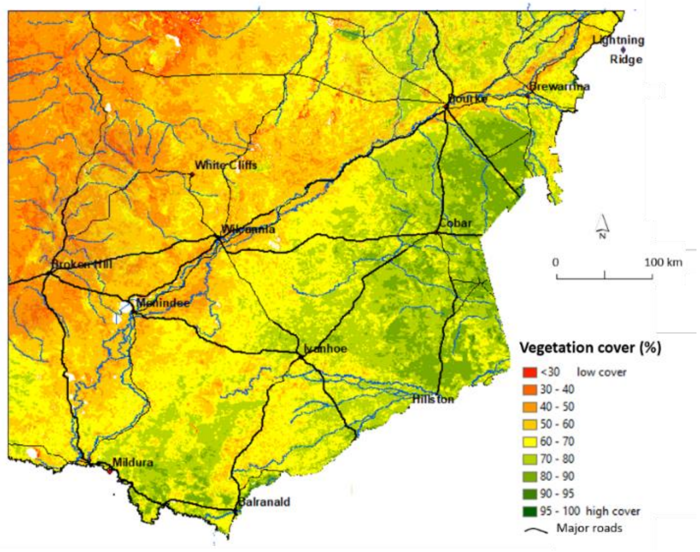
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Wilcannia
Cobar
Broken Hill
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Ivanhoe
Hillston
Mildura
Balranald
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100 km
Vegetation cover (%)
<30 low cover
30 - 40
40 - 50
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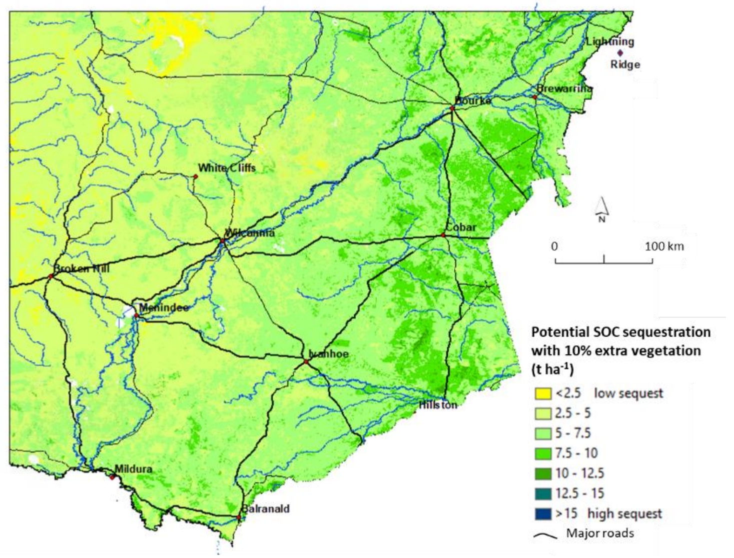
80 - 90
90 - 95
95 - 100 high cover
Major roads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Menindee
Ivanhoe
Hillston
Mildura
Balranald
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0
100 km
Potential SOC sequestration with 10% extra vegetation (t ha-1)
<2.5 low sequest
2.5 - 5
5 - 7.5
7.5 - 10
10 - 12.5
12.5 - 15
>15 high sequest
Major roads

Appendix VI. Factors influencing adoption of strategies to reduce enteric methane emissions

Summary of the practicality, risks, barriers and co-impacts that are likely to influence adoption, and therefore the realization of the technical of enteric methane mitigation strategies. An estimate of feasible abatement potential per unit dry matter intake is provided, based on expert judgement, for different livestock production systems. Except where otherwise indicated, the estimates of abatement potential are based on Almeida et al *(in preparation)*.

Abate-ment strategy	Abatement mechanism	Ease of implementation	Risks and barriers	Co-benefits/ disbenefits	Abatement potential (% reduction per unit DMI)	Feasible abatement in 2030 **Effectiveness**[2] & Adoption[3]	Confid-ence[4]
Dietary modification:							
Macroalgae (*Asparag-opsis* seaweed)	Bromoform inhibits methano-genesis	Suitability: intensive systems Theoretically simple: Easy to supply in ration to lot-fed and supplemented cattle. Availability: Unavailable. Early stages of commercialisation Requires scaling up seaweed production and development of supply chain. Possibility to produce active ingredient using biosynthesis. Will not require APVMA registration as plant-based and making no label claim.	**Risks**: *Environmental, human health*: ozone depleting, volatile, potentially carcinogenic hydrocarbon *Animal*: high risk of failure: Few in vivo studies; impacts on production uncertain; potential for adverse impact on animal health. **Barriers**: availability, cost of algae production and drying. Unknown volatility.	-ve Halogenated ozone-depleting substance Potentially carcinogenic. Stability in dried form unknown. Seaweed production could impact water quality. Land required for algae production. Biosynthesis alternative also requires land for sugar production.	30-69	**50%** Ext cattle[5] 5% Int cattle[6] 5% Feedlot 60% Dairy 60% Sheep 5%	M
3-NOP	Inhibits methanogenesis by inactivating	Suitability: intensive systems	**Risks**:	+ve	18-39	**29%** Ext cattle 0%	H

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[2] Bold values: Reduction in enteric methane emissions per unit DMI in the year 2030 compared with 2020
[3] Plausible level of adoption if price and regulatory barriers are overcome
[4] Confidence that the estimated abatement will be delivered in 2030: L - low; M - medium; H - high.
[4] Extensive grazing - rangelands
[5] More intensive grazing systems, generally on improved pastures

	the enzyme methyl coenzyme M reductase	Potentially simple: lick-block or feed additive No impact on feed intake and fibre digestibility at mod levels. Moderate cost Availability: Commercialised Undergoing registration in Europe Registration required for Australian use. Slow-release forms being tested.	*Environmental, human health:* none known *Animal:* excess (>200 mg/kg DM) can lower DMI *Product:* No known residue problems **Barriers**: Not registered Requires frequent ingestion	Enhanced productivity (3% gain recorded)		Int cattle 2% Feedlot 60% Dairy 60% Sheep 0% *Adoption if slow release available*: Ext cattle 30% Int cattle 30% Feedlot 70% Dairy 70% Sheep 10%	
Nitrate	Alternative hydrogen sink	Suitability: all grazing cattle and sheep; feedlots, dairy Simple: provide in lick block. No impact on feed intake and fibre digestibility. Current ERF method for grazing cattle in lick-blocks. Availability: Commercially available	**Risks** *Environmental, human health:* potentially explosive *Livestock*: Risk of death at high rate (Risk controlled using lick or slow release forms.) Some adverse dairy experience *Product*: Low risk of nitrate and nitrite in milk **Barrier**: cost	+ve May enhance wool production -ve Nitrate production is GHG-intensive process	10-22	**16%** Adoption: Ext cattle 30% Int cattle 10% Feedlot 80% Dairy 40% Sheep 20%	H
Oils	Suppression of ciliate protozoa and archaea, biohydrogenation of free unsaturated fatty acids, reduction in organic matter fermentation, replacing	Suitability: intensive systems Simple: Easy to supply in ration to lot-fed and supplemented cattle. Commercially available Grazing animals. Not suitable, except as oilseed like whole cotton seed Availability: unrestricted	**Risks** *Environmental, human health:* None *Livestock:* 7% limit in diet No serious risk but can reduce DMI and fibre digestibility, so may not be suitable for animals on high-fibre diet (grazing lower quality pastures)	+ve Opportunity to improve *ω–3* fatty acids for meat quality. Can lift energy intake & so performance -ve Land required to produce oil crops.	12-20	**15%** Ext cattle 0% Int cattle 5% Feedlot 80% Dairy 40% Sheep 5%	H

	fermentable carbohydrates		*Product:* may be additional opportunity to alter ω–3: *ω*–6 positively **Barriers**: cost & unsuitability for grazing				
Phyto-chemicals feed additive Eg grape marc, tannins saponins Forage: eg Leucaena	Antimicrobial action of tannins	Moderate complexity: Additive: not readily available in formulation for easy delivery Availability: limited, inconsistent spatially and temporally Legumes: require establishment and management	**Barriers**: Feed additives: cost Not APVMA-approved May reduce productivity Logistics Legumes: Cost to establish and manage forage spp Leucaena not approved for planting in NSW (weed risk). Tagasaste possible alternative	+ve Legumes: Provides additional protein source in dry season to lift intake and performance -ve Tannins can reduce protein availability and diet acceptability Legumes: Weed risk on escape	8-14	**10%** Feed additive: Ext cattle 0% Int cattle 5% Feedlot 10% Dairy 20% Sheep 5% Forage: Ext cattle 20% Int cattle 10% Feedlot 0% Dairy 10% Sheep 5%	L to M
Ionophores	Inhibit ciliate protozoa	Suitability: feedlots, dairy. Simple in feedlot, dairy (add to ration/supplement) Moderate complexity for grazing animals: capsules? Availability: Commercially available (Monensin, Salinomycin, Lasalocid)	**Barrier**: Low efficacy cost Antibiotic rumen modifier	+ve Enhanced productivity Lower risk of acidosis -ve Perceived antimicrobial stewardship conflict with use	0.5-7.4 Short-term effect only	**4%** Feedlot 90% Dairy 70% Ext cattle 0% Int cattle 0%	H
Protozoa control	Elimination or long term suppression of protozoa	Suitability: feedlots, dairy Availability: No commercial protozoa control strategy available	**Risks**: variable according to methodology **Barriers**: Lack of practical technology	+ve Increase protein flow so may increase productivity and wool growth -ve May affect all eukaryotic cells (including animal gut & tissue)	-0.6-+14	**2%** If commercially available: Ext cattle 60% Int cattle 20% Feedlot 10% Dairy 60% Sheep 40%	M
Non-dietary strategies							

Vaccines	Inhibits rumen Archaea by salivary immuno-globulins	Suitability: All stock Simple delivery Low cost Availability: unavailable	**Risk**: Principle of vaccine for rumen microbe may be faulty. **Barriers**: Unproven, Unavailable		5-20[7]	**20%** Dairy & feedlot: 80% beef & sheep: 20%	L by 2030 M by 2050
Breeding	Select for reduced methane yield	Suitability: All stock Slow to deliver results, but easy uptake, permanent cumulative benefit.	**Risk** (low): Selection may compromise other economic traits **Barrier:** Insufficient economic incentive due to slow gain	+ve Increased profitability Enhanced growth rate	1.45% reduction per year[8] 2030: 3-7% reduction 2050: 15% reduction Adoption: dairy 50-90% beef/sheep 30-50%[9]	**5%** Dairy 10% beef 4% sheep 20%	H
Herd management	Improved emissions intensity: Cull unproductive animals, supplementary feeding, grazing management, to increase product yield per unit feed consumed	Suitability: All stock but mostly grazed cattle and sheep Simple: Known nutritional and animal management strategies	**Risk**: Low Barriers: none significant (consistent with best practice)	+ve Increased profitability -ve May lead to more productive animals so higher total emissions in sheep and beef enterprises despite lower emissions intensity	Effectiveness: variable Ext cattle 30% Int cattle 10% Feedlot 20% Dairy 10% Sheep 20%	**Dairy: 5%** Adoption: 80% **Beef: 15%** Adoption: 80% **Sheep: 10%** Adoption: 50%	H
Pasture management	Improved emissions intensity: Lower CH_4 per unit feed and faster growth rate with higher quality diet. Higher quality	Suitability: Grazed cattle and sheep More nutritional pastures lead to a lower % of consumed energy going to maintenance, so product per unit CH4 increased	**Risk (low)**: low risk for intensity effect on back of productivity rise but high uncertainty in methane yield effect **Barriers**: cost	+ve Increased SOC, higher returns, more resilient farming system -ve	Effectiveness: 0.4 -4.2%	**2%** Ext cattle 10% Int cattle 10% Feedlot 0% Dairy 10% Sheep 20%	M

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[7] MLA 2018

[8] Fennessy et al, 2018

[9] Reisinger et al., 2018

	pasture species through grazing management, pasture improvement		(limited abatement relative to cost) Emission mitigation varies throughout the year with seasonal variation in pasture quality	Higher fertiliser use may cause eutrophication, N_2O emissions			

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