10.1071/RJ20034_AC

Supplementary Material: *The Rangeland Journal*, 2020, **42(4–5), 293–307.**

Carbon farming for resilient rangelands: people, paddocks and policy

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Supplementary material

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 emission.

Table S1 provides a summary of current land sector methods for the ERF and recognised management activities. The methods most relevant to NSW rangelands are highlighted in **bold,** including key eligibility rules that apply to each method. These requirements were used to produce maps of technically suitable areas in rangelands of 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 actual area suitable.

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**	**HIR**	Management that assists recruitment (seed) of re-sprouting (rootstock).	Regrowth on cleared land in the past must have been supressed (e.g. by ongoing

	permanent even-aged Native Forest		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.	livestock grazing, feral animals, plants not native to the area, or mechanical or chemical destruction/suppression) Regrowth is expected
1.3 Reforestation and afforestation	**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 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
	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

Establishment of permanent tree plantings			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
1.5 Increasing soil carbon	**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 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	Land has been used for agriculture for at least 1 out of the last 5 years

			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

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. The forest cover must be at least 0.2 hectares in land size, and dominated by trees that are at least two meters tall. In addition, the forest area must cover at least 20 percent of the land area. Forest 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. All but one clearing content issued by 01 July 2010 have AD projects, and there are no further areas suitable for this method (*P. Theakston pers. comm).*

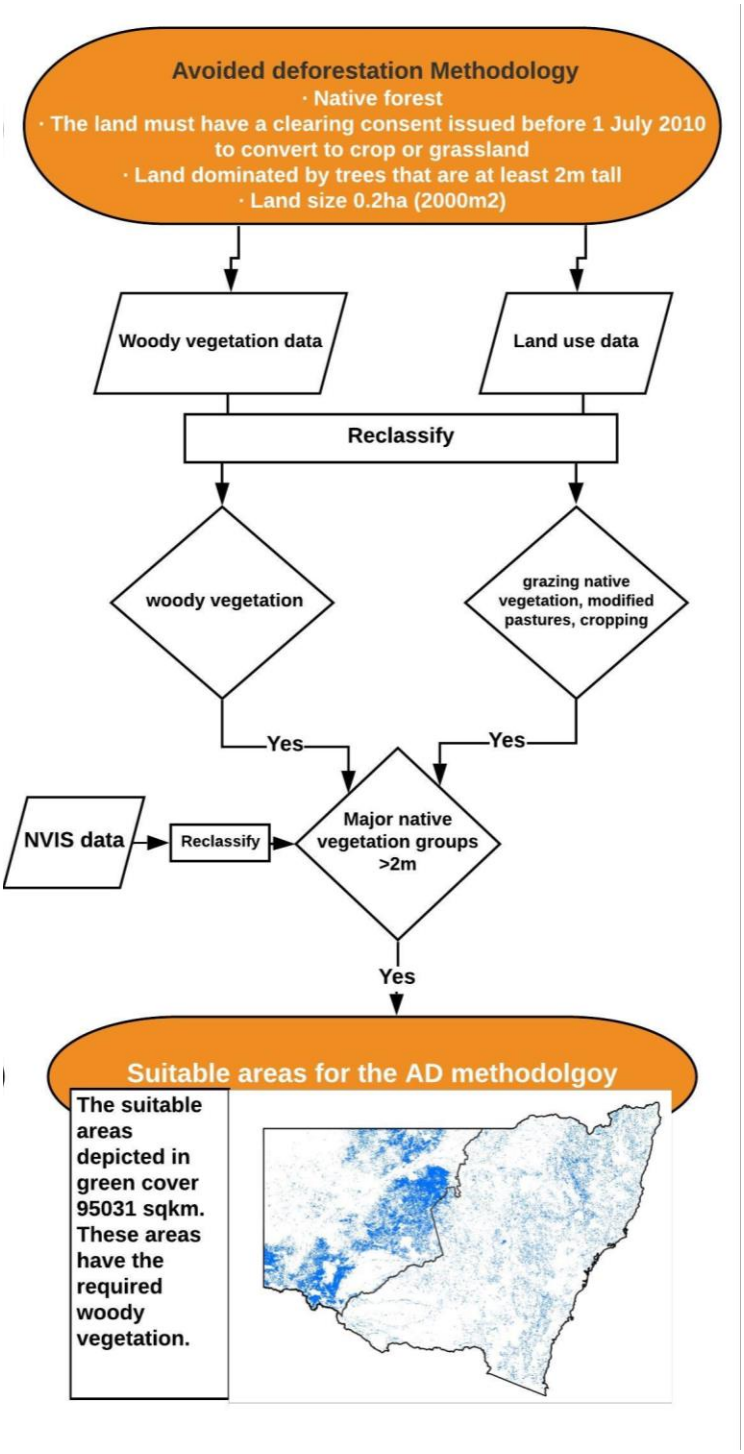

Figure S1. Flow diagram indicating the spatial analysis process and data sources used to identify areas theoretically suitable for AD in NSW. The output map shows 95,031 km^2 are suitable for AD, mainly in in the western NSW. However, the requirement of having a clearing consent issued by 01 July 2010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

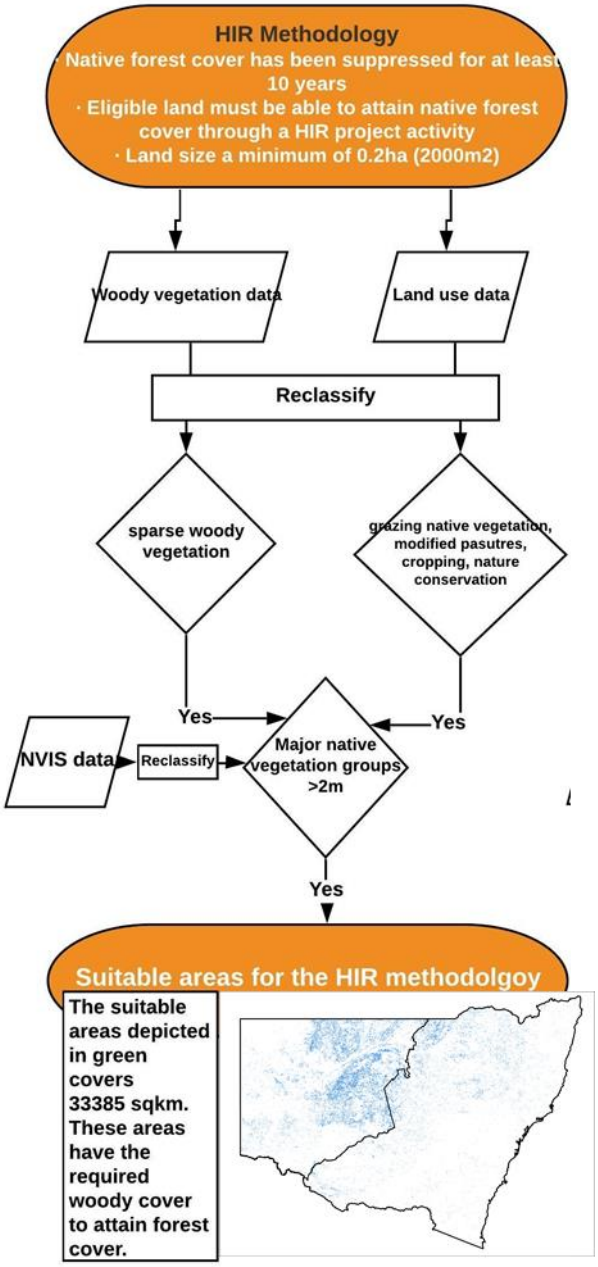

Figure S2. Flow diagram indicating the process and data sources used to identify areas theoretically suitable for HIR in NSW. The output map shows 33385 km^2 concentrated in western NSW are suitable for HIR.

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.

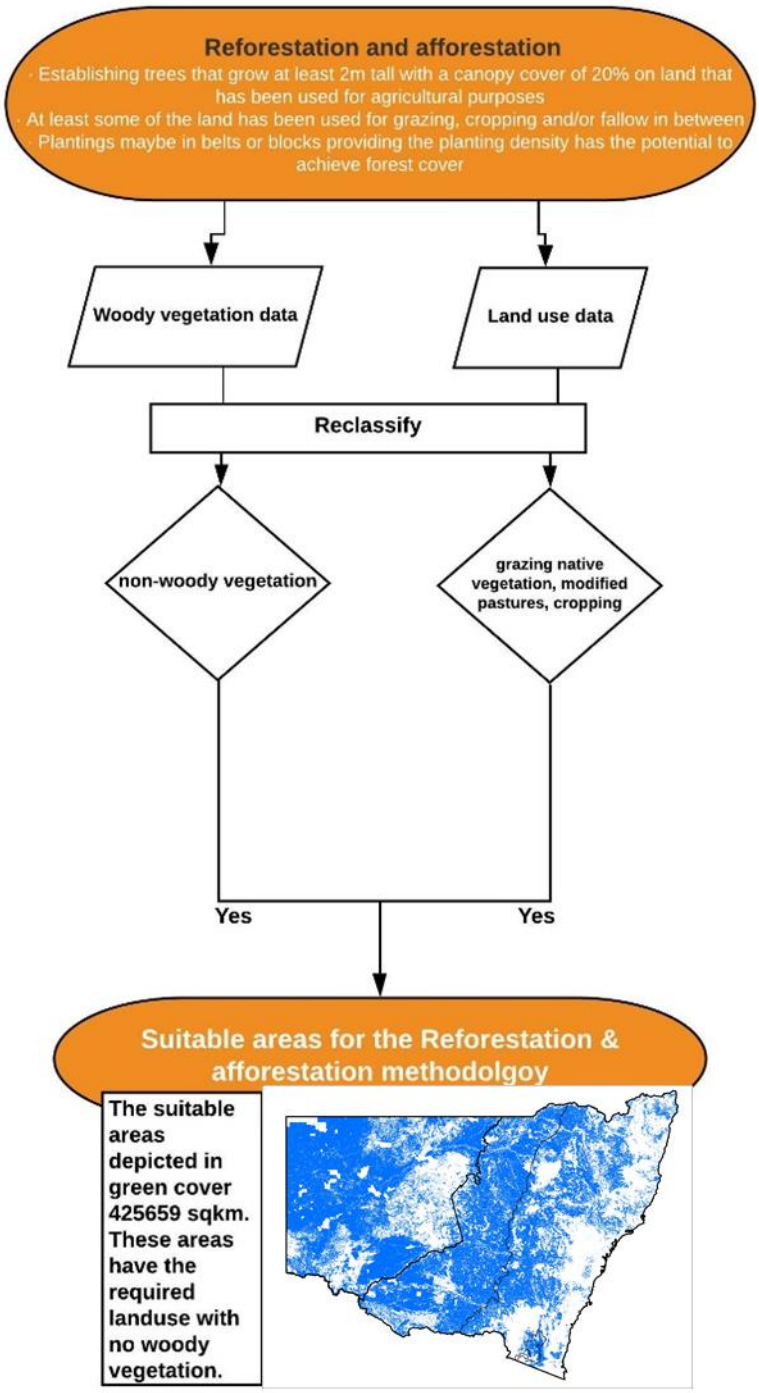

Figure S3. Flow diagram indicating the spatial analysis process and data sources used to identify areas theoretically suitable for Reforestation and afforestation methods in NSW. The output map shows 425,659 km^2 theoretically suitable (see Figure S4).

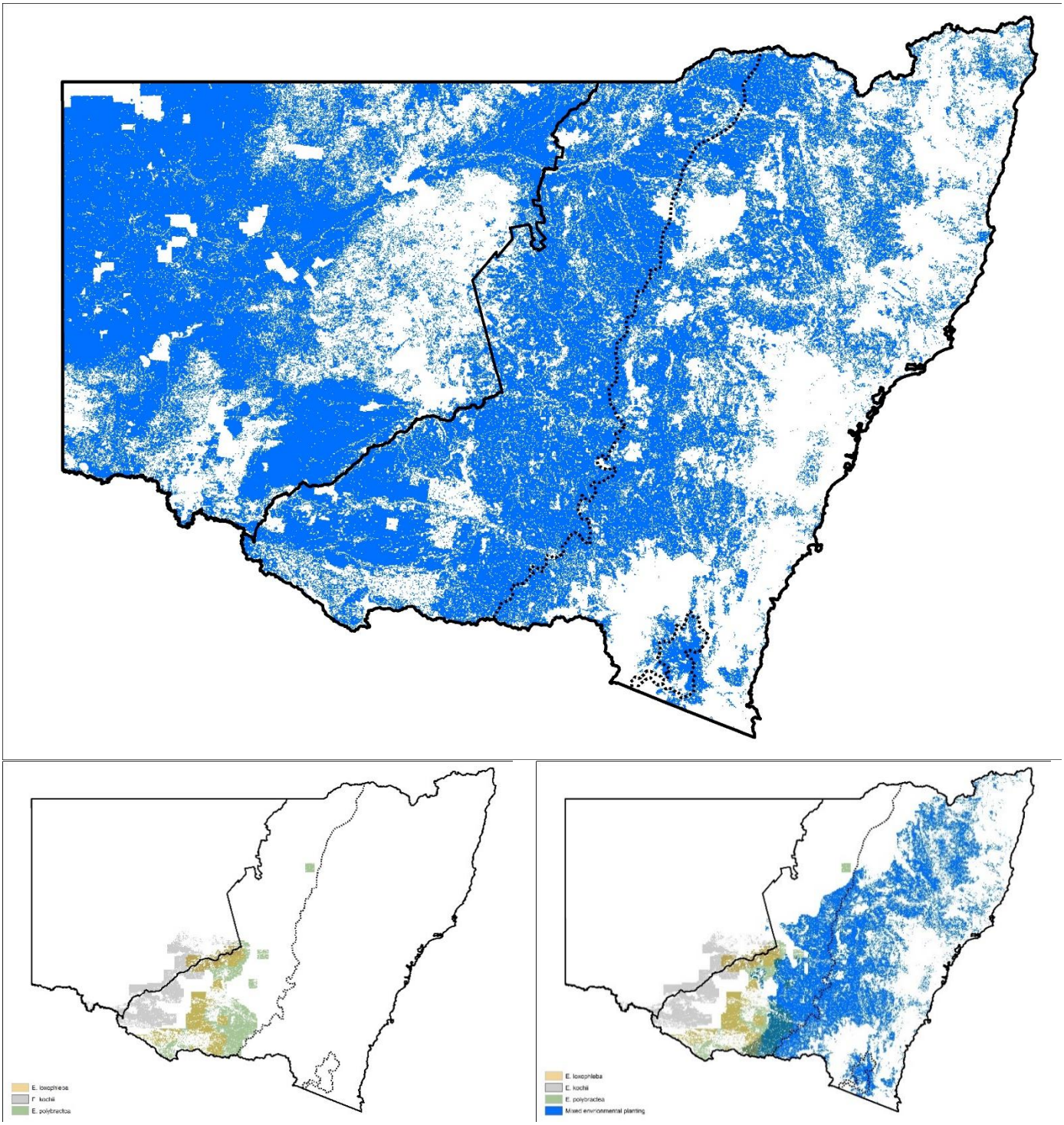

Figure S4. The top map shows areas of NSW theoretically suitable for Reforestation and afforestation by Environmental and Mallee Plantings; the bottom left shows the spatial distribution of the three Mallee species for the <600 mm rainfall zone. The lower right map overlays the three Mallee species distribution 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.

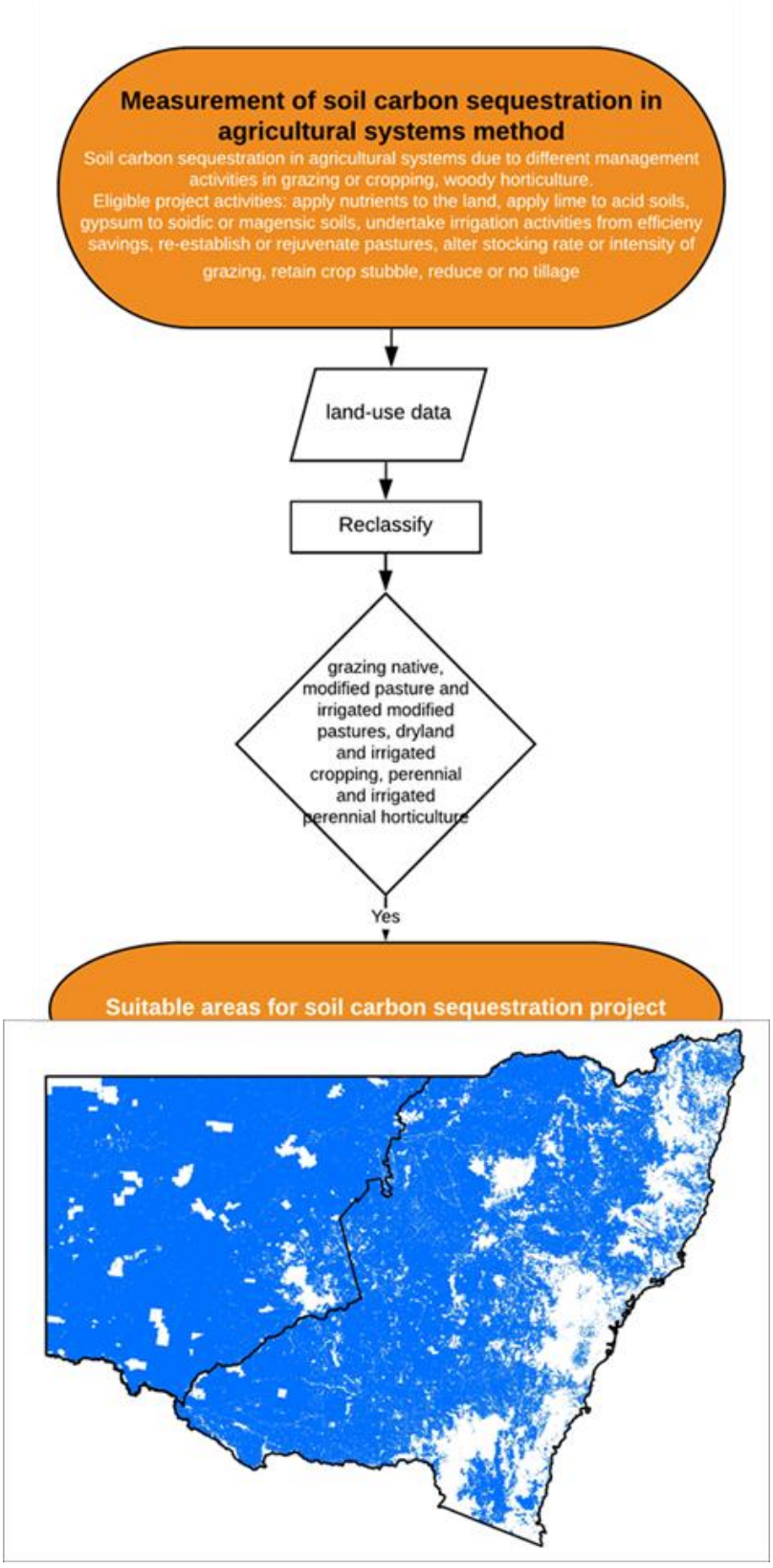

Figure S5. Flow diagram indicating the spatial analysis process used to identify areas theoretically suitable areas for soil carbon projects in NSW. The output map shows a total of 599,515 km^2 theoretically suitable.

2: Remote sensing to assess co-benefits of carbon farming

Table S2. Projects/initiatives applying remote sensing tools that could be used to assess co-benefits of carbon farming.

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
TERN Auscover TERN Landscape	**Fractional cover** Landsat, Joint Remote Sensing Research Program algorithm, Australia coverage Spatial resolution: 30 m Also known as Seasonal fractional cover - Landsat, JRSRP algorithm, Australia coverage	Provides **fraction of bare** (bare ground, rock, disturbed); **green vegetation**, **nongreen vegetation** (litter, dead leaf and branches), one composite image per season	• Reduced soil erosion (information on trends and a baseline is needed) • Salinity control (baseline is needed and combination with soil information (pH and EC) • Improved connectivity (using trends of the green fraction to map extent and changes over time) • Conservation of biodiversity and ecosystems (needs to be combined with field information or other programs of OEH (Turak et al., that measures ecological integrity using lizard assemblages and spatial modelling). • Increased habitat area • Livestock shelter • Wind breaks (depending on the width of the breaks)	Nil	This information could be used as proxy (with other variables) for mapping improved connectivity, increases in habitat area, conservation of ecosystems
	Landsat 2000-2010 woody vegetation cover. Spatial resolution: 30 m	Include maps of foliage projective cover and forest extent. It also includes a map of woody vegetation cover that can be used as a 'mask' of forest and other wooded lands for studies that are more focused on herbaceous cover	Can serve to determine baselines and benchmarking for assessing environmental co-benefits of carbon farming and/or to prioritise areas of intervention for carbon farming (e.g. decide on initiatives at landscape level rather than individual farms).	Nil	Could help aggregators or policymakers to identify priority areas for carbon farming

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
	Seasonal cover deciles - Landsat, JRSRP algorithm, Australia Coverage 30 m spatial resolution. Seasonally - At least one image per standard calendar season.	**Green cover** and **total cover**. For each pixel all cover values over the entire time-series of seasonal images are classified into deciles. Serves to identify areas of low or high cover, relative to what is normal at that location, at that time of year. Can be used to derive information on changes in cover and structure of vegetation (vertical- height; horizontal - patch changes).	• Reduced soil erosion • Salinity control • Enhancing biodiversity on farms (will need to be coupled with other on-ground measurements) • Conservation of ecosystems • Connectivity of habitats	Nil	Areas of constant high cover could be associated to good infiltration, low runoff, decreased erosion. Structural changes could be linked to biodiversity value.
	Seasonal persistent green - Landsat, JRSRP algorithm, Australia coverage. 30 m spatial resolution. Seasonally - At least one image per standard calendar season	Estimates persistent green cover per season (i.e. portion of vegetation that does not completely senesce within a year, which primarily consists of woody vegetation (trees and shrubs), although there are exceptions where non-woody cover remains green all year round).	Persistent green could serve as proxy for SOC estimation and for co-benefits related to: • Reduced soil erosion • Wind breaks • Salinity control • Livestock shelter (depending on size of patch) • Proxy for improved connectivity • Increases habitat area • Conservation of ecosystems	Nil	Persistent green can be associated to cover %, and high cover percentage could be associated to soil properties of infiltration (relating to reduced soil erosion)

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
	Water Count and **Prevalence** - Landsat, JRSRP algorithm, NSW coverage	**Water count** and **water prevalence.** Water count is the sum of number of observations with water present across the Landsat time series as a fraction of total number of possible observations in the 25 year period. Prevalence provides a measure of the relative persistence of water in the landscape (e.g. from always present to rarely and never present)	• Enhancing biodiversity on farms	Nil	For example, distance to locations of persistent water bodies can be modelled as a contributing indicator of potential biodiversity refugia.
	Green Accumulation Index - Landsat, JRSRP algorithm, NSW coverage. Spatial resolution: 30m. Temporal: 1988-2012	The **green fraction** has been analysed for a sequence of images to show how long an area stays green following a greening event, such as grass growth in response to rainfall. Areas exhibiting the highest values in an image are the areas of NSW that respond with high green cover for a long period after a greening event.	• Biodiversity (e.g. refugia) - could be helpful for planning priority areas of induced human regeneration.	Nil	This approach was taken by Gill et al. (2016) to identify biodiversity refugia in western NSW under climate change scenarios.

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
	Vegetation height and structure - derived from ALOS-1 PALSAR, Landsat and ICESat/GLAS 2009 updated for 2019 (Roxburgh et al. 2019)	**Height**, **cover**, **age class**. forest uses a version of the Walker and Hopkins (1990) structural classification	• Conservation of biodiversity and ecosystems • Improved connectivity, increases habitat area • Biomass is a proxy for habitat condition and ecosystem assessment. • Information on changes in height, cover can serve as proxy for condition, vegetation change (extent and health)	Nil	Needs to be used in combination with other TERN Auscover products
	Phenology - MODIS, derived from MOD13A1 EVI, NSW-Vic coverage 500 m spatial resolution, every 16 days. 2000-2015	Allows quantitative analysis of phenology; the product can be used to characterize phenological *cycles of greening and browning* and quantify the cycles' inter and intra annual variability from 2000 to 2015	Could be used as input layer for proxies in support of co-benefits related to: • Conservation of ecosystems • Pollination (phenology related work by Huete and team at UTS).	Nil	Computation ceased in 2015
	Ecosystem Disturbance Index - MODIS, (experimental) 500 m spatial resolution. Once a year, from 2000-2013	The Disturbance Index can be used to detect the timing, location and magnitude of major ecosystem disturbances such as wildfire, flooding, climate change and human-triggered land use.	• Ecosystem conservation • Habitat conservation (landscape scale)	Nil	Risk of loss of benefits?

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
EMAR (OEH NSW)	Environmental Monitoring Assessment and Reporting Framework (EMAR)	Working on new indicators of ecological integrity, biodiversity condition, using reptile species richness, small mammal population and birds. Focus on Mallee landscape	Depending on status of development and coverage it could serve to measure: Conservation of biodiversity and ecosystem (services) Enhancing biodiversity on farms (currently is being applied on reserves)	Indigen-ous cultural benefits	Project incorporates cultural burning
The VegMachine https://vegmachine.net/ (CSIRO, UQ, and others)	Measure **land cover change or estimate soil erosion rates** from satellite image land cover products. (integrates total ground cover, fractional cover, cover deciles green, cover deciles total, persistent vegetation)	It can help to better understand the links between **management, climate** and **cover** in grazing land.	• Reduced soil erosion • Windbreak (depending on size of the patch) • Salinity control • Livestock shelter • Improved connectivity • Increased habitat area • Conservation of ecosystems (proxy)	Nil	More of a visualisation tool - could be coupled to a decision support system
CSIRO SOIL GRID OEH SEED (Sharing and enabling environm-ental data)		Soil attributes Landscape attributes OEH SEED (Espade for soil information, etc.)	Can be input on landscape level estimations/proxies for: • Reduced soil erosion • Salinity control	Nil	

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
Habitat Condition Assessment System (HCAS) CSIRO	Approach to map change in habitat for biodiversity. Mix of remote sensing and environmental variables to model habitat condition in bioregions of Australia.	HCAS is designed to work with a range of long timeseries, nationally consistent remote-sensed data and derivatives that represent attributes of habitat structure, function and composition, primarily using vegetation as a surrogate.	• Conservation of biodiversity and ecosystems • Improved connectivity, increased habitat area	Nil	Final report not released yet
Australian Ecosystem Models Framework	CSIRO led	Provides a robust architecture for natural resource management prioritisation, as well as monitoring and evaluation activities, including supporting the development of methods to assess ecosystem resilience	Potentially good for conservation of biodiversity and ecosystems	Nil	Underway, no clear mention of indicators
Biodiversity Indicator Program for NSW	OEH/CSIRO and other experts from the Australian Museum and Macquarie University. To be published: Measuring biodiversity and ecological integrity in NSW: Method for the Biodiversity Indicator Program	Measuring **biodiversity** and **ecological integrity** in NSW: Method for the Biodiversity Indicator Program	• Conservation of biodiversity and ecosystems • Improved connectivity, increased connectivity	Nil	Confidential, not released to the public

Project/ Initiative	Products/ Tools	Description	Environmental co-benefits that could be assessed using these tools	Social/ cultural	Comments
Australia's Environm-ental Explorer	Soil water availability (2016) Runoff, exposed soil, etc.		• Reduced soil erosion • Salinity control	Nil	
Australia Beef Sustainability Framework	To report at an industry level using available data where appropriate, whilst identifying and addressing where there is a need to develop or improve indicators that better inform the understanding and attainment of sustainable practices. Across the entire value chain.	5.2a **Area of native vegetation managed for conservation** outcomes on-farm 5.2b **Maintaining grassland systems** from unproductive encroachment of native and introduced species 5.2c **No deforestation of primary forests** 5.2d **Increase in healthy grassland systems**	• Reduced soil erosion • Pest control • Salinity control • Enhancing biodiversity on farms • Conservation of biodiversity and ecosystems		Case studies. Use of remote sensing and field data. No national coverage