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**Title:** Promoting co-benefits of carbon farming in Oceania: Applying and adapting approaches and metrics from existing market-based schemes

**Authors:**

Alex Baumber[a]

Graciela Metternicht[b]

Rebecca Cross[c]

Laure-Elise Ruoso[d]

Annette L. Cowie[e]

Cathleen Waters[f]

[a] Faculty of Transdisciplinary Innovation, University of Technology Sydney, Australia

[b] School of Biological, Earth and Environmental Sciences, Palaeontology, Geobiology & Earth Archives Research Centre (PANGEA), UNSW Sydney, Australia

[c] Sydney Institute of Agriculture, School of Life and Environmental Sciences, University of Sydney, Australia

[d] Institute for Sustainable Futures, University of Technology Sydney, Australia

[e] NSW Department of Primary Industries, University of New England, Trevenna Road Armidale, NSW, Australia

[f] NSW Department of Primary Industries, cnr. Hampden and Cobra Streets, Dubbo, NSW, Australia

**Corresponding author:** Alex Baumber alex.baumber@uts.edu.au

## Abstract

Carbon farming in its various forms has the potential to deliver a range of ecosystem services in addition to climate regulation. In Australia, the main public 'co-benefits' that could result from carbon farming are conservation of biodiversity, increases in soil and water quality, and economic and cultural services for Indigenous communities. While there is a lack of empirical evidence that carbon farming is delivering these ecosystem services to date, various metrics have been developed by researchers and through other payment for ecosystem services schemes that may enable effective targeting of these co-benefits. In this article, we review previous studies and schemes and identify four main approaches for metrics that could be applied to carbon farming in Australia: (1) spatial modelling, (2) benchmarks; (3) environmental benefit indices; and (4) indicators. The relative value of each of these approaches varies, depending on the objectives of policy-makers. Spatial modelling and benchmarks can play a key role in decision support systems for landholders who may be interested in carbon farming. Indices are valuable for the development of new or modified market-based schemes that weigh up different co-benefits. Indicators are critical for outcome-based payment schemes and for verifying the effectiveness of co-benefit policies overall.


**Keywords:** carbon farming, sequestration, biodiversity, soil, indicators, indices

**Highlights**

1. Current availability of data on co-benefits of carbon farming is low
2. Spatial models, indirect indicators and benchmarks can assist with decision support
3. Indices could be employed in new or adapted market-based co-benefit schemes
4. Activity-based indicators can be used to link actions and proxies to predicted outcomes
5. Outcome-based indicators can be linked to payments and used to verify policy effectiveness

## 1. Introduction

An important emerging area of practice and policy development relating to ecosystem services is the management of vegetation to sequester carbon. Australia has been a key site of carbon market development within the Oceania region[1] in areas of compliance, public payment and private voluntary markets (Ecosystem Marketplace, 2015), and it has emerged as a global leader around policy innovation to incentivise the management of native vegetation and soils to sequester carbon (often referred to as 'carbon farming').

Many carbon farming practices, including human-induced regeneration, active tree planting, avoided deforestation and fire management, also offer the potential to provide a range of additional ecosystem services aside from climate regulation (Berkessy & Wintle, 2008; Lin et al., 2013; Bryan et al., 2014; Evans, 2018). These outcomes are often termed 'co-benefits' (Mayrhofer and Gupta, 2016) and, in the case of carbon farming, can cut across each of the four ecosystem services categories outlined by the Millennium Ecosystem Assessment.

Maynard et al (this issue) highlights the need to draw global attention towards environmental and socio-economic issues affecting the Oceania region, and to the consequences of policies and management relating to ecosystem services and the well-being of people of the region. In this regard, this article provides an overview of ecosystem services markets, including approaches and metrics relevant for quantifying, incentivising and understanding trade-offs and synergies around potential co-benefits (and dis-benefits) of carbon farming. To this end it

[1] The Oceania region and the sustainability issues are being discussed in the Introduction article of this special issue (Maynard et al), including Oceania boundaries. Furthermore, Sayre et al (this issue) characterizes the political Geography, Biogeography, and Terrestrial Ecosystems of the islands of Oceania.

draws on various approaches and metrics developed through previous research into co-benefits, or applied in other Australian payment for ecosystem services (PES) schemes. In doing so it seeks to enhance understanding of current knowledge and policy gaps associated with measuring and incentivising the potential of co-benefits of carbon farming.

The next section set the scene on co-benefits of carbon farming, and the use of approaches for metrics, explaining the policy environment for Australian carbon farming. Section 2 reviews previous studies on the potential co-benefits of carbon farming in Australia and it identifies various metrics they have developed or proposed. Section 3 then reviews the metrics used in other Australian market-based schemes, before discussing in Section 4 how different metrics could be applied to carbon farming in Australia. The objectives set make carbon researchers, natural resource managers and policy-makers new to ecosystem services concepts or unfamiliar with Australia the target audience.

### *1.1 Understanding carbon farming ecosystem services and co-benefits*

The co-benefits of carbon biosequestration may include supporting, regulating, provisioning and cultural services, and be either private or public in nature (Lin et al., 2013; Cowie et al., 2019). Private benefits to landholders may include additional income streams (Cockfield et al., 2019), productivity increases (Cunningham et al. 2015), savings of time, money or resources as a result of improved ecosystem service delivery (e.g. decreased need for pesticide application), and non-financial benefits such as improved aesthetics (Kragt et al., 2016). Other co-benefits are public goods, including environmental benefits relating to biodiversity conservation, soil and water quality, and cultural benefits such as Indigenous community development (Fig. 1). These public co-benefits are the focus of this article, as their public-good nature provides a key reason for governments to incentivise their delivery.

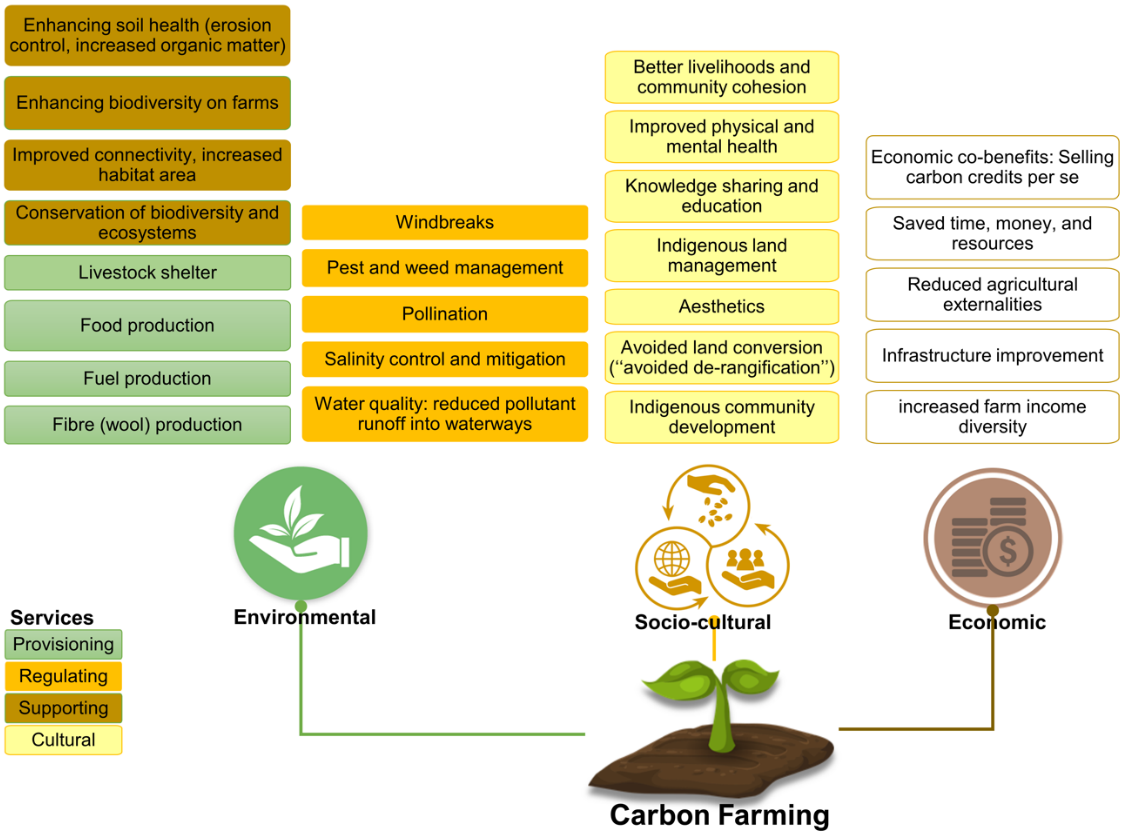


**Fig. 1.** Potential environmental and socio-economic co-benefits of carbon farming in addition to climate regulation. Source: The Carbon Market Institute (2017) and literature review from Sections 2 and 3.

In Australia, the term 'carbon farming' is commonly applied to vegetation, soil and fire management practices aimed at sequestering or avoiding the release of carbon. This terminology was given official recognition under the Australian Government's Carbon Farming Initiative (CFI), which formed part of the Carbon Pricing Mechanism that existed from 2011 to 2014. The CFI enabled landholders to earn credits for sequestration on their land and sell them to entities wishing to offset their emissions. The Carbon Pricing Mechanism was replaced in 2014 by the Emissions Reduction Fund (ERF), under which the Australian

Government acts as a single buyer of emissions reduction credits via an auction mechanism. A number of CFI methodologies relating to vegetation management were incorporated into the ERF in 2015. Despite the fact that the CFI no longer exists, the 'carbon farming' terminology lives on amongst researchers (e.g. Dumbrell et al., 2016; Morán-Ordóñez et al., 2017; Evans, 2018), policy-makers (e.g. Butler et al. 2014) and advocacy groups such as the Carbon Farmers of Australia and the Carbon Market Institute.

The most widespread carbon farming method employed under the ERF to date is human-induced regeneration (HIR), often referred to as assisted natural regeneration outside of Australia (e.g. Evans, 2018). This involves facilitating the natural regrowth of trees and shrubs through grazing management and other practices, and is concentrated in the rangelands of northwest New South Wales (NSW) and southwest Queensland (Evans 2018). Other ERF methods referred to as carbon farming include avoided deforestation (i.e. agreeing not to undertake tree-clearing that would otherwise be permitted), environmental plantings (i.e. direct planting of mixed native species), mallee eucalypt plantings, farm forestry and plantation forestry, savanna burning, and sequestering carbon in soils in grazing systems (Department of the Environment and Energy, 2019).

While the delivery of co-benefits from carbon farming has the potential to provide additional payments to landholders for the ecosystem services they are providing, barriers for adoption include a lack of effective market mechanisms, and of processes for measurement and verification. Evans (2018) argues that there is little incentive to monitor and report co-benefits of carbon farming. As a consequence, availability of data and information is low, hampering public and government understanding and knowledge around the co-benefits that carbon farming is delivering. Scarcity of data and information also hinders the ability to estimate risks associated with ‘dis-benefits’ or declines in ecosystem services that carbon farming can produce. Some of these risks, such as biodiversity loss if monocultures replace diverse habitats, and plantations impacting on water yield in regulated catchments, have been addressed within ERF methodologies (Butler et al., 2016), while others require further research, such as the risk that invasive native scrub may contribute to biodiversity- and soil-degradation at HIR sites (Waters et al., 2017; Cowie et al., 2019).

Market-based mechanisms such as Payment for Ecosystem Services (PES) schemes require at least one ‘seller’ and one ‘buyer’ who are able to enter into an exchange of a ‘well-defined’ ecosystem service or a land use activity likely to secure that service (Wunder, 2005). This requirement for services or activities to be ‘well-defined’ has resulted in a range of metrics applied across various PES schemes in Australia. The term metric is used here in a broad sense to refer to any ‘system or standard of measurement’, with other terms, including benchmarks, indicators, indices, models and proxies, used to refer to specific systems or approaches to measuring ecosystem services (Table 1).

**Table 1.** Terms relating to the measurement of ecosystem services used in this article

| **Term** | **Definition** (Oxford English Dictionary Online, 2019) |
|---|---|
| Metric | A system or standard of measurement |
| Benchmark | A point of reference, especially one from which measurements may be made |
| Indicator | That which serves to indicate or give a suggestion of something (including for prediction of future outcomes or trends) |

| | |
|---|---|
| Index | A number or formula expressing some property, form, ratio, etc. of the thing in question |
| Model | A simplified or idealized description or conception of a particular system, situation, or process |
| Proxy | A variable that can be used as an indirect estimate of another variable with which it is correlated |

Approaches for metrics applied to ecosystem services can be direct or indirect, quantitative or qualitative, and be predictive or measured after management practices have been implemented. For example, indicators, benchmarks and models may be either qualitative or quantitative, whereas an index necessarily requires a quantitative approach. Similarly, while indicators, benchmarks and indices may involve direct or indirect measurement, proxies and models imply an indirect approach. Metrics may focus on outcomes (outcome-based or performance-based), or on actions that are assumed to be linked to desired outputs (activity-based or input-based).

Stakeholders (e.g. government, finance and industry, carbon service providers, farmers, Indigenous communities, Natural Resource Managers) may have differing needs for the types of approaches and metrics defined in Table 1. Both buyers and sellers in a PES scheme have a need to ensure that the quantity of services being delivered (or likely to be delivered) is commensurate with the payment being made.

### *1.2 Markets related to carbon farming in Australia*

Carbon markets have gained momentum worldwide since 1992 when the United Nations Framework Convention on Climate Change designated them as one of its main policy instruments to mitigate anthropogenic climate change. The ratification of the Kyoto Protocol in 2007 led to substantial carbon market development and modification in Australia (Fig. 2). This included the use of fixed-price permits with offsetting options between 2011 and 2014, with this scheme repealed prior to its intended transition to a cap-and-trade system and replaced by the auction-based ERF (Baumber, 2016). The ERF was given an initial budget of AUD 2.55 billion in 2015 that was extended by a further AUD 2 billion in February 2019 (Clean Energy Regulator, 2019a).

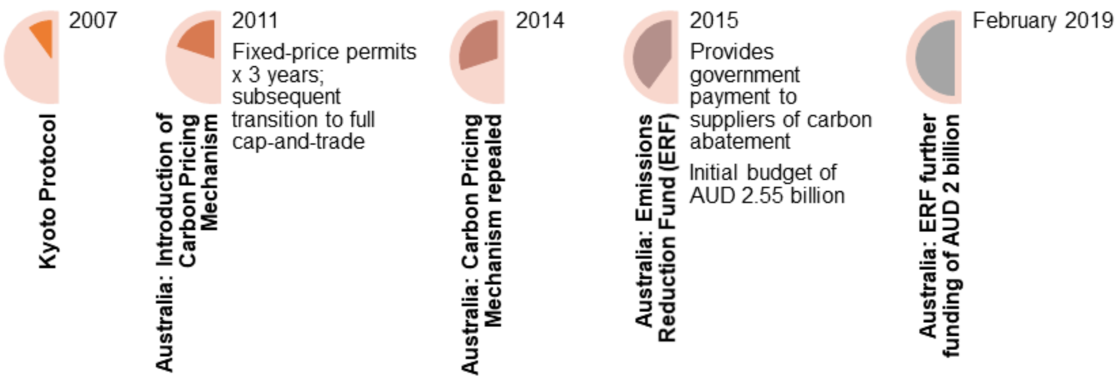


**Fig. 2.** Timeline of key carbon market developments in Australia

The ERF is a ‘baseline and credit’ scheme, under which entities can generate carbon abatement credits by developing projects that reduce emissions below (or sequester carbon above) a baseline scenario (Kollmuss et al. 2008). Under the ERF, the Australian Government acts as a single buyer of carbon abatement via a ‘reverse auction’ process that involves multiple potential suppliers of abatement bidding to sell abatement to the government for the lowest price. The credits awarded to successful bidders are known as Australian carbon credit units (ACCUs). While baselines of business as usual are used to ensure additionality (i.e. that credit is only earned for abatement that would not have happened anyway), Burke (2016) questions whether this has been effective, arguing that many of the projects funded are actions that would have happened anyway without ERF funding.

While the ERF covers a range of activities and sectors (e.g. vegetation management, livestock management, fertilisers, transport, energy efficiency, landfill and waste), vegetation management accounted for 57% of ERF projects (522 out of 912) and 54% of total ACCUs issued as of 29 March 2019 (Clean Energy Regulator, 2019b). Savanna burning accounts for another 8% of projects (10% of ACCUs) and soil carbon in grazing systems account for 5% of projects (but less than 0.001% of ACCUs due to the early stage of many projects). Of the vegetation management methodologies, human induced regeneration (HIR) includes the greatest number of projects (Fig. 3) and avoided deforestation (AD) has the greatest number of ACCUs issued. However, comparing ACCUs issued for different methodologies can be misleading, as AD projects have ACCUs issued annually, while HIR projects have ACCUs issued at the end of each five-year reporting period (Clean Energy Regulator 2018).

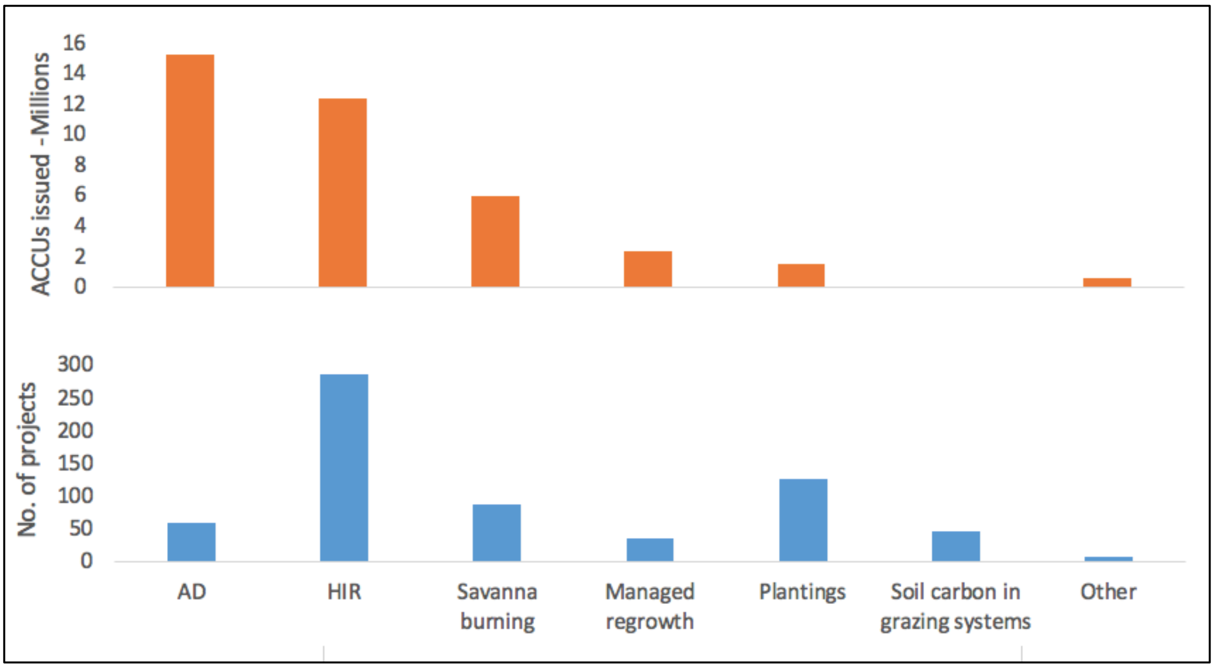


**Fig. 3.** Projects established and Australian carbon credit units (ACCUs) issued for vegetation management, savanna burning and soil carbon in grazing systems under the ERF. Source: Clean Energy Regulator (2019b). Note: 'Plantings' incorporates methodologies for reforestation, afforestation, environmental plantings, mallee plantings, plantations and farm forestry.

As shown in Fig. 4, ERF vegetation projects have been concentrated in the rangelands of NSW, Queensland and Western Australia (WA), while savanna burning projects are concentrated in the tropical north of Queensland, Western Australia and the Northern Territory.

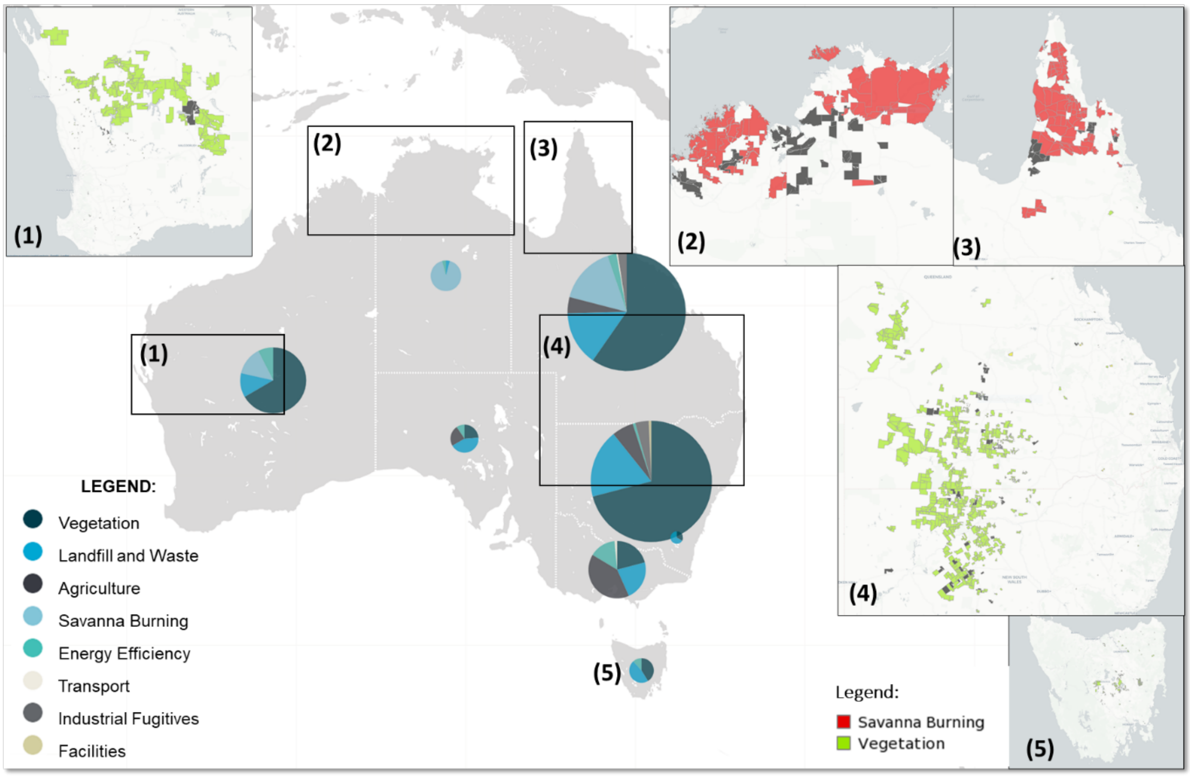


**Fig. 4.** Emissions Reduction Fund projects registered in each of Australia's states. The size of each pie chart represents the number of projects, and the coloured segments in each pie chart represent the percentage breakdown of methods used in each state, and correspond with the methods legend (lower left corner). Source: Clean Energy Regulator (2019b). Insets (1) to (5) showcase spatial distribution of projects related to savanna burning and vegetation management (lower right legend), black polygons are revoked projects. Source: www.nationalmap.gov.au Clean energy regulator area-based ERF projects layer.

The ERF does not specifically account for, or place an economic value on, the co-benefits of carbon farming. However, some of the ERF supporting material acknowledges and promotes these co-benefits, such as the guidance on human-induced regeneration that highlights 'additional benefits' such as 'improved quality of your land and water supply, increased biodiversity and shade and shelter for stock' (Clean Energy Regulator, 2018).

The ERF represents a 'public payment' PES scheme approach, with the Australian Government as the sole buyer of carbon sequestration services (Madsen et al., 2010; Mercer et al., 2011). However, while the ERF is the dominant source of demand for ACCUs, accounting for over 95% of demand, there is a broader ACCU market that involves other buyers (Clean Energy Regulator 2019a). This includes entities covered by the Safeguard mechanism, a compliance-driven scheme that requires liable entities to purchase offsets if their emissions exceed a set benchmark. Voluntary transactions are also made by private entities wishing to offset their emissions. State and territory governments represent a growing source of demand for ACCUs, driven by commitments to offset emissions for specific activities such as desalination plants and vehicle fleet emissions (Clean Energy Regulator 2019a). Government purchases of this nature are 'voluntary' in the sense that they are not being made to comply with regulatory obligations, but are often classed as 'public payments' to distinguish them from private voluntary payments for ecosystem services (Madsen et al., 2010; Mercer et al., 2011).

The National Carbon Offset Standard, developed by the Australian Government, helps to facilitate trade in a number of eligible offsets units (ACCUs, Golds Standard, Verified Carbon Standard) outside of the ERF, by verifying carbon credits from various sources. The Australia's Carbon Marketplace website (Carbon Market Institute, 2019) and the Australia's Clean Energy Regulator have developed interactive maps using data published on the ERF project register. ACCUs sold on the private market have been reported to sell at a price premium compared to ERF auction prices, with the spot price on the private market at 1 March 2019 being AUD 15.35, compared with an average price of AUD 13.87 per tonne of abatement for the previous ERF auction in December 2018 (Clean Energy Regulator 2019a).

## 2. Review of approaches and metrics from Australian carbon farming co-benefit studies

Through review of relevant literature this section identifies the co-benefits most commonly reported in Australian carbon farming studies, as well as metrics and associated approaches that have been developed or proposed for measuring co-benefits. The methodology involved first identifying academic articles on carbon sequestration co-benefits in Australia as of June 2019 using the Web of Science database. The keywords used were ‘carbon farming’, ‘carbon sequestration’ and ‘co-benefits’, with searches then refined using ‘Australia’. Articles were only included if they:

a) focused on Australia,
b) discussed the management of carbon stocks in vegetation or soils as the primary land use activity,
c) discussed benefits other than climate regulation, and
d) discussed public benefits.

Additional literature was identified through citations in reviewed articles and through personal networks, especially with regards to ‘grey’ literature such as government reports.

### *2.1 Potential co-benefits of carbon farming in Australia*

A range of potential co-benefits from carbon farming have been identified in recent Australian studies (Table 2). Biodiversity is by far the most commonly cited co-benefit, followed by soil quality, salinity and Indigenous economic and cultural benefits. Further details of each study reviewed are provided in the Supplementary Material. The most relevant articles are discussed hereafter, specifically those that relate to the most common carbon farming practices in Australia, human-induced regeneration (HIR) avoided deforestation (AD), and those that employ metrics that could be used to measure and promote co-benefits.

**Table 2.** Co-benefits identified and approaches and metrics employed across 29 recent studies discussing the co-benefits of carbon farming in Australia

<table>
<tr><th colspan="3">Practices, co-benefits and methods featured</th><th>No. of studies</th></tr>
<tr><td rowspan="6">Carbon farming practices</td><td colspan="2">Permanent plantings (monocultures and/or mixed-species)</td><td>23</td></tr>
<tr><td colspan="2">Plantation or farm forestry</td><td>3</td></tr>
<tr><td colspan="2">Human-induced regeneration</td><td>5</td></tr>
<tr><td colspan="2">Avoided deforestation</td><td>4</td></tr>
<tr><td colspan="2">Savanna burning</td><td>6</td></tr>
<tr><td colspan="2">Soil carbon management (e.g. stubble retention, no-till cropping, perennial pasture)</td><td>3</td></tr>
<tr><td rowspan="8">Ecosystem services identified<br>(in addition to climate regulation)</td><td rowspan="3">Regulating</td><td>Salinity mitigation</td><td>6</td></tr>
<tr><td>Water quality (e.g. sediment/nutrient levels)</td><td>3</td></tr>
<tr><td>Soil health (e.g. erosion control, soil quality)g</td><td>6</td></tr>
<tr><td rowspan="2">Supporting</td><td>Habitat for biodiversity</td><td>21</td></tr>
<tr><td>Nutrient cycling</td><td>1</td></tr>
<tr><td rowspan="3">Provisioning</td><td>Food production</td><td>2</td></tr>
<tr><td>Fuel production</td><td>1</td></tr>
<tr><td>Fibre (wool) production</td><td>2</td></tr>
</table>

| **Practices, co-benefits and methods featured** | | | **No. of studies** |
|---|---|---|---|
| | Cultural | Indigenous land management | 5 |
| | | Aesthetics | 1 |
| **Approaches and metrics used** to identify and analyse co-benefits | Qualitative | Stakeholder perceptions (i.e. survey/interview data) | 9 |
| | Quantitative | Spatial modelling | 4 |
| | | Other modelling (e.g. economics, biomass growth, biodiversity value, fire regimes) | 7 |
| | | Indicators for co-benefits (applied or proposed) | 2 |
| | | Indices | 1 |
| | Co-benefits theorised from previous studies (no metric developed or proposed) | | 12 |

The summary data in Table 2 reinforces Evans' (2018) argument that quantifying co-benefits remains as a significant barrier to adoption . Almost all of the studies reviewed relied on either modelling based on other land uses with similarities to carbon farming (Flugge and Abadi, 2006; Renwick et al. 2014; Cunningham et al. 2015; Russell-Smith et al. 2015; Evans et al. 2015; Bryan et al. 2016; Doran-Browne et al. 2016), stakeholder perceptions of co-benefits

(Robinson et al., 2011; Dumbrell et al., 2016; Kragt et al., 2016; Torabi et al. 2016; Robinson et al., 2016; Kragt et al., 2017) or theorised benefits based on previous studies (Fensham and Guymer, 2009; Wentworth Group of Concerned Scientists, 2011; George et al., 2012; Mitchell et al., 2012; Bradshaw et al., 2013; Net Balance Foundation, 2014; Bryan et al., 2014; Standish & Hulvey, 2014; Walsh et al., 2014; Cunningham et al., 2015; Nolan et al., 2018, Evans et al., 2018). Studies such as Renwick et al. (2014) measured carbon sequestration, but did not quantify other ecosystem services; whereas Perry et al. (2016) measured biodiversity, though not specifically at sites under carbon farming practices. Furthermore, Table 2 highlights the paucity of studies on HIR and AD. Of the 29 studies reviewed, five discussed HIR (Butler et al. 2014; Evans 2015; Kragt et al. 2016; Evans 2018; Nolan et al. 2018) and four covered AD (Wentworth Group of Concerned Scientists, 2011; Butler et al., 2014; Evans 2018; Nolan et al. 2018).

The dominant focus of the studies reviewed is tree-planting activities, including both mixed-species (i.e. environmental plantings) and monocultures of fast-growing species. This contrasts with arguments that human-induced regeneration is more likely to provide diverse and resilient ecosystems than direct tree planting (Fensham & Guymer, 2009; Evans, 2015; Lindenmayer et al., 2012), and that avoided deforestation should be prioritised because the area deforested in Australia is much higher than the area reforested each year (van Oosterzee, 2012). In terms of direct tree-planting, mixed-species environmental plantings are more likely to provide biodiversity co-benefits than monocultures (Lin et al., 2013; Munro et al. 2009), although plantations can provide habitat value when established on previously cleared land (e.g. Loyn, 2007; Smith, 2009; Felton et al. 2010; Kavanagh and Stanton, 2012; Law et al., 2013). The biodiversity value of regrowth and assisted regeneration sites depends on factors such as land use history, the dimensions of the site and the composition of species that regenerate (Hall et al., 2012). Key land use history factors that can impact on biodiversity include the degree of soil disturbance (e.g. grazing vs mechanical cultivation), the number of times that a site has been cleared, and the time lag between clearing and regeneration (Doherty, 1998).

Six of the 29 studies reviewed (Russell-Smith et al., 2015; Walsh et al., 2014; Robinson et al., 2011; Bradshaw et al., 2013; Perry et al., 2016; Moran-Ordonez et al. 2017) focus on the practice of savanna burning in Northern Australia. It emerges that low-intensity, early-season burns maintain carbon and reduce non-$CO_2$ greenhouse gas emissions by minimizing the amount of fuel burnt in large-scale, high-intensity late-season wildfires. The practice is considered to be generally commensurate with biodiversity conservation objectives as well as Indigenous cultural practice (Andersen et al. 2012; Moran-Ordonez et al. 2017). Three of the studies explicitly consider soil carbon increases in cropping and/or grazing systems (Dumbrell et al. 2016: Kragt et al. 2016; Kragt et al. 2017), including co-benefits for soil health, biodiversity and agricultural productivity (i.e. provisioning services).

*2.2 Approaches and metrics that have been developed to assess carbon farming co-benefits*

Of the 29 studies reviewed in Table 2, 11 involved some form of modelling, most commonly using spatial data. A case in point is Bryan et al.'s (2014) study that used principles of complementarity, connectivity and representation of plant species compositional diversity to identify priority locations for targeting mixed-species carbon plantings aimed at enhancing biodiversity. Carwardine et al. (2015) and Robinson et al. (2016) each prioritised areas that had less than 30% of their original vegetation remaining for the establishment of mixed-species carbon plantings. Moran-Ordonez et al. (2017) identified priority sites for savanna fire management in northern Australia, based on how many different species and communities occur there and the relative rarity of those species and communities. Other modelling approaches focused on biomass growth rates and carbon sequestration (Renwick et al. 2014; Doran-Browne et al. 2016), economic modelling (Evans et al. 2015; Bryan et al. 2016), recharge rates affecting salinity (Flugge and Abadi, 2006), modelling of fire regimes (Russell-Smith et al. 2015) and a conceptual model for managing trade-offs between carbon, biodiversity and water impacts (Cunningham et al. 2015).

Three of the studies reviewed focus on the development of quantitative indicators or indices, all in relation to biodiversity. Robinson et al. (2014) proposed a quantitative measure, levels of remnant vegetation, as an indicator of potential biodiversity benefit, whereas Perry et al. (2016) measured bird, mammal and reptile richness and abundance under different fire regimes. Paul et al. (2016) combined various quantitative indicators into a biodiversity potential index, including the proportion of eucalypts in a planting and the width of the block. This drew on previous research that has shown diversity of birds and other fauna are higher in plantings where eucalypts are less dominant and where planting blocks are wider.

Several studies employed qualitative indicators derived from stakeholder surveys or interviews. For example, Kragt et al. (2017) and Torabi et al. (2016) analysed the proportion of respondents identifying a potential co-benefit such as soil improvements or habitat provision as a driver for adoption of carbon farming, which could be used as a predictive indicator of co-benefit potential, albeit one based on social data (landholder perspectives) rather than biophysical data or modelling. Qualitative indicators proposed by Robinson et al. (2011) could be used to measure carbon farming impacts on Indigenous cultural assets and values (e.g. whether or not there was free and prior informed consent, whether local Indigenous people had control over benefit-sharing, and whether they reported increased quality of life as a result of the project).

## 3. Metrics applied in other Australian market-based schemes

This section reviews approaches and metrics applied in other Australian PES schemes (as examples of market-based mechanisms discussed in Section 1.1), as these appear the most relevant for the co-benefits of carbon farming in terms of the ecosystem services they cover, and the environmental, social and regulatory contexts in which they operate.

Existing PES schemes that cover the key ecosystem services discussed in the previous section (i.e. biodiversity, soil and water health and cultural services) include a wide range of metrics, including indicators, models, benchmarks and indices. While PES schemes require at least one 'seller' and one 'buyer' (Wunder 2005), they can take a variety of forms and vary in the extent to which they incorporate market-based elements such as substitutability and competition between buyers and sellers (Baumber 2017a). Three main categories of PES are identified based on their source of demand and transaction type (Madsen et al. 2010; Mercer et al. 2011):

1. Public payments: Where government pays landholders to implement management practices that enhance ecosystem services;
2. Compliance driven transactions: Where a market is established to achieve obligations imposed by government regulations (e.g. offset mechanisms, cap and trade markets); and
3. Voluntary transactions: Where demand is not driven by compliance with regulations, but rather by private entities voluntarily seeking to enhance ecosystem service delivery for ethical, philanthropic, profit or consumptive motives.

Many of the Australian public payment schemes discussed in section 3.1 are state-based, including the BushTender program (Victoria), the Nature Assist program (Queensland) and the Environmental Services Scheme (NSW). This is also true of the compliance-driven markets discussed in section 3.2, including biodiversity offsets schemes in NSW and Victoria. Under these schemes, demand is created by regulations that require entities that wish to degrade native vegetation to purchase offsets. The voluntary transaction schemes discussed in section 4.3 have broader coverage, especially voluntary carbon market schemes that are global in scope but have relevance to Australia due to being listed as eligible to generate Verified Carbon Units under Australia's National Carbon Offset Standard.

*3.1 Public payment markets*

While governments commonly provide grants and subsidies to encourage ecosystem service delivery, the degree to which these measures are 'market-based' depends on the levels of competition and substitutability they involve (Baumber 2017a). Conservation tenders have become one of the most common mechanisms for facilitating competition, primarily in relation to biodiversity, with almost 100 tenders conducted in Australia across various programs between 2001 and 2012 (Rolfe et al. 2017).

The Bush Tender program in Victoria, which began in 2001, is a prominent example of a conservation tender that uses a reverse auction mechanism to promote competition. Interested landholders have their property assessed by a field officer who determines the value of the site in 'habitat hectares'. This is based on its habitat score, an index that considers various habitat factors with differing weights (Fig. 5), with the maximum score of 100 corresponding to a mature, long-undisturbed site of the same vegetation type (DSE 2004). The habitat score is multiplied by the area being managed (in hectares) to determine habitat hectares. Proposed management actions are also evaluated to assess the extent to which they are predicted to deliver a 'gain' in habitat hectares, with eligible actions including fencing to control access of stock or pests, managing weeds and pests, preserving trees and other biomass, and planting additional vegetation in patches of native vegetation (Department of Sustainability and Environment 2009).

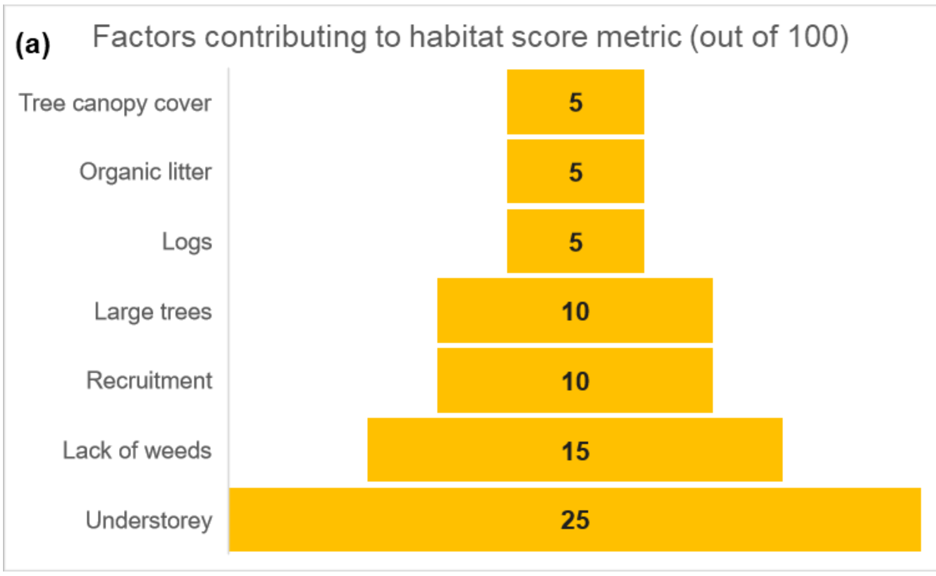


**Fig. 5** Factors contributing to habitat score under Victoria's habitat hectares metric (ELWP 2017).

Under the Bush Tender scheme, successful bidders offer the lowest price per unit gain measured in habitat hectares. The scheme employs an 'input-based' or 'activity-based' payment approach, where payments are linked to agreed actions, rather than an 'outcome-based' or 'performance payment' approach that links payments to measured outcomes (Burton & Schwarz 2013; Börner et al. 2017). A similar reverse-auction process to increase habitat quality and protect high quality remnants and nationally threatened species and ecological communities was applied in the Australia-wide Environmental Stewardship program that operated from 2007 to 2012 (Burns et al. 2016).

In 2005, Victoria trialled an expansion of Bush Tender through the Eco Tender pilot program. This pilot scheme focused on a variety of environmental outcomes, including better water quality, reduced erosion, increased carbon sequestration and native vegetation. This kind of ‘bundling’ approach recognises the synergies and trade-offs that can occur between different ecosystem services (Raudsepp-Hearne et al. 2010), whereby interventions around one service can impact the supply and use of other services and change the expression of the whole ES bundle (Vannier et al. 2019). Eco Tender’s eligible management activities were similar to Bush Tender, though the index used was multifunctional in the sense that it considered different environmental outcomes (e.g. biodiversity and erosion control) rather than just biodiversity.

Further Australian experiences of bundled public payment PES schemes include the Queensland Nature Assist program (2007-2013) and the NSW Environmental Services Scheme (2003). Both schemes employed multifunctional indices to assess potential sites. The Nature Assist index includes site suitability, management suitability and contract security, with site suitability further divided into cultural heritage, catchment health, representativeness of biodiversity and rarity and distinctiveness of biodiversity (Hajkowicz et al. 2009). The NSW Environmental Services Scheme (ESS) used an Environmental Benefits Index to weigh up multiple benefits related to carbon sequestration, reduced salinity, improved biodiversity, mitigation of acid sulphate soils and improvement of soil retention and water quality (Grieve & Uebel 2003; Cowie et al. 2007). Metrics developed through the ESS were subsequently incorporated into SCaRPA (Site and Catchment Resource Planning and Assessment), a related environmental benefits quantification system in NSW. The SCaRPA approach considered factors such as salinity, land and soil, biodiversity (aquatic and terrestrial), carbon and cultural heritage (Summerell et al. 2011). It applied the Biodiversity Incentive Tool (BIT) that generated a score based on vegetation condition and connectivity to the surrounding landscape under the proposed management changes. This site-scale index was complemented by catchment-scale modeling using a Biodiversity Forecasting Tool (BFT), which modelled how small site-scale changes influence the status of biodiversity at the catchment scale, considering habitat condition and configuration. This approach was explicitly designed to consider cumulative and non-linear impacts, based on the notion that 'the whole can be greater than the sum of its parts' (Summerell et al. 2011).

Noteworthy is also a pilot ground cover incentive program that operated across three properties of NSW between 2004 and 2008, as part of the Enterprise Based Conservation (EBC) program (Hacker et al., 2010). One key element that sets this scheme apart from most others discussed so far is that it employed outcome or performance-based payments, rather than payments based on inputs or activities undertaken. Participating landholders were paid based on the amount of ground cover on their properties relative to the rainfall conditions (including grasses, litter and cryptogamic crusts). For example, for landholders to receive 100% of their payment, they needed to maintain a ground cover of 40% in low-rainfall years (rainfall decile 6 or below), rising to a threshold of 70% in years where rainfall was in the top decile based on long-term rainfall records. Percentage ground cover was measured using a modified version of the step point method (Cunningham, 1962). A provision was included whereby the outcome-based payment system could be over-ridden where stock numbers were reduced to less than 10% of normal levels (an activity-based measure).

One scheme that is highly relevant, though at too early a stage to have produced measurable results, is the Queensland Government's Land Restoration Fund specifically aimed at maximising the delivery of co-benefits from carbon farming. The initial funding round in 2018 was made up of two grants programs: Kickstarting the Market and Catalysing Action (Queensland Government 2018). The former involves funding of pilot projects related to stakeholder engagement, analysis of business models and building understanding of carbon markets and carbon farming projects and risk management strategies. The latter focuses on 'on-ground' demonstration projects, such as strategic environmental plantings or regrowth. Projects are favoured if they address specified priorities such as Great Barrier Reef protection, koala habitat or agricultural soil health, but the specific details of the metrics used to assess competing proposals have not been publicly released. Projects involving regrowth are also required to use a Regrowth Benefits Tool that produces scores for both estimated carbon and estimated biodiversity benefit (Queensland Government 2018).

### *3.2 Compliance-driven markets*

The most relevant compliance-driven markets for the co-benefits of carbon farming in Australia are offset markets for biodiversity. The states of NSW and Victoria have each introduced offset schemes that allow developers wishing to undertake projects that degrade biodiversity to do so provided that they purchase offsets[2] to cover their impact. These offsets can be created by landholders who voluntarily agree to improve the quality of native

[2] Some Australian offset schemes can involve payment (as distinct from purchases) as the example of BioBanking that follows.

vegetation on their land by undertaking prescribed actions, or increase the level of protection by foregoing future opportunities to clear or degrade native vegetation.

The NSW state government introduced its Biodiversity Offsets Scheme in 2017, replacing the BioBanking scheme adopted in 2008, which attracted criticism around its use of baselines, trade-offs and other factors (Maron et al. 2016). Biodiversity offsetting involves landholders entering into voluntary conservation covenants in perpetuity and earning credits through eligible actions such as grazing management for conservation, weed control, ecological fire management, retention of regrowth, supplementary planting where natural regeneration is not sufficient, erosion control and the retention of dead timber and rocks (OEH 2014a). Credits can be sold to developers who are required to offset biodiversity impacts of their projects. If developers cannot find a suitable offset themselves or through a broker, they may pay into the Biodiversity Conservation Fund, with the Biodiversity Conservation Trust then taking responsibility for sourcing suitable offsets (OEH 2018). It is possible under the scheme for a single site to 'generate both biodiversity credits and carbon credits through the same management actions' (OEH 2014b p. 12).

Accredited assessors use a prescribed BAM (Biodiversity Assessment Method) Calculator to calculate the number and type of credits that a landholder can generate from an offset site. The calculator takes into account the site context, vegetation type and proposed management practices. Specific factors included in the BAM calculator include biogeographic region, % native vegetation cover, key attributes (e.g. connectivity, outstanding biodiversity value), vegetation type, listing status (i.e. threatened or not) and changes in condition as a result of management actions, including scores for composition, structure and function with and without the proposed management actions (OEH 2017). Like-for-like provisions are incorporated through two credit types: species credits, which cover impacts on specific threatened species, and ecosystem credits, which cover impacts on threatened ecosystems (Madsen et al. 2010).

The State of Victoria first introduced offsetting under the Bushbroker scheme in 2006, with the present Native Vegetation Credits scheme governed by regulatory reforms in 2017. As with the NSW scheme, Victoria's offset approach employs a like-for-like principle, with offsets divided into species offsets (where a rare or threatened species is affected) and general offsets (where no listed species are affected). Under Victoria's scheme, landholders can generate credits by undertaking management actions that are predicted to generate a certain biodiversity 'gain', using the habitat hectares metric discussed previously. Once a baseline score has been obtained, a predicted gain in site condition can be calculated based on the following gain categories (ELWP 2017):

- Prior management gain: improvements delivered prior to registering the site as an offset
- Security gain: when a landowner increases the protection of native vegetation
- Maintenance gain: achieved by giving up currently allowed land uses and controlling threats that would otherwise cause a decline in native vegetation condition
- Improvement gain: achieved from management commitments that are predicted to improve the site condition

Once the gain in habitat hectares has been calculated, this is then multiplied by a landscape factor that considers the strategic value of the biodiversity in the landscape (using a Strategic Biodiversity Values Map that assigns each land unit in the state a value from 0 to 1). The final result is a value in either Species Habitat Units or General Habitat Units, which can then be traded to someone wishing to degrade a commensurate number of units. To ensure that offsets are located in areas with strategic biodiversity value that is comparable to the native vegetation being removed, the strategic biodiversity value score of an offset must be at least 80 per cent of the strategic biodiversity value score of the native vegetation to be removed (ELWP 2017).

The NSW Hunter River Salinity Trading Scheme is an example of a compliance-based PES scheme that employs a cap-and-trade model (Selman 2009). Major emitters of salt into the Hunter River system are required to hold permits, with polluters who reduce their emissions able to sell their excess permits. Notable features of the scheme include a variable cap that can be lowered during periods of low flow and the direct monitoring of saline inputs into the river system at point sources (NSW EPA 2019). In contrast to the input-based payment approach used under most other PES schemes discussed so far, the Hunter River Salinity Trading Scheme employs an outcome-based approach that measures each participant's impact directly.

*3.3 Voluntary markets*

While Australia's government-funded ERF has a narrow focus on greenhouse gas emissions, there has been greater consideration of co-benefits in voluntary carbon markets. The Gold Standard and Verified Carbon Standard (VCS) can be used to certify carbon offsets under the National Carbon Offset Standard (Department of Environment and Energy 2018). The VCS acts as an umbrella standard and two of the schemes it covers have undertaken significant development of co-benefit benchmarks and indicators: the Climate, Community & Biodiversity Alliance (CCBA) and SocialCarbon.

The CCBA standards have been developed by Conservation International, the Rainforest Alliance, the Wildlife Conservation Society and others to identify projects that contribute simultaneously to climate change mitigation, community development and biodiversity conservation (CCBA 2017). The standards require proponents to use 'appropriate methodologies' to estimate changes based on the CCBA Social and Biodiversity Impact Assessment Manual (Richards and Panfil 2011). The manual suggests indicators for both biodiversity and community development, including 'output indicators' such as the number of trees planted, as well as 'impact indicators' such as the percentage increase in the population of an endangered species. The benchmark for certification is that monitoring is being implemented (i.e. input-based and qualitative) rather than participants having to meet quantitative, outcome-based benchmarks.

SocialCarbon uses a six-factor framework (Social, Human, Financial, Natural, Biodiversity and Carbon) and offers a range of approved indicators that can be applied to each factor (using a scoring system from one to six). As with CCBA, certification is based on the implementation of monitoring and the selection of indicators rather than the scores obtained. However, the framework enables participants to benchmark themselves in a quantitative, outcome-based manner. For example, approved indicators relating to natural resources and biodiversity in forest projects that participants may choose from include (SocialCarbon 2011):

1. Percentage of native ecosystems present and their connectivity (>50% and thoroughly interconnected = 6 points)
2. Level of land degradation (>50% of area degraded = 2 points, voluntary recovery of degraded areas outside project site = 6 points)
3. Level of ecological community degradation (totally degraded = 1 point, undisturbed = 6 points)
4. Species of conservation interest (complete absence = 1 point, several species with populations stable or growing = 6 points)

Aside from carbon offsets, voluntary markets have also emerged around other ecosystem services in Australia, particularly in relation to water quality. One example is the salinity credits trial in the Macquarie River catchment of NSW in the early 2000s. This trial involved an irrigators' group, Macquarie River Food and Fibre Association (MRFFA), paying State Forests (a government-owned corporation) for salinity control services provided through plantation establishment in upstream groundwater recharge areas. With regards to metrics, Walsh et al. (n.d.) state that, while payment would have 'ideally' be based on the net reduction in recharge due to the planted forest (i.e. quantitative and outcome-based), payments were instead based on the estimated transpiration rate of the planted forest (i.e. a predictive proxy indicator based on modelling), as measurement of the actual water use of both the forest and the prior vegetation under the previous land use would incur 'high compliance costs'.

*3.4 Summary of approaches and metrics from previous and current Australian PES schemes*

Table 3 provides a summary of how ecosystem services metrics have been employed in the PES schemes reviewed, using four main approaches: indicators, indices, benchmarks and models. Table 4 also indicates whether these approaches applied metrics in a predictive fashion (i.e. measuring an input or activity to predict outcomes) or involved measurement of actual outcomes (ie. Performance-based), and whether they are primarily quantitative or qualitative in nature.

**Table 3.** Summary of approaches and metrics used in Australian PES schemes

| Type of metric | Scheme |
|---|---|
| Indicators | 1. Habitat hectares (Victoria) – incorporates predictive indicators for tree canopy cover, understory and other factors |

| | |
|---|---|
| | 2. Macquarie salinity credits trial (NSW) – estimated transpiration rate used as predictive indicator of net reduction in recharge<br>3. Ground cover incentive pilot scheme (NSW) - % ground cover used as outcome-based indicator<br>4. Hunter river salinity scheme (NSW) – saline discharge recorded as outcome-based indicator at point sources<br>5. Voluntary carbon certification (CCBA & SocialCarbon) – mix of indicators (activity-based, outcome-based, qualitative, quantitative) |
| Indices | 1. Bush Tender/Eco Tender/Native Vegetation Credits (Victoria) – Biodiversity Benefits Index based on predictive scores across multiple habitat categories<br>2. Environmental Services Scheme (NSW) – multifunctional Environmental Benefits Index incorporating predicted carbon sequestration, salinity, biodiversity, soil health and water quality<br>3. Nature Assist (Queensland) – multifunctional index based on predictive scores for cultural heritage, catchment health and biodiversity |
| Benchmarks | 4. Ground cover pilot scheme (NSW) - % ground cover thresholds used as trigger for payments<br>5. Voluntary carbon certification (CCBA & SocialCarbon) – qualitative benchmarks (monitoring implemented or not), with some optional quantitative benchmarks (SocialCarbon) |

| | |
|---|---|
| Models | 6. Strategic Biodiversity Value Map (Victoria) and Biodiversity Forecasting Tool (NSW) – spatial mapping tools to predict where biodiversity benefit will be greatest<br>7. BAM Calculator (NSW) – predictive modelling tool that incorporates site context, vegetation type and proposed management practices<br>8. Offset and Impact Calculators of the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) offset policy. The tools compute habitat quality, time over which the loss is averted, time until ecological benefit of proposed offset is realised.<br>9. Regrowth Benefits Tool (Queensland) – Predictive modelling tool with scores for both carbon and biodiversity benefit |

## 3. Discussion: Linking metrics and approaches to policy objectives

Table 4 summarises key metrics identified from the review of previous studies (section 3) and PES schemes (section 3) and discusses their relevance for enhancing information on carbon farming co-benefits in Australia. Indicators have been subdivided into outcome-based and activity-based, while indices have been divided into those that focus on a single ecosystem service and those that are multifunctional. Fig. 6 matches these metrics to potential policy objectives relating to carbon farming co-benefits. The policy implications presented in Table 4 and Fig. 6 are discussed further in sections 4.1 to 4.4 in relation to indicators, indices, benchmarks and models.

**Table 4.** Approaches and metrics from PES,  relevant to carbon farming co-benefits in Australia.

| **Type of tool for metric** | **Ecosystem services to which they have been applied** | **Examples of how it can be used in PES schemes** | **Potential application to carbon farming in Australia** | |
|---|---|---|---|---|
| | | | **Advantages** | **Disadvantages** |
| Indicators – outcome-based | Watershed protection (e.g. ground cover), water quality (e.g river salinity) | Used to measure direct impact on ecosystem services for outcome-based PES schemes | Reduces the risk that actions may be incentivised that do not actually produce desired outcomes. | Can have higher monitoring costs and create risks for landholders who cannot deliver expected outcomes |
| Indicators - activity-based (predictive) | Biodiversity, soil quality, water quality, cultural services | Used to predict outcomes based on proposed actions | Lower monitoring costs, reduces risk to landholders, can be used to assess cost and benefits prior to project development | Risk of disconnect between action and outcome (although not as high as for standards/ eligibility rules) |
| Indices – single ecosystem service | Biodiversity | Predicting outcomes from competing bids | Could be used to promote biodiversity benefit of carbon plantings based on multiple aspects that influence biodiversity benefit | Not useful for promoting benefits other than biodiversity |
| Indices - multifunctional | Biodiversity, soil quality, water quality, cultural services | Predicting outcomes of competing bids involving multiple ecosystem services | Could be used to promote and balance multiple co-benefits | Allows substitution of one benefit for another; trade-offs may not be transparent to users |

| **Type of tool for metric** | **Ecosystem services to which they have been applied** | **Examples of how it can be used in PES schemes** | **Potential application to carbon farming in Australia** | |
|---|---|---|---|---|
| | | | **Advantages** | **Disadvantages** |
| Benchmarks | Biodiversity, soil quality, water quality, cultural services | Used to define eligible actions (qualitative) or level of benefit required for release of payment (quantitative) | Flexible - can be either qualitative or quantitative and input-based or outcome-based | Risks if benchmarks are set too high or too low or if there is a disconnect between indicator chosen for benchmark and desired outcomes |
| Modelling (especially spatial) | Biodiversity, salinity, soil erosion | Can be used to prioritise areas when evaluating competing bids or determining level of payment | Enables prediction of likely impact, can incorporate complex relationships between variables | May not be relevant to non-fragmented landscapes such as the NSW rangelands |

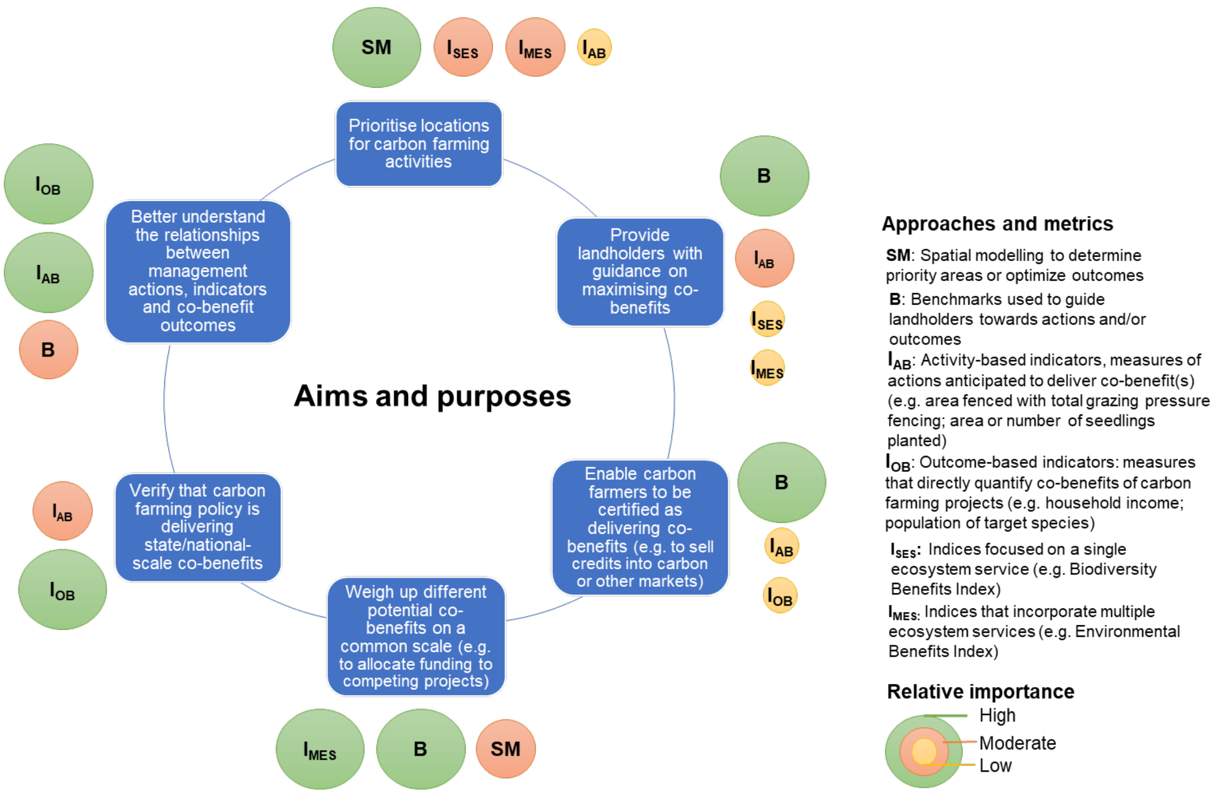


**Figure 6:** Potential co-benefit approaches and metrics matched to different policy aims and purposes. The size of the circle indicates the relative importance of each metric to the desired aim/purpose.

### *4.1 Indicators*

In relation to indicators, our review of existing PES schemes has demonstrated that those that can be measured at the design stage based on inputs or actions (i.e. input-based or activity-based) are far more common in than direct, outcome-based or performance-based indicators. While some PES schemes, such as the Hunter River Salinity Trading Scheme and the ground cover incentive pilot scheme (both in NSW) have used outcome-based indicators, the biodiversity schemes reviewed employ activity-based indicators to predict biodiversity outcomes and the Macquarie salinity credits trial found that outcome-based indicators were nonviable due to the cost of monitoring (Walsh et al. n.d.). Börner et al. (2017) argues that linking landholder payments to outcome-based indicators is only appropriate in cases where participants have a low risk-aversion, and external factors do not have a strong influence on the ability of landholders to provide positive environmental outcomes. In the arid and semi-arid regions of Australia where much carbon farming has taken place to date, external factors such as fire and climate have been identified as major sources of risk affecting the ability of landholders to predict the level of co-benefit that carbon farming can deliver (Nolan et al. 2018; Nolan et al. 2019).

Intermediate indicators or proxies may play a role in bridging the gap between activity-based and outcome-based indicators. In developing their biodiversity potential index, Paul et al. (2016) used the proportion of eucalyptus trees within a planting as a proxy for structural complexity and combined this with site width, which has shown a positive correlation to faunal diversity in previous studies (Munro et al. 2007). The Forest Stewardship Council (2018) has developed metrics such as a forest intactness index for biodiversity, and visual assessment protocols for soils and streams. Spatial models can also be used to produce indicators of biodiversity benefits based on factors such as remnant vegetation percentage, presence of threatened species or connectivity (e.g. Bryan et al. 2014; Robinson et al. 2016; Moran-Ordonez et al. 2017).

Outcome-based indicators are useful for verifying the effectiveness of carbon farming policies at state and national scales, as well as developing proxies, models and benchmarks. Such metrics may also be used as optional components of monitoring programs, as they are under voluntary standards such as CCBA and SocialCarbon. Remote sensing data could also be used to develop new indicators, such as the use of Landsat data to develop indicators of vertical foliage distribution in rangelands (Dean et al. 2015), which could in turn be linked to structural complexity and related outcomes such as bird nesting and seedling establishment (Lindenmayer & Hobbs 2004; Munro et al. 2009; Paul et al. 2016).

*4.2 Indices*

Given that the co-benefit concept involves a focus on multiple benefits, multifunctional indices covering a bundle of benefits would appear to be more relevant than single benefit indices (e.g. covering biodiversity only) for any new or adapted PES schemes that may be developed around carbon farming co-benefits in Australia. These indices could potentially be used to weigh up the relative co-benefits of different carbon farming projects competing for public funds, following examples such as Environmental Services and Nature Assist schemes in NSW and Queensland, respectively.

As the ERF employs an auction-based system for selecting and assigning payments to carbon farming projects, a key question for policy-makers is whether it should be adapted to consider benefits other than just the amount of carbon sequestered by a project. One issue this would raise is that the ERF would no longer be delivering emissions abatement at the lowest cost to government, but rather would be aimed at delivering a bundle of environmental benefits in a cost-effective manner. The extent to which carbon abatement could be 'traded off' against other benefits in a multifunctional index would be a key consideration. However, as challenging as this approach may be, it is not impossible or without precedent. For example, the US Conservation Reserve Program (CRP) began in 1985 with a primary objective of reducing soil erosion on erodible cropland areas using an auction-based approach to achieve this in a cost-effective manner (Baylis et al. 2008). Additional environmental objectives were subsequently added in 1990 (Ribaudo et al. 2001), such that the CRP now aims to deliver a bundle of environmental outcomes including wildlife, water quality and air quality benefits (Hajkowicz et al. 2009). Similarly, renewable energy auctions, which often have climate change mitigation as a central objective, have been modified in countries such as China to include criteria relating to local economic benefit rather than just delivering the greatest amount of electricity generation per dollar spent (Azuela et al. 2014).

Another precedent that could be drawn on from the renewable energy sector is the use of technology-specific auctions (Baumber 2017a), which could be reframed as method-specific auctions under the ERF. For example, some auctions could be open only to carbon farming that provides co-benefits (with a multifunctional index used to measure these) while other auctions would be open to other methods such as waste or energy efficiency (where no index would be applied). Alternatively, state and territory governments could develop their own auction schemes to source the voluntary carbon credits they are planning to purchase in coming years (Clean Energy Regulator 2019a). Given that many of the existing PES metrics used in Australia are state-specific (e.g. habitat hectares in Victoria, ecosystem and species credits in NSW, the Regrowth Benefits Tool in Queensland), incorporating co-benefits into new state auction schemes may be simpler than incorporating them into the ERF.

*4.3 Benchmarks*

Benchmarks can be used to guide landholders in designing and managing carbon farming projects and can also be used as threshold for payments related to co-benefits. While some voluntary carbon standards (e.g. CCBA, SocialCarbon) apply qualitative benchmarks for co-benefits relating to biodiversity and community development (e.g. an appropriate monitoring plan has been implemented), these present a number of issues:

a) benchmarks they impose are not quantitative,

b) standards have not been designed for Australian conditions (Kapambwe and Keenan 2009; Robinson et al. 2016) and

c) the voluntary credit market is only 5% the size of the ERF market (Clean Energy Regulator 2019a).

Torabi and Berkessey (2015) argue that the potential exists to create demand for bundled credits that promote both carbon and biodiversity through landscape-scale planning, building confidence in the market. Confidence could also be strengthened by developing Australia-specific regeneration or afforestation standards that verify co-benefits using benchmarks drawn from the guidance provided by previous research on maximising outcomes for biodiversity, soil and water health (e.g. Lindenmayer & Hobbs 2004; Munro et al. 2012; Paul et al. 2016).

State and territory governments represent a growing source of demand for voluntary carbon credits in Australia and also have policy objectives relating to biodiversity conservation, soil and water health, and Indigenous affairs. Policy decisions by state and territory governments to not only offset their emissions but to maximise co-benefits in doing so could create significant demand for certified multifunctional carbon credits that incorporate co-benefits. Any such approach would require updated standards, with the potential for both qualitative and quantitative benchmarks to be incorporated to guide the design and management of carbon farming projects to optimise co-benefits.

Aside from their use in new or adapted PES schemes, benchmarks also have relevance for decision support tools for landholders wishing to maximise the co-benefits of carbon farming for private benefit. Previous studies have identified landholder motivations to engage in carbon farming due to its potential outcomes for biodiversity (Torabi et al. 2015; Cowie et al.

2019), soil condition (Kragt et al. 2017) and Indigenous connection to land (Robinson et al. 2016) irrespective of payment for these services.

*4.4 Models*

Spatial modelling approaches are likely to be applicable to new or adapted PES schemes relating to co-benefits, as they feature strongly in both the co-benefits literature and existing PES schemes, particularly where biodiversity outcomes are a priority. Previous co-benefit studies have sought to identify priority sites for carbon farming based on biodiversity criteria, such as mapping ecosystems with less than 30% of their original vegetation remaining (Carwardine et al. 2015; Robinson et al. 2016), areas with high numbers of rare species occurring (Moran-Ordonez et al. 2017), and sites that score well in terms of complementarity, connectivity and representation (Bryan et al. 2014). As with benchmarks, these mapping tools may be of value to landholders weighing up a decision on whether to engage in carbon farming on their land.

While spatial modelling based on remnant vegetation percentages and connectivity are applicable in highly fragmented landscapes, such approaches may not be directly applicable in rangeland areas of Australia with different fragmentation patterns. Alternative approaches to spatial mapping in rangelands could involve a focus on biodiversity refugia under future climate change scenarios (e.g. Gill et al. 2016) or identifying areas where the difference between the current state and the future state under carbon farming is likely to be greatest (e.g. the Regrowth Benefits Tool used under the Queensland Land Restoration Fund; Queensland Government 2018).

*5.5 Principles for selection of metrics for co-benefits*

Based on the preceding discussion, the following principles are proposed for selecting metrics for assessing co-benefits of carbon farming.

1. Apply metrics with the following attributes :
    - The metrics capture the relevant range of ecosystem services likely to be impacted (positively or negatively) by vegetation and soil management “carbon farming” projects (e.g. biodiversity conservation and habitat features; soil health/quality; hydrological impacts; economic and social/cultural benefits) ;
    - The metrics may include a single indicator or an array/composite;
    - The metrics may be quantitative or qualitative;
    - The metrics are responsive to the impacts of carbon farming and/or management (activity or outcome based); activity-based metrics are useful for slow response variables and/or when climatic conditions mask management impacts;
    - The metrics are readily and cost-effectively measured, interpreted, and independently verified;
    - The metrics are suited to, and tested in, an Australian context (environment, farming systems).
2. Balance accuracy/precision and practicality, according to the purpose of assessment. Simple, less precise methods are suitable for predictive assessments to be used in project planning and voluntary market; whereas more accurate, precise methods are needed for market-based schemes involving public payments, or for offsets in compliance markets, for which fungibility (like-for-like substitution) is critical.

3. Consider limitations of indices that combine multiple ecosystem services (e.g . is weighting of variables to be avoided because it is perceived as being subjective; or should it be included because it allows the importance of an indicator to reflect the local site conditions?) Lack of explicit weighting can hide trade-offs. Prioritisation and weighting should be determined by stakeholders.
4. Use single issue indices for combining different aspects of one impact category; e.g. aspects relevant for biodiversity conservation.
5. Use proxies and models for predictive assessment, and where outcome-based measures are not feasible (e.g. due to transaction costs). Proxies and models should be developed and tested from direct measurements.
6. Use multiple lines of evidence for quantifying selected variables (e.g. remote sensing and ground-based methods).

## 4. Conclusion

Australia has been an important site of policy innovation around carbon farming and the various ecosystem services it can provide, across both the Oceania region and the world more broadly. Australia's policy experimentation around land-based carbon sequestration has spawned a diverse and evolving carbon farming sector that has the potential to deliver a range of co-benefits aside from climate regulation, including in relation to biodiversity, soil health, water quality and cultural services. The quantities and types of ecosystem services that are currently being delivered are subject to substantial uncertainty, as are the methods that may be most appropriate for quantifying these services. Evidence from previous studies on reforestation and regeneration has been used to develop design principles and management practices that are likely to maximise these co-benefits. Moreover, existing PES schemes in

Australia present a range of ways of linking such practices to landholder payments, including through the use of indicators, indices, benchmarks and models.

Given the existing policy environment for carbon farming in Australia, benchmarks and spatial models that prioritise certain areas for carbon farming are likely to provide the most immediate benefits by supporting landholders in maximising co-benefits for private benefit, achieving certification under existing voluntary schemes that value co-benefits (e.g. CCBA, SocialCarbon) and earning additional payments from other PES schemes (e.g. biodiversity offset schemes). Multifunctional indices have been developed in Australia previously and have the potential to play a role in new or adapted PES schemes that target the co-benefits of carbon farming. Spatial models and predictive indicators that link design and management actions to likely outcomes could be incorporated into multifunctional indices, as well as being used to assess the effectiveness of Australian carbon farming in delivering co-benefits more broadly.

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**Supplementary Material:** Recent studies identifying potential co-benefits of carbon farming in Australia

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Flugge & Abadi 2006 | Western Australia | Farm forestry | Hydrology (salinity mitigation) | | | | Salinity benefit modelled based on results of previous studies |
| Fensham & Guymer 2009 | Queensland | Reforestation | | Habitat for biodiversity | | | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Wentworth Group of Concerned Scientists 2011 | Australia-wide | Avoided deforestation and reforestation | | Habitat for biodiversity (including riparian and critical habitats) | | | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Robinson et al. 2011 | Indigenous land – Australia-wide | Environmental plantings, savanna burning | | | | Co-benefits support Aboriginal and Torres Strait Islander peoples' interests, values, assets and priorities | Devised indicators to measure carbon farming impact on Indigenous value, assets and priorities |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Mitchell et al. 2012 | Australia-wide | Afforestation and reforestation | | Habitat for biodiversity | | | Theorised from previous studies |
| George et al. 2012 | Western Australian wheatbelt | Mallee plantings, environmental plantings | Hydrology (salinity mitigation) | Habitat for biodiversity | Fuel | | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Bradshaw et al. 2013 | Australia-wide | Environmental plantings, savanna burning | Soil & water (water quality, salinity mitigation, sediment and nutrient flows) | Habitat for biodiversity | | | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Net Balance Foundation 2014 | Australia-wide | Reforestation and afforestation | Soil, water and air quality benefits | Habitat for biodiversity | | | Theorised from previous studies |
| Bryan et al. 2014 | High to medium rainfall zone | Environmental plantings, carbon plantings (monocultures) | | Habitat for biodiversity | | | Theorised from previous studies, modelled using a prioritisation approach based on connectivity and complementary of species/ecosystem type |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Butler et al. 2014 | Queensland & NSW – diverse biomes | Diverse – HIR avoided deforestation, environmental plantings, farm forestry etc. | Hydrology (salinity mitigation)<br><br>Water quality (reduced sediment load) | Habitat for biodiversity | | | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Standish & Hulvey 2014 | High to medium rainfall zone | Environmental plantings | | Habitat for biodiversity | | | Theorised from previous studies |
| Walsh et al. 2014 | Northern Australia | Savanna fire management | | | Improved access for hunting/harvesting, reduced mustering costs and land condition improvement | Indigenous hunting access | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Renwick et al. 2014 | Indigenous land – Australia-wide | Environmental plantings | | Habitat for biodiversity | | Indigenous land management | Used Polglase et al. (2013) and measured the potential carbon that could be sequestered by growing environmental tree plantings. |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Carwardine et al. 2015 | Australia - high to medium rainfall zone | Environmental plantings | | Habitat for biodiversity | | | Modelled using a prioritisation approach based on areas with <30% remnant vegetation |
| Cunningham et al. 2015 | Eastern Australia | Reforestation | Water quality<br><br>Nutrient cyclcing | Habitat for biodiversity | Water yield | | Theorised from previous studies. Outlined conceptual model for balancing carbon, biodiversity and water outcomes. |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Evans et al. 2015 | Queensland – medium-low rainfall | Assisted regeneration, environmental plantings | | Habitat for biodiversity | | | Modelled using economic model |
| Russell-Smith et al. 2015 | NT national parks | Savanna burning | | Habitat for biodiversity | | | Modelled using GIS fire regime metrics assessment |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Dumbrell et al. 2016 | Western Australian wheatbelt | Environmental or mallee plantings, stubble retention, mulch, biochar, no-till cropping | | Maintaining soil health (reduced erosion & improved soil quality) | | | Stakeholder perspectives (landholders) |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Kragt et al. 2016 | Australia-wide | Environmental plantings, regeneration, stubble retention, no-till cropping, permanent pastures | | Habitat for biodiversity | | Aesthetics | Stakeholder perspectives (public willingness to pay for co-benefits) |
| Perry et al. 2016 | Cape York Peninsula Queensland | Savanna burning | | Habitat for biodiversity | | | Direct sampling of 202 sites. |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Torabi et al. 2016 | Victoria – medium-high rainfall | Environmental plantings | | Habitat for biodiversity | | | Stakeholder perspectives (landholders) |
| Bryan et al. 2016 | Australia – medium high rainfall | Plantings (monocultures and mixed-species) | | Habitat for biodiversity | | | Modelled using economic model |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Doran-Browne et al. 2016 | Case study site - farm north of Canberra | Environmental plantings | Salinity | Habitat for biodiversity<br><br>Soil erosion control | Livestock shelter | | Case study approach using on-ground modelling to measure livestock (using GrassGro, a mechanistic model containing interacting modules for climate, soil dynamics, pasture growth and animal production) and soil and tree sequestration of carbon (using FullCAM). |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Robinson et al. 2016 | Australia – various biomes | Environmental plantings | | Habitat for biodiversity | | Indigenous land management | Biodiversity: Direct measurement of area of carbon plantings (with assumption that benefit is greatest in areas with <30% remnant vegetation).<br><br>Indigenous management: Stakeholder perspectives |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Paul et al. 2016 | Temperate and tropical Australia | Plantings (mixed-species & monocultures) | | Habitat for biodiversity | | | Biodiversity potential index developed based on proportion of eucalypts and site width |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Moran-Ordonez et al. 2017 | Northern Australia – tropical savanna | Savanna fire management | | Habitat for biodiversity | | Indigenous land management | Biodiversity: Modelled priority locations (with assumption that benefit is greatest where rare species are present)<br><br>Indigenous management: Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Kragt et al. 2017 | Western Australia wheatbelt | Environmental plantings, tree belts, stubble retention, no-till cropping | | Maintaining soil health (improved soil quality) | Increased crop yield | | Stakeholder perspectives (landholders) |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Nolan et al. 2018 | Rangelands (especially in NSW & QLD) | Assisted regeneration, avoided deforestation | Salinity mitigation | Habitat for biodiversity<br><br>Maintaining soil health (reduced erosion) | | | Theorised from previous studies |

| **Study authors** | **Location and context** | **Carbon farming practices** | **Potential ecosystem services (beyond climate regulation)** | | | | **How have co-benefits been identified/measured?** |
|---|---|---|---|---|---|---|---|
| | | | **Regulating** | **Supporting** | **Provisioning** | **Cultural** | |
| Evans 2018 | WA wheatbelt and NSW/QLD rangelands | Assisted regeneration, avoided deforestation, environmental plantings | | Habitat for biodiversity<br><br>Maintaining soil health (improved soil quality) | Shelter for livestock | | Theorised from previous studies |