

Carbon farming for resilient rangelands: people, paddocks and policy

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Abstract. Carbon farming is a new land use option over extensive areas of the Australian rangelands. This land use change has been promoted by government incentives to mitigate climate change, with most of Australia's land sector abatement to date being delivered in rangelands. Aside from these mitigation benefits, carbon farming has also demonstrated potential co-benefits that enhance socio-ecological resilience by diversifying land uses and income streams, providing opportunities for sustainable land management to enhance soil and vegetation and creating opportunities for self-organisation and collaboration. However, factors such as policy uncertainty, perceived loss of future land use flexibility and the potential for carbon farming eligibility to create social divisions may negatively affect resilience. In this paper we weigh up these risks, opportunities and co-benefits and propose indicators for measuring the impact of carbon farming on the resilience of rangeland systems. A set of land policy principles for enhancing resilience through carbon farming are also identified.

Additional keywords: co-benefits resilience, risk, sustainable land management.

Received 8 May 2020, accepted 9 July 2020, published online 7 August 2020

Introduction

In recent years, carbon farming has rapidly expanded in the southern Australian rangelands. Here we explore how this expansion of carbon farming practices may affect the socio-ecological resilience of rangeland systems (i.e. their capacity to absorb disturbances and reorganise while maintaining essential functions). Focusing primarily on the rangelands of north-western New South Wales (NSW), we review the risks and opportunities for the socio-ecological resilience of rangeland systems, as well as potential management options and policy principles to respond to these risks and opportunities.

Starting with a profile of carbon farming in Australia, we identify potential benefits and disbenefits highlighted in prior research, with a brief introduction to the concepts of resilience and rangelands as socio-ecological systems. The conceptual framework used to synthesise these opportunities and risks is based on six enabling conditions for general resilience identified from previous research – reserves, diversity, monitoring, scale,

feedbacks and social capital (Armitage 2007; Erol *et al.* 2010; Carpenter *et al.* 2012; Walker and Salt 2012). The discussion of these enabling conditions includes a consideration of appropriate policy settings to maximise the opportunities carbon farming presents for enhancing rangeland resilience while minimising the risks. This analysis has implications for rangeland systems in other countries, such as the United States, where resilience-based approaches have been used to evaluate the carbon sequestration potential of different vegetation systems (Dass *et al.* 2018).

Profiling carbon farming in the Australian rangelands

Carbon farming encompasses a range of land management activities designed to either increase carbon sequestered in vegetation and soils or reduce greenhouse gas emissions from vegetation, soils and livestock (Government of Western Australia 2020; Queensland Government 2020). Carbon farming has recently emerged as a significant and rapidly-growing land use option for the Australian rangelands. The expansion of carbon

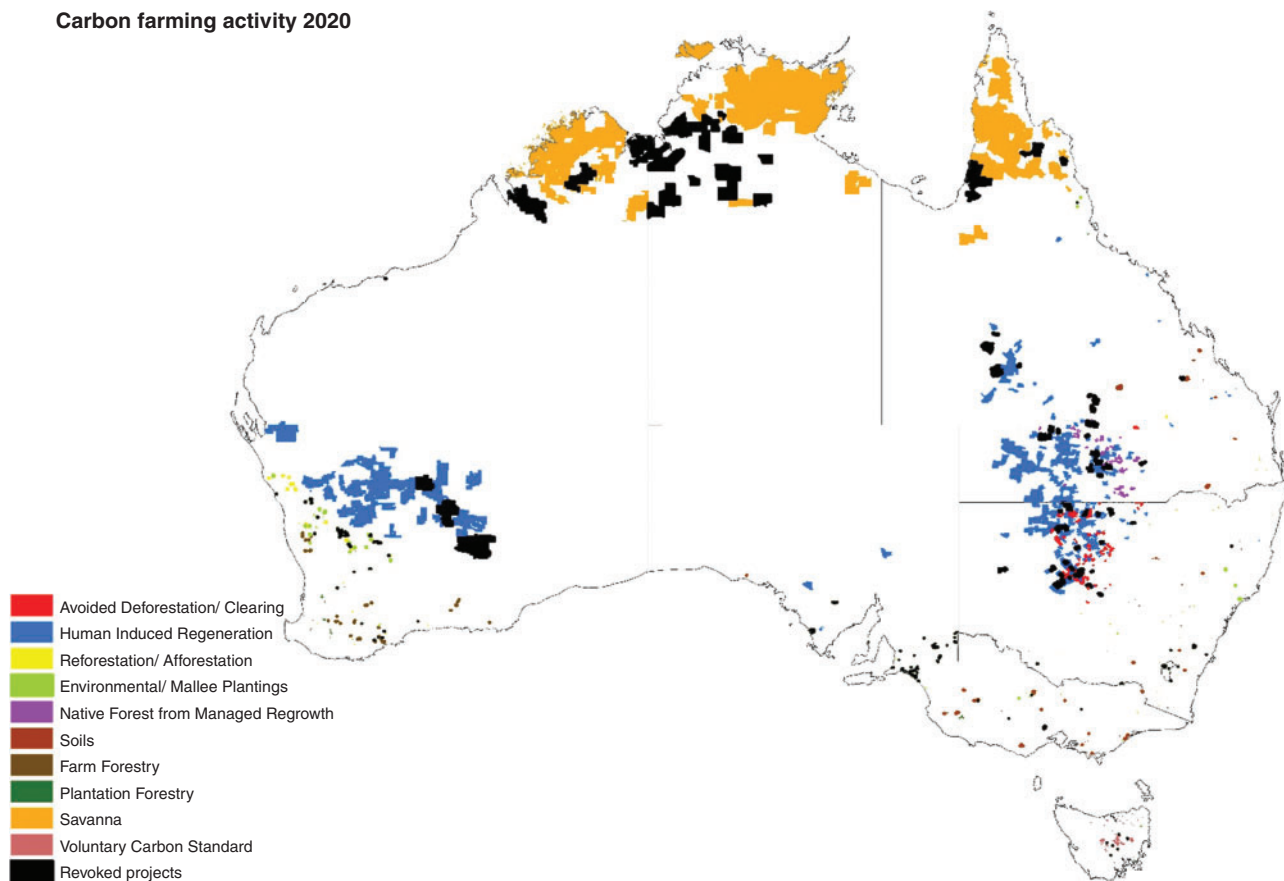
Carbon farming activity 2020

Fig. 1. Current distribution of different carbon farming projects in Australia. The greatest concentration of Avoided Deforestation (AD) and Human Induced Regeneration (HIR) projects occurs on the rangelands of north-western New South Wales (NSW) and south-western Queensland. Other important rangeland locations for carbon farming include the southern rangelands of Western Australia and Australia's northern tropics, where savannah burning projects cover large areas, albeit accounting for a much smaller proportion of ACCUs than either AD or HIR (9% as of February 2020) Source: Clean Energy Regulator (2020).

farming in Australia between 2015 and 2020 was primarily driven by the Australian Government's purchasing of Australian carbon credits (ACCUs) under the AUD\$2.5 billion Emissions Reduction Fund (ERF). The ERF represents a key mechanism for delivering on Australia's commitment of 26–28% reduction on 2005 emission levels by 2030 under the 2015 Paris Agreement and employs UNFCCC (United Nations Framework Convention on Climate Change) rules on accounting for emissions reductions and sequestration through reforestation and avoided deforestation. The 2019 announcement of a further AUD2 billion Carbon Solutions Fund will enable a continuation of the investment that has begun under the ERF (Clean Energy Regulator 2019b).

Eligible activities under the ERF (detailed in the Supplementary Materials table S1 available at the journal's website) include the management of vegetation to offset anthropogenic carbon emissions which predominantly requires the prevention of land clearing (avoided deforestation, AD) or regeneration (human induced regeneration, HIR). As of February 2020, AD and HIR account for 24 and 23%, respectively, of all ACCUs issued (Fig. 1; Clean Energy Regulator 2020). Participation in the ERF is largely voluntary, but to ensure emissions reductions are not displaced by increased emissions elsewhere, an involuntary

safeguard mechanism that requires large emitters to purchase offsets for emissions above specified baseline levels has also been built into the scheme (Clean Energy Regulator 2019b).

Following rapid growth in ERF investment between 2015 and 2018, market opportunities have dampened more recently. The reduced volumes of ACCUs being sold under the ERF has been attributed to the Clean Energy Regulator's unwillingness to pay higher prices and potential sellers being deterred by the administrative complexity of the scheme (Reputex 2020). To increase the value of carbon farming activities, 'core benefits' or 'value-stacking' mechanisms have been identified as having the potential to maximise the opportunities that carbon farming may provide (Lin *et al.* 2013; Kragt *et al.* 2017). Valuing co-benefits (production, environmental and social) from carbon farming is currently being realised at the state level in Australia under the Queensland Government's Land Restoration Fund (LRF) and new third-party schemes such the Reef Credits currently under development (GreenCollar 2020). Should these co-benefit markets continue to grow, further expansion of carbon markets may be expected. Additionally, non-government sources for a demand in carbon credits are becoming an increasingly important driver of carbon markets. This growing demand is

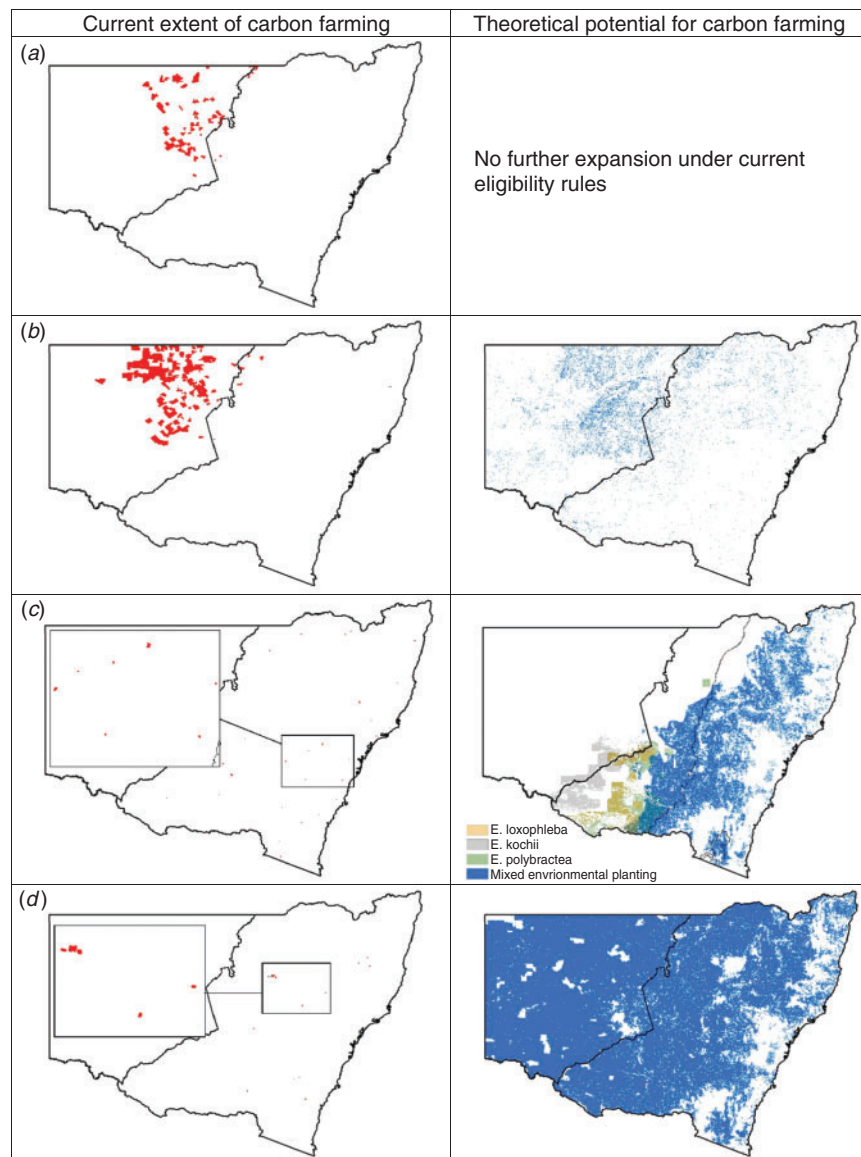


Fig. 2. Current extent (red) and theoretical potential (blue) of Australian Government Emissions Reduction Fund (ERF) carbon farming activities in New South Wales: (a) Avoided Deforestation (AD)¹; (b) Human-induced Regeneration (HIR)¹; (c) Environmental or Mallee Plantings² (EP); and (d) Sequestering Carbon in Soils in Agricultural Systems (SOIL). The black line indicates the boundary for western NSW (rangelands) and the black dotted line the 600 mm rainfall isohyet². Under current eligibility rules, there is no further expansion of AD. There are currently no SOIL or EP projects in the rangelands of western NSW. Details for estimation of theoretical potential can be found in the Supplementary Materials figures S1–S5.

¹The actual extent of a project activity is a sub-set of this area known as the carbon estimation area (CEA) which is defined by rules set out for each ERF method. A project can contain one or many CEA's e.g. may have both AD and HIR projects. These are property boundaries and therefore may be an overestimate of carbon estimation area.

²Mallee plantings are restricted to ≤ 600 mm long-term average annual rainfall.

represented by voluntary purchases by individuals, businesses or state governments looking to offset their carbon footprint.

The potential supply of carbon credits from the Australian rangelands is considerable. For example, 599 515 km² could theoretically deliver abatement under the soil carbon methods in

NSW alone (Fig. 2). Garnaut (2019, p. 147) has argued that Australia is 'uniquely well placed to lead and prosper from the land use transformation' that carbon farming offers. Australia's comparative advantage in land sector emissions reductions and sequestration has also been recognised both globally (Lin *et al.*

2013) and within Australia (Dean *et al.* 2015; Fleming *et al.* 2019) as a means to support multi-use landscapes which co-deliver climate mitigation, production and biodiversity benefits (Cunningham *et al.* 2015). In addition, Australia also has a competitive advantage in carbon offsets as it features a policy environment where a combination of market rigour and integrity is supported through eligibility rules, method development, auditing standards and ERF purchasing of ACCUs (CMI 2020a). However, policy uncertainty, complex rules and high transaction costs could pose risks to this competitive advantage and limit further expansion of carbon markets and opportunities for some pastoralists (Evans 2018).

Benefits and disbenefits of carbon farming for rangelands: perceptions and reality

Although carbon farming has been identified to have a range of economic, social and environmental impacts on rangeland systems, there is uncertainty around how these impacts may manifest in different contexts and the interactions and relationships between them. As carbon farming is relatively recent in the Australian rangelands, most research into benefits and disbenefits has relied on stakeholder perceptions, modelling or speculations by rangeland experts based on similar practices rather than empirical evidence from carbon farming sites (Baumber *et al.* 2019).

Potential economic benefits identified by previous studies include increases in landholder income, diversification of income sources, increased availability of capital to invest in farm infrastructure and improvement, ability to hire labour, and flow-on effects for surrounding towns and communities (Crossman *et al.* 2011; Evans *et al.* 2015; Salas Castelo 2017; Jassim 2018; Cowie *et al.* 2019; Cross *et al.* 2019). Potential social benefits include improved mental health and community resilience (Cowie *et al.* 2019), innovative community initiatives and networks (Fleming *et al.* 2019), enhanced community development and cultural connection to land for Indigenous communities (Jackson *et al.* 2017) and enhanced potential for inter-generational farm management and succession on agricultural properties (Cross *et al.* 2019). Potential ecological benefits of carbon farming include increased biodiversity, increased habitat provision, improved soil health, structure and water holding capacity, management of erosion and salinity and improved water quality (Baumber *et al.* 2019; Cross *et al.* 2019). The potential for income to be reinvested into regenerative farming practices and improved farm efficiency also has potential sustainability benefits for farm resilience in the long term (Cross and Ampt 2017; Cross *et al.* 2019).

The Australian Government has promoted co-benefits to landholders, such as 'improved quality of your land and water supply, increased biodiversity and shade and shelter for stock' (Clean Energy Regulator 2018) and the Queensland state government has introduced a Land Restoration Fund to incentivise carbon farming projects that offer 'co-benefits' of this type. However, a range of potential 'disbenefits' have also been identified from carbon farming that could pose threats to the future expansion of the industry as well as affecting the socio-ecological resilience of rangeland systems. These disbenefits include perceived risks of increases in invasive native scrub (INS) or woody weeds (Butler *et al.* 2014; Jassim 2018; Cross

et al. 2019), which have the potential to reduce land use flexibility due to long-term land management commitments (Kragt *et al.* 2017) and decreased land value (Baumber *et al.* 2011). Further disbenefits may include a perceived risk of fire and pest occurrence (Torabi *et al.* 2016) caused by landholders shifting from pastoralism to carbon farming and moving off site (absenteeism) and social divisions which may also occur with an increasing gap between those who have eligible land for carbon farming and those who do not (Cowie *et al.* 2019; Cross *et al.* 2019).

What is a resilient rangeland?

To understand whether a new practice such as carbon farming might increase or decrease the resilience of a socio-ecological system, it is first necessary to define resilience. Resilience relates to the way that a system deals with disturbances or shocks. Here we follow the definition of resilience as 'the capacity of a social-ecological system to absorb disturbance, reorganise, and thereby retain essential functions, structures and feedbacks' (Carpenter *et al.* 2012, p. 3249). Under this definition, resilience is more than just 'bouncing back' – it requires an element of adaptation and reorganisation. This approach also requires an initial consideration of the 'resilience of what' (Walker and Salt 2012), that is, deciding which key functions, structures and relationships the stakeholders within a system might wish to maintain over time in the face of potential disturbances. In the case of Australia's rangelands, important functions may include the provision of habitat for biodiversity, protection of soil and water quality, supporting landholder and community livelihoods, cultural connections to land and inter-connections with neighbouring systems or higher system levels through trade, culture and governance.

The impacts of carbon farming on the socio-ecological resilience of the NSW rangelands has previously been explored by Cowie *et al.* (2019), who applied the RAPTA (Resilience Adaptation Pathways and Transformation Approach) framework developed by O'Connell *et al.* (2016). This research included workshops and a survey involving technical experts and local stakeholders to identify key system relationships, potential disturbances, thresholds for system change and possible pathways for the system to respond to these shocks. Key relationships identified by Cowie *et al.* (2019) included those between woody cover, ground cover, total grazing pressure and profitability, which were in turn influenced by factors such as infrastructure, enterprise options and debt levels. The major external shocks of concern included extreme seasonal conditions (both wet and dry periods), commodity price shocks, and government programs aimed at changing land use practices, including carbon farming and other NRM incentives.

Rangelands are complex adaptive systems that may be regarded as operating within certain states, or 'basins of attraction' where system elements interact with one another in a set of relationships that are relatively predictable (Walker *et al.* 2004). For example, in a rangeland grazing system, humans move livestock around, livestock eat grass, grass and trees compete for resources. Where climatic or other disturbances act to push a system out of its current state, balancing feedbacks act to pull it back towards a particular set of relationships and values that define its essential functions and structures (Fig. 3). In rangeland systems, such feedbacks may include the persistence of

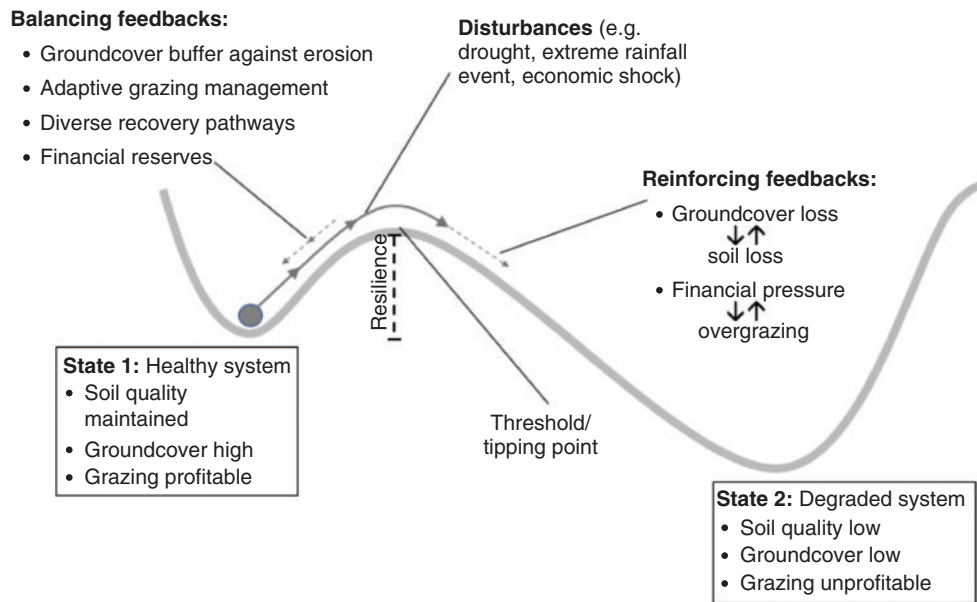


Fig. 3. Conceptual model of system states, thresholds and feedbacks using the analogy of a 'ball in a basin' (Levin *et al.* 1998; Walker *et al.* 2004).

seedbanks within the soil, adaptations that allow trees to resprout after fire and human management practices such as proactive adjustment of stocking rates or maintaining financial reserves to enable reinvestment following drought. Provided that such feedbacks remain in place, the present state may be regarded to be relatively resilient, even if the system does not stabilise for any length of time due to the constant interplay between disturbance and recovery.

Balancing feedbacks may help to maintain essential functions and structures following a disturbance, but resilience has its limits. For example, although some tree species such as eucalypts may exhibit adaptations that help recovery after a fire disturbance by resprouting (a strong balancing feedback), species that lack these adaptations (e.g. mulga and cypress pine) may experience large mortality events from fire declining resilience under climate change (Nolan *et al.* 2019). Thresholds that, once crossed, produce runaway change as a result of balancing feedbacks being overwhelmed by reinforcing feedbacks that bolster the direction of change may exist. For example, intense rainfall following drought may wash away a critical mass of topsoil, preventing vegetation from re-establishing, making the landscape susceptible to further erosion and 'locking' the system into a new degraded state. Furthermore, the disturbance that pushes the system over such a tipping point need not be especially large by historical standards if the resilience of the system has been eroded, such as by a gradual weakening of the balancing feedbacks that work to keep the system in its non-degraded state (e.g. through climate change, loss of income streams or overgrazing).

Enabling factors for rangeland resilience

Various resilience theorists have sought to identify factors that can enhance or reduce resilience in complex systems, including Carpenter *et al.* (2012), Erol *et al.* (2010) and Armitage (2007).

Table 1 identifies six types of enabling factors for general resilience, drawn primarily from Carpenter *et al.* (2012), with additional points from other researchers relating to self-organisation, agility, collaboration and social capital (Armitage 2007; Erol *et al.* 2010; Walker and Salt 2012).

The factors shown in Table 1 are termed 'general' resilience factors, and are relevant to a wide variety of complex systems that may incorporate diverse ecological, social and economic features and face a range of possible disturbances (Walker and Salt 2012). The application of these general factors may be appropriate in cases where there is a high degree of uncertainty around the nature, scale and frequency of disturbances. Based on historical trends, Australia's rangelands have characteristically experienced climatic disturbances such as drought, high-rainfall events and heatwaves, the frequency and intensity of which are expected to increase in the future (Godde *et al.* 2019). However, as human-induced climate change progresses, past experiences may no longer be a reliable guide to predicting future climatic extremes and modelling climate change impacts for some important drivers of climate, such as El Niño-Southern Oscillation, are subject to high levels of uncertainty (IPCC 2012).

As with environmental disturbances, socioeconomic trends may be partially predicted from past experience (e.g. shifts in commodity prices, migration trends), but new disturbances may emerge under conditions that have not been experienced before. For example, recent social and economic disruptions — without precedent in modern times — include the rise of China as an economic superpower, the structural shift to a 'permanent' era of low interest rates and inflation (Garnaut 2019, p. 65), and the emergence of the COVID-19 pandemic during the course of writing this manuscript. As such, extreme events may be expected to be a defining feature of rangeland systems into the future and current norms related to climatic and economic conditions may continue to be challenged in unpredictable ways.

Table 1. Enabling factors for general resilience

Enabling factor	Description
Reserves/buffers/redundancies	Extra capacity that is held in reserve that can minimise the severity of a disturbance or enable recovery (e.g. capital, labour, water, organic matter, social memory)
Diversity	Includes economic diversity, cultural diversity, biological diversity and response diversity (i.e. having a range of pathways available)
Monitoring/ information flows	Capacity to gather information in a shared, transparent and regular fashion.
Management at the right scale	Striking the right balance between: (i) connectedness – maintaining connections to neighbouring systems and higher system levels to enable exchange, support and replenishment; and (ii) modularity – enabling autonomous units in which agility, responsiveness and self-organisation is enhanced at the local level and threats are quarantined to stop them spreading.
Feedbacks	Maintain strong balancing feedbacks that push back against disturbance, as well as the capacity to interrupt reinforcing feedbacks that could lead to undesired runaway change
Social capital	Includes effective leadership, trusted relationships between key stakeholders, collaboration and reciprocity

Where the type, scale and frequency of likely disturbances is relatively well understood, it may be possible to complement ‘general’ resilience strategies with those aimed at ‘specified’ resilience. Specified resilience strategies often align with the broader general resilience categories shown in Table 1, but allow for a more targeted focus due to a better understanding of the nature of the disturbances faced. For example, insurance may be taken out against specific threats such as flood or fire, stockpiles of food and medicine may be planned based on the likely length of a supply disruption, local communities may be trained to respond to known threats and monitoring may be focussed on key thresholds of concern (Carpenter *et al.* 2012).

The application of the RAPTA framework to the NSW rangelands by (Cowie *et al.* 2019) is an example of a ‘specified resilience’ approach, including the identification of likely climatic, economic and policy disturbances, along with key thresholds of concern, such as ground cover levels falling below 50%, three consecutive months with <75 mm rainfall and total grazing pressure rates exceeding 30% utilisation of perennial grass cover. Such thresholds can act as triggers for specified actions under an adaptive management approach to maintaining essential functions and structures. However, they should not necessarily be seen as targets to be maintained at all costs, particularly in non-equilibrium systems that periodically experience shifts between multiple stable states while maintaining the critical climatic and soil conditions that determine ecological function and structure (Booker *et al.* 2013).

Potential impacts of carbon farming on rangeland resilience

Each of the general resilience factors from Table 1 is explored below. This includes an analysis of the potential opportunities and risks that carbon farming presents for these resilience factors, as well as policy options to enhance these opportunities and minimise the risks. Table 2 highlights examples of how carbon farming could potentially support or detract from each of these resilience factors, along with potential management and policy responses identified by carbon farming research to date.

Building up reserves, buffers and redundant capacity

Designing policy and management interventions that enhance rangeland resilience requires understanding the different ways in which buffers and reserves affect resilience. At its core,

carbon farming is about building up reserves of carbon in vegetation and soils. The ERF incentivises this by purchasing ACCUs periodically via auction and facilitates it by providing a range of approved methodologies and associated tools such as the Full Carbon Accounting Model (FullCAM) used to estimate carbon stores (Richards and Evans 2004). In addition, carbon farming may also help to build up financial reserves for landholders and increase the amount of native habitat that can act as refugia for biodiversity during droughts and other disturbances.

Building up reserves of carbon in vegetation and soils can enhance resilience in two ways. First, these reserves may help to dampen the effects of disturbances, such as the role played by ground cover in preventing heavy rainfall from eroding soils. Second, reserves provide redundant capacity that is not used under normal conditions but may be available to draw on when resource levels are low, such as increased persistent, palatable, productive perennial grass cover that retains feed-base and ground cover under deteriorating seasonal conditions. Achieving both objectives simultaneously requires nuanced policy settings. For example, building up ground cover to buffer against extreme climatic events is consistent with the principle of ‘permanence’ that underpins both the HIR and AD methods, but if the goal is to build up reserves of biomass to access in times of need, a more flexible, non-permanent approach is required that allows biomass reserves to be drawn down periodically.

The current Australian HIR rules include several elements that enable landholders to enhance both permanent buffering capabilities as well as adaptively managing biomass reserves. The focus of the HIR methodology is on the permanence of woody vegetation, while biomass levels in grasses and soils are able to fluctuate. Furthermore, landholders are able to choose between a 100- or 25-year permanence period, use HIR areas for limited strategic grazing and implement a ‘growth pause’ in the HIR FullCAM model, where grazing does not suppress forest growth (Department of the Environment and Energy 2016). However, those landholders choosing to sign up for a 100-year permanence period with total exclusion of stock may need to consider whether, from a resilience perspective, the increase in financial reserves from selling carbon credits compensates for a loss of future land use flexibility.

In developing new policy measures to promote the ‘co-benefits’ of carbon farming, the twin goals of buffering against

Table 2. Relationship between resilience and observed (stakeholder opinion on) co-benefit/dis-benefit from carbon farming (CF) activities under the Australian Emissions Reduction Fund
Examples of the management context for each resilience indicator are provided for the major rangeland CF activities, Avoided Deforestation and Human-induced Revegetation. Policy considerations are also identified to increase resilience under carbon farming

Resilience indicator	Resilience description	Management context	Examples of potential co-benefit/dis-benefits	Policy considerations
Reserves, buffers and redundant capacity	Buffering against disturbance	As above-ground biomass increases (carbon sequestration) so does below-ground biomass and soil carbon, however the value of the latter two carbon pools is not recognised under vegetation-based methods, providing little incentive for farmers to manage, e.g. increased soil carbon ^A	Increased carbon reserves in soils Increased ground cover	Incentivising co-benefits and developing new income streams with a focus on soil quality
	Enhancing redundant capacity	Adaptive and flexible land management such as strategic stocking of CF area ^E Total grazing pressure fencing surrounding the CF area to enable effective periods of pasture rest and recovery ^F Exclusion fencing to avoid harbouring of vertebrate pests (goats, pigs and wild dogs) ^F Longer-term financial security enabling farm planning to secure income for future generations ^B	Variable ground cover targets Increased ground cover Reduced grazing from unmanaged feral herbivores and pest control Secure income stream based on expected carbon sequestration	Incentivising maintenance/increased ground cover adjusted to prevailing seasonal conditions Aligning carbon farming income with drought cycles to balance loss of grazing income during droughts
	Enhancing financial reserves		Ability to hire labour and improve social capital	
	Income diversification	Intensification of rangeland management. Where CF is undertaken in areas of low production potential, funds can be redirected to on-farm rehabilitation practices (water spreading, total grazing pressure management through exclusion fencing) allowing foregone agricultural production in CF area to be offset against increased production elsewhere on-farm. Redirection of capital on-farm may also increase local employment (e.g. purchasing contractors and fencing supplies) ^{A,B,C}	Increased area of rehabilitated land Increased on-farm production Increased ground cover Increased farm infrastructure and improvements Regional socioeconomic benefit through local employment opportunities	Incentivising co-benefits and developing new income streams Encouraging reinvestment of CF profits in the rangelands
Enhancing diversity	Protection and enhancement of biodiversity	CF income has been used to clear non-CF paddocks (more intensive production in pastoral areas) but allowed the retention of interconnected remnants of trees. This increases the cost of clearing but CF income provides the additional income and greater financial security to undertake more conservative approaches to land management ^D The landscape scale changes in areas of CF may result in changed regional hydrology and microclimates as well as altered connectivity for pest and fire management ^F	Increased on-farm habitat extent	Restriction in scale of landscape simplification, restricting the percentage of the property that is included in CF Incentivising biodiversity benefits
			Simplification of vegetation composition and structure where CF results in invasive native scrub	Impact of CF considered with regional natural resource management (NRM) plans

(Continued)

Table 2. (Continued)

Resilience indicator	Resilience description	Management context	Examples of potential co-benefit/dis-benefits	Policy considerations
Monitoring/information flows	Monitoring	There is an opportunity to expand the current ERF monitoring and reporting requirements to also collect on-site co-benefit data ^A	Support for enhanced risk management	Incentivising co-benefits and developing new income streams, developing a monitoring and evaluation framework
	Transparency	While the financial value of ERF projects is publicly available information, there remains misconceptions over the value of carbon projects and community divisions between traditional pastoralism and CF. ^A	Increase regional social cohesion, increased regional community resilience	Conducting open forums for information sharing
	Information sharing	There is a lack of easily accessible, trusted CF information, particularly on financial, legal and tax implications of entering into CF limiting ERF uptake or poor decisions and revoking of contracts ^{A,B}	Lack of trust in CF markets	Finance and property sector specific information forums established by regional NRM bodies
Management at the right scale	Openness and nestedness	A concern from non-carbon farmers is that CF will result in a higher rate of absenteeism and with it reduced community capacity to undertake collaborative management activities such as pest management or fire control ^A	Reduced regional ability to strategically control invasive species	Active management requirements for CF project sites
Feedbacks	Modularity	Increased opportunities to develop local provenance 'branding' for CF rangeland products ^G CF could strengthen feedback loops where increased monitoring and information sharing occurred but may also weaken loops if it reduces landholder flexibility over future management decisions ^A	Additional market opportunities opened Reduced flexibility of land-use and decreased property values	Ensuring that Australian and state-based carbon market rules are tailored to local conditions. Strategic alignment of CF payments to be received or reserved for use in drought. Regional advice that considers pathways to enable reinvestment of CF income to enhance farm enterprise long-term sustainability. Provision of regional forums that enable farmer-to-farmer information sharing.
Social capital	Leadership	In the absence of information, carbon farmers looked to key innovators. ^B (trusted farmers who were early adopters) for advice and help with decision making	Building of community of practice around CF	Developing guidelines on ways that trust can be built during the expansion of new practices such as CF.
	Trust and collaboration	Regional NRM bodies (local land services) and aggregators (brokers linking landholders to the ERF) have important roles in building trust around CF Collaboration and trust may be reduced when divisional lines are drawn between the haves (carbon farmers) and have nots (non-carbon farmers) ^B Where landholders have previously undertaken (without incentive) rehabilitation practices, they may be unwilling to continue providing these services without similar payments ^A	Trust-building by aggregators and NRM bodies in western NSW ^A	Conducting open forums for information sharing. Additional, changed land management valued along with retrospective activities under co-benefit incentive scheme.

^ACross *et al.* (2019).^BCowie *et al.* (2019).^CCockfield *et al.* (2019).^DR. J. Manns, pers. comm.^EButler *et al.* (2014).^FWaters *et al.* (2019).^GCMI (2020b).

disturbances and enhancing redundant capacity need to be considered. For example, co-benefit payments could be linked to the maintenance of adequate buffers, with Cowie *et al.* (2019) proposing a threshold of 50% ground cover maintained 50% of the time as an indicator of adequate buffering against wind erosion, and 30% perennial grass utilisation as a threshold above which pasture reserves may be depleted. Flexibility and adaptive management could be further enhanced by employing variable ground cover targets that take into account seasonal conditions, such as those employed under the 2004–2008 ground cover incentive scheme in western NSW (Hacker *et al.* 2010), or by using ‘activity-based’ metrics that reward landholders for following certain practices rather than achieving specific outcomes (Baumber *et al.* 2019).

The security of reserves is also a key consideration, with the potential for policy design to offer greater incentives for landholders to provide and maintain reserves that are more secure against disturbances such as fire. Dass *et al.* (2018) present evidence that below-ground carbon in US grasslands may offer more secure sequestration than forests in fire-prone environments. Carbon farming sites that act as refugia for biodiversity in times of extreme drought could also be prioritised for incentive payments (e.g. wet refugia in landscapes, Gill *et al.* 2016).

Enhancing diversity

Carbon farming in the Australian rangelands has the potential to enhance diversity in several ways, including diversifying enterprise options for landholders (Cowie *et al.* 2019) and encouraging the protection and enhancement of biodiversity (Butler *et al.* 2014). However, it is important to note that the ERF auction mechanism is not designed to promote diversity, but rather has a singular focus on carbon that stems from a legislated goal of ‘purchasing carbon abatement at the least cost’ under the *Carbon Credits (Carbon Farming Initiative) Act 2011* (section 20G). This singular focus creates the risk that carbon farming incentives could potentially reduce ecological, economic and social diversity by valuing only one component within complex rangeland ecosystems. Walker and Salt (2006) highlight how policy approaches based on efficiency or optimisation may reduce resilience by over-simplifying complex systems, ‘keeping only those things that are directly and immediately beneficial’ (Walker and Salt 2006, p. 7).

To ensure that carbon farming enhances the diversity of habitat types, enterprise options and community development pathways in the Australian rangelands, targeted policy measures are required that go beyond the least-cost abatement model of the ERF. Globally, there are precedents for auction-based schemes to be modified to promote a diversity of objectives, as has occurred with the US Conservation Reserve Program (Baumber *et al.* 2019). However, the ERF’s legislated requirement to deliver least-cost abatement makes such an option unlikely in Australia. Instead, complementary co-benefit schemes provide a promising option, such as the Queensland Government’s Land Restoration Fund and its associated co-benefits standard for assessing carbon farming projects (Queensland Government 2020). Australian state governments are well placed support this further market expansion, as they not only have constitutional responsibility for natural resource management (NRM) and regional development, but they also

represent one of the fastest-growing sources of demand for carbon credits to offset emissions from vehicle fleets, desalination plants and other activities (Clean Energy Regulator 2019b).

Aside from incentivising the co-benefits of carbon farming, regulators may also need to impose constraints on activities that simplify diverse ecosystems. Precedents for such limitations can be found in other market-based environmental policy schemes, such as the restrictions that prevent biofuels being counted towards EU renewable energy targets if they are grown on land converted from primary forest or biodiverse grassland (European Parliament and Council of the European Union 2009). Plantations in Australia are already restricted from earning carbon credits in areas with greater than 600 mm annual average rainfall to manage competition for water resources (Department of the Environment and Energy 2019). This restriction helps to improve the competitiveness of assisted regeneration methods such as HIR, which are preferable from a diversity perspective to monocultural plantations (Evans 2018).

The biggest risk of landscape simplification in Australian rangelands comes from invasive native scrub (INS) or woody weeds. Regional NRM agencies have long recommended active management of INS to prevent the formation of dense monocultures that reduce pastoral production, inhibit pasture growth and make soils susceptible to erosion (Central West LLS and Western LLS 2014). However, evidence is currently mixed as to whether carbon farming increases INS. A survey by Cowie *et al.* (2019) found mixed perceptions in western NSW, with government stakeholders, landholders with HIR projects and pastoralists (non-carbon farmers), tending to hold the view that carbon farming contributes to INS, whereas researchers and carbon farming service providers disagreed with this proposition.

The above examples provide evidence that further restrictions may need to be considered if carbon farming approaches that simplify complex ecosystems start to become widespread. Moreover, if a link can be established between carbon farming and increases in INS that simplify landscapes, it may be necessary to modify eligibility rules to prevent forms of INS that simplify rangeland ecosystems from earning ACCUs.

Monitoring key variables and sharing information

Carbon farming has the potential to enhance monitoring and information-sharing across Australian rangelands due to the need for regular, systematic collection of data on vegetation growth rates and the impact of management actions on sequestration levels as part of auditing and compliance under the ERF. Carpenter *et al.* (2012) argue that monitoring and sharing information can enhance general resilience by enabling adaptive management and providing early warnings that critical thresholds may be crossed. Reid *et al.* (2014) also highlighted the important role played by monitoring and learning in enhancing rangeland resilience.

Supplementary Material table S2 provides a review of remote sensing-based projects and initiatives with the potential to provide information for monitoring key variables associated with co-benefits of carbon farming. Though not developed specifically for carbon farming or to assess soil rehabilitation outcomes at carbon farming sites, they can be combined with expert and local knowledge through modelling to then be applied to planning or incentive schemes. Some of the most

Table 3. Key system thresholds identified through expert analysis (adapted from Cowie *et al.* 2019)

Category	Thresholds (anticipated system response) ^A
Ground cover and type	>50% Bare ground (reduced rates of wind erosion) >three months below 75 mm results (increased perennial grass mortality)
Woody cover and type	Probability of >75 mm rainfall in two successive wet summers (recruitment and growth of woody vegetation increased)
Number of livestock	>30% Perennial grass utilisation (conservation of perennial pasture species)
Unmanaged herbivores	>30% Perennial grass utilisation (conservation of perennial pasture species) >50% Bare ground (50% of the time half the ground is covered) (reduced rates of wind erosion)
Total grazing pressure	>30% Perennial grass utilisation (conservation of perennial pasture species) Demand for feed-base (pasture) exceeds feed supply (limited rest and recovery of pasture species from herbivores; reducing ground cover; alternating pasture composition with reduced productive, palatable perennial species)

^ASystem responses need to be considered within the local context (e.g. current landscape condition and levels of degradation, seasonal conditions and vegetation/soil type).

promising tools listed in table S2 are those relating to the TERN Landscape (formerly TERN AusCover) initiative. Of these data layers, woody cover, seasonal cover and seasonal persistent green data could be used to develop proxies for vegetation quality and soil condition. Woody vegetation height and structure data could be used to develop proxy indicators for habitat value, as done by Dean *et al.* (2015) for rangelands.

While data collection related to carbon farming is currently skewed towards factors that influence carbon sequestration (e.g. tree growth, ground cover and type), such monitoring events provide opportunities to collect a wider array of data to elicit key thresholds that can be used to assess and monitor resilience of carbon farming sites across the NSW rangelands (Table 3). In this way, risks may be managed as monitoring of key variables can provide an early warning of system changes which may lead to land degradation. The introduction of incentives schemes for co-benefits such as the LRF has the potential to increase the collection of data on soil condition and biodiversity, helping to support adaptive management and the progressive development of monitoring platforms that can meet assessment, inventory and monitoring information needs across multiple scales. Good practices and lessons exist to that end from the USDA Bureau of Land Management (Toevs *et al.* 2011) that focus on data-driven adaptive management.

Information transparency is critical to ensure that monitoring efforts enhance general resilience (Carpenter *et al.* 2012). In this regard, carbon farming offers an advantage over other rangeland land use options, as public registers for carbon farming projects have been established at both the state and federal level. Federally, the Clean Energy Regulator publishes an ERF register that includes a project summary along with the project owner's name and property details for all ERF-funded projects (Clean Energy Regulator 2020). Under its LRF, the Queensland Government has established a LRF register that will also include details on specific co-benefits classes and methods used to monitor such co-benefits (Queensland Government 2020).

Transparency could be further increased through the sharing of monitoring results from properties being managed for carbon sequestration and other co-benefits. The transparency provided by ERF and LRF registers has the potential to enhance shared understanding around carbon sequestration and other co-benefits. Anecdotal evidence from landholders indicates that

such transparency could, in some cases, clash with established social norms around privacy and commercial confidentiality in rangeland Australia (Cross *et al.* 2019). For example, the ERF register makes it possible for landholders to estimate their neighbours' income from carbon farming much more easily than for grazing or other rangeland enterprises. Future options that could attempt to strike a balance between transparency and privacy include sharing de-identified data, such as monitoring results that have names and locations removed, or using de-identified data to calibrate online estimators of carbon sequestration and co-benefits, such as the prototype LOOC-C tool launched by the CSIRO in 2019 (CSIRO 2020).

Management at appropriate scales

This resilience principle brings together a need for openness, nestedness and modularity, which often need to be balanced against one another when managing for socio-ecological resilience (Carpenter *et al.* 2012). Openness refers to strong interconnections between neighbouring systems, whereas nestedness relates to the way that subsystems link to higher system levels. Strong links to neighbouring systems and higher system levels can provide vital support following a disturbance (e.g. neighbours and governments providing disaster relief after a flood, drought or storm). Modularity involves creating localised domains of management that are weakly connected to neighbouring subsystems, which enables for greater autonomy and self-organisation and more rapid responses that are tailored to local conditions (Armitage 2007). Weaker connections to neighbouring systems may also quarantine a system from disturbances that have the potential to spread across system boundaries, such as fire, disease, social conflict or economic shocks (Walker and Salt 2012).

The policy environment surrounding carbon farming in the Australian rangelands shows elements of modularity, openness and nestedness (Fig. 4). Carbon farming sites, particularly under the HIR methodology, are separated from neighbouring paddocks using fencing to keep out domestic stock, and in some cases other herbivores such as kangaroos and goats. Self-organisation is facilitated by the removal of 'unmanaged' grazing pressure, mechanical clearing and/or fire. However, graziers managing such sites share social, economic and environmental connections to neighbouring properties and they are linked to higher system levels through the ERF (national level),

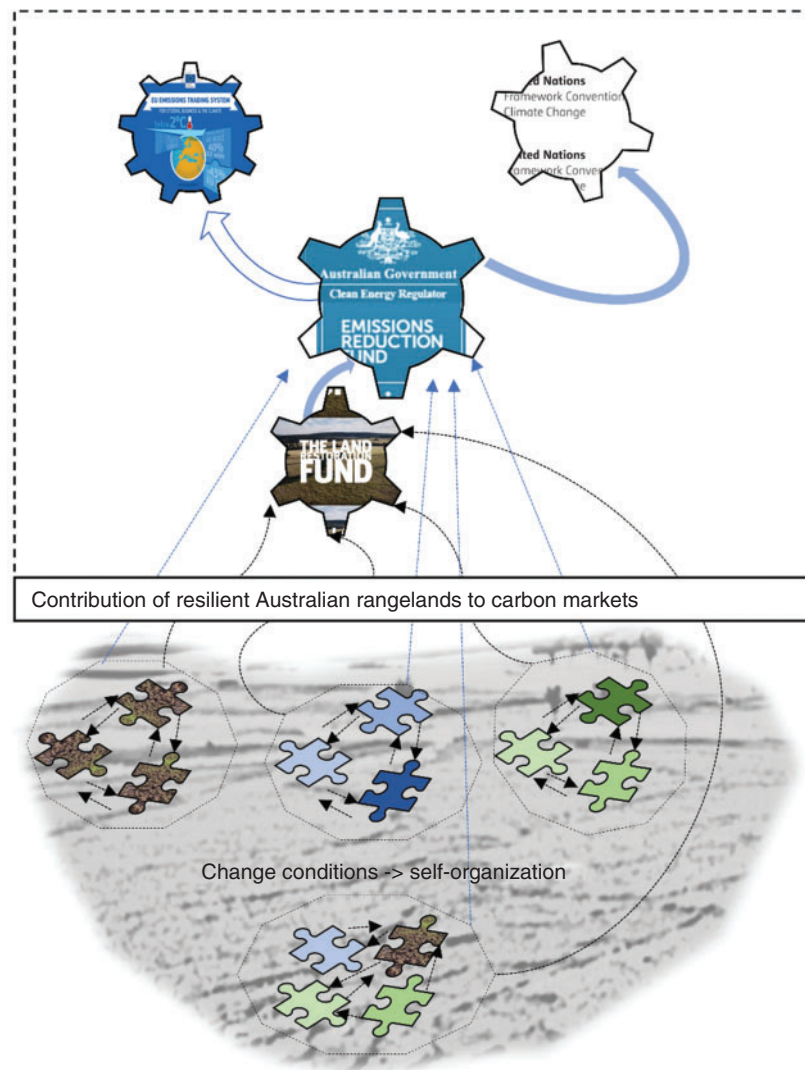


Fig. 4. schematic representation of modularity, openness, nestedness and self-organisation of Australian carbon farming.

emerging co-benefit schemes such as the LRF (state level) and global carbon accounting and trading systems operated under UNFCCC rules.

A key question for carbon farming is whether resilience can be enhanced by increasing the level of connectedness to neighbouring or higher system levels. Ross Garnaut has argued that linking Australia to overseas carbon markets, such as the EU Emissions Trading Scheme, would enable Australian landholders to sell carbon credits for higher prices and to become a carbon credit exporting 'superpower' (Garnaut 2019). However, although this may benefit landholder resilience by increasing incomes and financial reserves, it may also expose the Australian carbon market to future risks such as having to comply with rules that are set by external bodies or having to compete with international credits with lower prices but lacking in co-benefits for biodiversity, soils or communities. If such risks transpire, this could make it harder to strategically promote the most desirable forms of carbon farming (e.g. those offering environmental or social

co-benefits). For example, the EU has historically set restrictive rules around reforestation credits due to concerns about their permanence and additionality in other jurisdictions with weaker regulations (European Commission 2012).

A scenario where Australia is required to tighten its rules to link to other markets such as the EU (e.g. through additional monitoring across extensive rangelands properties) could increase transaction costs and ultimately reduce the amount of forest land being restored (and the co-benefits that may come with that). Although not necessarily implying that Australia's system should never be linked to global carbon markets, this scenario highlights the need to maintain a degree of national autonomy to set rules based on local conditions and policy objectives.

One option for balancing modularity and openness is to use voluntary carbon schemes to provide links to overseas carbon markets. This may allow Australian carbon farmers to sell credits for higher prices on overseas markets without requiring

all carbon farmers to follow rules set in other jurisdictions or having to compete with cheaper, poorly regulated credits from other countries. Another advantage of voluntary schemes is that they may enable carbon farmers to obtain a price premium for biodiversity, cultural or other co-benefits in cases where purchasers of carbon offsets value such factors. In this regard, two of the voluntary schemes that can be used to certify carbon offsets under Australia's National Carbon Offset Standard, CCBA (Climate, Community and Biodiversity Alliance) and SocialCarbon, include benchmarks and indicators relating to environmental and social co-benefits: (Baumber *et al.* 2019).

Feedbacks

As socio-ecological systems mature, feedback loops often become weaker and less direct, due to such reasons as system managers experiencing less of the impact of their actions, or regulatory restrictions making it more difficult for managers to respond quickly (Walker and Salt 2012). In turn, this can reduce the ability of system managers to implement balancing feedbacks that help to keep the system in its current state, such as graziers removing stock from a paddock in response to information about declining ground cover or increased pasture utilisation. Carbon farming may help to strengthen feedback loops if it is linked to increased monitoring and information sharing, but may weaken such loops if it reduces landholder flexibility over future management decisions.

One issue related to feedbacks that is yet to receive attention in the development of carbon farming policy is the timing of carbon payments and how these link to drought cycles. Drought relief in Australia has been criticised for perpetuating unsustainable land management practices by masking feedbacks to landholders that indicate their land management practices may not be viable (Walker 2019). In their 2019 ABARES report on the impact of drought on Australian agriculture, Hughes *et al.* (2019) argue that, in order to build resilience, farm policy needs to shift towards investment in structural adjustment and change at times when the land is not in drought. The Australian Government controls the timing of carbon farming investment through the ERF and could investigate ways in which it could be strategically aligned to drought cycles or targeted at regions where structural adjustment is most required. Such considerations may also be relevant to co-benefit payment schemes under development by state governments.

Social capital: leadership, trust and collaboration

While conventional market economics is underpinned by the assumption that people act according to rational self-interest, resilience-based approaches emphasise the importance of trust, leadership and collaboration in building 'social capital' (Walker 2019). Australia's National Strategy for Disaster Resilience emphasises that trust is particularly important in relation to information sources and that leadership is something that can be enacted by a wide variety of stakeholders within their own sphere of influence, rather than being the responsibility of political or institutional leaders (COAG 2011). In the case of carbon farming, leadership may be shown by various stakeholders, including graziers who become early adopters of carbon farming, regional NRM agencies (e.g. Local Land Services in

NSW), the 'aggregators' who act as brokers between landholders and carbon markets and trusted advisors such as rural financial planners, bankers, accountants and consultants.

There is some distrust in government due to policy uncertainty brought about by the politically-contentious nature of climate change policy in Australia and a lack of clear and reliable information for landholders about the pros, cons, rules and risks associated with carbon farming (Cowie *et al.* 2019). Specific measures aimed at enhancing these information flows may help to overcome misinformation and enhance trust between key stakeholders. Lessons in building trust for new land use practices may also be gained from other sectors such as mining and renewable energy, where examples of trust-building measures include deliberately making and keeping small promises, prioritising quality of contact with local communities over quantity of contact, and viewing moments of crisis as opportunities to demonstrate that proponents are acting in the community's best interest (Baumber 2018).

One challenge associated with market-based instruments (MBIs) such as the ERF is their potential to reduce trust and collaboration by 'crowding out' altruistic behaviour and creating divisions between those who get paid and those who do not. Crowding out refers to the phenomenon whereby people who see others getting paid for something that was previously being done for free, such as maintaining or restoring native vegetation, become unwilling to continue providing these services without similar payments (Chervier *et al.* 2019). Although evidence of this occurring in relation to carbon farming is yet to be reported, it is something that needs to be monitored based on experiences with MBIs in other sectors.

The introduction of environmental MBIs can lead to social divisions within a community if the allocation of payments is seen as unfair or the land use activity being promoted does not align with community perceptions of how land should be used. Cowie *et al.* (2019) identified some concerns around the potential for carbon farming in the NSW rangelands to increase the gap between the 'haves' who have eligible land for AD or HIR, and the 'have nots' whose land is ineligible. Other concerns relate to the potential for carbon farming to increase landholder absenteeism, which can reduce the population engaging in local community activities and supporting local businesses, as well as causing pest or fire impacts for neighbouring properties due to a lack of active property management.

Kerr *et al.* (2017) recommend careful consideration of existing social norms before implementing MBIs aimed at community-scale behaviour change. If there is no existing social norm in favour of the desired action, then payment may be an effective way to increase that behaviour, but payments cannot in themselves be expected to create a new social norm in favour of the behaviour. Conversely, if there is an existing social norm around the behaviour, payment schemes need to be designed carefully so that they are seen to be recognising and supporting that norm rather than replacing it. Important considerations include the inclusion of local people in the design of the scheme to ensure it is seen as fair, as well as autonomy for local people to operate the scheme. Future research is needed to evaluate whether the potential for local people to influence ERF rules is linked to their perceptions of whether carbon farming is fair, inclusive and aligned with accepted norms and values around

how land should be used. The Clean Energy Regulator (2019a) has recognised this need to draw on and enhance social capital by involving local communities in co-designing guidelines and providing feedback to refine systems and processes around carbon farming rules.

Concluding remarks

The emergence of carbon farming has increased income-generating opportunities for landholders in some parts of the Australian rangelands, as well as enabling practices with the potential to deliver a range of environmental and social co-benefits. However, depending on how it is implemented and incentivised, carbon farming also has the potential to erode the socio-ecological resilience of rangelands, with careful management and policy responses required. This has implications not only for Australia, but also for other countries that possess extensive rangeland areas that have been identified as having carbon sequestration potential, such as the United States and China.

This review has indicated that carbon farming aligns with many of the enabling factors for general resilience, including increasing the diversity of livelihood options, protecting habitat for biodiversity, buffering soils through increased groundcover, increasing biomass reserves that may enable landholders to better survive and recover from drought, and collecting and sharing new monitoring data that could improve decision-making and responsiveness. However, there are also some inherent risks in relying on a market-based instrument such as the ERF to deliver rangeland resilience. The principle of least-cost carbon abatement that underpins the ERF has the potential to preferentially value carbon at the expense of other ecosystem components, to reduce redundant capacity that does not appear to be of immediate value, and to overlook social capital by focusing on individual economic self-interest. These risks need to be carefully monitored and managed if carbon farming is to truly enable greater rangeland resilience.

If carbon farming is to fulfil its potential in enhancing rangeland resilience, an adaptive approach is required in which critical factors are monitored and modifications are made to the suite of policy measures being applied where necessary. Some important thresholds for ecosystem health relate to ground cover and grazing pressure, but it is also important for future social and ecological research to evaluate whether carbon farming is contributing to potential risks around INS, the simplification of diverse ecosystems, landholder absenteeism, community divisions and the crowding out of voluntary behaviours. Policy options to be considered for the future include complementary incentive schemes that value co-benefits, modifications to ERF eligibility rules to prevent the simplification of ecosystems and/or to require active management, striking the right balance between maintaining the autonomy of Australia's carbon markets and connecting it to markets overseas, and policy measures aimed at building social capital. Careful consideration of these factors will increase the likelihood that carbon farming fulfils its potential as an enabler of greater socio-ecological resilience in the Australian rangelands.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

This research was undertaken as part of the New South Wales Department of Primary Industries Climate Change Research Strategy, 'Accessing Carbon Markets' project funded by the NSW Climate Change Fund.

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