



Research article

Risks to carbon dynamics in semi-arid woodlands of eastern Australia under current and future climates



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ARTICLE INFO

Keywords:

Wildfire
Drought
Grazing
Climate change
Forest
Mortality

ABSTRACT

Extreme disturbance events, such as wildfire and drought, have large impacts on carbon storage and sequestration of forests and woodlands globally. Here, we present a modelling approach that assesses the relative impact of disturbances on carbon storage and sequestration, and how this will alter under climate change. Our case study is semi-arid Australia where large areas of land are managed to offset over 122 million tonnes of anthropogenic carbon emissions over a 100-year period. These carbon offsets include mature vegetation that has been protected from clearing and regenerating vegetation on degraded agricultural land. We use a Bayesian Network model to combine multiple probabilistic models of the risk posed by fire, drought, grazing and recruitment failure to carbon dynamics. The model is parameterised from a review of relevant literature and additional quantitative analyses presented here. We found that the risk of vegetation becoming a net source of carbon due to a mortality event, or failing to realise maximum sequestration potential, through recruitment failure in regenerating vegetation, was primarily a function of rainfall in this semi-arid environment. However, the relative size of an emissions event varied across vegetation communities depending on plant attributes, specifically resprouting capacity. Modelled climate change effects were variable, depending on the climate change projection used. Under 'best-case' or 'most-likely' climate scenarios for 2050, similar or increased projections of mean annual precipitation, associated with a build-up of fuel, were expected to drive an increase in fire activity (a 40–160% increase), but a decrease in drought (a 20–35% decrease). Under a 'worst-case' climate scenario, fire activity was expected to decline (a 37% decrease), but drought conditions remain similar (a 5% decrease). These projected changes to the frequency of drought and fire increase the risk that vegetation used for carbon offsetting will fail to provide anticipated amounts of carbon abatement over their lifetime.

1. Introduction

The terrestrial carbon sink is estimated to absorb over a quarter of anthropogenic carbon emissions annually, slowing the rise in atmospheric CO₂ concentration (Le Quere et al., 2014). The size of this sink has been increasing over time, possibly as a result of the fertilisation effect from increased atmospheric CO₂, nitrogen deposition and forest expansion (Pan et al., 2011). Given the importance of terrestrial vegetation for offsetting the progression of global climate change,

considerable emphasis has been placed on understanding how gradual processes inherent in climate change alter carbon sequestration by vegetation. For example, elevated temperatures may increase productivity in temperature-limited environments (Vitasse et al., 2011). Conversely, declines in precipitation in mid-latitude regions may reduce productivity (Suarez and Kitzberger, 2008). However, the strength of the terrestrial carbon sink is also strongly affected by fast-acting processes, including disturbances such as fire, drought, heat stress, and grazing. For example, wildfires are estimated to reduce terrestrial carbon uptake

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<https://doi.org/10.1016/j.jenvman.2019.01.076>

Received 15 May 2018; Received in revised form 17 August 2018; Accepted 21 January 2019

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by around 20% annually (Yue et al., 2015). Similarly, severe drought can cause widespread mortality, resulting in large emissions of carbon to the atmosphere (Ciais et al., 2005). Grazing effects by livestock and wild herbivores are variable, but can negatively impact recruitment (DeMalach et al., 2014; Eldridge et al., 2011). Although evidence for the effect of these sharp changes on terrestrial carbon uptake is growing, climate change is likely to significantly alter carbon dynamics by changing the frequency and severity of many of these disturbances (Galik and Jackson, 2009), as well as by directly affecting plant recruitment patterns. Thus, it is critically important to understand the current and future risk posed by disturbances to carbon dynamics in terrestrial ecosystems.

The vulnerability of the terrestrial carbon cycle to disturbance varies across vegetation types as a function of vegetation attributes, including plant functional traits and vegetation age. For example, post-fire mortality will be less for vegetation that is capable of regenerating vegetatively rather than being fire-killed (Clarke et al., 2013). Mortality following fire may also be higher in younger vegetation, with small-sized trees, compared to mature vegetation. This is because smaller trees have thinner bark which is less effective in insulating against the high temperatures generated during fire (Vines, 1968). Although species which are capable of resprouting from underground lignotubers, such as eucalypts, may resprout following fire even as seedlings (Fensham et al., 2017). Risk of death from drought may also be correlated with plant size, but risk tends to be greater for larger trees (O'Brien et al., 2017). Thus, some vegetation communities and age classes are more at risk from current and future disturbance regimes.

Quantifying the current and future vulnerabilities of ecosystem carbon fluxes to a range of disturbances is particularly important where vegetation is managed to offset anthropogenic carbon emissions. The use of such carbon offsets is increasingly being implemented globally. These offset programs require changes to management, such as prevention of land clearing or interventions to revegetate agricultural or degraded land. These vegetation offsets may also provide a number of environmental co-benefits, in particular for biodiversity conservation, reduced erosion and salinity management (Cunningham et al., 2015). Given the long-term (50–100 y) nature of these offsets, there is a risk that changes in disturbance regimes driven by climate change will cause these vegetation offsets to fall short of their maximum sequestration potential, or to become net sources of carbon emissions over the life of the project (Galik and Jackson, 2009; Nolan et al., 2018). Assessing the relative importance of climate-related disturbances for vegetation offsets will be important to inform risk management strategies, and may also reduce uncertainty around carbon payments, thereby encouraging landholders to enter carbon markets (Kragt et al., 2017).

Here, we aim to assess the relative influence of biophysical risk factors on vegetation used for offsetting carbon under current and future climates. We do this by developing a Bayesian Network model parameterised with probabilities derived from a review of relevant literature and additional quantitative analyses presented here. Bayesian Network models are well suited to risk analyses because of their capability to combine multiple probabilistic models, and identify the relative contribution of different factors to the final probability of an event. (Martin et al., 2005; Penman et al., 2011). We focus on the arid and semi-arid rangelands of Australia because there is large potential for carbon sequestration activities to occur in rangelands, due to the extensive areas they occupy globally, and the low opportunity costs for carbon abatement (Dean et al., 2015; Lal, 2004). Further, the majority (> 70%) of the vegetation projects under Australia's Emissions Reduction Fund occur in the eastern rangelands, with over 122 million tonnes of carbon abatement projected to be achieved from these vegetation offsets (<http://www.cleanenergyregulator.gov.au/ERF>, accessed December 2017). Our objectives are to: (i) identify the relative importance of biophysical risk factors (fire, drought, grazing) on carbon storage and assimilation; and (ii) identify the risk of recruitment failure in any given year for regeneration type projects.

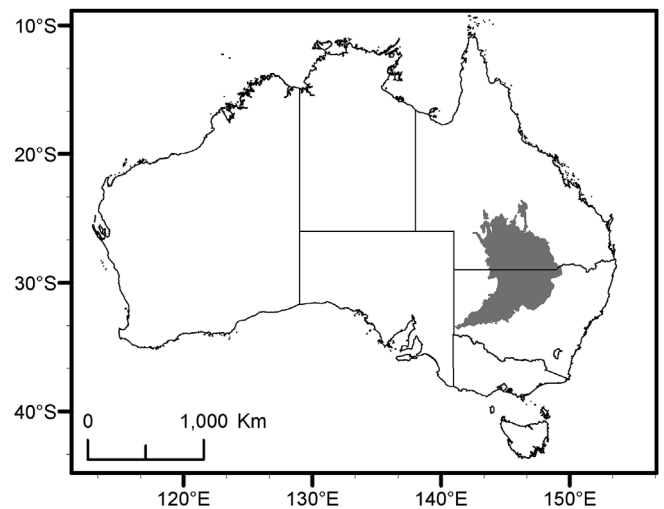


Fig. 1. Location of the study region in eastern Australia (shaded area), in the states of New South Wales and Queensland. Over 70% of vegetation abatement projects under the Australian Emissions Reduction Fund are located within this region.

2. Materials and methods

2.1. Study area

The study region is located in eastern Australia (Fig. 1), where over 70% of vegetation abatement projects are located (centred around 146°16'; –29°2'). This region falls within a Köppen climate classification characterised by hot and persistently dry conditions, with mean annual rainfall of 200–500 mm (Australian Bureau of Meteorology, <http://www.bom.gov.au/climate/>). Bioregions include Mulga Lands, Cobar Peneplain, Darling Riverine Plains, Murray Darling Depression and Brigalow Belt South (Thackway and Cresswell, 1995). Our study focuses on two types of carbon abatement projects: (1) avoided clearing projects, where vegetation is in a mature state; and (2) regeneration projects, where natural regeneration of vegetation on cleared land is facilitated by removing disturbances, for example by fencing to remove grazing by livestock and wild herbivores.

2.2. Bayesian Network model

Bayesian Network models represent variables and their cause-and-effect relationships in an acyclic graphical model with variables represented as nodes, and arrows representing directional relationships between nodes (Fig. 2; Pearl, 1986). All nodes are associated with a conditional probability table (Marcot et al., 2006). Root nodes, which are not influenced by other variables, have a conditional probability table containing a single probability for each state in that node. Child nodes, which are influenced by one or more variables, have a conditional probability table that represents the probability for each state in that node, given the state(s) in the parent node(s). The model then produces results in the form of likelihoods that can provide a basis for risk assessment (Penman et al., 2015).

The first step in the development of a Bayesian Network model is the construction of a conceptual model describing the relationships, or influence, among different risk factors for vegetation abatement projects (Marcot et al., 2006). A conceptual model was developed through a review of the literature and then refined at a workshop on biophysical risks to vegetation carbon-abatement projects in Australian rangelands. The workshop was attended by the authors and others (listed in the acknowledgements). The resulting conceptual model comprised four parent nodes, two of which were vegetation attributes (vegetation community and vegetation state); and two biophysical risk factors

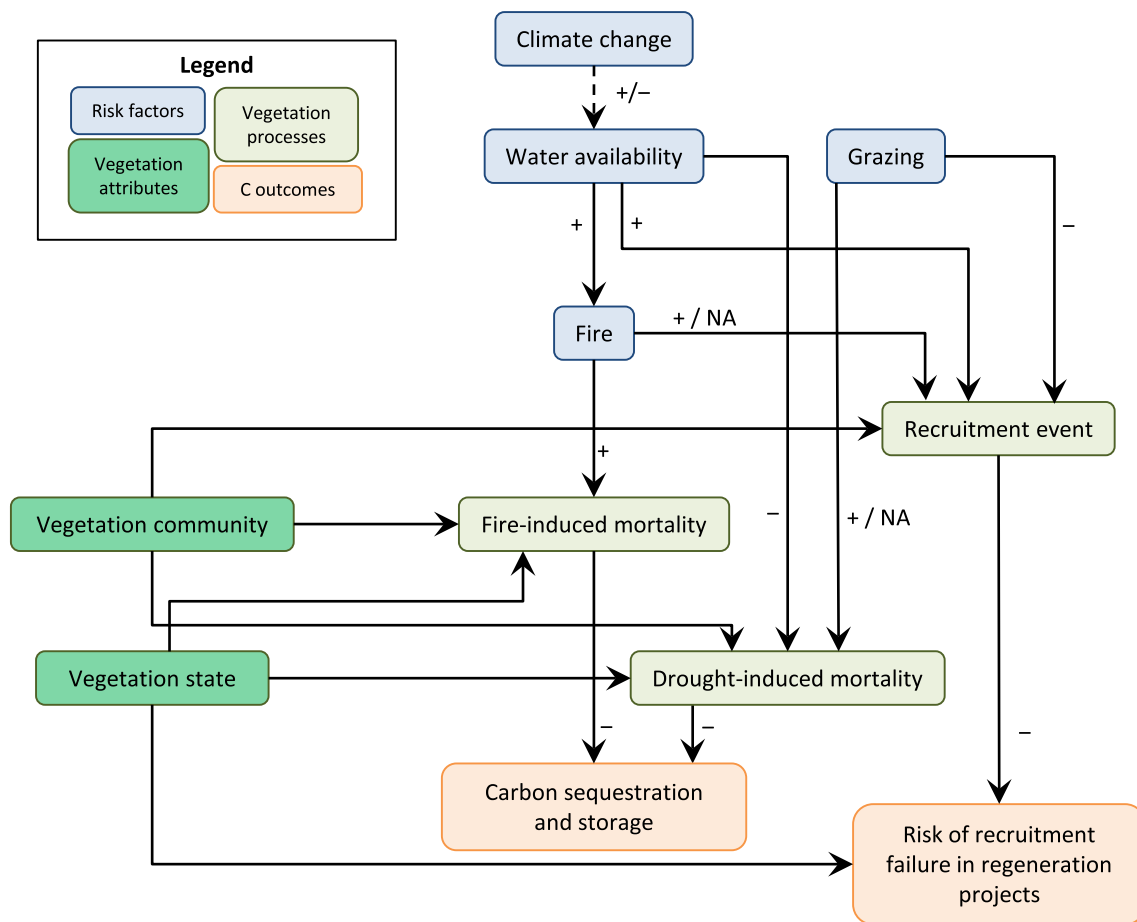


Fig. 2. Conceptual model of the relationship between biophysical risk factors, vegetation attributes and outcomes for vegetation abatement projects, specifically carbon sequestration and storage, and risk of recruitment failure for regeneration projects. The direction of arrows indicates the direction of influence, with “+”, “-” and “NA” indicating positive, negative and no effect of the parent node on the child node.

(water availability and grazing) (Fig. 2). Water availability and grazing influenced rates of carbon sequestration and storage indirectly through influences on fire occurrence, and vegetation processes, specifically recruitment and mortality (Fig. 2). Climate change is also identified as an additional risk factor through effects on rainfall. In the interests of developing a parsimonious model that could be parameterised with existing data, we did not consider other risk factors such as CO₂ fertilisation, the influence of vegetation type on the rate of recovery, or the optimal fire return interval.

The conceptual model was developed into a Bayesian Network model (Fig. 3) that was similar in form to the conceptual model, using Netica™ version 6.04, by Norsys Systems Corp. Following Marcot et al. (2006), we endeavoured to limit the number of parent nodes for each factor to three or fewer, and the number of states in each node to five or fewer, although this was not always possible. The rationale for limiting the number of parent nodes and states is to keep the resultant conditional probability tables tractable (Marcot et al., 2006). The probability for each state within each node was determined through either a review of the literature or analysis of quantitative data. Details of the data source for each node are detailed below and summarised in Table 1. The probabilities within each node must sum to 100%. The conditional probability tables for each node are also available in supplementary material.

2.3. Vegetation attributes

2.3.1. Vegetation community

There are four dominant vegetation communities within carbon

abatement project areas. These are: (1) White Cypress Pine (*Callitris glaucophylla*) woodlands, to 20 m height; (2) Mallee woodlands, which are characterised by multi-stemmed *Eucalyptus* trees with a low canopy (generally < 10 m), overstorey species include *Eucalyptus dumosa*, *Eucalyptus gracilis*, *Eucalyptus morrisii*, *Eucalyptus socialis* and *Eucalyptus viridis*; (3) Mulga woodlands and shrublands, dominated by *Acacia aneura*, which generally ranges in height from 5 to 10 m; and (4) Poplar box (*Eucalyptus populnea* subsp. *bimbil*) woodlands, to 20 m height.

2.3.2. Vegetation state

Vegetation states were characterised using a state-and-transition model developed for rangelands within the study area (Hall et al., 1994). Four states are described, these are: (1) woodland, which is a mix of overstorey tree species with a basal area of 1–8 m² ha⁻¹ and native perennial grasses; (2) grassland, which is dominated by perennial grass; (3) grassland and scattered woody species, which is a mix of perennial grasses, tree seedlings and shrub species; and (4) dense shrubland, which is characterised by dense regrowth of tree species and shrubs.

2.4. Biophysical risk factors

2.4.1. Water availability/drought index

We categorised patterns in dry and wet periods using a probabilistic drought index, the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010). The SPEI is calculated from the difference between monthly totals in precipitation and potential evapotranspiration. A time-series of monthly values are fitted using a

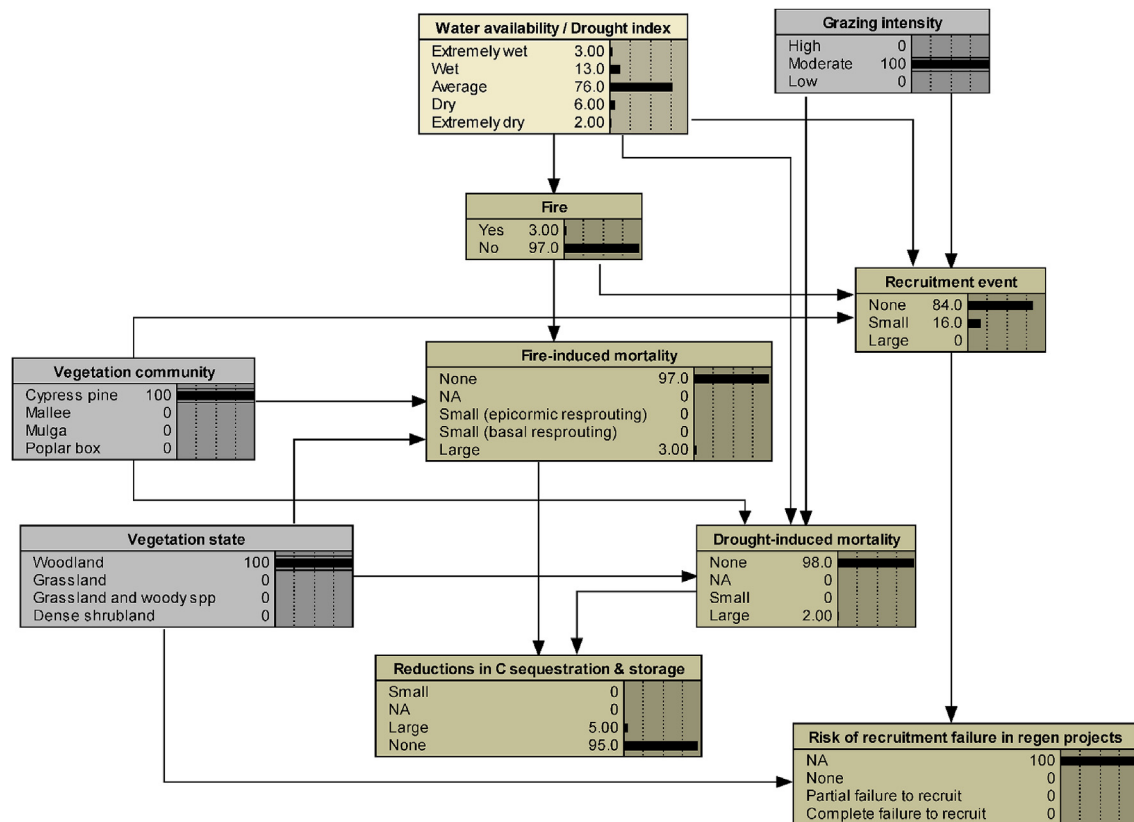


Fig. 3. Bayesian Network model with completed conditional probability distributions. Nodes in grey are those that vary across vegetation abatement projects.

probability density function and normalised, such that negative and positive values, ranging from -3 to 3 , represent relatively dry and wet conditions respectively. The SPEI can be calculated across different time-scales, similar to averaging periods, e.g. 3-month, 12-month. The SPEI provides a means to assess drought in a consistent and standardized fashion, allowing comparisons across different climates. We used observations and expert input to define climate-based thresholds associated with key disturbances and vegetation processes.

Extremely dry conditions are those associated with canopy collapse and/or mortality. In a study of 17 die-off events across a range of vegetation types in Australia, including events within our study area, Mitchell et al. (2014) found that across all events the 6-month SPEI value reached values of less than 2% probability of occurrence. Thus, a probability of 2% was assumed to represent extremely dry conditions capable of inducing severe water stress. We defined a second threshold of dry conditions associated with a cessation of net primary

Table 1

Description of each node within the Bayesian Network model, and the source of information for parameterising the conditional probability tables associated with each node.

Node	Description and source	States
Vegetation community	Parent node describing most common vegetation communities, identified from field surveys across all vegetation abatement projects (unpublished data).	White Cypress Pine woodlands, Mallee woodlands, Mulga woodlands and shrublands, Poplar box woodlands.
Vegetation state	Parent node, characterised using state-and-transition models developed for rangelands in central and southern Queensland (Hall et al., 1994; Jones and Burrows, 1994).	Woodland, grassland, grassland and scattered woody species, dense shrubland.
Water availability/drought index	Parent node, categorises rainfall with a drought index: the Standardized Precipitation Evapotranspiration Index (SPEI).	Extremely wet, wet, average, dry, extremely dry.
Grazing intensity	Incorporates all herbivores and defined in relation to carrying capacity.	Low (no livestock grazing and low densities of wild herbivores), moderate (grazing at or below carrying capacity), high (grazing exceeds carrying capacity).
Fire	Likelihood of fire determined from quantitative analysis of fire history records and 24-month SPEI (Supplementary material).	Yes (fire likely following 'extremely wet' conditions), no (fire unlikely).
Fire-induced mortality	If fire occurs, mortality assessed from ecological responses to fire, determined from the literature (Table 2).	NA (i.e. in a 'grassland' state), none, small - epicormic resprouting, small - basal resprouting, large
Recruitment event	Assessed from rainfall, fire occurrence and grazing intensity. Probabilities determined from the literature (Table 2).	None, small, large.
Drought-induced mortality	Assessed from rainfall and grazing intensity. Probabilities determined from the literature (Table 2).	NA (i.e. in a 'grassland' state), none, small, large.
Reductions in C sequestration and storage	Determined from the 'fire-induced mortality' and 'drought-induced mortality' nodes.	NA (i.e. in a 'grassland' state), none, small, large.
Risk of recruitment failure in regeneration projects	Determined from the 'recruitment event' node, only for vegetation in a 'grassland' or 'grassland and scattered woody species' state.	NA (i.e. in a 'woodland' or 'dense' shrubland state); none, partial failure to recruit, complete failure to recruit.

Table 2

Ecological responses to fire and vulnerability to grazing for common woody species within the study area. Note, vegetation in a ‘dense shrubland’ or ‘grassland with scattered woody species’ state is characterised by a mix of shrub species and tree seedlings.

Vegetation type and species	Fire induced mortality?	Fire required for germination?	Tree seedling and shrub vulnerability to grazing
Cypress pine: <i>Callitris glaucophylla</i>	High, no resprouting ^a	No, but fire will stimulate germination ^{e,f}	Grazing, particularly by rabbits and livestock, significantly increases seedling mortality ^{f,m}
Mallee: <i>Eucalyptus dumosa</i> , <i>Eucalyptus gracilis</i> , <i>Eucalyptus morrisii</i> , <i>Eucalyptus socialis</i> or <i>Eucalyptus viridis</i>	Low, basal resprouting in trees ^a and basal resprouting likely in seedlings ^b	Yes ^g	Unaffected by grazing, particularly rabbits, kangaroos and sheep ^g
Mulga: <i>Acacia aneura</i>	High, no resprouting ^a	Limited germination in absence of fire ^h	Very high mortality under grazing, particularly by livestock ^a
Poplar box: <i>Eucalyptus populnea</i> subsp. <i>Bimil</i>	Low, epicormic resprouting in trees ^a and basal resprouting in seedlings ^c	No, but fire will stimulate germination ^{i,j}	Unaffected by grazing, particularly by sheep ^o
Shrubs:			
<i>Dodonaea lobulata</i>	Low, basal resprouting ^d	Yes ^k	Unknown
<i>Dodonaea viscosa</i>	High, no resprouting ^a	Yes ^k	Declines in seedling density under grazing ^{n,p,q}
<i>Eremophila deserti</i>	Low, basal resprouting ^a	No ^k	Unknown
<i>Eremophila mitchellii</i>	Low, basal resprouting ^a	No ^k	Seedlings unaffected by grazing ^q
<i>Eremophila sturtii</i>	Low, basal resprouting ^a	No ^k	Seedlings unaffected by grazing ^q
<i>Geijera parviflora</i>	Low, basal resprouting ^a	No ^k	Seedlings unaffected by grazing ^q
<i>Senna artemisioides</i>	Low, basal resprouting ^a	Limited germination in absence of fire ^l	Very high mortality of seedlings under grazing, particularly by livestock ^u

^a Clarke et al. (2015).

^b Tozer and Bradstock (1997).

^c Fensham et al. (2008).

^d NSW National Parks and Wildlife Service (2002).

^e Read (1995).

^f Zimmer et al. (2017).

^g Wellington and Noble (1985).

^h Wright et al. (2016).

ⁱ Arnold et al. (2014).

^j Walker et al. (1981).

^k Hodgkinson (1979).

^l Pound et al. (2014).

^m Allcock and Hik (2004).

ⁿ Munro et al. (2009).

^o Moore and Walker (1972).

^p Denham and Auld (2004).

^q Harrington (1979).

productivity (NPP), i.e. stomatal closure. The probability of stomatal closure was estimated through combining observations of the response of stomatal conductance to leaf water status, or water potential, and field observations of the response of leaf water potential to climatic water deficit (SPEI) through time (Mitchell et al., 2016). These type of data are currently lacking across our study area. However, in a study of two species from contrasting environments (*Eucalyptus globulus* in Tasmania and *Pinus edulis* in New Mexico, USA), Mitchell et al. (2016) found that declines in leaf water potential inducing stomatal closure for both species occurred when SPEI reached probabilities $\leq 8\%$. Thus, in the absence of species-specific data for our study site, we set the combined probability of dry and extremely dry conditions to 8%.

The probability of wet conditions, required for recruitment, and extremely wet conditions, which precede fire in these semi-arid environments, are described in the “fire” and “recruitment” nodes below. Given the sum of probabilities in each node must sum to 100%, the probability of ‘average’ rainfall conditions were calculated by subtracting the probability of extremely wet, wet, dry and extremely dry conditions from 100.

2.4.2. Grazing

Common herbivores in the study area include sheep (*Ovis aries*), cattle (*Bos taurus*, *Bos indicus*), goats (*Capra hircus*), rabbits (*Oryctolagus cuniculus*) and kangaroos (*Macropus* spp.) (Eldridge et al., 2016). Different species can have differing effects on biomass; however, it can be

difficult to disentangle the effects of one species from another, because a large proportion of grazing studies focus on comparisons between grazed sites and grazing exclusion sites (Eldridge et al., 2016). Given this, grazing states defined here do not differentiate between herbivore species but are defined by total grazing intensity. We defined grazing intensity as discrete categories in relation to carrying capacity. Carrying capacity is generally calculated from estimates of forage growth, which are strongly influenced by rainfall (Johnston et al., 1996). Maximum carrying capacity is usually set at a pasture utilisation rate of $\sim 20\text{--}30\%$ of forage, and varies with woody cover and vegetation type (Johnston et al., 1996). Categories of grazing are defined as low (no livestock grazing and low densities of wild herbivores); moderate (total grazing at or below carrying capacity); and high (total grazing exceeds carrying capacity).

2.4.3. Fire

Extremely wet conditions generally precede fire in the rangelands, since above-average rainfall stimulates the growth of grassy vegetation, providing the fuel connectivity that is usually absent from these environments (Turner et al., 2011). We used historical observations of fire occurrence and associated values of the 24-month SPEI to determine the probability of extremely wet conditions leading to increased fuel loads (see supplementary material). These analyses estimated the probability of extremely wet conditions conducive to fire as 3%.

During extremely wet conditions we classified the probability of a

fire occurring as 100%, although in reality the probability of fire will be less. The risk of fire may be influenced through additional factors such as ignition source, and may be reduced through management actions (Nolan et al., 2018). Thus, setting the probability of fire to 100% during extremely wet conditions represents the maximum risk, or worst-case scenario, for carbon abatement projects. We did not model the influence of these additional factors on the probability of fire, in part because this would substantially increase model complexity, but also because there is little information available on the effect of these factors on fire probability in rangeland environments. But see Turner et al. (2011) for modelling the determinants of fire size across arid and semi-arid Australia, and Penman et al. (2013) for modelling the determinants of fire ignition.

2.5. Vegetation processes

2.5.1. Fire induced mortality

The probability of fire-induced mortality is influenced by vegetation state and the ecological response to disturbance of constituent species. Most species in the study area resprout vegetatively following fire, with the exception of Mulga and Cypress Pine, which are killed by fire and regenerate from seed (Table 2). Thus, following fire we define a 100% probability of ‘large’ rates of fire-induced mortality for Mulga and Cypress Pine woodlands. Poplar box seedlings, Mallee trees and seedlings and a majority of the common shrub species resprout via basal resprouting, i.e. from roots or lignotubers (underground storage organs; Table 2). This is in contrast to Mallee and Poplar box woodlands and most shrub species that regenerate from epicormic resprouting, i.e. much of the aboveground biomass survives fire. Thus, following fire we define a 100% probability of a ‘small’ mortality event for Mallee and Poplar box woodlands, all dense shrublands, and all grasslands with scattered woody species. We differentiate between whether vegetation resprouts via basal or epicormic resprouting, as this has implications for the proportion of aboveground biomass killed by fire.

2.5.2. Recruitment event

Extended wet conditions are required for the recruitment of many arid zone plant species across the study region, with recruitment including flowering, seed production, germination and establishment (Cohn and Bradstock, 2000; Friedel et al., 1993; Preece, 1971; Zimmer et al., 2017). In a recent study on *C. glaucophylla* recruitment, Zimmer et al. (2017) observed that recruitment events were associated with conditions where 12-month SPEI reached probabilities > 84%. Thus, in the absence of information for other species in the study area, we set the combined probability for wet and extremely wet conditions leading to recruitment at 16%.

We define the states within the ‘recruitment event’ node as ‘none’, ‘small’ and ‘large’. Wet conditions are required for germination of all common species in the study area, with some species additionally requiring fire (Table 2). Grazing effects on seedling recruitment are variable across species, with seedlings of Mallee, Poplar box and many of the shrub species largely unaffected by grazing, but Cypress Pine and Mulga seedlings highly vulnerable (Table 2).

2.5.3. Drought induced mortality

We set the probability of a ‘large’ mortality event, i.e. where there is widespread canopy dieback and mortality, to 100% under extremely dry conditions. There is also potential for mortality to occur under dry conditions, particularly in combination with grazing, but only for plants below browse-height (Dawson and Ellis, 1996; Fensham, 1998; Fensham et al., 2012; Harrington, 1979). Browsing of shrubs by livestock and wild goats is only likely when other forage is not available, i.e. under dry conditions (Harrington et al., 1979). Thus, under dry conditions, we set the probability of a ‘small’ mortality event, i.e. < 25% mortality of aboveground biomass, to 100%, but only for dense shrublands and grassland with scattered woody species.

2.6. Carbon outcomes

2.6.1. Carbon sequestration and storage

We defined the risk of reduced carbon sequestration and storage as either relatively ‘large’ or ‘small’. Large reductions result from a large rate of aboveground biomass killed by drought or fire. For fire, this includes fire-killed species, as well as those that resprout from roots or lignotubers, i.e. where aboveground biomass is fire-killed. Small reductions result from either low rates of drought-induced mortality, or if there is a low rate of fire-induced mortality and post-fire epicormic resprouting occurs, i.e. a large proportion of the aboveground biomass is not fire-killed. Note, that while fire and drought can rapidly transfer living biomass to dead and decomposing carbon pools, rates of decomposition and subsequent emissions of carbon can occur over years to decades, particularly in semi-arid regions where decomposition is heavily dependent upon rainfall (Munoz-Rojas et al., 2016).

2.6.2. Risk of recruitment failure in regeneration projects

Regeneration projects are those where the vegetation state is in a grassland or a grassland and scattered woody species state. The risk that vegetation in these states will not regenerate is calculated from the probability of a recruitment event occurring, which we set at 16%. We did not explicitly model the risks to regeneration projects as seedlings transition to saplings and trees, for example the risk of drought during the sapling phase. Although drought risk at the seedling stage is likely to be important (Fensham et al., 2008; Read, 1995), there is little information available that defines what constitutes a drought for seedlings. An added complication is that long term studies have shown that recruitment of woody plants occurs across all seasonal conditions, even during droughts (e.g. Eldridge and Westoby, 1991). Thus, the probability of recruitment failure in regeneration type projects may differ to that assessed here.

2.7. Analyses

2.7.1. Bayesian Network model– sensitivity analysis

We assessed the relative sensitivity of vegetation abatement projects to biophysical risk factors, using the ‘sensitivity to findings’ function in Netica™ version 6.04. This function provides a measure of the relative influence of a change in one variable on another variable. We examined the sensitivity of the nodes ‘reductions in C sequestration and storage’ and ‘risk of recruitment failure in regeneration projects’ to each of the parent nodes.

2.7.2. Climate change effects on biophysical risks

We assessed the effects of climate change to biophysical impacts on carbon sequestration and storage and on recruitment by incorporating projected changes to the SPEI into our Bayesian Network model, following Mitchell et al. (2014). Briefly, we used climate projections for three global circulation models (GCMs) at 2050 using the 8.5 representative concentration pathway and a medium sensitivity. The three GCMs were chosen to represent ‘best’ (NORESM1-M), ‘most-likely’ (HADGEM2-CC), and ‘worst’ (GFDL-ESM2M) conditions based on changes in mean annual temperature and mean annual rainfall for the region, following the approach by Whetton et al. (2012) and data from the Coupled Model Inter-comparison Project Phase 5 (CMIP5; <https://cmip.llnl.gov/cmip5/>). These models are available at a coarse spatial and temporal resolution (monthly values, typically at 100–200 km resolution). To generate fine-scale values of projected climate, historical observations of climate (from 1981 to 2010, <https://www.longpaddock.qld.gov.au/>; Jeffrey et al., 2001) were adjusted by applying projected changes in climate using a pattern scaling approach following Ricketts et al. (2013). This produced gridded data (0.05° resolution, daily values) of temperature, rainfall, solar radiation and humidity. The SPEI was then calculated over a 6-month, 12-month and 24-month analysis window, consistent with the influence of these

Table 3

Risk of reductions in carbon sequestration and storage or recruitment failure estimated from Bayesian Network analysis under current climate conditions. Note, the risk of reductions in carbon sequestration and storage was only calculated for woody vegetation, i.e. not for vegetation in a ‘grassland’ state; and the risk of recruitment failure in regeneration projects was only calculated for vegetation in a ‘grassland’ or ‘grassland and scattered woody species’ state. NA = not applicable.

Vegetation community	Vegetation state	Risk of reductions in carbon sequestration and storage (%)		Risk of recruitment failure in regeneration projects (%)	
		Small reductions	Large reductions	Partial failure	Complete failure
Cypress pine	Woodland	0	5	NA	NA
	Grassland	NA	NA	0	84
	Grassland and woody spp.	6	5	0	84
	Dense shrubland	6	5	NA	NA
Mallee	Woodland	0	5	NA	NA
	Grassland	NA	NA	0	97
	Grassland and woody spp.	6	5	0	97
	Dense shrubland	6	5	NA	NA
Mulga	Woodland	0	5	NA	NA
	Grassland	NA	NA	13	84
	Grassland and woody spp.	6	5	13	84
	Dense shrubland	6	5	NA	NA
Poplar box	Woodland	3	2	NA	NA
	Grassland	NA	NA	0	84
	Grassland and woody spp.	6	5	0	84
	Dense shrubland	6	5	NA	NA

differing averaging periods on different biophysical risk factors, as previously described (i.e. 6-month SPEI correlated with drought, 12-month SPEI correlated with recruitment, and 24-month SPEI correlated with wildfire). All analyses were performed in R (R Development Core Team, 2017).

3. Results

3.1. Bayesian Network model sensitivity analyses

Under current climate conditions, the probability of a small reduction in carbon sequestration and storage over the life of the carbon offset projects ranged from 3 to 6% while the probability of a large reduction ranged from 2 to 5% (Table 3). The vegetation community least at risk from either small or large reductions was Poplar box, because of its ability to sprout epicormic shoots following disturbance. All other vegetation communities had the same estimated risk. The likelihood of regeneration projects having complete failure in recruiting overstorey/tree species ranged from 84 to 97% (Table 3). The vegetation community most at risk was Mallee, and the vegetation community least at risk was Poplar box.

The sensitivity analysis indicated that the primary factor driving the risk of both reductions in carbon sequestration and storage in established woody vegetation, and the risk of recruitment failure on degraded agricultural land, was rainfall (Fig. 4). Vegetation attributes, notably vegetation community and vegetation state, were less influential. Grazing had little effect, particularly on the risk of reductions in carbon sequestration and storage.

3.2. Climate change effects on biophysical risk factors

Climate change projections for 2050 across the study area indicate warmer mean annual average temperatures, ranging from an increase of 1.7–3.4 °C under the three different scenarios (Table 4; Fig. 5a). In addition to increased average temperatures, there is also a projected increase in the number of days above 40 °C. There is currently an average of 11 days above 40 °C, but this is expected to increase to anywhere from 13 to 37 days (Table 4). Projected changes to precipitation are more variable, with increased, decreased, or little change in mean annual rainfall projected, depending on the GCM (Table 4; Fig. 5b).

These varying projections for rainfall lead to varying estimates in the likelihood of disturbances (i.e. drought and fire) and the subsequent

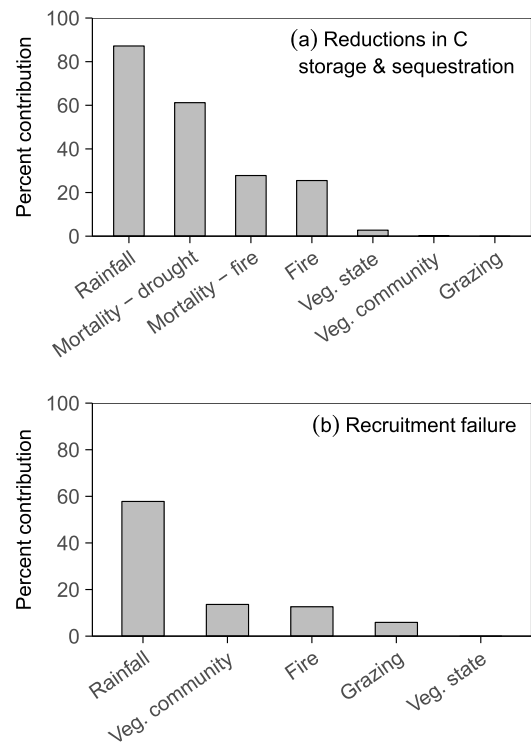


Fig. 4. Sensitivity of the carbon outcome nodes of: (a) reductions in carbon sequestration and storage and (b) recruitment failure to their parent nodes.

likelihood of net reductions in carbon sequestration and storage from carbon abatement projects. Under the best-case scenario, the probability of extremely wet conditions (associated with fire) is likely to increase (from 3 to 7.8%), while dry (cessation of NPP) and extremely dry (canopy dieback and mortality) conditions are likely to remain similar or have negligible decreases: from 6 to 5.9% for dry conditions, and from 2 to 1.3% for extremely dry conditions. Similarly, under the most-likely climate scenario, the probability of extremely wet conditions is also expected to increase (to 4.2%), while extremely dry conditions are likely to decrease (to 1.6%). However, dry conditions are expected to increase (6.9%). In contrast, the worst-case scenario predicts a reversal in the trend of extremely wet and dry/extremely dry conditions, with the probability of extremely wet expected to decrease

Table 4
Current and projected changes in temperature, rainfall and critical SPEI thresholds. NPP = net primary productivity.

	Current climate	2050 climate projections		
		Best-case	Most likely	Worst-case
Mean annual temperature (°C)	22.4	24.1	24.4	25.8
Days above 40 °C	11	13	19	37
Mean annual rainfall (mm)	401	444	390	279
Probabilities of conditions exceeding SPEI thresholds				
Extremely wet (fire)	3.0	7.8	4.2	1.9
Wet conditions (recruitment)	13.0	14.2	8.8	2.3
Dry (cessation of NPP)	6.0	5.9	6.9	9.3
Extremely dry (canopy dieback)	2.0	1.3	1.6	1.9

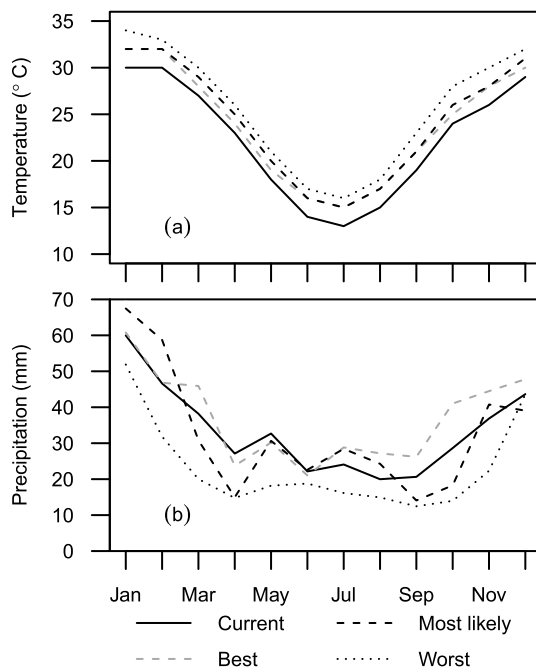


Fig. 5. Mean monthly temperature (a) and precipitation (b) under current climate conditions and projections of climate for 2050.

(to 1.9%) while dry and extremely dry conditions are expected to remain similar or increase (to 9.3% and 1.9% for dry and extremely dry conditions respectively).

These differences in climate projections for conditions associated with drought and fire risk variously predict that the likelihood of reductions in carbon sequestration and storage will either increase or remain at similar levels. Specifically, the risk of large reductions in carbon stocks is expected to increase for vegetation types that are fire-killed or have basal resprouting (i.e. aboveground biomass fire-killed) under the best-case climate scenario (from 5 to 9.1%; Fig. 6a); and under the most-likely climate scenario (to 5.8%). Under a worst-case climate scenario, these vegetation types are expected to have overall declines in the risk of large reductions in carbon sequestration and storage (to 3.8%). For vegetation that recovers from disturbance through epicormic resprouting (i.e. above ground biomass is largely not fire-killed), the risk of reductions in carbon sequestration and storage

remains similar or there are negligible decreases (from a current likelihood of 2% to 1.3–1.9%). However, the risk of events resulting in small reductions in carbon sequestration and storage is more variable, with an increase expected under the best-case and most-likely climate scenarios (from a current likelihood of 3%–4.2–7.8%) and a decrease expected under the worst-case climate scenario (to 1.9%; Fig. 6b).

The combined probability of wet and extremely wet conditions required for recruitment events are expected to increase under the best-case climate scenarios (from a current probability of 16% to 22%), but decline under the most-likely and worst-case climate scenario (to 12.9 and 4.2%; Table 4). Consequently, the risk of a complete failure of recruitment remains similar or declines across all vegetation types under the best-case and most-likely climate scenarios; but increases under the worst-case climate scenario (Fig. 6c). The probability of a partial recruitment failure (i.e. for vegetation that has limited germination in the absence of fire), likewise remains similar or declines under the best-case and most-likely climate scenarios; but increases under the worst-case climate scenario (Fig. 6d).

4. Discussion

Rainfall is the primary driver of carbon dynamics in this semi-arid environment. Rainfall patterns determine the risk of canopy dieback from drought, the likelihood of large wildfires, the likelihood of successful recruitment, and the rate of decomposition of dead biomass. Specifically, the drought index node of the model contributed to over 87% of the likelihood of reductions in carbon sequestration and storage and over 57% of the likelihood of recruitment failure (Fig. 4). The occurrence of drought and wet conditions were found to be of much greater importance than grazing, vegetation community type or vegetation state in driving the risk of reductions in carbon sequestration and storage.

4.1. Risk of reductions in carbon sequestration and storage

While rainfall was the primary factor determining the likelihood of carbon projects experiencing reductions in carbon sequestration and storage, the relative size was a function of whether the aboveground biomass was killed by wildfire, triggered by high antecedent rainfall, or recovered through epicormic resprouting (Fig. 6a and b). Larger reductions in carbon sequestration and storage following fire are expected when aboveground biomass is fire-killed, for example in vegetation that recovers through seed banks, or that resprouts from underground storage organs (lignotubers). Although not explicitly considered here, the recovery times vary with vegetation communities. Resprouting vegetation types, including vegetation that resprouts from epicormic shoots or lignotubers, are generally expected to recover faster than vegetation recovering from seed alone (Clemente et al., 2005; Nolan et al., 2015). Another factor that may influence carbon sequestration that was not considered is the optimal fire return interval, particularly for those vegetation communities that require fire for recruitment. The optimal fire return interval is highly uncertain for many vegetation communities in Australia's rangelands (Noble, 1984), which may be due in part to the infrequent, irregular nature of large rainfall events (van Etten, 2009), and subsequent fire in these environments. For example, observed fire return intervals for Mulga range from 3 to 52 years (Ward et al., 2014). Given the large extent of carbon abatement projects in this region, uncertainty around recovery times and optimal fire return intervals represent important knowledge gaps in incorporating vegetation offsets into climate change mitigation schemes.

Given the overarching importance of rainfall in driving carbon dynamics in these semi-arid environments and the long-term nature of these carbon abatement projects, climate change projections of future rainfall patterns are particularly important in understanding the potential of these systems to accumulate and store carbon over long time-periods, e.g. 100 years. Hence, further uncertainty in long-term carbon

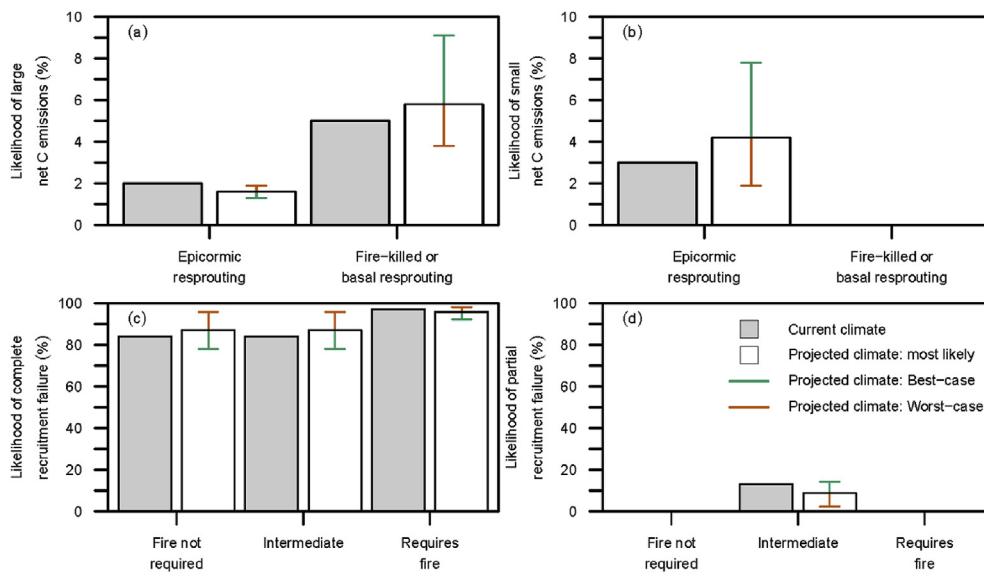


Fig. 6. Likelihood of (a) large and (b) small reductions in carbon sequestration and storage; (c) complete recruitment failure or (d) partial recruitment failure in carbon abatement projects under current climate conditions and projected climate for 2050. For climate change projections, the bars represent the ‘most-likely’ scenario, with the lower and upper error bars representing either the ‘best-case’ or ‘worst-case’ scenarios. The likelihood of reductions in carbon sequestration and storage is only modelled for established vegetation (i.e. in a woodland state) and the likelihood of recruitment failure is only modelled for vegetation regeneration projects (i.e. vegetation in a ‘grassland’ or ‘grassland and scattered woody species’ state), assuming low grazing intensity.

dynamics in vegetation offsets arises due to uncertainty in climate change projections in this semi-arid region. The influence of climate change on rainfall, and subsequent effects on carbon dynamics, varied depending on which climate change scenario was used. Under the best-case and most-likely climate scenarios for 2050, similar or increased mean annual precipitation is projected. This is expected to drive either similar or increased fire activity, due to above-average rainfall triggering an increase in grassy biomass, and hence fine fuel loads. At the same time there is a projected decrease in the likelihood of extremely dry conditions (Table 4). In contrast, under the worst-case climate scenario, where rainfall is projected to decline, fire activity is also expected to decline, but dry and extremely dry conditions remain similar or increase (Table 4). Thus, although climate-change driven changes to precipitation in this region may potentially reduce the incidence of extreme drought events, any reductions in carbon emissions from drought-induced mortality are likely to be offset by an increase in the incidence of fire. In addition to affecting the likelihood of carbon offset projects becoming net sources of carbon, any increase in fire activity, a syndrome termed ‘interval squeeze’, increases the risk that current vegetation communities will not recover, and will instead transition to a different vegetation community which may or may not have carbon implications (Enright et al., 2015). For reseeding vegetation types, repeated fire before vegetation reaches reproductive maturity may trigger such a transition. For example, in one of the vegetation communities studied, Cypress pine woodland, maturation occurs around 10–15 years (Bradstock and Cohn, 2002). Thus, a repeat fire in this period may cause localized decline in Cypress pine but may increase dominance by eucalypts. For resprouting vegetation types, the effect of increased fire frequency is highly uncertain. However, it is hypothesised that there may be limits to resprouting, with increased fire frequency leading to increased mortality in resprouting vegetation types (Fairman et al., 2016; Karavani et al., 2018).

Climate change is also expected to lead to an increase in mean monthly temperatures and an increase in the number of days above 40 °C (Table 4; Fig. 5a). The contribution of heat stress events to mortality in forests and woodlands has not been well-studied, in part because heat stress often occurs in concert with water-stress (Kiem et al., 2016), but also because thermal tolerance studies have largely focused on agriculturally important species (Curtis et al., 2014). Although there has been limited research on the tolerance of forests and woodlands to heat stress events, research on arid and semi-arid Australian species has found that thresholds of thermal tolerance (assessed by damage to photosystem II over short time-periods) range from 48 to 54 °C (Curtis

et al., 2014). Across the study area, historical maximum temperatures (to 2010) have reached 46 °C, suggesting that some species may be vulnerable to mortality under the most-likely and worst-case climate change scenarios (with mean increases of 2 °C and 3.4 °C likely; Table 4). However, local-scale patterns in microclimate and water availability are likely to influence vegetation vulnerability to high temperatures (Curtis et al., 2016).

4.2. Risk of recruitment failure

Given the reliance of arid and semi-arid zone species on above-average rainfall and fire for recruitment, there is a large risk that regeneration projects will fail to recruit overstorey/tree species, depending on the climate change trajectory (Fig. 6c and d). Under climate change, the likelihood of a recruitment event is projected to remain similar or increase under the best-case and most-likely scenario, but decrease under the worst-case scenario, particularly for vegetation types that require fire to trigger a seeding response. In the absence of a recruitment event that leads to establishment of overstorey species, regeneration projects are likely to become dominated by herbaceous or shrubby species. In addition to decreased fire frequency, shrub encroachment in rangelands environments has also been attributed to grazing and increases in atmospheric CO₂ (Eldridge et al., 2011). If shrub encroachment does occur, aboveground and belowground carbon storage will nonetheless be higher than that in areas managed for pasture (Daryanto et al., 2013). Thus, although there is a large risk that regeneration projects will fail to recruit overstorey species, and thus fail to reach the sequestration potential of mature woodlands, these areas may still have some value for offsetting carbon emissions.

It should be noted that current methods under Australia's emissions reduction fund for human induced regeneration of native vegetation require that land already has ‘forest potential’ when it is registered as a carbon project. This means that there are already sufficient young plants present to develop forest cover if left to grow. This requirement, if applied appropriately, should address the annual risk of recruitment failure identified here. However, for areas of land which may be targeted for carbon projects but require a recruitment event to provide forest potential, the annual risk of recruitment failure is substantial. A 16% likelihood of a recruitment event implies that landholders may need to wait a decade or more for forest potential to develop, assuming suitable seed sources are nearby. In practice, regeneration on previously cleared land can often take advantage of forest potential provided by small plants and root stock the survived previous clearing.

4.3. Model limitations and uncertainties

Limitations and uncertainties in the modelling approach presented here largely reflect the uncertainty in our understanding of the effects of disturbances on carbon stocks and the effects of climate change on the frequency and intensity of disturbances across the study area. A large uncertainty is the length of time for carbon stocks to recover following disturbance. For example, if a large mortality event occurs in a carbon offset project, either through fire or drought, the cumulative impacts on carbon sequestration and storage over the life of the project will depend on the length of time for vegetation recovery and when during the life of the project the disturbance occurs. A further limitation of the model presented here is the lack of error associated with each of the disturbances. It was not possible to include an estimate of error due to the limited number of studies across the study area. For example, to parameterise the probability of recruitment, we relied heavily on a study of *C. glaucophylla* (Zimmer et al., 2017) due to the absence of other studies explicitly quantifying recruitment success as a function of rainfall anomaly. A further limitation of the model is interactions between model components, for example the influence of grazing on fire risk. Despite these limitations, the Bayesian Network analysis approach presented here provides a good framework for modelling risk, as it can be readily updated when new information becomes available.

4.4. Management implications and conclusions

Given that the primary influence on carbon dynamics in semi-arid environments is rainfall, management options to mitigate biophysical risks to current carbon offset projects may be limited to strategies that reduce disturbance risk. These strategies range from careful planning on the size and location of vegetation offset projects, managing fuel loads during periods of high fire-risk, and managing the intensity of livestock and wild goats during periods of high vulnerability, e.g. during the germination and establishment phases of natural regeneration projects (Nolan et al., 2018). For future carbon offset projects, careful planning on the size and location of vegetation offset projects and expectations on the level of quantum abatement are required if globally we are to meet targets under international treaties. Australia's carbon offsetting scheme withholds 5% of credits from sequestration projects as a buffer against the risk of reversal inherent in carbon projects. The analysis presented here suggests that 5% is an appropriate estimate of the risk at the scale of the entire scheme. However, there is an inherent unavoidable risk that current carbon offset projects will fail to provide anticipated amounts of carbon abatement over their lifetime. This highlights the importance of explicitly considering the long-term risks posed to carbon offset projects. Our results also demonstrate that assessments of climate change impacts in this semi-arid region should consider the risk of both a drier and a wetter climate, given the variability in the direction of change of rainfall projections.

Acknowledgements

This work was supported by an Innovations Connections Grant (49080) awarded to Daniel Ramp and funding by GreenCollar. The workshop on biophysical risks to vegetation carbon-abatement projects in Australian rangelands was attended by: Rachael H. Nolan (workshop convener), Jennifer Sinclair, Cathleen M. Waters, Keryn I. Paul, Stephen Roxburgh, Don Butler, Megan Surawski, Daniel Ramp, James Schulz, Marta Ruiz-Colmenero and Bevan Yu.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2019.01.076>.

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