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Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF)

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Executive summary

The Emissions Reduction Fund (ERF) is central to Australia's domestic response to meeting the international climate challenge, the key mechanism of which is a voluntary scheme that seeks to provide incentives for organisations and individuals to adopt new practices and technologies to reduce their emissions. Under the scheme, participants adopt new (or 'additional') management activities or technologies that either reduce emissions, or sequester carbon. The Climate Change Authority is tasked with reviewing the ERF scheme every three years. Based on stakeholders concerns, the Climate Change Authority identified climate risk as a key focus area for the 2020 review. To help inform the 2020 review consideration of climate risk, CSIRO was requested to undertake an analysis of physical risks to carbon sequestration under current ERF land sector methodologies, including the proposed 'Blue Carbon' methodology. Twelve methodologies were identified that include sequestration as either all or part of their recognised abatement (Table S1). For the purposes of analysis these twelve methodologies were classified into six broad classes, on the basis of similarity in underlying management activity, and thus likely similarity in risk profile.

Sequestration activities require carbon to be stored in the landscape over the long-term. Under the ERF, projects can choose a 25 or 100 year permanence period during which carbon stored by the project must be maintained; projects electing a 25 year permanence period receive a 20% reduction in carbon credits issued. Because of the permanence requirements, there are therefore risks associated with ensuring both the establishment and ongoing maintenance of the stored carbon. For example, prolonged dry periods can limit recruitment and subsequent growth of woody vegetation, thus leading to lower sequestration than anticipated – a risk to abatement accumulation. Likewise, events such as forest wildfire can release sequestered carbon back to the atmosphere – a risk to the maintenance of existing abatement.

The risk analyses involved a literature review followed by qualitative assessment of risk across a range of identified risk factors. To guide the analysis a formal risk assessment protocol was followed, that combined for each identified risk factor an estimate of its probability of occurring (the 'likelihood'), together with an estimate of its 'consequence' for sequestration. The resulting risk priority matrix yielded a four-class classification of risk to each factor (Low, Medium, High and Extreme). Where possible, an indication of the level of scientific certainty associated with each rating was also given, and also whether the risk factor is likely to impact on the ERF portfolio for each activity as a whole (e.g. through the impacts of a regional drought), or whether the impacts will be localised. The scope of the analysis covers biophysical risks only. Policy-related risk mitigation measures were not taken into account in the risk assessment, but are briefly reviewed. In addition, any positive sequestration outcomes (such as arising from a change to more favourable growth conditions), are also noted.

The primary risks considered were those associated with current and future projected climate drivers, including ecological disturbances such as drought, fire, and pests and diseases. Eighteen risks factors were identified, with eight associated predominantly with changes in climatic variables that typically have direct impacts on sequestration (such as projected changes in temperature, frost exposure etc.), and ten associated primarily with the indirect impacts due to environmental disturbances (such as fire and storm damage) (Table S2). To guide the analysis twenty-one climate variables were obtained from a summary of up to 40 Global Circulation Model

(GCM) projections, as provided by the *Climate Change in Australia*[1] research program. The timeframe for analysis was focussed on 2050 (with climate change summaries typically integrated over the period 2040-2059), consistent with the 25 year crediting period specified for the majority of the sequestration methods. Implications for projected climatic changes up until the end of the century (2090) are also briefly discussed. The *Climate Change in Australia* analysis classified the Australian continent into 15 NRM regions for reporting climate projection results. Therefore for each of the six ERF methodology classes, the relevant NRM regions of activity were identified, and the climate projection information for each obtained to inform the risk assessments. In general, differences in climate projections between NRM regions within an ERF class were relatively consistent, and hence the risks tended to be relatively consistent.

Table S1. List of ERF Methodologies (and the years they were published) included in the analysis, classified into six broad activity categories.

Activity category	ERF Methodology	Included activities
Re-establishment of native forest cover	Human-Induced Regeneration of a Permanent Even-Aged Native Forest (2013) Native Forests from Managed Regrowth (2013)	A change in land management (e.g. a change in grazing management; cessation of regular clearing; control of feral browsers) that facilitates the natural regeneration of forest cover[2] from an initial non-forest state.
Planting of new forests	Reforestation by Environmental or Mallee Plantings – FullCAM (2014) Reforestation and Afforestation (2015) Plantation Forestry (2017) Measurement Based Methods for New Farm Forestry Plantations (2014)	The establishment of forest cover on currently non-forested land, via direct seeding and/or planting of tube stock seedlings. The methods include environmental plantings, as well as the establishment of commercial plantation species.
Protection of existing forests	Avoided Deforestation (2015) Avoided Clearing of Native Regrowth (2015)	Includes the cessation of land clearing to facilitate forest recovery (Avoided Clearing), and the protection of existing forest cover through relinquishment of clearing permits awarded for the purposes of converting forest cover to cropland or grassland (Avoided Deforestation).
Management of agricultural soils	Measurement of soil carbon sequestration in agricultural systems (2018) Estimating Sequestration of Carbon in Soil Using Default Values (2015)	Changes in land management that build and maintain soil organic carbon. A wide range of activities are allowed, including adding nutrients, lime, gypsum; Irrigation; pasture management; stubble retention and no/reduced till.
Savanna fire management	Savanna Fire Management Sequestration and Emissions Avoidance (2018)	Manipulation of the timing and extent of fire management in the northern Savanna to reduce GHG emissions and to sequester additional carbon in woody debris.
Management of intertidal ecosystems	Blue carbon (proposed new method)	Manipulation of tidal flooding to restore coastal ecosystems and build soil carbon.

A range of Representative Concentration Pathways (RCPs) are simulated across the GCMs, to represent a range of possible futures based on different global emissions reduction scenarios. The analyses in this report focus primarily on the RCP4.5 pathway, which reflects a 'middle-ground' policy outcome with emissions peaking at around year 2040, and the atmospheric CO_2 concentration stabilising at approximately 540 ppm by 2100. To provide an indication of the

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[1] www.climatechangeinaustralia.gov.au

[2] Forests include all vegetation with a tree height of at least 2 metres and crown canopy cover of 20 per cent or more, of an area of at least 0.2 ha

possible upper range of outcomes under a less favourable emissions reduction scenario, results from the RCP8.5 pathway are also considered, and which represent a future with little curbing of emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by 2100.

In addition to the assessment of risk, a review of the potential climate adaptation options and co-benefits associated with ERF sequestration activities was also undertaken, to provide some insights into how aspects of the current methodology design and rules help to mitigate against the identified risks, and what additional management options might be available to further contribute to risk mitigation and farm resilience. Adaptation responses are classified into three classes or 'zones'. Zone 1 adaptation responses are incremental in nature, requiring only minor modifications to existing practices. Zone 2 adaptation responses are required as climate change becomes more extreme, and involve increasing complexity, risk and cost, and where Zone 3 responses require a transformational change in management, for example a change in land use that may or may not be compatible with continued ERF activities. Overall the climate change scenarios described in this report suggest that, in the short term (i.e. up to 2050), Zone 1 and 2 strategies will be sufficient in most cases for adaptation. However, the more extreme climate changes projected for later in the century may require transformational change.

Overall findings

For each of the 18 identified risk factors an assessment was made on the level of overall risk associated with each category of activity, based on a combination of a review of the current literature, projected changes in the underlying climate variables, and expert opinion (Table S2). As expected, there was marked variability across the risk profiles, with some activity classes being most sensitive to changes in disturbance regimes (Management of intertidal ecosystems), some activity classes being most sensitive to changes in climate change factors (Management of agricultural soils; Planting of new forests), and some activities indicating relatively even sensitivity to both factors (Re-establish native forest cover; Protect existing forests; Savanna fire management). The maximum risk rating was 'High', indicating the risk factor is likely to occur in the future, with a potential consequence of 'Major', nominally tagged as either a loss of up to 50-80% of the stored carbon (or an under-delivery of up to 20-50% of that expected). Note that these nominal losses should not be interpreted as predictions of actual sequestration outcomes, as they were introduced primarily as a mechanism for allowing visualisation of what each category might correspond to in real terms. Actual quantification of sequestration losses or shortfalls is beyond the scope of the qualitative analysis presented here. No 'Extreme' risk ratings were identified.

Of the identified risk factors drought-induced stress, heat stress, and increased aridity/reduced soil water availability were the most prevalent. Changes to fire regimes were also a commonly identified risk factor. Risk factors associated with the potential impacts of pests and diseases, and changes to exposure to frost, were generally uncertain and are marked in the table with question marks. These can be considered gaps requiring further research.

Some of the identified climate factors might be expected to have a positive impact on carbon sequestration in ecosystems, such as via the increasing atmospheric CO_2 concentration that has been implicated in increasing woodiness across arid Australia, and changes in rainfall patterns that might increase rates of tree and grass production. Such climate-driven changes in carbon storage interact with, and potentially enhance, the outcomes of changes in land management, and hence may have implications for the additionality requirements under the ERF.

Table S2 Risk assessment summary. Risk assessments are shown for each combination of impact factor and activity category, separated by maintenance, accumulation and combined risks. Note each impact factor can contribute to both maintenance and accumulation risk. Overall rating is based on a simple weighted sum across all risk factors to give a composite score for each activity category and risk type. The weightings were: Not rated = 0; Low risk = 1; Medium risk = 3; High risk = 6.

	Combined risk						Maintenance risk						Accumulation risk					
	Manage agricultural soils	Planting new forests	Savanna fire management	Intertidal ecosystems	Re-establish native forest cover	Protect existing forests	Manage agricultural soils	Planting new forests	Savanna fire management	Intertidal ecosystems	Re-establish native forest cover	Protect existing forests	Manage agricultural soils	Planting new forests	Savanna fire management	Intertidal ecosystems	Re-establish native forest cover	Protect existing forests
Direct impacts via primary climate change variables																		
Heat-stress limiting plant growth and increasing mortality rates	🟥	🟧	🟧	🟨	🟧	🟨	🟥	🟧		🟨		🟨	🟥	🟧	🟧	🟨	🟧	
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	🟥	🟥	🟥		🟧	🟨	🟥					🟨	🟥	🟥	🟥		🟧	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	🟥	🟥	🟧	🟨	🟧	🟨	🟥			🟨		🟨	🟥	🟥	🟧	🟨	🟧	
Changes in timing/occurrence of suitable conditions for tree and crop establishment	🟧	🟧			🟧		🟧	🟨					🟧	🟧			🟧	
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	?	?			?		?						?	?			?	
Decreased frost days with implications for increased seed dormancy and reduced germination rates	?	?			?		?						?	?			?	
Changes to soil respiration and soil microbial processes	🟥			🟨			🟥			🟨			🟥			🟨		
Changes to timing/seasonality of crop growth	🟥						🟥						🟥					
Increased flooding, with implications for establishing crops and trees; greater susceptibility to pests and diseases	🟨	🟨		🟧	🟨	🟨	🟨			🟧		🟨	🟨	🟨		🟧	🟨	
Flood-related soil erosion and deposition	🟨			🟧	🟨		🟨			🟧			🟨			🟧	🟨	
Mechanical damage from wind and storms		🟨	🟨	🟧	🟨	🟨		🟨	🟨	🟧	🟨	🟨		🟨	🟨	🟧	🟨	
Coastal storm surges with implications for blue carbon stability				🟧						🟧						🟧		
Direct impacts via secondary climate change variables																		
Sea level change, with implications for blue carbon stability				🟧						🟧						🟧		
Drought-induced plant mortality, with possibility of recruitment failure.	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	🟨	🟧	🟧		🟨	🟨	🟨	🟧	🟧		🟨	🟨	🟨	🟧			🟨	
Indirect impacts via climate change impacts on weeds, pests and diseases																		
Increase in invasive weeds		🟨	🟧						🟧					🟨				
Increase in browsing by feral animals		🟨												🟨				
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	🟧		?	?	?	?	🟧		?	?	?	?	🟧		?	?	
Overall rating	39	31	22	21	19	9	39	14	10	21	5	9	39	31	16	21	19	0

Individual risk rating

?	Not rated (0)
🟨	Low (1)
🟧	Medium (3)
🟥	High (6)

Composite risk score

▢	≤10
▤	11-20
▦	21-30
■	>30

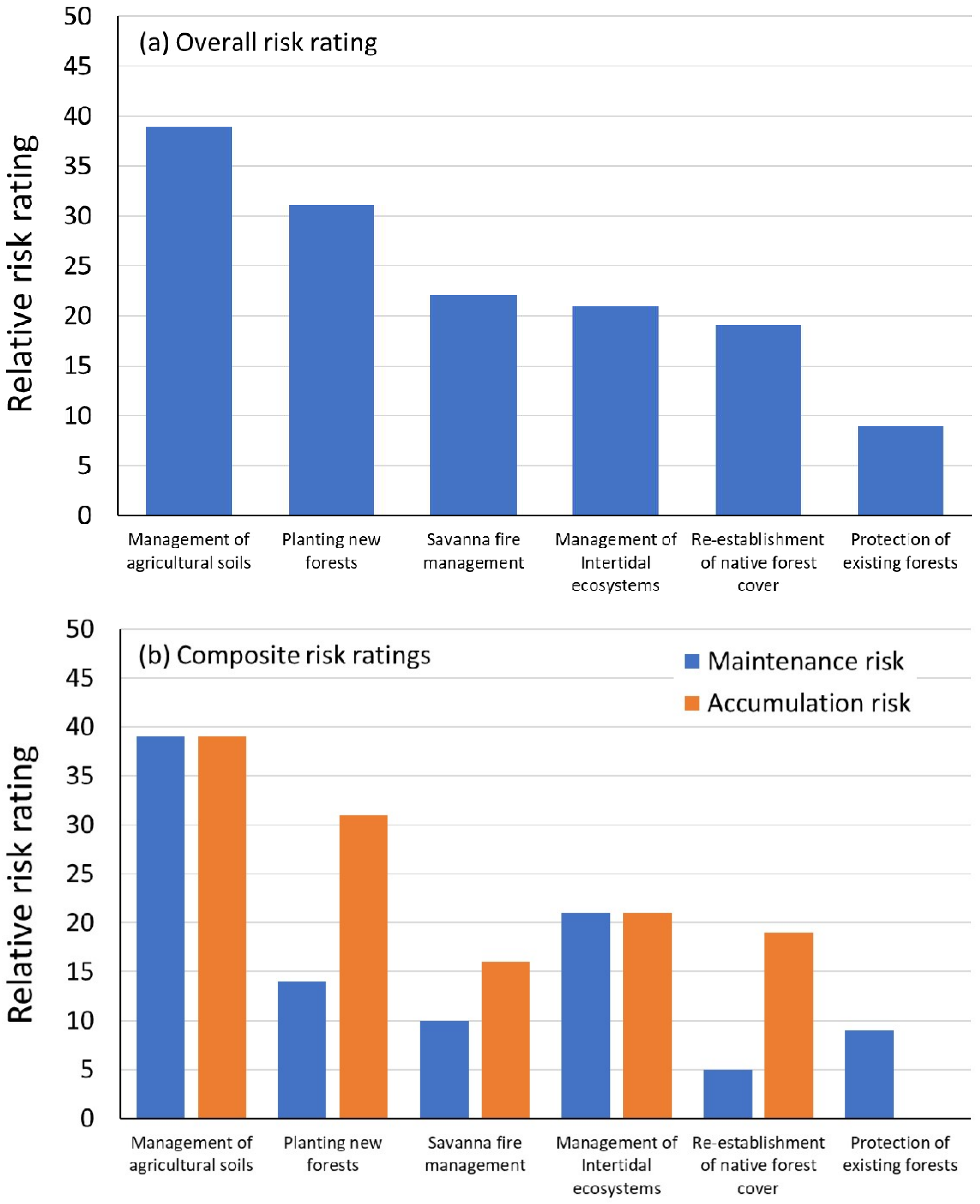

Figure S1. Composite relative risk rating for each activity category. (a) Overall risk rating. (b) Separation of risks into maintenance and accumulation. See text for details.

To integrate the findings across all risk factors a simple index was formulated that summed up, for each class of activity, the risk rating across each identified climate risk factor. Risk ratings of 'Low' were assigned a value of 1; risk ratings of 'Low/Medium' or 'Medium' were assigned a value of 3; and risk ratings of 'Medium/High' or 'High' were assigned a value of 6. Risk ratings marked as uncertain were excluded, and hence had a value of 0. Because a simple and transparent index was desired, there was no further attempt to weight the risk factors by uncertainty. This index therefore combines a measure of both how many risk factors were identified for each class of activity, and the relative magnitude of those factors (Figure S1). As noted above, the resulting number cannot be used to infer a particular level of expected carbon loss or shortfall, but rather should be interpreted as an index to compare relative risks across activities.

The index suggests Management of agricultural soils and Planting of new forests have the highest composite risk rating (Figure S1a). This is followed by Savanna fire management, Management of intertidal ecosystems and Re-establishment of native forest cover, with intermediate values. Protection of existing forests has the lowest risk rating. The index also shows the different methodology categories have different risk profiles with respect to accumulation risks and maintenance risks (Figure S1b). For the activities involving soil carbon sequestration (management of agricultural soils and management of intertidal ecosystems) the risks are evenly split, with all risk factors identified as having potential impacts on both accumulation and maintenance. This is because changes in soil carbon are driven by changes in the rates of organic matter input, as well as losses from soil respiration; and the impacts of climate change can simultaneously affect both pathways. Further work is required to tease apart the relative sensitivities to soil carbon loss and gain for each climate impact factor. For the Planting of new forests, Savanna fire management and Re-establishment of native forest cover categories, risks to the accumulation of carbon were greater than risks to the maintenance of that carbon, mostly arising from potential impacts to plant growth and decomposition processes. For the protection of existing forests category, only maintenance risks are significant, given the carbon store is present at the start of the project.

Although the index cannot be used as a basis for quantifying potential carbon losses, in conjunction with the more detailed information in Table S2, this ranking could be used as a basis for prioritising attention on the methodologies and associated risk factors that are suggested to be most vulnerable. This could include further investigation of the policy settings underlying each methodology to determine if they could be modified further to alleviate exposure to carbon loss, and to prioritise further research effort on those sectors and activities deemed to be most at risk.

Activity-specific findings

MANAGEMENT OF AGRICULTURAL SOILS

The dominant risks to sequestration for the Management of agricultural soil activity, for both risks to accumulation and maintenance, were associated with climate change impacts on the rates of organic matter input to soil, and the rates of loss through changes to soil respiration and the microbial biota. Based on the qualitative review undertaken here it was not possible to quantify relative differences in risks between accumulation and maintenance – for example a reduction in plant growth can simultaneously reduce the rate of input (accumulation risk), and by doing so also indirectly increase soil carbon loss (maintenance risk) through changing the balance between the rates of organic matter accumulation and soil respiration. The vulnerability of soil organic carbon (SOC) to loss has been recently highlighted by a number of studies suggesting the majority of the spatial and temporal variability observed in SOC can be attributed to non-management related factors. For example Badgery et al.[3] showed, across 10 locations in NSW and over a 16 year period, that all of the SOC gains made over the early years following changes in management, designed specifically to build SOC, were lost by year 16. Moreover, the SOC that did accumulate following

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[3] Journal of Environmental Management 261, 110192

management change was predominantly Particulate Organic Carbon (POC), which has a fast turnover rate and is thus most vulnerable to loss. Finally, the patterns of subsequent reversal of the sequestration were similar over widely differing management interventions, suggesting the primary factor controlling the reversal was not solely related to management. The associated risks to SOC storage apply at the portfolio-level, as well as to individual projects. Although the soil measurement methodologies only require the measurement and reporting of total organic carbon, information on the composition of different soil carbon fractions (such as POC) would provide valuable additional information for understanding the potential future vulnerability of the sequestered carbon. Because of the wide range of management activities allowed under the methodology, there are also a wide range of adaptive measures that can be taken to ensure success of the management change with respect to such factors as productivity and economic returns, and associated co-benefits regarding soil health. Zone 1 adaptive measures focus on actions to enhance or maintain rates of organic matter input to the soil, such as pest control, and adjusting the timing of crop establishment. Zone 2 measures involve activities such as selecting, or breeding for, species/genotypes more tolerant of extreme climate. Although a number of adaptation options were identified, their effectiveness in helping to secure SOC over the long term remains untested. No specific actions were identified that could be currently undertaken to directly manage respiratory losses of soil carbon, although manipulation of microbial function to enhance soil carbon sequestration is an active area of research.

PLANTING OF NEW FORESTS

The majority of risks identified for the Planting of new forests activity were associated with accumulation risks, arising from reductions in tree growth (and hence sequestration rates) from persistent increases in temperature, persistent increases in water stress, and disturbances from heat-stress and droughts. The greatest risk period is soon after planting or germination, when plants are young and more vulnerable to climatic stress. Wildfires were also identified as a particular risk factor, associated with risks to maintenance, but predominantly at the project level due to suitable project locations being spatially distributed across the continent. Of all the activity categories Planting of new forests has the widest range of opportunities for adaptation, many of these involving incremental Zone 1 responses. Examples include varying planting species and genetic stock, altering planting configuration to reduce risks of resource limitations, careful site preparation and timing of establishment, and fire risk reduction management (Zone 2). Selective breeding for genotypes that confer increased resilience to climate extremes is a Zone 2 response option. Many of the adaptive measures are currently applied in the context of plantation forestry, but can also be modified for environmental plantings.

SAVANNA FIRE MANAGEMENT

A persistent increase in water stress was judged to be a high risk to both accumulation and maintenance for the Savanna fire management activity. This is because a decrease in water availability will lead to a decline in maximum biomass potential, and thus, the potential for sequestration with fire management. For example, it has been shown that savanna vegetation types with relatively high maximum biomass potential have a much greater potential for sequestration with fire management when compared to savanna vegetation types with relatively low maximum biomass potential. However, this will be partly negated by increases in water stress also resulting in slower rates of post-fire recovery and increased seasonality of turnover. These two factors will both increase the extent of abatement potential from fire management when compared to a baseline that has higher fuel accumulation in the late dry season and slow recovery of biomass post-fire. Of all the regions in Australia, the increases in temperature are projected to be the highest in the regions where savanna fire management projects occur. It is also a region that experiences cyclones, and these are projected to intensify. There are several factors that can interact to either lead to increased or decreased opportunities for sequestration, leading to an intermediate-level overall risk rating (Figure S1). Savanna burning projects have an extensive history of delivering co-benefits, particularly with respect to indigenous livelihoods and biodiversity outcomes. However, given the large spatial extent of most projects, and the ubiquitous nature of the risk factors (e.g. temperature increase; cyclone activity) relatively few adaptation opportunities were identified that have the potential to significantly mitigate the identified risks. Control of gamba grass was identified as a key risk mitigation strategy, in those areas under threat from this invasive species.

MANAGEMENT OF INTERTIDAL ECOSYSTEMS (BLUE CARBON)

Given a Blue Carbon methodology is currently being designed, undertaking an initial assessment of potential risk is timely. Intertidal ecosystems can be considered ’high energy’, in that they are subject to regular and profound environmental perturbations, from the daily tidal cycle through to runoff and freshwater inundation. There are risks to both accumulation and maintenance for sequestration activities in Blue Carbon ecosystems, however the primary drivers are connected and interacting, involving changes to sea levels (both short-term declines and long-term increases), drought, flooding and storm impacts, extreme temperatures, and impacts to rates of sedimentation and erosion. Because these factors can cause either accretion or loss of carbon, the magnitude and direction of change in carbon storage is uncertain, and hence identifying where and under what conditions particular sites might be at risk requires further detailed analysis. Because the primary management intervention involves the re-introduction of tidal flows to restore mangrove and tidal marsh ecosystems, this implies candidate project areas will be relatively close to human occupation (compared to the vast expanses of mangrove forest in Northern Australia), and that the management interventions are likely to include modification of existing infrastructure, such as levees and embankments. Because of this level of control in how projects are designed and implemented, it is possible this could provide Zone 1 opportunities to mitigate against some of the major risk factors, such as carefully designed engineering to simultaneously promote increased tidal flows, but also provide protection to the regenerating systems from disturbances such as tidal surges and storm damage. Adaptive responses to address risks associated with the sensitivity of vegetation to a changing climate are difficult to identify, and may have to rely in the first instance on regular evaluation to assess where vegetation might be at greatest risk, to help inform where the activity should be best targeted in the future.

RE-ESTABLISHMENT OF NATIVE FOREST COVER

This activity includes the Human Induced Regeneration (HIR) methodology that significantly contributes to the current ERF portfolio, in addition to the Native Forest from Managed Regrowth methodology. From the perspective of abatement accumulation, the main risks are associated with changes in the climate that affects the survivorship of young regenerating stands, and the growth rates of mature stands. The main drivers were identified to be changes in average and maximum temperature, and the associated variables potential evapotranspiration and relative humidity, which have the potential to reduce net primary productivity, and hence rates of carbon sequestration. Regarding abatement maintenance, the main risk factor identified was from mortality associated with extreme drought, although the ultimate consequences for carbon abatement are uncertain as they are a function of the combined rates of subsequent debris decay and other losses (such as from termites), and rates of post-drought recovery. The drought risk is exacerbated through the regional concentration of projects in north west New South Wales, and south west Queensland. Because fire is not a major feature in the areas where these activities have been established, or are likely to be established in the future, it was not considered a significant risk factor, although fire does occur within the region, and hence individual projects should have in place appropriate fire management plans. The key stage of vulnerability for these projects is during the establishment and early years of growth. The embedded methodological requirements of having to demonstrate a potential for forest cover to be achieved (through e.g. evidence of seedlings or young regrowth), and for having to demonstrate advancement of the vegetation towards forest cover over time, provides strong mitigation against the impacts of climate change on the vulnerable early stages of regeneration. Other Zone 1 and 2 adaptation responses include fuel management to reduce the likelihood of fire, management of any grazing to protect the vegetation when it is most vulnerable (for example during drought or after fire), and site selection protocols to ensure adequate propagules are present to support regeneration towards the required 20% canopy cover. These could involve ensuring adequate seedlings or vegetative reproduction on-site, or proximity to existing seed sources from adjacent forest stands.

PROTECTION OF EXISTING FORESTS

Because both the Avoided Deforestation and Avoided Clearing methodologies within this activity class involve the protection of existing forests, the question of risks to accumulation are not relevant, and risks associated with initial forest regeneration are avoided. The main risks are therefore associated with abatement maintenance, which were identified to be mortality associated with extreme drought, although as noted above the ultimate consequences for carbon abatement are uncertain as they are a function of the combined rates of subsequent debris decay and other losses, and rates of post-drought recovery. Because of the potentially broad spatial scale of drought events, and given the concentration of current projects geographically, there are implications at both the whole portfolio level, as well as the individual project level. Opportunities for mitigating these risks are limited, but include control of invasive weeds (an existing requirement of the methodology), which also helps mitigate against risks from wildfire. In the areas most suited to the Avoided Clearing methodology the fire risk is relatively higher, due to higher productivity and greater contiguity of ground fuels. Zones 1-2 adaptation responses therefore include fuel management to reduce the likelihood of fire, and management of any grazing to protect the vegetation when it is most vulnerable (for example following severe drought, or after fire disturbance).

Next steps

The qualitative risk assessments undertaken in this study, based on literature review, projections of future climate change, and expert opinion, provide a starting point for more detailed analysis that could provide more specific, and quantitative, information on the potential losses of abatement under various scenarios of climate, disturbance regimes, and abatement activity. Although the risk rankings developed here cannot be used for quantitative analysis, they could be used as a basis for prioritising attention on the activities within the methodologies that were identified to be most at risk. This could include deeper investigation of current and future policy settings on risk mitigation, and the prioritisation of further research effort on those sectors and activities deemed to be most at risk.

A logical extension of the work presented here is to embed the risk analysis framework within a process-based modelling environment capable of simulating changes in plant growth and decomposition, soil organic carbon dynamics, and disturbance regimes, all linked to the key climate drivers. This would allow actual estimates of risks to achieving abatement to be made, e.g. in units Mt CO_2e yr^{-1}, and would facilitate more informed decision making for both project proponents, and policymakers. The component models for undertaking such an assessment currently exist, but the challenge would be in bringing them together within the one analysis framework.

1 Introduction

1.1 Background

Under the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement Australia has pledged a 26-28% reduction in 2005 greenhouse gas (GHG) emissions by 2030. Over 190 countries have lodged commitments under the Paris Agreement, agreeing to take practical steps to reduce emissions to pursue efforts to keep warming below 2.0°C above pre-industrial levels. The Emissions Reduction Fund (ERF) is central to Australia's domestic response to meeting this challenge, the key mechanism of which is a voluntary scheme that seeks to provide incentives for organisations and individuals to adopt new practices and technologies to reduce their emissions. Under the scheme, participants adopt new (or 'additional') management activities or technologies that either reduce emissions, or sequester carbon. Australian Carbon Credit Units (ACCUs, priced per unit of tonnes of carbon dioxide equivalent, t CO_2-e) are awarded to recognise abatement that is achieved. Within the ERF, the land sector plays a significant role contributing approximately 70% of the abatement that has been delivered thus far under the scheme (Section 3, below).

Activities that seek to reduce emissions (rather than sequester carbon) create abatement that is non-reversible, with atmospheric greenhouse gas benefits that are realised immediately. In contrast, sequestration activities are required to store the accrued carbon in the landscape over the long-term. Under the ERF, projects can choose a 25 or 100 year permanence period during which carbon stored by the project must be maintained; projects electing a 25 year permanence period receive a 20% reduction in carbon credits issued. Because of the permanence requirements associated with sequestration, there are therefore risks associated with ensuring both the establishment and ongoing maintenance of the stored carbon. For example, prolonged dry periods can limit recruitment and subsequent growth of woody vegetation, thus leading to lower sequestration than anticipated – a risk to abatement accumulation. Likewise, events such as forest wildfire can release sequestered carbon back to the atmosphere – a risk to abatement maintenance (Figure 1).

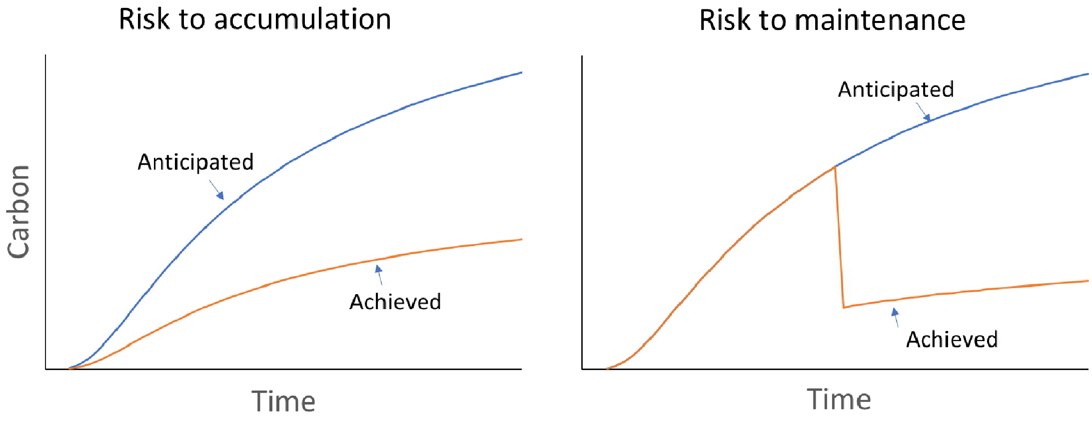

Figure 1. Illustration of risk to carbon accumulation and risk to carbon maintenance associated with sequestration projects. In both cases the abatement that is achieved (orange line) is less than that anticipated (blue line).

Within the ERF such risks are formally managed via the ‘risk of reversal buffer’, a mechanism whereby 5% of all abatement credits are withheld. Less formally, companies can manage risks through portfolio diversification, for example investing across a range of activities, and/or a range of spatial locations (noting that the ERF as a whole does not ensure such spatial risk-spreading, as the primary selection criteria under the reverse-auction mechanism is lowest-cost abatement). At the individual project level management actions can also be taken to influence carbon storage and risk exposure (Galik and Jackson 2009). Whilst the requirement to manage risks for sequestration projects is well appreciated (Nolan et al. 2018a), the effectiveness of such actions remains largely unknown, due to the complexity of (and interactions amongst) the key risk drivers, and the lack of national-scale frameworks for monitoring and evaluating the effectiveness of different risk mitigation approaches (Nolan et al. 2018b).

In addition to greenhouse gas abatement, there are also significant environmental, social and economic co-benefits that are associated with carbon sequestration activities, and whilst co-benefits are also vulnerable to a range of risk factors, there are also opportunities for co-benefits to buffer or otherwise protect sequestration. Co-benefits are integral to carbon farming, with such outcomes as enhanced farm productivity and improved soil fertility associated with building soil carbon likely being main drivers of abatement activity in the agricultural sector, rather than increasing carbon storage *per se*. (Fleming et al. 2019). It should also be recognised that alongside generating carbon co-benefits is also the potential for dis-benefits, such as reduced water availability through forest regeneration, and reductions in the area of agriculturally productive land. These must also be borne in mind.

1.2 Study aims and report outline

The overall aim of this study is to provide information to the Climate Change Authority on the biophysical risks associated with the accumulation and maintenance of carbon sequestration in the land sector, within the constraints of the activities allowable within the ERF. This work will inform the Climate Change Authority’s consideration of climate risk, a key theme in its 2020 legislative review of the ERF. The primary risks considered are those associated with current and future projected climate drivers, including ecological disturbances such as drought, fire, and pests and diseases. A second aim of the study is to assess the co-benefits associated with ERF sequestration activities, and provide a review the potential for these co-benefits to contribute to protecting carbon stocks, and farm resilience and climate change adaptation more broadly; as well as identifying other activities that are consistent with ERF project management, and that could confer farm-scale adaptive capacity.

Twelve ERF methodologies (eleven developed and one proposed) were identified that include activities that sequester carbon in either vegetation or soils (Table 1). For the purpose of analysis these methodologies were grouped into six categories, based on overall similarity in activity, and hence likely similarity of risk profile. Although the specified carbon pools included in the accounting under each method are the focus of this review, carbon pools that are not included in the accounting, but could nevertheless be vulnerable to loss, are also considered. For example, all of the vegetation methods include both biomass and forest debris as part of the accounting envelope, but none include soil organic carbon. The included and excluded carbon pools for each methodology are also listed in Table 1, together with a brief description of the allowable activities.

To assess future risks under a changed climate, extensive use is made of the data syntheses provided by the *Climate Change in Australia* study (CSIRO and Bureau of Meteorology 2015; www.climatechangeinaustralia.gov.au). This study aggregated results across approximately 40 Global Circulation Models[4] (GCMs) for the Australian continent, providing summaries of a wide range of climate variables within a regional categorisation designed to capture the key attributes of sub-continental variability in climate projections. The analysis timeframe adopted here is centred on the year 2050 (with climate change summaries typically integrated over the period 2040-2059). Based on the current year (2020), this timeframe is consistent with the 25 year crediting period specified for the majority of the sequestration methods[5]. To provide an indication of the potential longer-term implications, climate change summaries centred on the year 2090 (2080-2099) are also discussed.

A range of Representative Concentration Pathways (RCPs) are simulated across the GCMs, to represent a range of possible futures based on different global emissions reduction scenarios. The analyses in this report focus primarily on the RCP4.5 pathway, which reflects a 'middle-ground' policy outcome with emissions peaking at around year 2040, and the atmospheric CO_2 concentration stabilising at approximately 540 ppm by 2100. To provide an indication of the possible upper range of outcomes under a less favourable emissions reduction scenario, results from the RCP8.5 pathway are also considered, and which represent a future with little curbing of emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by 2100.

The remainder of the report is structured as follows:

In Section 2 the risk analysis framework is presented, with the consequences and likelihoods associated with different risk factors defined, combining to yield a four-class rating of risk for each sequestration activity (low, medium, high, extreme). Section 2 also reviews the key climate impact drivers most relevant to land-based sequestration, and provides a summary of the regional classification within which the risk analysis is undertaken, together with a summary of the climate variables available for each region.

Section 3 briefly reviews the current ERF portfolio of sequestration projects, including the spatial distribution of activities, and then applies the risk framework developed in Section 2 to the six classes of ERF activity summarised in Table 1. Each class of ERF activity is assessed against the climate impact drivers from the perspective of risks to abatement accumulation and maintenance, but also taking into account any identified positive sequestration outcomes (such as arising from a change to more favourable growth conditions). Also taken into account are the regional differences in the risk factors, to provide a spatial context to the risk ratings. The final risk assessment for each activity is then obtained from combining the risk ratings across the different impact drivers.

Section 4 briefly reviews the main ERF mechanisms that are designed to mitigate risk and to provide flexibility for proponents to help manage climate related and other physical risks to

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[4] GCM simulations come from the archive developed by modelling groups from around the world through the Coupled Model Intercomparison Project phase 5 (CMIP5)) which also underpins the science of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Results from the latest research (CMIP6) are due to be released in April 2021.

[5] The crediting period is the period of time over which a project is able to apply to claim ACCUs. All sequestration activities in Table 1 have a crediting period of 25 years, with the exception of Avoided Deforestation, which is 15 years.

sequestration. This assessment considered the risk reversal buffer, permanence requirements, flexibility to source ACCUs from the secondary market, and options contracts (i.e. where a proponent has the right, but not the obligation, to sell ACCUs to the Commonwealth).

Section 5 turns to the question of the broader co-benefits (and dis-benefits) that are implicated across the different ERF activities, and their potential role in conferring resistance and resilience of farm enterprises to the identified climate risks. Section 5 also considers the opportunities for how methods could be implemented (or modified) to mitigate against risks and to provide resilience against a changing climate. Finally, the results from the study are summarised in Section 6.

Table 1. List of ERF Methodologies included in the analysis, classified into six broad activity categories. 'Included carbon pools' are included in the abatement calculations for the methodology. 'Excluded carbon pools' and not included in the accounting, but may nevertheless be susceptible to loss.

Activity category	ERF Methodology	Included activities	Included carbon pools	Excluded carbon pools
Re-establishment of native forest cover	Human-Induced Regeneration of a Permanent Even-Aged Native Forest (2013) Native Forests from Managed Regrowth (2013)	A change in land management (e.g. a change in grazing management; cessation of regular clearing; control of feral browsers) that facilitates the natural regeneration of forest cover[1] from an initial non-forest state.	Above- and below-ground alive and dead biomass carbon	Soil organic carbon
Planting of new forests	Reforestation by Environmental or Mallee Plantings – FullCAM (2014) Reforestation and Afforestation (2015) Plantation Forestry (2017) Measurement Based Methods for New Farm Forestry Plantations (2014)	The establishment of forest cover on currently non-forested land, via direct seeding and/or planting of tube stock seedlings. The methods include environmental plantings, as well as the establishment of commercial plantation species.	Above- and below-ground alive and dead biomass carbon; harvested wood products (Plantation Forestry)	Soil organic carbon
Protection of existing forests	Avoided Deforestation (2015) Avoided Clearing of Native Regrowth (2015)	Includes the cessation of land clearing to facilitate forest recovery (Avoided Clearing), and the protection of existing forest cover through relinquishment of clearing permits awarded for the purposes of converting forest cover to cropland or grassland (Avoided Deforestation).	Above- and below-ground alive and dead biomass carbon	Soil Organic carbon
Management of agricultural soils	Measurement of soil carbon sequestration in agricultural systems (2018) Estimating Sequestration of Carbon in Soil Using Default Values (2015)	Changes in land management that build and maintain soil organic carbon. A wide range of activities are allowed under the method, including adding nutrients, lime, gypsum; Irrigation; pasture management; stubble retention and no/reduced till	Soil organic carbon	Above- and below-ground alive and dead biomass carbon
Savanna fire management	Savanna Fire Management Sequestration and Emissions Avoidance (2018)	Manipulation of the timing and extent of fire management in the northern Savanna to reduce GHG emissions and to sequester additional carbon in woody debris.	Above-ground dead biomass	Below-ground dead biomass; Soil organic carbon; Live biomass.
Management of intertidal ecosystems	Blue carbon (proposed new method)	Manipulation of tidal flooding to restore coastal ecosystems and build soil carbon.	Soil organic carbon; Above- and below-ground live biomass	Above- and below-ground dead biomass.

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[1] Forests include all vegetation with a tree height of at least 2 metres and crown canopy cover of 20 per cent or more, of an area of at least 0.2 ha

2 Assessment of the key climate risk impact drivers for land-based sequestration

2.1 Defining and reporting risk

Risk is broadly defined as the effect of uncertainty on objectives, where objectives can have financial, health and safety, and environmental aspects (ISO Guide 73:2009). A number of approaches can be taken to the analysis of risk. In this report we follow the general risk analysis procedure of Hennessy et al. (2015), which is itself based on Standards Australia (2009)[6]. The Standard risk assessment involves three broad steps, which also guide the structure of this report (Figure 2, grey box). Prior to risk assessment the context first needs to be defined (outlined in Section 1 above). The risk assessment step is the primary focus of this study, and is explained further below. Following risk assessment, it is then recommended that decisions are made on appropriate actions to mitigate and/or adapt to the identified risks, with this 'risk treatment' step lying outside of the scope of this study.

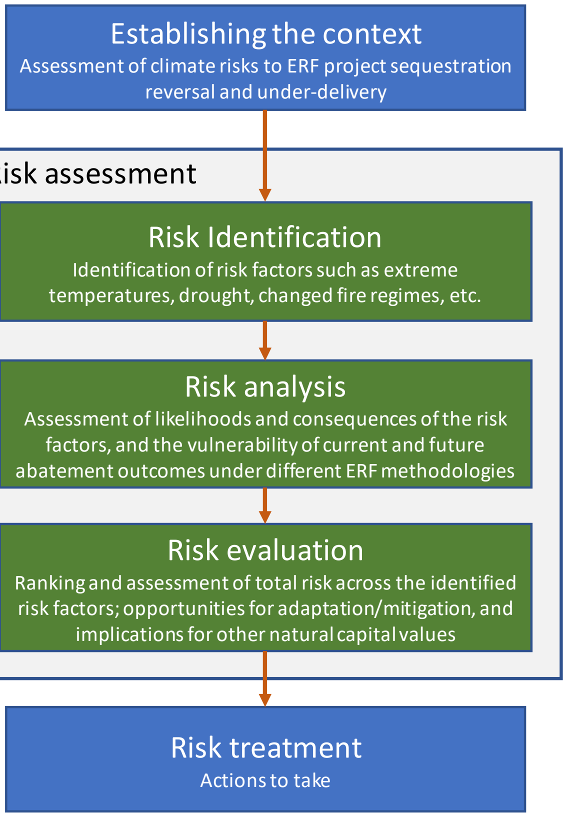

Figure 2. Simplified climate change impact assessment pathway. This study is primarily concerned with the steps within the 'Risk assessment' boundary. Adapted from Hennessy et al. (2015).

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[6] Note Standards Australia (2009) (ISO 31000:2009 has been updated to ISO 31000-2018, available at https://www.iso.org/obp/ui#iso:std:iso:31000:ed-2:v1:en

The first component of the risk assessment step, Identification, involves recognising and describing the risk factors relevant to the context under consideration. Within the context of this study this requires identifying the risk factors that could potentially impact, either positively or negatively, abatement accumulation and maintenance for ERF sequestration projects. The second step, Analysis, involves understanding the consequences of the risk factors, together with their likelihood (or probability of occurrence). When combined, consequences and likelihoods provide the framework for establishing the overall level of risk. Consequences are defined relative to the magnitude of change in abatement expected as a function of both exposure to the risk factor, and the sensitivity to the factor. The third step, Evaluation, involves the assessment of the risk analysis in the context of future climate impacts or benefits, across all of the risk factors identified.

In this study consequences are specified separately for abatement maintenance and accumulation (Table 2), and include only environmental consequences (with financial and other non-environmental impacts beyond the scope of this review). A five-class classification is adopted, ranging from 'Insignificant', with less than a 5% expected loss of abatement over the long term, through to 'Catastrophic', where greater than 80% of achieved abatement is lost (or less than 20% of planned abatement is achieved), combined with a subsequent loss in capacity to sequester additional carbon into the future. Although the consequence classes are defined numerically, in the absence of detailed modelling to quantify the possible impacts of the risk factors across the different ERF activities on sequestration outcomes, the numerical classes are here used as a guide to ranking outcomes, based largely on qualitative information.

Table 2. Five-class classification of the consequences of identified risk factors to abatement accumulation and maintenance.

Rating	Abatement accumulation	Abatement maintenance
Catastrophic	<20% of expected abatement achieved, and/or lost capacity to re-establish activity.	>80% of all previously sequestered abatement lost back to the atmosphere, and/or lost capacity re-sequester lost carbon.
Major	20-50% of expected abatement achieved, with potential to re-establish activity.	50-80% of sequestered abatement lost, with potential to re-establish activity.
Moderate	50-80% of expected abatement achieved, with potential to re-establish activity.	20-50% of sequestered abatement lost, with potential to re-establish activity.
Minor	80-95% of expected abatement achieved, with potential to re-establish activity.	5-20% of sequestered abatement lost, with potential to re-establish activity.
Insignificant	≥95% of expected abatement achieved	Abatement maintained or increased through time with no material losses

Given the large uncertainty on the magnitude and direction of future changes to many climate factors, and also uncertainties associated with the likely impacts of those factors for sequestration, a relatively simple three-class classification of likelihoods is adopted. Risk factors are assessed as being likely to occur (with >66% probability), unlikely to occur (with < 33% probability), or as likely to occur as not (33-66% probability). As per the consequences classification (Table 2), where quantitative information is not available, then these numeric constraints are used to guide the analysis based on the available qualitative information. Where appropriate, the likelihood classification is applied at both the scale of an individual project, and also at the scale of the ERF scheme as a whole. At the project scale, and depending on the likelihood and the spatial and temporal distribution of the risk factors, it is possible for individual projects to be significantly impacted, but where the net impact at the portfolio-level may be minimal. However, if the risk factors operate simultaneously over large spatial domains, or are correlated through time, then there is the potential for co-ordinated losses (or failures), which could have immediate and long-lasting consequences for the portfolio as a whole.

Table 3. Three-class classification of the likelihoods of identified risk factors, considered both at the portfolio level, and the individual project level.

Rating		**Project-level risks**	**Portfolio-level risks**
Likely	>66% probability	Likelihood of individual projects being impacted, but risk factors not necessarily coordinated in time or space	Likelihood of risk factors impacting sequestration simultaneously across space or time, with greater opportunity for portfolio-wide consequences
About as likely as not	33-66% probability		
Unlikely	<33% probability		

Combining the consequence (Table 2) and likelihood (Table 3) classifications gives a matrix of risk priority classes that can be assigned to combinations of ERF activities and risk factors (Table 4). Four classes are defined relative to the various combinations of consequence and likelihood; low, medium, high and extreme.

Table 4. Risk priority classification arising from the various combinations of consequence and likelihood.

			Consequences		
Likelihood	Insignificant	Minor	Moderate	Major	Catastrophic
Likely	Low	Low	Medium	High	Extreme
About as likely as not	Low	Low	Medium	High	Extreme
Unlikely	Low	Low	Low	Medium	High

Climate projection science is inexact, with varying levels of confidence ascribed to predicted changes across different climate variables. This has additional implications for the interpretation of the risk priority classes in Table 4. For example, a rating of ‘medium’ risk may be based on knowledge that is well established and accepted (i.e. with ‘high’ confidence); or may be based on knowledge that is fragmentary and/or with limited scientific consensus (i.e. with ‘low’ confidence). To recognise this embedded uncertainty, the confidence ratings determined by the *Climate Change in Australia* synthesis (CSIRO and Bureau of Meteorology 2015) are applied where available. These confidence ratings are based on the IPCC approach, whereby overall confidence is determined through combining a ranking of the degree of scientific agreement (low, medium and high) together with a ranking of the degree of confidence in the scientific evidence base (limited, medium, robust). The resulting classification yields four confidence ratings (low, medium, high and very high; Table 5). Therefore, when results of the risk assessment are discussed, both a risk rating is given (e.g. medium risk), together with an indication of the level of uncertainty associated with the climate projection data underpinning that rating (e.g. with Low confidence). In this study a formal propagation of the uncertainties associated with the climate projections through to the final risk ratings was beyond scope, hence the level of scientific uncertainty associated with the risk ratings was not formally assessed. For the climate variables on which the analyses here are based, the associated confidence ratings, as synthesised by CSIRO and Bureau of Meteorology (2015), are summarised in Appendix C.

Table 5. Levels of confidence in model projections as defined by the degree of robustness of the understanding of the underlying science evidence base, and the consensus across different GCMs.

Confidence rating	Scientific agreement		Evidence base
Very high	High agreement	+	Robust evidence
High	High agreement	+	Medium evidence
	Medium agreement	+	Robust evidence
Medium	High agreement	+	Limited evidence
	Medium agreement	+	Medium evidence
	Low agreement	+	Robust evidence
Low	Low agreement	+	Medium evidence
	Medium agreement	+	Limited evidence

2.2 A spatial framework for risk analysis and reporting

Current climate projections are based on results from global circulation modelling, and by necessity are often of low spatial (but high temporal) resolution (Appendix A). The spatial resolution of GCMs varies, but is typically in the order of 200km x 200km. National-scale climate projection analyses are therefore typically undertaken at a regional level, given low sub-regional confidence in model outputs at finer spatial scales. To provide greater spatial resolution a number of prior studies have applied regional down-scaling algorithms to the global data (e.g. CSIRO 2012). Such down-scaled analyses are relevant to this project, and are included in the overall consideration of the risk factors where appropriate, and where available (Section 2.3.2); although development of a spatial analysis capability for assimilating and integrating down-scaled climate projection data across the continent was beyond the scope of this review.

Much prior thought has been given to the appropriate scale at which climate projection information is best summarised at a regional level for Australia. Here we adopt the NRM-regional based classification (Figure 3) that formed the basis of the CSIRO Climate Change in Australia synthesis (Whetton et al. 2015). Eight regions, with seven sub-clusters, form the basis of the synthesised reporting and data summaries. This existing information forms the basis for both guiding the required regionalisation, and for providing the information on trends in key climate drivers, under both current and future climate conditions.

Consideration was given to conducting a further finer-scaled sub-regionalisation of the two large rangelands sub-clusters, given the importance of the Human Induced Regeneration ERF methodology in south-west Queensland and north west NSW, with also a number of registered (but yet uncontracted) projects in western Australia. However, it was deemed the extensive additional analyses required to further sub-divide the rangelands zones would not be matched by an appreciably improved or discriminated set of climate projection data, given the high level of between-model variability in most climate variables, particularly those associated with rainfall which is the predominant driver of vegetation and soil dynamics in arid Australia. The summary data for the two rangeland sub-clusters was therefore retained, but augmented as required with additional relevant information such as finer-scaled vegetation type and soil mapping.

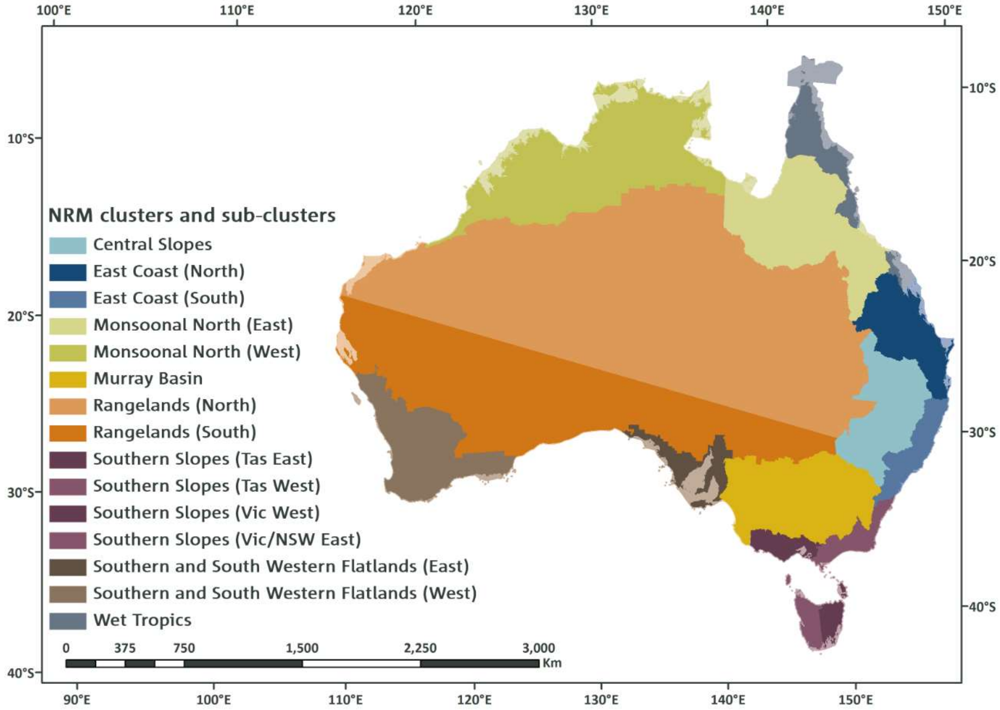

Figure 3. NRM sub-cluster regionalisation for climate projection summaries.

2.3 Review and classification of key climate impact drivers

The list of primary climate variables and their potential impacts on sequestration was based on the generic classification provided by the Australian Greenhouse Office (2006), although modified and extended specifically for land-based sequestration (Table 6). Secondary climate variables (direct or indirect impacts of primary climate variables, e.g. sea-level rise, drought, fire risks) and elevated atmospheric CO_2 concentrations were also considered given their impact on land-based sequestration. The impacts include those that arise directly from changes in individual climate forcing variables (such as temperature directly affecting seedling germination, or soil respiration), in addition to changes in disturbance regimes associated with an overall changing climate (such as fire, drought, and coastal storm surges). A comparison of projected changes in the impact drivers relative to current climate conditions and disturbance regimes provides a basis for both assessing the risks under current conditions, and how those risks might change into the future. The potential importance to both the risk of abatement maintenance, and accumulation, for each of the identified impacts is also indicated in Table 6.

Table 6. Key primary and secondary climate variables, and their potential impacts on risk to abatement and maintenance of carbon stocks that are sequestered by ERF projects.

Change in climate variable	Impacts	Accumulation risk	Maintenance risk
	Primary climate variables		
Higher average temperature, with associated: Increased evapotranspiration Lower runoff Reduced soil water content Reduction in frost risk days	Changes to timing/seasonality of crop/forest growth.	X	
	Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	X	
	Reduction in timing of suitable conditions for tree and crop establishment	X	
	Extended range of pests/diseases	X	X
	Changes to soil respiration and soil microbial processes	X	X
Higher minimum temperatures	Reduction in frost risk days	X	
	Reduced cold temperature hardening leading to greater frost damage	X	
	Increased overwintering of some pests and diseases resulting in faster build-up in the growing season	X	X
	Increased dormancy in seed related to lack of cold stratification, resulting in reduced germination rates	X	
Higher maximum temperatures; increased number of hot days and heat waves.	Heat-induced mortality of crops and trees, particularly during early growth / establishment leading to recruitment failure.	X	X
	Greater plant stress leading to lower growth and greater susceptibility to pests/diseases.	X	X
	Reduced opportunities for undertaking planned burning for wildfire mitigation.	X	X
Decrease in rainfall (annual and/or seasonal)	Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress and greater susceptibility to pests and diseases.	X	
	Reduction in the operational window for tree and crop establishment.	X	
	Decreased landscape moisture content, with implications for fire risk.	X	X
Decreased relative humidity	Potential implications for stomatal function and plant growth	X	

Table 6. Contd.

	Increased fire danger		**X**
Greater intensity of rainfall events	Increased flooding, with implications for young and establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	X	X
	Increased soil erosion and deposition	X	X
Increased intensity of storms/cyclones	Potential for mechanical damage to tree plantings	X	X
	Coastal storm surges with implications for blue carbon stability	X	X
Secondary climate variables (direct or indirect impacts of primary climate variables)			
Changes in mean sea level	When combined with coastal storm surges, implications for blue carbon stability	X	X
Increased drought severity/occurrence	Decreased growth and survival in crops and trees, and possibility of recruitment failure.	X	
Increased frequency of fire weather and days with high fire danger index	Increased emissions from fire and reduction in the average carbon storage within pools of live and dead biomass in response to increased fire frequencies and severities	X	X
Increasing atmospheric CO_2 concentration			
Increasing atmospheric CO_2 concentration	Increased growth of crops and trees in response to increasing photosynthetic rates and water use efficiency		

Although increasing atmospheric CO_2 concentration is the primary driver of human-induced changes to the primary and secondary climate variables, elevated atmospheric CO_2 concentration may also directly impact ERF sequestration projects. Research has indicated there are direct effects of increasing atmospheric CO_2 concentration on tree growth by increasing photosynthetic rates and water use efficiency (e.g. Curtis 1996; Nowak et al. 2004; Norby et al. 2005), and which have been implicated in the observed 'greening' of arid ecosystems across continental Australia (Donohue et al. 2013). Attributing the impacts of elevated atmospheric CO_2 concentration on carbon storage (as opposed to productivity and growth) however remains uncertain, with many limiting factors (e.g. pests, weeds, soil nutrient limitations, water stress etc.) that need to be understood first (Korner et al. 2005; Ainsworth & Long 2005; Tubiello & Ewert 2002; Karonsky 2003; Fuhrer 2003). For example, Jiang et al. (2020) detected no change in ecosystem-level carbon storage after four years of exposure to elevated CO_2 concentration in an Australian Eucalyptus woodland, despite a 12% increase in gross primary productivity over the same period. Despite this uncertainty, the potential effects of increasing CO_2 concentration on carbon storage are also included as part of the broader discussion of climate impacts.

Elevated atmospheric CO_2 concentration is not considered in this study when assessing and ranking the risks of ERF sequestration projects to climate change given the high uncertainty associated with this impact, and how it could potentially interact with other factors such as disturbance regimes. However, other indirect impact of climate change were assumed to be of high importance to consider here. These included the climate change induced changes in the prevalence and distribution of weeds, pests and diseases. Hence, based on these assumptions and the list of climate variables in Table 6, the climate change impacts assessed and ranked in this study were grouped as shown below:

Direct impacts via primary climate change variables

- Heat-stress limiting plant growth and increasing mortality rates
- Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.
- Persistent increase in temperature, exceeding species climate envelope for optimal growth
- Changes in timing/occurrence of suitable conditions for tree and crop establishment
- Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.
- Decreased frost days with implications for increased seed dormancy and reduced germination rates
- Changes to soil respiration and soil microbial processes
- Changes to timing/seasonality of crop growth
- Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases
- Flood-related soil erosion and deposition
- Mechanical damage from wind and storms
- Coastal storm surges with implications for blue carbon stability

Direct impacts via secondary climate change variables

- Sea level change, with implications for blue carbon stability
- Drought-induced plant mortality, with possibility of recruitment failure.
- Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk

Indirect impacts via climate change impacts on weeds, pests and diseases

- Increase in invasive weeds
- Increase in browsing by feral animals
- Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season

The primary source of information for quantifying changes in the climate impact drivers are the outputs from Global Circulation Models (GCMs, Whetton & Holper 2015). The current suite of climate change projections across approximately 40 models has been summarised for each regional sub-cluster (Figure 3) and made available via a web-based data portal[7]. There are, however, a number of caveats regarding the use and interpretation of this information when

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[7] https://www.climatechangeinaustralia.gov.au/

applied at sub-continental scales. First is the low horizontal spatial resolution of GCM model outputs, as described in Section 2.2. A second caveat is the often large variability in the overall predictions between different GCMs, especially for rainfall and rainfall-related phenomenon such as drought occurrence (Kirono et al. 2011), where model projections can differ both in magnitude and direction. Because rainfall is a key driver of carbon sequestration projects that involve managing vegetation or soils, this means discussion of the risk factors associated with many ERF activities have a high embedded level of uncertainty, reflected in the assigned confidence ratings (Table 5). Finally, climate projection results are typically summarised over 20-year timeframes to remove the vagaries of [modelled] annual variability.

To satisfy the requirements for this study, results for the periods 2040-2059 and 2080-2099, centred on 2050 and 2090 respectively, were extracted from the *Climate Change in Australia synthesis* database, with the 2050 projections being consistent with the 25-year crediting period of the majority of the ERF methods in Table 1. Downloaded data included projections for the two Representative Concentration Pathways (RCPs) of interest, RCP4.5 and RCP8.5 (Section 1).

Using the primary and secondary climate change variables listed in Table 6, 21 climate data products were obtained to provide a basis for obtaining the likelihood component of the risk assessment (Table 7). A graphical summary of each of the 21 variables, for each NRM sub-cluster, is provided in Appendix B. The 21 variables span changes in average climate conditions across a range of climate variables, changes in extreme values, and changes in the two main climate-related disturbances; drought and fire.

The overall approach for the risk assessment was to combine two broad sources of information:

(i) the numerical results across the 21 factors in Table 7, together with the information embedded within the consensus summaries provided for each sub-cluster in Appendix C, and associated published literature, to provide insight to the magnitude and direction of expected changes in the climate factors for each zone, to inform the likelihood status (and confidence in) of each projection; and

(ii) Information from the published literature to inform the consequences of these factors and their possible future changes on the range of activities embedded within the current suite of land-based ERF sequestration activities, with a particular focus on risks to sequestration in new projects, and risks to the maintenance of carbon in existing projects.

The final assessment of risk for each activity/methodology across the NRM sub-cluster zones is therefore based on a ‘multiple lines of evidence’ approach, with the intention of categorising overall risks as low, medium, high, or extreme (Table 4), together with a statement of uncertainty for each classification.

Table 7. Climate Indicators for which quantitative changes (for years 2050 and 2090 relative to the baseline years 1986-2005) were available for each NRM sub cluster zone**.**

Climate change factor	Units	Notes
Primary climate variables		
Mean temperature change	Degrees	Obtained from climate summary data explorer. Annual and seasonal summaries from up to 40 GCM projections (median, and 10th and 90th percentiles).
Maximum temperature change	Degrees	
Minimum temperature change	Degrees	
Precipitation change	%	
Shortwave radiation change	%	
Potential-evapotranspiration change	%	
Windspeed change	%	
Relative humidity change	%	
Coldest night change	Degrees	Obtained from climate extremes data explorer. Annual and seasonal summaries from up to 40 GCM projections (median, and 10th and 90th percentiles.
Hottest day change	Degrees	
Wettest day change	%	
Wettest 1-in-20 year change	%	
Change in number of days/year below 0 degrees	Days	Obtained from the climate thresholds calculator, based on down-scaled projections applied to 384 Weather stations across the continent.
Change in number of days/year above 35 degrees	Days	
Change in days/year > 99.9th percentile rainfall	Days	
Change in number months/year < 10th percentile rainfall	Days	
Secondary climate variables (direct or indirect impacts of primary climate variables)		
Changes in mean sea level		
Change in time in drought	%	Extracted from cluster reports. https://www.Climatechangeinaustralia.gov.au/en/publications-library/cluster-reports/
Change in extreme drought frequency	Days/20 years	
Change in extreme drought duration	Months	
Change in annual average cumulative forest fire danger index	-	Based on 39 weather station locations and three GCMs that had the appropriate climate outputs to inform the FFDI
Change in number days/year with FFDI > High	Days	
Changes in atmospheric CO_2 concentration		

Combined and interactive effects of disturbance

Many environmental disturbances can co-occur, with the potential for their effects to be interactive. Documented examples include the relationships between prior drought conditions and wildfire risk (Hennessy et al. 2005); between drought and heat stress (Sippel et al. 2018; Fahad et al. 2019); and between drought and insect defoliation (Mitchell et al. 2013).

For the risk assessment in Section 3 the potential for such interactions is noted, but no attempt was made to quantify the nature of those interactions, or how they manifest as an aggregate (i.e. multi-disturbance) risk factor. In some cases, such as the relationship between fire and prior drought, the interaction is already embedded within the risk rating (e.g. through the representation of drought impacts on fuel dryness). However for many cases, such as interactions with pest and disease dynamics, the evidence is fragmentary, with further work required to tease apart the contributing mechanisms.

3 Implications for the current Emissions Reduction Fund project portfolio

3.1 Overview of the current ERF portfolio

Storing carbon in the landscape and changing the emissions profile from rural land use has the potential to offset a significant proportion of Australia's total GHG emissions (Eady et al. 2009). Indeed, 70% of the abatement that has been delivered thus far under the ERF has been generated by activity within the land sector, and if all of the contracted abatement is delivered, the land sector contribution would rise to 82% (Table 8). The land sector contribution is dominated by Human Induced Regrowth/Native Forest from Managed Regrowth (49.5% of total contracted abatement), Avoided Clearing/Avoided Deforestation (13.8%), management of Savanna Burning (7.0%), Soil Carbon management (7.2%), and Reforestation (2.0%). Across all sectors 192.8 Mt of CO_2-e has been contracted under the fund, with 54.4 Mt (or 28.2%) already delivered.

The permanence period for ERF sequestration projects is either 25 or 100 years, and this is the time period over which the project proponents must maintain carbon stores for which ACCUs have been issued. However, the contract period for ERF projects is the time period over which the project is contracted to deliver ACCUs. This period differs between methodologies, ranging from 1 year to 10 years, with an average period of 7.9 years. Dividing contracted project abatement by the delivery period yields a total annualised abatement rate of 21.7 Mt CO_2-e yr^{-1}, or approximately 4% of current total annual emissions. Performing the same calculation on the abatement that has already been delivered yields 14.7 Mt CO_2-e yr^{-1} (Table 8). For the land sector sub-set of projects, the corresponding annualised amounts are 16.3 Mt CO2-e yr^{-1} contracted, and 10.9 Mt CO_2-e yr^{-1} for the abatement that has already been delivered. Note that actual annual delivery will differ from these average values, due to differing rates at which abatement is generated within projects.

The gap between the average rates of annual abatement required under contract, and the achieved rates over the first few years of project delivery, means that rates of abatement must increase significantly over the remaining lives of the contracts for the total contracted abatement to be achieved, or be sourced from other projects. In some cases, such as methods based on tree growth projections from FullCAM, this is expected, as sequestration in vegetation starts off slow and then accelerates to a maximum after about 5-10 years.

The annualised abatement rates for the land sector in Table 8 are consistent with earlier projections for the year 2020 (Battaglia 2012), estimated to be in the range 4 – 34 Mt CO_2-e yr^{-1}, but are significantly lower than what has been suggested as being possible over the longer term. For example, across all land sector activities and for just the state of Queensland, Eady et al. (2009) suggested 140 Mt CO_2-e yr^{-1} might be achievable by 2050, with somewhat lower estimates of 53 – 141 CO_2-e yr^{-1} (also by 2050, but at the national scale) suggested by Battaglia (2012).

Table 8. Summary of contracted ERF projects as at 17 May 2020[1]. Green text indicates land-based ERF methodologies considered in this project. Revoked projects have been excluded from this table**.**

Activity category	Activity	Number of registered projects	Number of contracted projects	Contracted abatement (t CO_2-e)	Annualised contracted abatement[2] (t CO_2-e yr^{-1})	Delivered abatement – contracted (t CO_2-e)	Annualised Delivered abatement – contracted[3] (t CO_2-e yr^{-1})	% Delivered	Contracted abatement as % of total
Re-establishment of native forest	Human-Induced Regeneration	267	188	95,355,316	9,761,211	16,450,466	5,877,640	17.3%	49.5%
	Native Forest from Managed Regrowth	36	16	3,472,700	355,190	2,411,733	750,131	69.4%	1.8%
Planting of new forests	Reforestation by Environmental or Mallee Plantings	44	5	1,839,216	195,771	616,808	130,888	33.5%	1.0%
	Reforestation and Afforestation	19	7	930,549	93,577	419,237	128,524	45.1%	0.5%
	Plantation Forestry	22	9	980,901	98,090	15,156	14,336	1.5%	0.5%
	Measurement Based Methods for New Farm Forestry Plantations	2	0	-	-	-	-	-	0.0%
Protection of existing forests	Avoided Deforestation	60	56	26,181,536	2,683,218	13,699,949	2,906,913	52.3%	13.6%
	Avoided Clearing of Native Regrowth	3	2	354,258	35,426	251,500	62,363	71.0%	0.2%
Soil carbon	Measurement of soil C sequestration in agricultural systems	50	11	13,825,000	1,387,500	295,800	58,369	2.1%	7.2%
Savanna burning	Savanna Fire Management	75	43	13,580,089	1,480,100	3,260,998	825,133	24.0%	7.0%
	Other – Land-Based[4]	22	11	1,864,661	239,009	891,436	200,456	47.8%	1.0%
	Landfill Gas	110	93	21,534,796	3,289,788	12,735,297	2,851,432	59.1%	11.2%
	Commercial & Public Lighting	10	3	2,694,927	384,990	314,962	78,380	11.7%	1.4%
	Other	85	26	10,168,481	1,670,348	3,003,565	841,270	29.5%	5.3%
	Total – Land-Based	600	348	158,384,225	16,329,092	38,313,083	10,954,753	24.2%	82.2%
	Total – All	805	470	192,782,429	21,674,217	54,366,907	14,725,835	28.2%	-

[1] Source: Carbon abatement contract register & Emissions Reduction Fund project register, updated 17 May 2020. http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers. Modified from Roxburgh et al. (2020). [2] Calculated over the delivery period as specified in each contract. [3] Calculated over the time since contract commencement data. [4] Includes the emissions reduction activities beef cattle herd management, and methane destruction (animal effluent). Note that contracted and delivered abatement are based on the method of the contracted project. For the vast majority of contracts, ACCUs delivered may be generated by a project other than the contracted project.

The current spatial spread of ERF projects provides information on the range of environments and jurisdictions within which current activity is occurring, and also some indication of the spatial footprint of individual projects (Figure 4). Although many projects are not discernible when displayed at a continental scale, Figure 4 clearly illustrates the dominance of Savanna Burning projects in northern Australia (24.8 million hectares, Mha), the dominance of HIR projects in central western New South Wales and Queensland and Western Australia (17.5 Mha), and the presence of Avoided Clearing/Avoided Deforestation projects in New South Wales and Queensland (0.97 Mha). Note that Figure 4 also identifies the 10.5 Mha of projects that were registered, but have since been revoked.

Although the project boundaries in Figure 4 provide a general indication of the locations and extents of abatement activity, the Carbon Estimation Areas (CEAs) within those project boundaries on which abatement activity is being conducted (and therefore on which permanence obligations apply) may be much less; for example HIR where the project boundaries are often the property boundaries, and where the CEAs may only be a small fraction on the total mapped area.

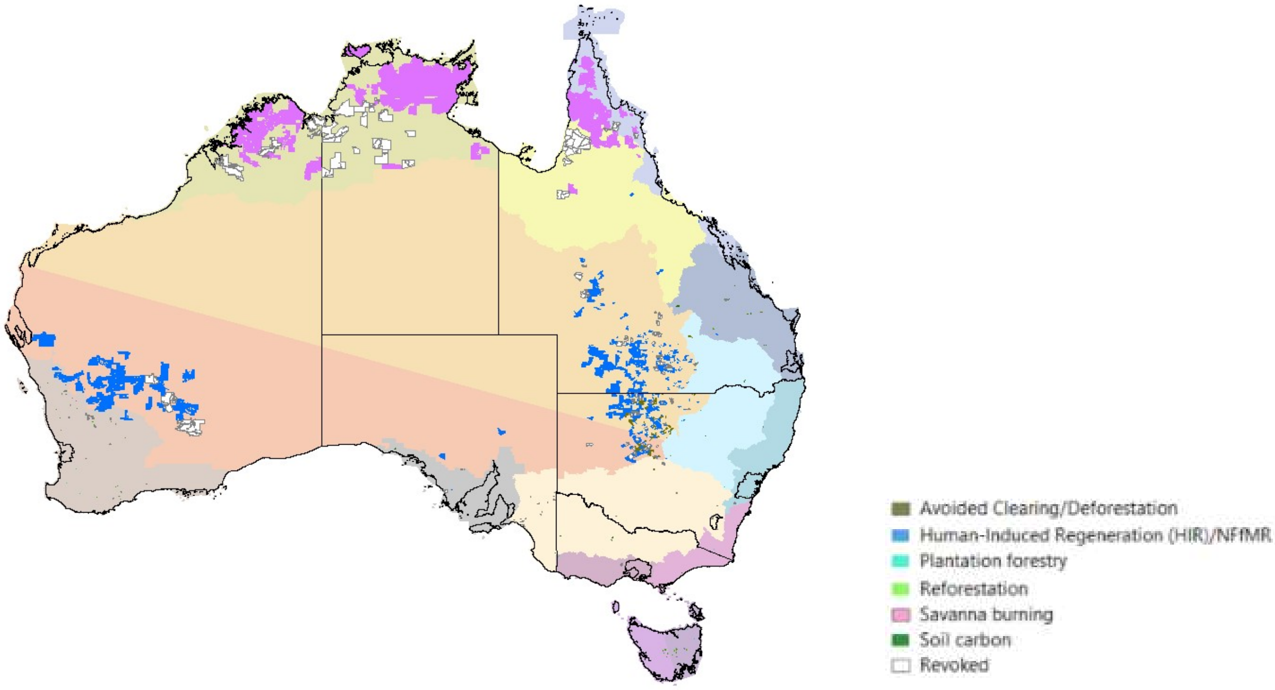

Figure 4. Spatial distribution of current ERF project activity relative to the NRM climate projection regionalisation.

Table 9. Total area occupied by ERF projects.

Active projects	Total area (ha)	Mean area per-project (ha)
Savanna burning	24,765,597	400,712
HIR/NFfMR	17,533,523	58,445
Avoided Clearing/Deforestation	967,943	15,612
Reforestation	144,917	2,734
Soil carbon	79,170	1,799
Plantation forestry	7,347	490
Total	48,385,585	88,295

Revoked projects	Total area (ha)	Mean area per-project (ha)
Savanna burning	7,848,051	560,575
Reforestation	1,694,795	29,221
HIR/NFfMR	819,111	24,822
Soil carbon	81,288	27,096
Avoided Clearing/Deforestation	5,420	5,420
Total	10,448,666	

3.2 Identification of key land sector activities and their risk profiles

The six classes of ERF activity in Table 1, encompassing the 11 existing methodologies and the proposed new Blue Carbon methodology, are grouped together on the basis of assumed similarity of their risk profiles. For each ERF activity class the most important climate impacts from Table 6 were identified from a combination of literature review and expert opinion. The impacts have been separated on the basis of (i) risks posed by climate change factors directly, such as long-term trends of increasing average surface temperature, humidity, evapotranspiration and their associated impacts on vegetation establishment success, plant growth rates, and soil microbial activity; and (ii) risks posed indirectly by changes to disturbance regimes (i.e. frequency, intensity, duration, extent and timing of disturbance events; Shea et al. 2004) such as drought, fire, flooding and storms. It is also important to recognise the key role played by extreme climatic events, such as heatwaves, on triggering mortality events or other threshold-related phenomena that can affect ecosystem carbon storage.

Only the risk factors that were considered most important for each ERF activity were considered in the analysis (Table 10). A number of the potential impacts in Table 10 are common across the majority of the ERF activities, and includes combinations of climate factors such as increasing temperature, increasing evapotranspiration and declining average rainfall that lead to reduced soil water availability and associated predicted declines in tree and crop growth; the potential for heat-induced mortality, particularly for young or regenerating plants; overall greater plant stress leading to greater susceptibility to pests, diseases and other disturbances; and overall intensification of drought, fire and storm-related disturbance (such as flooding and erosion).

Table 10. Mapping of climate impact factors to ERF activities.

Direct impacts via primary climate change variables	Re-establish native forest cover	Planting of new forests	Protect existing forests	Manage agricultural soils	Savanna fire management	Management of intertidal ecosystems
Heat-stress limiting plant growth and increasing mortality rates	■	■	■	■	■	■
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	■	■	■	■	■	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	■	■	■	■	■	■
Changes in timing/occurrence of suitable conditions for tree and crop establishment	■	■		■		
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	■	■		■		
Decreased frost days with implications for increased seed dormancy and reduced germination rates	■	■		■		
Changes to soil respiration and soil microbial processes				■		■
Changes to timing/seasonality of crop growth				■		
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	■	■	■	■		■
Flood-related soil erosion and deposition	■			■		■
Mechanical damage from wind and storms	■	■	■		■	■
Coastal storm surges with implications for blue carbon stability						■
Direct impacts via secondary climate change variables						
Sea level change, with implications for blue carbon stability						■
Drought-induced plant mortality, with possibility of recruitment failure	■	■	■	■	■	■
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	■	■	■	■	■	
Indirect impacts via climate change impacts on weeds, pests and diseases						
Increase in invasive weeds		■			■	
Increase in browsing by feral animals		■				
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	■	■	■	■	■	■

3.3 Methodology-specific analyses

3.3.1 Re-establishment of native forests

Embedded Methodologies

HUMAN-INDUCED REGENERATION OF A PERMANENT EVEN-AGED NATIVE FOREST (2013) (HIR)
NATIVE FORESTS FROM MANAGED REGROWTH (2013) (NFMR)

The HIR (Human-Induced Regeneration) methodology currently has the highest uptake of the ERF methodologies, comprising 49.5% of all contracted abatement under the scheme, and 60% of all contracted land-based abatement. Under the HIR methodology, Australian Carbon Credit Units (ACCUs) are awarded on the basis of a change in management that allows a forest to re-grow, with subsequent accounting of the accumulation of carbon in the recovering vegetation and forest debris over time.

The eligibility requirements to register an HIR project are that, in the 10 years prior to the project, the land was non-forest, with active management preventing forest cover being attained (such as grazing and/or clearing). The land must also be non-forested at the commencement of the project and must have the potential to attain forest cover through natural regeneration. Whilst purchasing land specifically to undertake an HIR project is likely uneconomic, for existing landholders, the HIR methodology can be cost-effective, particularly in more arid areas where the opportunity costs are low. This likely explains, at least in part, the widespread uptake of the activity to date in low rainfall, semi-arid regions of Australia (averaging <500 mm per year). Unlike many carbon projects, HIR requires minimal upfront costs, greatly reducing the financial risk to proponents. The main management actions include the removal of clearing pressures, management of grazing from livestock, feral animal control, and weed management.

Thus far, the majority of contracted projects have been developed in inland regions of northern NSW (particularly around Cobar) and southern Queensland. This likely reflects relatively low returns from grazing in these regions, and perhaps the diffusion of the method through landholder social networks. There are currently several registered projects in WA, where adoption has so far been slower due to uncertainties as to the compatibility of carbon activities with pastoral lease conditions, which have now been resolved.

The Native Forest from Managed Regrowth (2013) methodology allows native vegetation to grow and become forest by stopping activities involving the chemical or mechanical destruction or suppression of native vegetation, with the cessation of these activities (and the optional introduction of new management practices to support regeneration) allowing native trees to regenerate and become forest. The project area must be currently non-forested, have been cleared at least once for pastoral use, and there must have been forest cover on that land before it was cleared. The main differences between the Native Forest from Managed Regrowth and Human Induced Regrowth methodologies lie in the requirement to demonstrate that the land has previously been cleared of forest cover, and the potential to include some existing woody biomass as part of a baseline calculation, although zero baseline projects are also permitted. With respect to risks to sequestration, the two methodologies are based on the same mechanism (facilitation of the re-growth of native forest from an initially non-forest state).

For both methodologies, the included pools for accounting are above- and belowground living and dead biomass. Soil organic carbon is excluded from the accounting, but is briefly considered as part of the risk assessment below.

Spatial domain

Activity under both methodologies is located within the semi-arid rangeland zone (Figure 5). Contracted projects for both methodologies are concentrated towards the eastern edge of the Rangelands-North NRM sub-cluster, with a number of registered (but not contracted) projects for HIR located at the western extremity of the Rangelands-North sub-cluster.

Acacia communities are the dominant woody vegetation of arid and semi-arid Australia, and are also the predominant vegetation type managed under the HIR and NFMR methodologies. The environment is characterised by infrequent seasonal rainfall punctuated by occasional large rainfall events that stimulate reproduction, productivity, and the associated rapid growth of an ephemeral herbaceous ground cover. Following a return to dry conditions this ground cover ‘cures’, facilitating the spread of large landscape fires, particularly in grassland-dominated ecosystems (Nano et al. 2017). Soils are infertile with low levels of phosphorus and nitrogen, and it has been suggested the ability of acacia species to fix atmospheric nitrogen is at least partly the reason for their success in this harsh environment (Beadle 1981), along with a suite of traits that allow them to persist and reproduce under the ‘boom and bust’ nature of the rainfall patterns (Nano and Pavey 2011; Foulkes et al. 2014). For example, many of the current HIR projects were established following the extensive La Niña rains in 2010 and 2011, that eventually broke the millennium drought.

Rainfall is therefore the major determinant of forest potential, and because of its unpredictability is central to many of the climate impact factors associated with risk to abatement accumulation. Following a review of these two methodologies (ERAC 2019) the management of this inherent risk has been recently extended beyond the scheme-wide 5% risk of reversal buffer, to include additional project-level reporting requirements to ensure land is both capable of supporting forest cover, and that regeneration towards forest cover indeed is occurring over time, with a need to demonstrate at least 90% forest cover over the carbon estimation area for a certificate of entitlement to be issued (CER 2019).

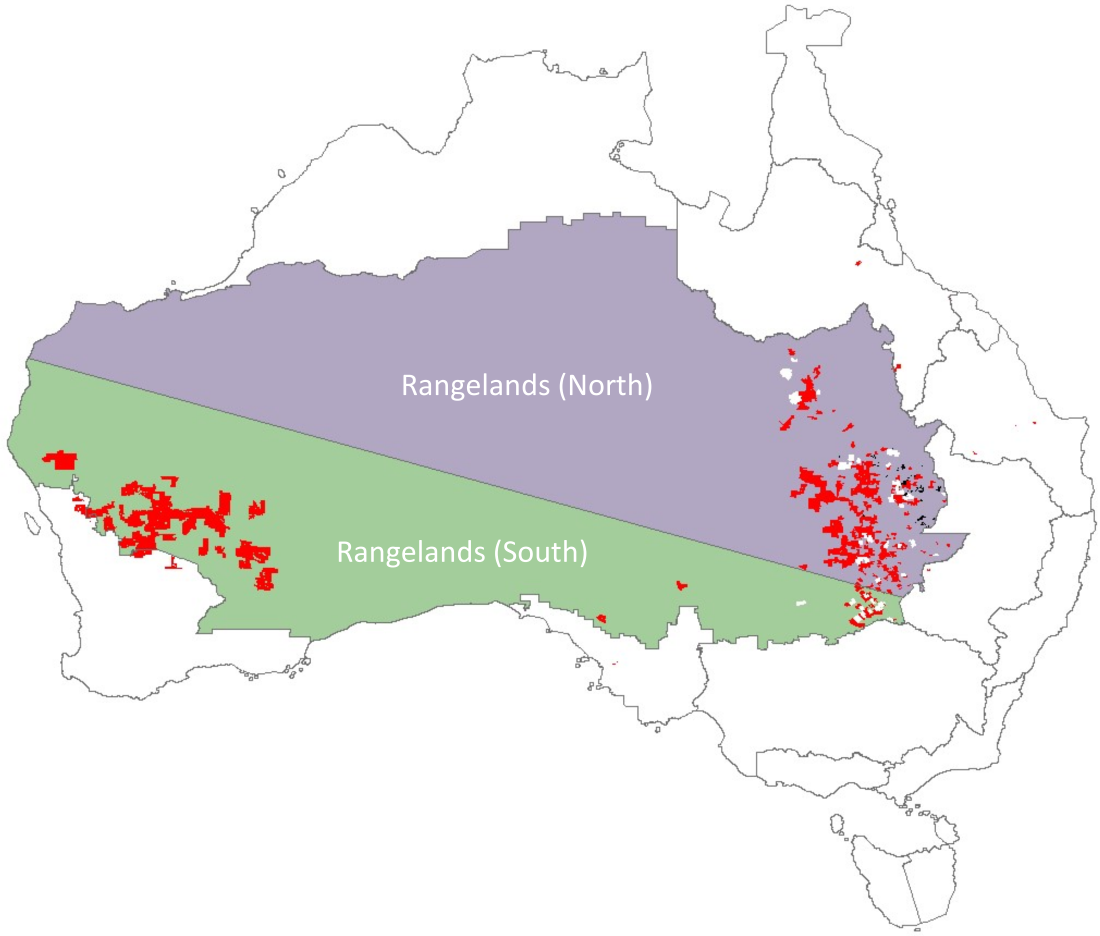

Figure 5. Locations of registered Human-Induced Regeneration projects (red) and Native Forest from Managed Regrowth projects (black). As of the time of data compilation (7 August 2020) no projects had been contracted under the ERF in Western Australia. Revoked projects shown in white.

Risk assessment against identified climate impact factors

Factors affecting initial tree establishment and growth

Factors affecting longer-term vegetation growth rates

Future climatic conditions up to 2050 suggest a number of climate change risk factors have the potential to combine to place constraints on the ability of the forests to regenerate, and to limit subsequent forest growth; both of which could contribute to reduced abatement accumulation. Risks to maintenance from the factors identified here are considered negligible.

Increasing average annual temperatures are predicted to increase by 1.0(1.5)1.8[8] degrees Celsius for the Rangelands South sub-cluster, and 1.0(1.5)2.1 degrees Celsius for the Rangelands North sub-cluster, both with *very high confidence*[9]. Annual potential evapotranspiration is predicted to increase by 1.5(3.8)5.6 mm year^{-1} and 1.7(4.5)6.6 mm year^{-1} for the rangelands South and North sub-clusters respectively (*high confidence* in the direction of the trend for both sub-clusters, but *medium confidence* in the magnitude). Projected changes in relative humidity by 2050 are small

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[8] The convention adopted for reporting projections is 10(50)90, where '10' is the 10th percentile projection across the range of GCMs considered in the analysis, '(50)' is the median projection, and '90' is the 90th percentile projection.

[9] The confidence ratings of the projections are shown in italics; see Table 5.

(median change approximately -1% for both sub-clusters, with *medium confidence*). In the Rangelands South sub-cluster, changes in annual rainfall suggest a decline in the winter (-24.8(-9.2)6.1 % with *high confidence*), however in the Rangelands North sub-cluster the direction of change cannot be confidently projected, with a wide spread of model results. Time spent in drought is also expected to increase over the coming century, although by mid-century the consensus amongst model projections is less strong (-8.4(3.9)17.8 % change, against a current baseline of 36.25% time in drought). Taken together, these trends are consistent with an overall prediction of decreasing soil moisture over the century, particularly in winter (*medium confidence*), and increasing plant stress, which would be expected to reduce plant productivity. Extreme temperatures are also expected to increase significantly, with substantial increases in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence)*. For example, the change in the number of days year^{-1} expected to be greater than 35°C for the Rangelands South sub-cluster is 7.3(16.2)28.5 (compared to the current average of 55.2 days year^{-1}), and a change of 16.0(29.8)46.9 days year^{-1} for the Rangelands South sub-cluster (with a current average of 120.2 days year^{-1}). These represent median increases of 30% and 24% for the South and North sub-clusters, respectively.

One particular aspect of a changing climate that has received relatively little attention and which has the potential to impact tree establishment and early growth is the predicted decline in the number of frost risk days (*high confidence*). This could operate via two mechanisms. One is the requirement for seeds to undergo cold treatment to ensure adequate germination, therefore a decline in opportunities of exposure could limit seed regeneration. The second is the reduced exposure to cold temperature required for 'frost-hardening', such that when frost does occur plants may be less acclimated and more vulnerable to damage through photo-inhibition and other physiological mechanisms. Frost-related mortality affects both the living biomass, and also the subsequent turnover of plant material to litter and the soil. In the Rangelands South sub-cluster the expected reduction in days below 0.0 °C is -10.3(-0.2)0.0 days year^{-1} (relative to a current baseline of 5.3 days year^{-1}), and in the Rangelands North sub-cluster -4.0(-0.1)0.0 days year^{-1} (relative to a current baseline of 1.8 days year^{-1}).

Taken together, these projections suggest the likelihood of experiencing by 2050 a reduction in the timing of suitable conditions for tree regeneration, reduced soil water, and the potential for heat-stress induced limitations to plant productivity are all likely, with an overall confidence of *high*. Similarly, the reduction in frost days is also likely, with *high confidence*.

There is also evidence that in rangeland regions, newly germinated and young tree seedlings are susceptible to excessive solar radiation and extreme temperatures, with the potential for high mortality rates during heatwaves (e.g. Ferrar et al. 1989; Good et al. 2014).

Regarding the potential for the decline in frost days to impact upon the delivery of abatement, there is very little in the way of supporting science from these ecosystems to reliably assess what the consequences might be, and at this stage a formal risk rating is not possible (Table 11).

Although there is some evidence that increased woodiness (increase in stem number, stem size or crown cover) is a global phenomenon (e.g. Zhou et al. 2001, 2003; Fensham et al., 2005; Julien et al. 2006; Lucas et al., 2008; Ballantyne et al., 2012; Canadell et al., 2007; Fensholt et al., 2012; Nemani et al., 2003; Stevens et al. 2017), in Australia the increases in woodiness appear to be most pronounced in the rangeland regions of Australia (e.g. Donohue et al. 2013). This increased woodiness appears to be at least partly attributable to increases in atmospheric CO_2 concentrations since the industrial revolution, leading to a 'CO_2 fertilization effect' that enhances rates of photosynthesis. Elevated CO_2 also enhances leaf-leaf level water-use efficiency (WUE) via reduced stomatal conductance per unit leaf assimilation (Polley et al. 1997; Medlyn et al. 2001), improving seedling survival and plant growth rates. Faster biomass accumulation can however result in greater whole plant water use under elevated CO_2. Based on this many workers have argued that the impacts of CO_2 fertilisation and improved WUE have contributed to increased woodiness (e.g. Eamus & Jarvis 1989; Farquhar 1997; Medlyn et al. 1999; Bond & Midgley 2000; Berry & Roderick 2002; Higgins & Scheiter 2014; Eamus & Palmer 2008; Donohue et al. 2013; Zhu et al. 2016), although it is recognised changed disturbance regimes (particularly fire), land-use change, and changes (and interactions with) other resources required for growth such as light, water and nutrients all likely play a role as well.

With persistent declines in rainfall, increases in temperature, and increased woodiness, it is predicted that grass production and biomass in rangelands may decline (e.g. Webb et al. 2012), which in turn may make grazing livestock in much of the Australian rangelands less economically viable. High grazing intensities have also decreased the woody:grass ratio due to the supressed emergence and growth of trees due to livestock browsing and trampling of saplings (Brand 2000; Eldridge et al. 2011), and from competition from an increase in abundance of weeds and under-storey species that are unpalatable to livestock (Diaz et al. 2007; Close et al. 2008; Duncan et al. 2008). If livestock numbers decline in the rangelands, this may facilitate the recovery of the woody:grass ratio. For example, Witt et al. (2011) found that the removal of grazing pressure in semi-arid woodlands over periods of 14-44 years resulted in a significant increase in regenerating trees. Similar results were found by Daryanto et al. (2013) in mulga woodland.

Regarding the consequences to plant growth and establishment, the relatively harsh climatic conditions of arid Australia have produced a range of species adaptations to cope with long periods of dry conditions and low growth, and traits to take advantage of the advantageous growth conditions when they occur. The nature of the vegetation would thus help to mitigate against the projected changes above, and that catastrophic (<20% of expected abatement achieved) or even major (20-50% of expected abatement achieved) consequences are unlikely. Indeed, Nolan et al. (2019) note that whilst the risks of recruitment failure in these ecosystems are, in general, high (estimated to be >80%), the rules of the HIR and NFMR methodologies that require 'forest potential' to be already established on a site when a project is registered (such as evidence of existing successful regeneration) significantly mitigates this risk. Although there is little in the way of quantitative data to draw upon, here we assess the residual risks to reduced growth and establishment success to be both Moderate, which when combined with the likelihood assessment above ('Likely') gives an overall risk rating of Medium (Table 11).

Because the risk factors discussed here simultaneously affect large areas of the continent, this risk rating applies to the portfolio of projects as a whole, as well as individual projects.

Pests and diseases

Insects and fungi are strongly influenced by climatic conditions, particularly temperature, relative humidity and rainfall. For many forest pests and diseases in Australia, a southward shift in distribution is projected in response to increasing temperatures and/or declining rainfall. The potential for new pest species to emerge in response to these shifts in distribution has been acknowledged.

There is little research on the pests and diseases of forest species within the HIR and NFMR activity areas, or on the implications of climate change for any pests and diseases. Mitchell (1989) highlighted the susceptibility of *Acacia aneura* to termite damage and defoliation from insects, but provided no details of relevant pest species. A study by Buczkowski and Bertelsmeier (2017) examined the effects of climate change on the distribution of termites, highlighting the species-specific nature of projected climate responses and the lack of physiological data for identifying species-specific environmental limiting factors. An example using one species, *Mastotermes darwiniensis*, suggested range contractions in NW Australia, and either no change or an expansion on the east coast, but no change in the area covered by the HIR and NFMR activity areas. Desiccation has been found to be an important determinant of termite abundance, suggesting that the drying trend projected for the activity area over the coming decades may reduce abundance into the future.

Rabbits, hares, deer, goats, kangaroos and wallabies are common browsers of young trees (Reid 2020). Rabbits are predicted to retreat southwards (perhaps away from many current project areas in the lower rainfall zones of the rangelands) and whole ecosystems in the higher rainfall zones of the rangelands will be affected because browsing rabbits prevent mulga and other dominant rangeland plants from regenerating (Lange and Graham 1983; Cooke and Hunt 1987).

Fire

Arid ecosystem vegetation dynamics within the HIR and NFMR activity areas are broadly correlated with a gradient from the west of the continent to the east, with greater aridity in the west and a more consistent ground cover due to the common association of overstorey trees with Spinifex hummock grasses, resulting in relatively higher ground fuel loads and fire activity, through central Australia where ground cover comprising tussock grasses become increasingly prevalent, and to eastern Australia with less predictability in herbaceous ground cover, and a corresponding reduction in the importance of fire. This trend can be seen in the historical record of fire occurrence over a 25 year period (1988-2013)(Figure 6a), where fire activity within the Western Australia group of registered projects is slightly more prevalent than within the current distribution of HIR projects in eastern Australia. In both regions, however, fire activity is relatively low, both in terms of spatial extent and frequency. Most available information on fire dynamics is from the mulga woodlands, which also comprises a large proportion of current HIR and NFMR projects.

Towards the eastern extent of the mulga distribution the evidence for fire as a primary driver of community dynamics is less compelling, due to a greater limitation of fuel loads, and a reliance on relatively rare sequences of rainfall events that provide the necessary growth condition to facilitate herbaceous growth and thus fire spread (Silcock et al. 2016). When fire does occur, the post-fire regeneration strategy and seed dynamics of mulga suggest a trajectory towards recovery of the vegetation.

In response to fire, mulga is capable of re-sprouting vegetatively from epicormic buds following low severity fire, but is readily killed by high severity fire (Wright and Fensham 2017). However, during normal growth conditions mulga communities are typically fire-resistant due to their low productivity and lack of ground vegetation cover (required to provide fuel connectivity).

Widespread fire therefore occurs only after significant rainfall; but because mast seeding in mulga is triggered by rainfall, this provides the capacity and the mechanism for subsequent community recovery (Wright and Zuur 2014; Wright and Fensham 2017). Mulga does not require fire to set seed and reproduce, though germination is enhanced by elevated soil temperatures associated with burning (Wright et al. 2016), and because the soil seedbank does not appear to have significant longevity, regeneration is likely tied to episodic rainfall events (Fensham et al. 2012). Whilst reductions in fire activity would seem to have limited impact on mulga, an increase in fire occurrence beyond the capacity of the mulga to self-reproduce has been suggested as a potential trigger leading to the local loss of the mulga overstorey (Nano and Clarke 2008; Nicholas et al. 2009; Ward et al. 2014). Though actual evidence for the contraction of mulga in response to this mechanism remains equivocal (Nano et al. 2017). Species able to vegetatively re-sprout from fire are generally considered to be at lower risk than vegetation that requires seedling germination for recruitment, given the potential for regenerating shoots to be somewhat buffered by their ability to relatively quickly re-sprout from the parent plant, and to be able to draw upon stored resources such as lignotubers (Nolan et al. 2019).

Within the Rangelands North sub-cluster the number of days year^{-1} with a Forest Fire Danger Index (FFDI) greater than 'High' is expected by 2050 to change by -2.3(9.5)32.6 days year^{-1}, corresponding to a median increase of 4% above the current baseline of 261 days year^{-1}. For the Rangelands South sub-cluster, the change is expected to be 3.6(18.5)37.0 days year^{-1}, corresponding to a median increase of 11% above the current baseline of 166 days year^{-1}. Corresponding changes for the annual cumulative FFDI are a 6% median increase for the Rangelands North sub-cluster, and 11% increase for the Rangelands South sub-cluster. Given fire activity is driven by preceding rainfall in the arid zone, and rainfall projections are highly uncertain, there is therefore overall *low confidence* in the projections for changes in fire risk.

Based on this analysis the current risks to sequestration from fire are deemed to be relatively low, given the low historical occurrence of fire in the affected vegetation types, even during high fire years (Figure 6c), and the regenerative traits of the vegetation that allow them to recover post-fire. By 2050 a modest change in the fire risk is expected across the region as a whole, but because of the high uncertainty the likelihood is considered to be 'about as likely as not'; and given the impacted vegetation types are largely fire resistant, then the consequences are considered 'minor' for both abatement accumulation and maintenance. The resulting risk rating for fire to significantly impact either abatement accumulation or maintenance is therefore low at the whole portfolio level, and whilst also low at the individual project level, there always remains a chance of some unplanned wildfire, and proponents should be prepared to manage for this this. For the HIR and NFMR activities the locations in western Australia are likely to be more impacted than eastern Australia, given the general differences in understory fuels and slightly greater prevalence of historical fire. If HIR or NFMR activities were to spread into more productive areas in the future, such as further east into Queensland, then it is likely the fire risk would also be relatively higher, again driven by higher grassy understory fuel loads, as evidenced by greater historical fire activity (Figure 6a).

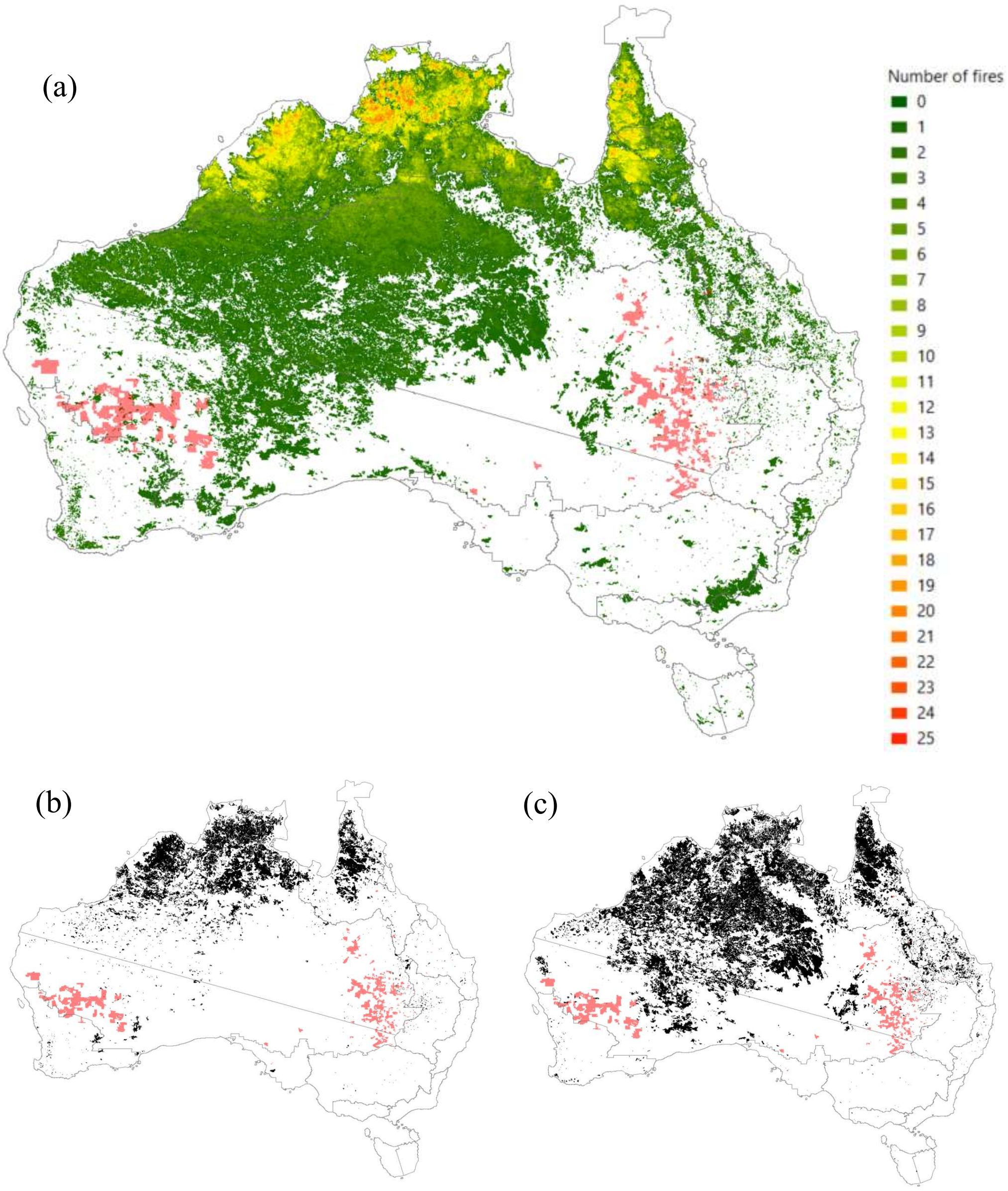

Figure 6. (a) Number of fires over the period 1988 to 2013. Red areas show the locations of HIR and NFMR project activity. (b) Combined fire burn areas for low-fire years 2004 and 2005. (c) Combined fire burn areas for high-fire years 2011 and 2012.

Drought

Many researchers studying semi-arid regions of Australia have suggested that there are boom-bust cycles of woodiness associated with multiple decades of episodic climate cycles (Fensham 2008; Silcock et al. 2013; Witt 2013; Silcock et al. 2016). Such cycles drive variability in the vegetation carbon sink within the vast amount of inland and northern Australia, which in turn, contributes significantly to the global vegetation sink (Houghton et al. 2012; Poulter et al. 2014; Ballantyne et al. 2015; Haverd et al. 2017).

Drought can be defined in many different ways. Here, three drought-specific statistics were available for analysis, all based on the Standardised Precipitation Index (SPI) which is calculated from temporal trends in rainfall, with three drought severity levels defined: moderate, severe and extreme (Whetton et al. 2015). The first statistic, time in drought (%), provides a broad indication of overall expected changes in the proportion of time spent in moderate drought conditions or above. This aspect of drought risk was considered above in the discussion of risks to recruitment and tree growth, in that case with a particular focus on risks to abatement accumulation.

The other two statistics quantify the occurrence of extreme drought conditions, and have implications for tree mortality and thus risks to abatement maintenance. Mortality from extreme drought in arid environments appears common. Fensham et al. (2019) provided evidence for 18% - 30% mortality from historical droughts in the 20th century in northern Australia, which is consistent with Silcock et al. (2016) who noted up to 20% mortality in eastern Australia mulga communities following the millennium drought at the start of this century. Mitchell et al. (2014) in their review of drought-related dieback events documented two historical mortality events within the HIR activity zone of eastern Australia (Wilcannia and Cobar), and in their analysis noted the importance of both extreme drought conditions and extreme temperatures as a mortality trigger. In an analysis of results from the CSIRO Mk 3.5 GCM applied to the locations of previous dieback events, Mitchell et al. (2014) also concluded droughts capable of inducing significant tree die-off could increase from 1 in 24 years to 1 in 15 years by 2050, together with a doubling in the occurrence of associated heat waves. This trend for increasing extreme drought risk and higher extreme temperature is consistent with the projections considered here, with an increase in the frequency of extreme drought by 2050 predicted to be -0.1(0.3)1.3 events every 20 years, corresponding to a change in median frequency from 1 in 18 years to 1 in 15 years, with *medium confidence* in trend for increasing time in drought. The change in the number of days year^{-1} expected to be greater than 35°C for the Rangelands North and South sub-clusters was noted above to be 7.3(16.2)28.5 and 16.0(29.8)46.9 days year^{-1}, corresponding to increases of 30% and 24% above historical conditions, respectively (*high confidence*).

Given the historical record of drought-induced dieback, with recorded mortality rates up to 30%, and potentially higher (Fensham et al. 2019), and the indication that the likelihood of such events will either stay the same or increase up to 2050, then the consequences of drought mortality are potentially Moderate (a potential for 20-50% of sequestered abatement lost). However, this may be overly pessimistic, given dead standing trees remain on-site and will continue to store carbon as the living vegetation recovers. Without further modelling or field observation the magnitude and time-course of the fate of mortality-induced carbon inclusive of both living and dead biomass remains unquantified. Given this uncertainty, the risk rating for maintenance due to drought is deemed to be Low/Moderate.

The consequences for combinations of extreme drought and temperature extremes to limit recruitment and long-term growth rates is rated Moderate (50-80% of expected abatement achieved).

Drought events are intimately related to trends in rainfall, and given the historical ‘boom-bust’ pattern of episodic rainfall are likely to continue into the future, and be exacerbated by climate change, the likelihood is considered ‘Likely’. When combined with the Moderate consequence rating, this leads to a Medium risk category. Because drought events can encompass broad spatial areas, this has implications both at the individual project level, as well as at the whole portfolio.

Flooding

Storm Damage

Direct mechanical damage from storms is possible in all forested ecosystems, but there is little evidence for widespread storm damage across arid Australia. Based on the uncertainty in rainfall projections the confidence in any changes in future storm activity are *low*. However, for both the Rangelands-South and Rangelands-North sub-clusters the projections are, with *high confidence*, of a future increase in the intensity of rainfall events. By 2050 the indication is an increase in the number of days per year that exceed the 99.9th percentile are projected to increase by -0.12(0.24)0.55 days for the Rangelands North sub-cluster, and -0.14(0.10)0.44 days for the Rangelands South sub-cluster. Whilst these values appear low, they represent the top 0.1% of rainfall events, and correspond to median increases of 45% and 18% for the North and South sub-clusters, respectively. Predicted changes in windspeed across the sub-clusters are small, at less than ±2%.

Floods in arid regions are generally caused by storms of high intensity over a smaller part of the catchment, thus the variability of flood is much greater from year to year and from site to site in the arid regions than elsewhere (Zaman et al. 2012). Flooding commonly follows large rainfall events, and tends to develop slowly and last for periods from weeks to months. Floods in Arid Australia can lead to losses of livestock and damage to crops, as well as extensive damage to rural towns and road and rail links, and can result in the isolation of whole communities. However, flood impacts on woody vegetation in arid Australia are largely undocumented. Whilst there is the potential for localised erosion impacts, these are likely confined to drainage channels and not generally impact the broader landscape. Rather than being a negative impact on sequestration, it is possible any increase in flood events, through increasing water availability, would lead to a net benefit on sequestration.

Because of the localised nature of storm damage, there are unlikely to be portfolio-wide implications on either risks to abatement accumulation or maintenance. Through the high confidence in the prediction of the increased intensity of rainfall events the likelihood of floods occurring and possibly increasing into the future is ‘Likely’, however the consequences are rated as Insignificant, leading to an overall risk rating for both flood and storm disturbance as ‘Low’. The consequence for storm-related damage is rated as minor, as for an individual project the potential for some storm-related mortality is possible, though the overall risk rating remains low.

Heat stress

Heat stress is a climate change risk factor common to many sequestration projects. In addition to increasing mortality, heat stress may also decrease long-term carbon storage due to the diversion of resources away from growth to heat shock proteins (Bita and Gerats 2013; Teskey et al. 2015), particularly when the frequency of heat stress is relatively high compared to the time required for tissue recovery (Curtis et al. 2014). One risk that is specific to the re-establishment of native forests is the impact of heat stress on seed bank persistence. Projected increased temperatures will produce significantly higher soil temperatures (particularly in semi-arid and rangeland regions where these Methodologies are common), and this may hinder regeneration due to an accelerated decline of seed viability (Ooi 2012; Ooi et al. 2014). There is also some evidence that seed production (at least in some plants) may be hindered by heat stress (e.g. Ozga et al. 2016), and this may also hinder rates of regeneration.

Other carbon pools

Sol organic carbon is excluded from the accounting rules for the HIR and NFMR methodologies. Given increasing vegetation cover is generally associated with increasing soil carbon, the exclusion of soil carbon likely represents a conservative assumption. Risks to soil carbon in the arid zone largely arise from management decisions, particularly grazing pressure, which lies outside of the scope of this review. Climate-related risks will be mostly associated with changes to average conditions such as temperature, and long-term trends in soil moisture, which will both affect soil microbial function and organic matter decomposition. The consequences for soil carbon across arid Australia, which is characterised by infertile soils and low carbon stocks, remains unknown.

Summary

From the perspective of abatement accumulation, the main risks are associated with changes in the climate that affect the survivorship of young regenerating stands, and the growth rates of mature stands. The main drivers were identified to be changes in average and maximum temperature, and the associated variables potential evapotranspiration and relative humidity, which have the potential to reduce net primary productivity, and hence rates of carbon sequestration. The overall risk rating was judged to be Medium (with *high* confidence), corresponding to a possible limit of 50-80% of expected abatement achieved. A large unknown is the implication of the predicted significant reduction in frost days by 2050, which may have both negative (via changes to frost-hardening and possibly adversely affecting germination requirements) and positive (through a reduction of frost-related tissue damage) aspects. No attempt was made to assign a risk rating to these factors. Because of the broad spatial influence of these risk factors, there are implications at both the whole portfolio level, as well as the individual project level.

For risks to the maintenance of abatement, the main risk factor identified was from mortality associated with extreme drought, although the ultimate consequences for carbon abatement are uncertain as they are a function of the combined rates of subsequent debris decay and other losses (such as from termites), and rates of post-drought recovery. Because of this uncertainty the overall risk rating was judged to be Low/Medium (with *medium* confidence). Because of the potentially broad spatial scale of drought events, and given the concentration of current projects geographically, there are implications at both the whole portfolio level, as well as the individual project level.

Fire is undoubtedly a major driver of vegetation dynamics across all of Australia, including the vegetation types managed under HIR and NFMR. Despite this, most projects have been established in areas of low historical fire, driven by naturally low contiguity of ground fuels, even in years following major rainfall events. The overall conclusion is that risks from changed fire regimes for these methodologies are low, and localised at the project-scale. There are three caveats to this. First, in western Australia the ground fuel loads tend to be higher, with correspondingly higher historical fire activity; therefore the registered projects in that region should carefully consider their fire management programmes and local fire risks. Second, expansion of existing activity into more productive lands, for example further east into Queensland, will increase the fire risk. Third, the role of the invasive buffel grass has not been considered here, but has the potential to increase fuel connectivity and increase fire intensity. Management of exotic weeds like buffel grass will be required in order to safeguard sequestration in areas where this invasive is establishing, or is established. Note there are no specific requirements written into the methodologies to require weed control (or wildfire management plans). Rather, state laws that place requirements on landholders to manage weeds and fire risks are expected to be adhered to as part of undertaking ERF project activities.

Table 11. Risk assessment for the Re-establishment of Native Forest activities.

Direct impacts via primary climate change variables	**Science confidence in projection**	**likelihood**	**Consequence**	**Risk rating**	**Portfolio-level risks?**	**Risk to accumulation**	**Risk to maintenance**
Heat-stress limiting plant growth and increasing mortality rates	High	Likely	Moderate	Medium	X	X	
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium	Likely	Moderate	Medium	X	X	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Likely	Moderate	Medium	X	X	
Changes in timing/occurrence of suitable conditions for tree and crop establishment	High	Likely	Moderate	Medium	X	X	
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	High	Likely	?	?		X	
Decreased frost days with implications for increased seed dormancy and reduced germination rates	High	Likely	?	?		X	
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	High	Likely	Insignificant	Low		X	
Flood-related soil erosion and deposition	High	Likely	Insignificant	Low		X	
Mechanical damage from wind and storms	Low	About as likely as not	Minor	Low		X	X
Direct impacts via secondary climate change variables							
Drought-induced plant mortality, with possibility of recruitment failure.	Medium	Likely	Moderate	Low/ Medium	X	X	X
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Low	Likely	Minor	Low		X	X
Indirect impacts via climate change impacts on weeds, pests and diseases							
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	?	?	?		X	X

3.3.2 Protection of existing forests

Embedded Methodologies

AVOIDED CLEARING OF NATIVE REGROWTH (2013) (AVOIDED-C)
AVOIDED DEFORESTATION (2015) (AVOIDED-D)

The Avoided-C and Avoided-D methodologies both recognise abatement through retaining areas of native forest that would otherwise have been cleared as a result of normal business practice, though the eligibility requirements and method of abatement calculation differ.

The Avoided-D methodology currently contributes significantly to the ERF scheme, with a total contracted abatement of 26 Mt CO2-e, delivering on average 2.9 Mt CO_2-e yr^{-1}. The key eligibility requirement is the possession of a valid clearing consent that was issued before 1 July 2010, for the purposes of permanent conversion of forest cover to cropland or grassland. In effect, this has limited the scope of the activity to properties in NSW that have permits to clear vegetation through an Invasive Native Scrub Property Vegetation Plan (INS PVP), issued prior to 2010 under the New South Wales Native Vegetation Act 2003 (repealed 2017). The abatement calculation method is by field-based measurement. Because only a small number of permits remain relinquished (relative to the total eligible number of permits), it would appear future abatement opportunities under this methodology are negligible.

In comparison to Avoided-D, the Avoided-C methodology has had limited uptake, with only two contracted projects and a total contracted abatement of 0.35 Mt CO2-e. Abatement under the method is calculated using FullCAM. The key requirements are the need to provide evidence of the two most recent clearing events. There is also a requirement to demonstrate that the vegetation satisfies the requirements of forest cover, that the forest comprises native species, that there is an unrestricted right to clear the land, and that following clearing the forest regenerates. There is also a requirement that each Carbon Estimation Area (CEA) within a project shares the same management history.

Because both methods involve essentially the same activity – a management change that ensures the retention of native forest cover – the risk factors are therefore considered similar.

Spatial domain

All of the registered and contracted projects under Avoided-D are located in the same geographic region in eastern Australia as the HIR and NFMR projects. This is understandable, given both categories of activity involve a change in the management of woody vegetation in predominantly grazed areas, and hence the underlying economics are similar, leading to a focus of activity in areas of similar environmental conditions, vegetation composition, and in areas with relatively low opportunity costs. Although there are relatively few Avoided-C projects (with three registered and two contract projects), the indications are that the optimal location for these projects is in the slightly more productive (higher rainfall) semi-arid woodland areas within the East Coast – North (ECN) and Central Slopes (CS) sub-clusters (Figure 7a). This aligns with the focus of this methodology on areas that have been subject to repeated tree clearing, primarily to promote understory grass production for cattle farming via the reduction in competition between fodder grasses and trees (Walker et al. 1972).

Because of the overlap in land use amongst the HIR, NFMR and Avoided-D activities (rangeland grazing), the range of native forest types is therefore similar also, dominated by acacia and eucalypt woodlands (see Section 3.3.1 and Figure 7b). This is also generally true for the areas most likely to support Avoided-C activity in the ECN and ES sub-clusters, although the potential for more consistent ground cover following periods of high rainfall in these woodlands has additional implications for fire risk (see below), and where the dominant tree species is less likely to be mulga, which is confined predominantly to the more arid areas (Peeters and Butler 2014) (Figure 7b). The risk assessments are based on analysis of the regions identified in Figure 7, and are not weighted by the current level of project activity (which for Avoided-C is low). The risk analysis therefore encompasses both current and potential future project activity.

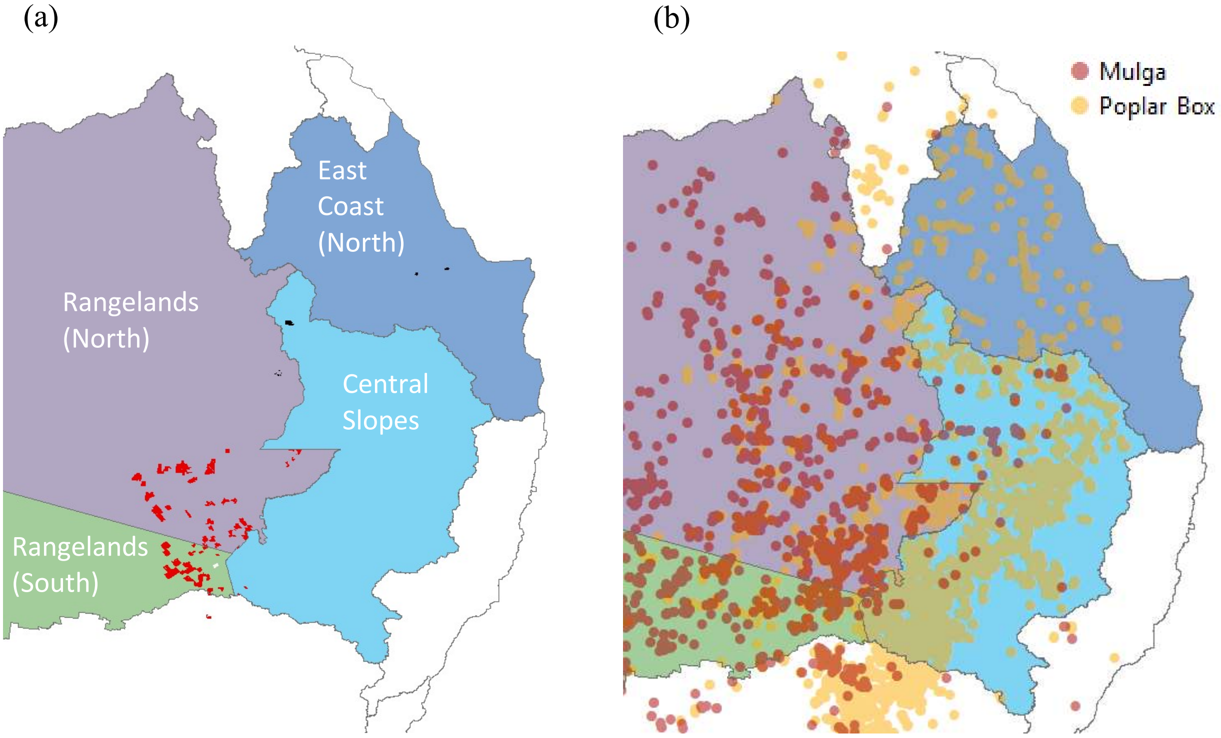

Figure 7. (a) Locations of registered Avoided-D (red) and Avoided-C (black) projects. Revoked projects shown in white. (b) Spatial distribution of two main vegetation types applicable to Avoided-D and Avoided-C (*Acacia aneura* (mulga woodlands) and *Eucalyptus populnea* (Poplar Box woodlands)). Species locations from the Atlas of Living Australia (https://doi.org/10.26197/5f2e149ee5182).

Risk assessment against identified climate impact factors

Factors affecting initial tree establishment and growth

Factors affecting longer-term vegetation growth rates

Because the Avoided-D and Avoided-C activities both involve the maintenance of existing forest cover, risks associated with establishment and initial growth are much lower than activities involving the regeneration of new forests. This is because established vegetation is generally more resilient to such factors as changing temperature and rainfall patterns, due to traits such as the ability of mature vegetation to moderate physiological activity, the support of physiological maintenance requirements through the use of stored reserves of photosynthate, and deep roots to access groundwater. The timing of suitable regeneration conditions to offset natural mortality is also less critical for Avoided-D and Avoided-C activities, given adult woodland trees are long-lived (with decadal to century lifespans). In the case of mulga, seedling regeneration occurs readily, but is particularly vigorous after wet periods and if animal stocking rates are low (Peeters and Butler 2014). In a study of recruitment and mortality of eucalypt woodland species in central western NSW, there was evidence mortality is balanced by new recruitment at the regional scale, although variable between locations (Taylor et al. 2014). There does remain an interesting ecological question regarding the very long-term persistence of Australia's arid and semi-arid woodlands over coming centuries, relating to stand replacement dynamics and the potential for the gradual species replacement over time, but this is beyond the scope of this review. The risks associated with Avoided-D and Avoided-C activities are therefore focussed on maintenance, rather than accumulation, given all of the delivery is attained at the beginning of each project.

Although risks associated with regeneration success are low, of potentially greater significance is the effect of climate impact factors such as heat stress and reduced soil water availability on the growth rates of adult plants, and the consequences of the interactions between increased plant stress and susceptibility to disturbances (see next section).

For the Avoided-D activity the climate impact factors relating to the potential for reduced growth and their likelihoods are the same as identified for HIR and NFMR, given the spatial overlap in their occurrence. Therefore, the potential for heat- and water-stress induced limitations to plant productivity are considered likely, with an overall confidence of *high*. Because existing forest cover is more robust to such impacts, and given the many adaptations the species possess for coping with existence in harsh, arid environments, the consequences of reductions to growth and the ability of the forests to self-regenerate are considered minor, leading to an overall risk rating of low (Table 12).

For the Avoided-C activity the risk profile is also the same given the similarity in activity, but because of the geographic separation in the activity areas (with activity more likely to occur in the relatively higher rainfall areas within the ECN and CS sub-clusters) there is the potential for the likelihoods and consequences to differ. The increase in average annual temperatures for the ECN and CS sub-clusters are within 15% in magnitude and spread compared to the two rangelands zones, as are the predictions for potential evapotranspiration (Appendix B). For the ECN sub-cluster rainfall changes are possible but uncertain, with natural variability expected to be the main driver over coming decades. For the CS sub-cluster natural variability in rainfall is also expected, although by the end of the century a trend towards lower winter rainfall is expected (*high confidence*). Thus, these factors are all similar to those applicable to Avoided-D.

For both the CS and ECN sub-clusters the change in time spent in drought is predicted to be lower than the two rangeland sub-clusters, with increases less than 1% against a baseline of 35-40% of time in drought (compared to increases of approximately 4% for the rangeland sub-clusters). Variability in projections across models for both the ECN and CS sub-clusters is high however, with a range of approximately -15% to +20%. Taken together, these trends are also consistent with an overall prediction of decreasing soil moisture over the century (*medium confidence*), and increasing plant stress, which would be expected to reduce plant productivity. Extreme temperatures are also expected to increase significantly, with substantial increases in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence)*. For example, the change in the number of days year^{-1} expected to be greater than 35°C for the ECN sub-cluster is 1.8(11.9)39.6 (compared to the current average of 21.6 days year^{-1}), and a change of 2.9(15.2)31.2 days year^{-1} for the CS sub-cluster (with a current average of 26.4 days year^{-1}). These are, again, similar in magnitude to Avoided-D.

Taken together, these projections suggest the likelihood of experiencing by 2050 heat- and water-stress induced limitations to plant productivity are all likely, with an overall confidence of high. Similarly, the reduction in frost days is also likely, with high confidence. Regarding the impacts on plant growth, because the Avoided-D and Avoided-C activities involve retention of mature forest with minimal exposure to regeneration losses, the consequences of reduced growth are assessed to be minor, which when combined with the likelihood assessment above ('Likely') gives an overall risk rating of Low (Table 12).

Pests and diseases

The conclusions regarding pests and diseases from Section 3.3.1 apply here also, with the potential for shifts in the distributions, and the potential for new pest species to emerge, generally acknowledged, although with insufficient information to make definitive projections regarding either the acacia or eucalypt woodlands that underlie the Avoided-D and Avoided-C methodologies.

One identified risk, noted in Section 3.3.1 in the context of expansion of current HIR and NFMR activities eastwards, is the presence of the invasive weed buffel grass (*Cenchrus ciliaris*). Buffel grass is native to parts of Africa, Asia and the Middle East, and was introduced into Australia to improve livestock production and for soil stabilisation. The species is currently relatively uncommon in the core HIR and NFMR regions of the Rangelands North and South sub-clusters, but in the SC and ECN sub-clusters where Avoided-C activities are most likely to take place it can be a dominant component of the understory, particularly where intact woodlands are fragmented from clearing and other anthropogenic disturbance (Franks 2002; Eyre et al. 2009). The main risk factor associated with buffel grass in the context of the native forest re-establishment and protection methodologies is via its effect on fire regimes, which are discussed further under 'Fire' below. Projections of buffel grass spread under a 2070 high emissions scenario indicate significant potential for the species to migrate southwards over the coming decades (Martin et al. 2015).

Fire

Risks to Avoided-D projects from fire are considered to be the same as those for HIR and NFMR, given the overlap in spatial extent, management, and vegetation type. The conclusion from the HIR and NFMR analysis was the current risks to sequestration from fire are deemed to be relatively low, given the low historical occurrence of fire in the affected vegetation types, even during high fire years, and the regenerative traits of the vegetation that allow them to recover post-fire. Because of the high uncertainty associated with fire prediction, the likelihood is considered to be 'about as likely as not'; and given the impacted vegetation types are largely fire resistant, the consequences are considered 'minor'. The resulting risk rating for fire to significantly impact maintenance is therefore low at the whole portfolio level. Whilst also low at the individual project level, there always remains a chance of some unplanned wildfire, and proponents should be prepared to manage for this.

The CS sub-cluster has relatively higher historical fire activity, due to relatively higher rainfall and associated higher connectivity of ground layer vegetation, particularly grasses (Figure 8). Within the CS sub-cluster the number of days year^{-1} with a Forest Fire Danger Index (FFDI) greater than 'High' is expected by 2050 to change by 10.7(17.7)33.0 days year^{-1}, corresponding to a median increase of 14% above the current baseline of 124 days year^{-1}. For the ECN sub-cluster the change is expected to be 4.0(7.1)24.0 days year^{-1}, corresponding to a median increase of 12% above the current baseline of 57.5 days year^{-1}. Corresponding changes for the annual cumulative FFDI are a 9% median increase for the CS sub-cluster, and 6% increase for the ECN sub-cluster. Given fire activity is driven by preceding rainfall in the arid zone, and rainfall projections are highly uncertain, there is therefore overall *low confidence* in the projections for changes in fire risk.

Whilst fire is relatively more common across the ECN sub-cluster, and the projections are for increased fire danger by mid-century and beyond, the risks to the maintenance of sequestration is also deemed to be low (i.e., a likelihood of 'about as likely as not', and a consequence of 'minor'). This rating is due to the adaptations of the woodland species in these regions to fire that allow them to recover following disturbance. For example *E. populnea* woodlands can recover biomass within 7 years after severe mechanical removal and fire (Playford et al 2009), and in a controlled burn experiment Fensham et al. (2008) recorded seedling survival rates (via post-fire sponsorship from lignotubers) of *E. populnea* and *E. melanophloia* of 87-93%, concluding fire may not be a factor limiting structural development in woodlands where these species dominate.

As noted above, the spatial distribution of buffel grass is predicted to shift in response to a changing climate, and high densities of buffel increase the frequency and intensity of woodland fires through increasing ground fuel loads (Butler and Fairfax 2003; Peeters and Butler 2014). Whilst the incursion of buffel grass has a negative impact on the recruitment and growth of many ground cover species (Franks 2002), and has been implicated in accelerated degradation through increased fire (Butler and Fairfax 2003), the longer-term implications for sequestration in the overstory trees remains unknown. Where buffel grass is likely to be present, then management that includes both fire mitigation and control of exotic grasses would seem prudent (Peeters and Butler 2014).

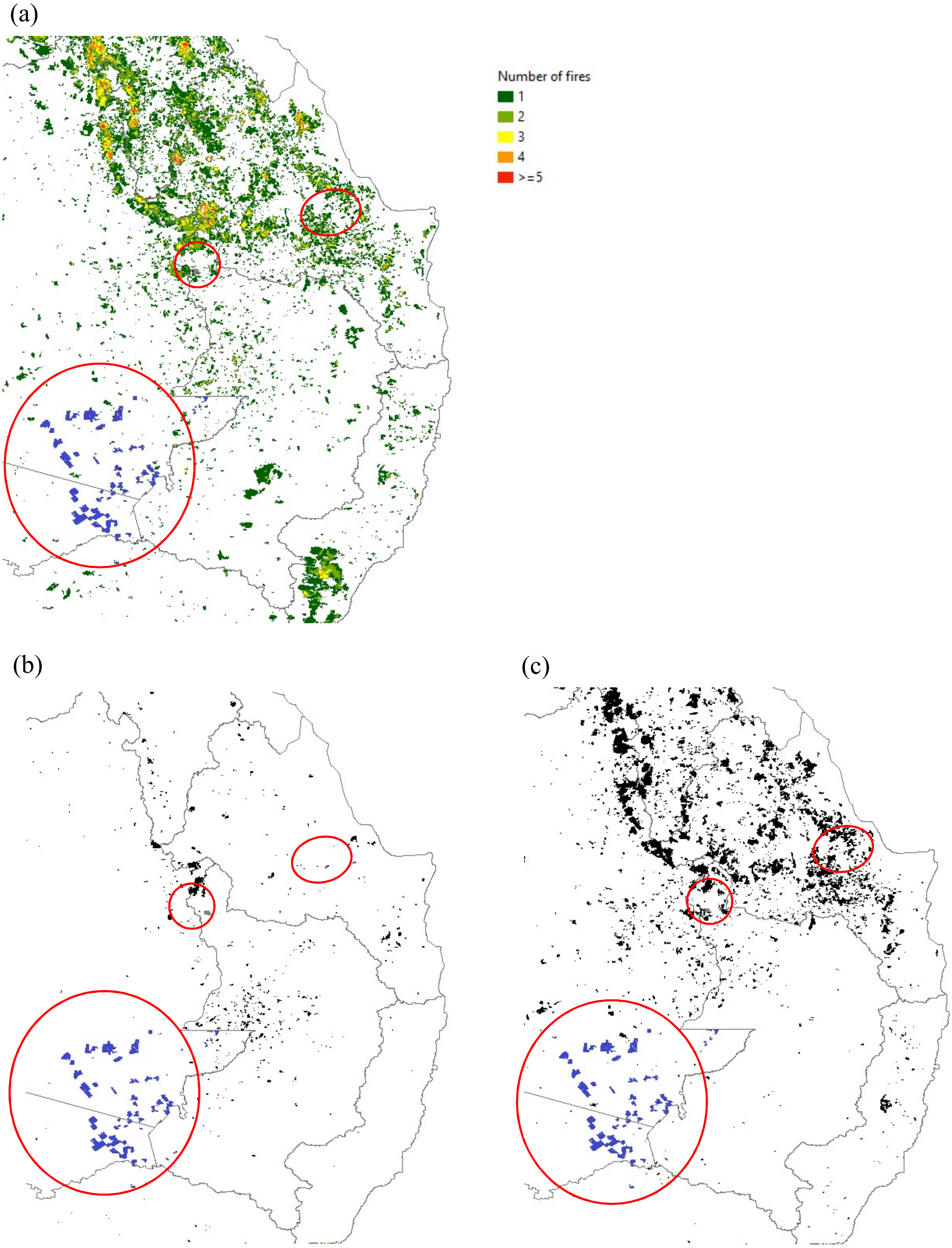

Figure 8. (a) Number of fires over the period 1988 to 2013. Circled areas show the locations of Avoided-D and Avoided-C project activity (in blue). (b) Combined fire burn areas for low-fire years 2004 and 2005. (c) Combined fire burn areas for high-fire years 2011 and 2012.

Drought

The potential for extreme drought conditions to cause tree mortality and thus impact on the risks to abatement maintenance in the context of HIR and NFMR were discussed in Section 3.3.1 – the conclusions from which are directly applicable to Avoided-D also. For Avoided-D the risks to maintenance due to drought are therefore deemed to be Low/Moderate, based on the historical record of drought-induced dieback, with recorded mortality rates up to 30% or more, and the indication that the likelihood of such events will either stay the same or increase up to 2050. The split rating Low/Medium recognises the uncertainty associated with the fate of dead standing trees arising from mortality-inducing drought, post-drought recovery, and the implications for ecosystem-level carbon storage.

For Avoided-C, the risk factors and projected changes for the CS and ECN sub-clusters are similar to those impacting Avoided-D. The increase in the frequency of extreme drought by 2050 is projected to be -1.0(0.3)1.9 and -0.9(0.4)1.6 events every 20 years for CS and ECN, respectively (corresponding to a change in median frequency from approximately 1 in 16 years to 1 in 12 years). These compare to -0.8(0.3)1.4 (a change in median frequency from 1 in 18 years to 1 in 15 years) for the Rangelands North and South zones. With respect to extreme drought duration, the historical record shows on average 24 and 26 months for the CS and ECN sub-clusters respectively, with an expected change of -7.2(0.9)8.8 months for CS, and -3.2(2.9)9.0 months for ECN. Based on this analysis it is concluded the exposure to extreme drought for Avoided-C is similar to Avoided-D, with an overall risk rating of Low/Medium.

Heat stress

In addition to increasing mortality, and as noted in Section 3.3.1, heat stress may also decrease long-term carbon storage due to the diversion of resources away from growth to heat shock proteins (Bita and Gerats 2013; Teskey et al. 2015), particularly when the frequency of heat stress is relatively high compared to the time required for tissue recovery (Curtis et al. 2014).

Flooding
Storm Damage

Based on the uncertainty in rainfall projections the confidence in any changes in future storm activity are *low*. However, for all four sub-clusters across the Avoided-D and Avoided-C activities (Rangelands-South, Rangelands-North, SC, ECN) the projections are, with *high confidence*, of a future increase in the intensity of rainfall events. For the SC and ECN sub-clusters the number of days per year that exceed the 99.9th rainfall percentile are projected to increase by -0.07(0.21)0.58 days for the CS sub-cluster, and -0.14(0.11)0.55 days for the ECN sub-cluster, which are similar to the projections for Rangelands North and Rangelands South reported in Section 3.3.1. Predicted changes in windspeed across the sub-clusters are small, at less than ±2%.

Following the discussion of the likelihoods and consequences of storm damage and flooding in woodlands in Section 3.3.1, the overall risk rating for Avoided-D and Avoided-C activities are deemed similar to those for HIR and NFMR. That is, because of the localised nature of storm damage, there are unlikely to be portfolio-wide implications on risks to abatement maintenance. Through the high confidence in the prediction of the increased intensity of rainfall events the likelihood of floods occurring and possibly increasing into the future is ‘Likely’, however the consequences are rated as Insignificant, leading to an overall risk rating for both flood and storm disturbance as ‘Low’. The consequence for storm-related damage is rated as minor, as for an individual project the potential for some storm-related mortality is possible, though the overall risk rating also remains Low.

Other carbon pools

Soil organic carbon is excluding from the accounting rules for the Avoided-D and Avoided-C methodologies. Given reduced mechanical disturbance to the soil profile due to the cessation of clearing will reduce SOC losses and likely restore lost carbon over time, the exclusion of soil carbon likely represents a conservative assumption. Risks to soil carbon in the arid zone largely arise from management decisions, particularly grazing pressure, which lies outside of the scope of this review. Climate-related risks will be mostly associated with changes to average conditions such as temperature, and long-term trends in soil moisture, which will both affect soil microbial function and organic matter decomposition. The consequences for soil carbon across arid Australia, which is characterised by infertile soils and low carbon stocks, remains largely unknown.

Summary

Because both the Avoided-D and Avoided-C activities involve the protection of existing forests, the question of risks accumulation are less relevant. The main risks are associated with the maintenance of abatement. As per the HIR and NFMR analyses the main risk factor identified was from mortality associated with extreme drought, although as noted the ultimate consequences for carbon abatement are uncertain as they are a function of the combined rates of subsequent debris decay and other losses (such as from termites), and rates of post-drought recovery. The overall risk rating was judged to be Low/Medium (with *medium* confidence). Because of the potentially broad spatial scale of drought events, and given the concentration of current projects geographically, there are implications at both the whole portfolio level, as well as the individual project level.

Avoided-D projects have been established in areas of low historical fire, driven by naturally low contiguity of ground fuels. The overall conclusion is that risks from changed fire regimes for Avoided-D is low, and localised at the project-scale. For Avoided-C, the sub-regions most suited to this activity (Central Slopes and East Coast North) have relatively higher productivity, with greater potential for contiguity in ground fuels loads, and greater historical fire activity. However, given the ability of the major woodland types to recover strongly post-fire, the overall risk rating was deemed low. The major caveat to this is potential future impact of the invasive buffel grass on fire regimes, particularly in the Central Slopes and East Coast North sub-clusters where it is more commonly found. Because the long-term impacts of buffel grass on tree carbon sequestration are not well understood, management of exotic weeds like buffel grass will be required in order to safeguard sequestration in areas where this invasive is establishing, or is established, particularly given projections for a southward shift in its distribution under climate change.

The potential for wide-spread tree mortality from increased levels of pests and diseases is theoretically possibility, but the likelihoods of such an outcome are unknown. Risks associated with storm damage and flooding were deemed to be low.

Table 12. Risk assessment for the Protect Existing Forest activities.

Direct impacts via primary climate change variables	**Science confidence in projection**	**likelihood**	**Consequence**	**Risk rating**	**Portfolio-level risks?**	**Risk to accumulation**	**Risk to maintenance**
Heat-stress limiting plant growth and increasing mortality rates	High	Likely	Minor	Low	X		X
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	High	Likely	Minor	Low	X		X
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Likely	Minor	Low	X		X
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	High	Likely	Insignificant	Low			X
Mechanical damage from wind and storms	Low	About as likely as not	Minor	Low			X
Direct impacts via secondary climate change variables							
Drought-induced plant mortality, with possibility of recruitment failure.	Medium	Likely	Moderate	Low/ Medium	X		X
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Low	Likely	Minor	Low			X
Indirect impacts via climate change impacts on weeds, pests and diseases							
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	?	?	?			X

3.3.3 Planting of new forests

Embedded Methodologies

REFORESTATION BY ENVIRONMENTAL OR MALLEE PLANTINGS – FULLCAM (2014) (Refor-Model)
REFORESTATION AND AFFORESTATION (2015) (Refor-Measure)
MEASUREMENT BASED METHODS FOR NEW FARM FORESTRY (2014) (FarmFor)
PLANTATION FORESTRY (2017) (Plantation)

These four methodologies together currently comprise only 1.2% of all contracted abatement under the ERF scheme. This relatively low uptake probably being largely attributable to the relatively high up-front costs associated with planting trees (Roxburgh et al. 2020).

The Refor-Model, Refor-Measure and FarmFor methodologies all require the establishment of new trees on land that has been cleared of forest. These methodologies differ in what can be established. Refor-Model requires the establishment of permanent environmental or mallee plantings. Refor-Measure can entail the planting any species, so long as they are not classified as a weed. The FarmFor methodology allows for the planting of either commercially harvestable or permanent (i.e. non-harvested) species, within the context of integration with existing agricultural enterprises. The Plantation methodology is specifically targeted at commercial plantation growers.

There are also differences between these methodologies in the way in which abatement is calculated. Refor-Model and Plantation uses FullCAM. Refor-Measure uses field-measurements. FarmFor uses a combination of field-based measurements and FullCAM (for calculating expected (100 year) abatement under the proposed management change). Unlike Refor-Model or Refor-Measure, FarmFor has strict limits to project size, based on rainfall. In areas less than 400mm rainfall projects must be no bigger than 300 hectares or 30 per cent of farm area, whichever is smaller. In areas greater than 400 mm rainfall projects must no bigger than 100 hectares or 30 per cent of farm area, whichever is smaller.

The Refor-Model, Refor-Measure and Farm-For methodologies all only account for carbon sequestration in biomass and debris. In contrast, the Plantation methodology accounts for these as well as carbon sequestration in harvested wood products. There are also two different types of Plantation method projects: (i) establishment of new commercial plantation forestry estates on currently cleared agricultural land, and (ii) conversion of short rotation management regimes to long rotation. The spatial extent of Plantation activities is limited to current National Plantation Inventory (NPI) regions. For projects in locations above 600 mm rainfall there are eligibility requirements related to tree water use, with the purchase of water rights one option to meet those eligibility criteria. Whether a project is required to purchase water is determined by state regulations.

For all of the three methodologies entailing new tree plantings, for any project that is affected by fire (either planned fire or wildfire) there are rules that specify how the modelling must be modified to account for any fire emissions incurred, and any re-stratification of the project extent that might be required in case of significant fire-induced tree mortality.

Spatial domain

In contrast to HIR and NFMR methodologies, there are currently very few existing projects to gauge where methodologies entailing new plantings will predominately be established. However, recent work by Roxburgh et al. (2020) showed that the most economically viable areas for these types of projects were mostly encompassed within the NRM cluster areas of East Coast, Murray Basin, Central Slopes, Southern Slopes, Southern and South Western Flatlands (Figure 9).

Compared to most other regions of Australia (e.g. rangelands), the NRM cluster areas most likely to support new plantings have a relatively high potential for production of woody biomass. However, sites with high productivity also present relatively high risks to maintaining this productivity in the face of climate change and providing high biomass and fuel loads for facilitating rapid spread of pest and disease outbreaks and severe fires, respectively.

Another key feature of the NRM cluster areas most likely to support new plantings are that they are within regions where land use tends to be relatively intensive. Therefore, in addition to the establishment costs, opportunity costs (e.g. foregone agricultural production) for implementing new plantings is another key factor limiting the extent of uptake of these projects. Climate change risks to the viability of various agricultural enterprises will change the dynamics of this opportunity cost.

Specific changes in the climatic conditions impacting the vulnerability of new plantings is discussed in detail in the next section. However, in general terms, across all NRM clusters in the spatial domain considered (East Coast, Murray Basin, Central Slopes, Southern Slopes, Southern and South Western Flatlands), future climatic projections up to 2050 suggest average temperatures will continue to increase in all seasons (*very high confidence*), such that by 2050, under the RCP8.5 and RPC4.5 scenarios, the median projected increase in mean annual temperature is between about 1 to 2 ^{o}C. The highest increases in mean temperature are projected to be in the Central Slopes (particularly in summer and spring), and the lowest in Southern Slopes of Tasmania (East and West). The mean maximum and minimum temperatures are projected to increase at a similar rate to the mean temperature, again with the greatest increases expected for Central Slopes (particularly in summer and spring), and the lowest in Southern Slopes of Tasmania.

When compared to temperature, projected changes in rainfall are less clear in the Central Slopes, East Coast (North and South), Murray Basin and Southern Slopes Vic/NSW (East and West). In these areas natural climate variability is projected to remain the major driver of rainfall changes in the next few decades. In these regions, models show a range of results, with little change or decrease being more common, particularly in winter and spring (*medium confidence*) where the median decrease in rainfall is about between 2 and 10% in the RPC4.5 and RPC8.5 scenarios. For the Southern and South Western Flatlands (East and West) and the Southern Slopes Tas (East, and particularly West), the projected changes in mean rainfall over the next few decades are for a median decrease within the range of about 2 to 20% in the RPC4.5 and RPC8.5 scenarios. For the Southern and South Western Flatlands, most of the decline in rainfall is in the winter months (median decreases of about 10-15%), whereas in the Southern Slopes Tas, most of the decline in rainfall is in the summer and spring months (median decreases of about 5-10%).

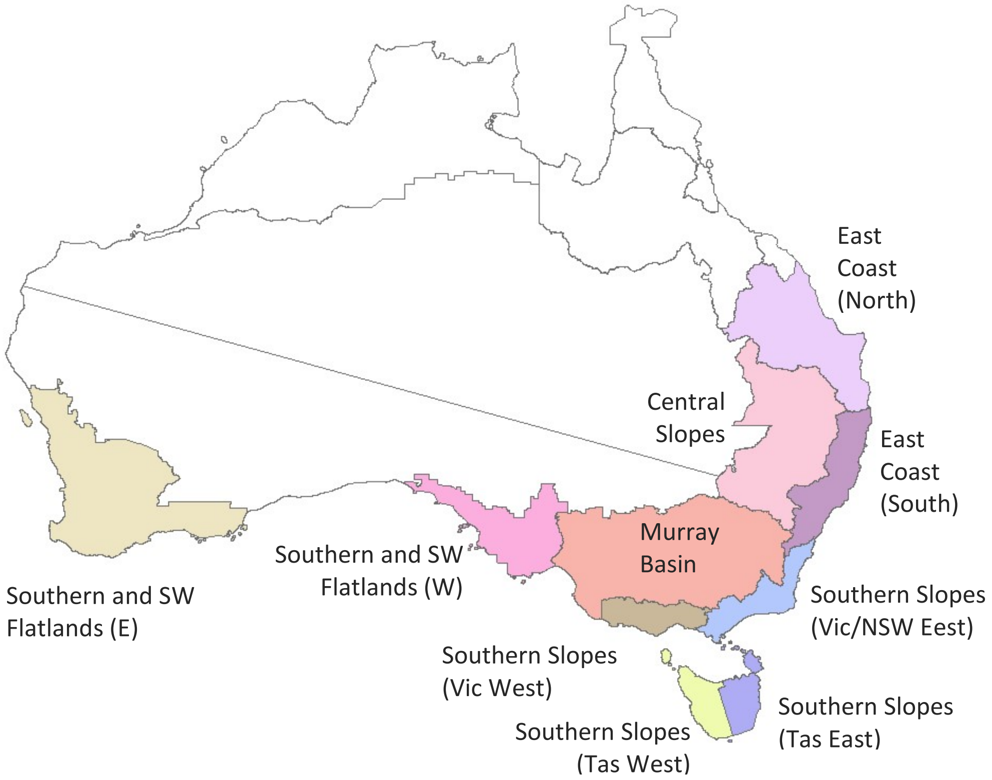

Figure 9. Sub-clusters containing existing ERF projects undertaking new planting activities.

Risk assessment against identified climate impact factors

Factors affecting initial tree establishment and growth

- Surface soil conditions

  Low availability of water in the surface soil associated with drought conditions can impact initial tree establishment and growth (e.g. Close and Davidson 2003), and this is discussed in the section below. However, the importance of soil moisture storage prior to planting has been shown to be particularly important in minimising the risk of failure tree plantings as it removes the reliance on rainfall to provide water to the young trees in a variable climate (Huth et al. 2008). Indeed, the value of planting moisture for cropping within the eastern grain growing regions of Australia is well understood (Freebairn et al. 1991; Whish et al. 2007) and there is no reason why this would not also apply to tree plantings.

  Waterlogging results in insufficient oxygen in the pore space for plant roots to be able to adequately respire. It has been found to be an important factor influencing the survival and early growth of new tree plantings in southern Australia (e.g. Bell 1999; Stephen 1994; England et al. 2013). Waterlogging occurs when the soil profile or the root zone of a plant becomes saturated. In rain-fed situations, this happens when more rain falls than the soil can be absorbed, or that the atmosphere can evaporate.

  Saline surface soils also impact growth and survival of tree seedlings in Australia (e.g. Sun and Dickinson 1993; Ritson et al. 2015). Dryland salinity has resulted where land clearing post European settlement meant that a larger proportion of rainfall remains unused by plants and enters the groundwater, and so the groundwater tables have risen, dissolving and mobilizing accumulated salts as they do (e.g. Morris and Thomson 1983). Therefore, like waterlogging, the cause of saline surface soils relates to excess water and can thereby be mitigated by periods of low rainfall and high evapotranspiration. Although all Australian states have salinity-affected lands, the Southern and SouthWest Flatlands (West) of Western Australia are the most affected of the Australian agricultural landscapes (Bell 1999).

In response to climate change in the NRM clusters where most new trees are being established, there is an increased risk that the extent of surface soils with low planting moisture will increase. Conversely there is a decreased risk of waterlogging and, thus, saline surface soils. The change in these risks are associated with a general drying trend associated with changes to rainfall, evapotranspiration and relative humidity.

As described above, mean annual rainfall is expected to decrease in many of these NRM clusters. Consistent with this, a projected increase in potential evapotranspiration was also clear and consistent across the entire spatial domain for new planting projects, although the extent of increase for a given cluster NRM region was not related to the extent of increase in the temperate in that region. The median projected increases in potential evapotranspiration were generally between about 4 and 8%. Although highly uncertain, most of these increases are expected in the winter months, particularly in the Southern Slopes (all sub-clusters) and Murray Basin, where median increases reached between about 7 to 10% for those months. Consistent with the rise in potential evapotranspiration, there was a general (albeit small) decline in relative humidity projected across all clusters.

- Weeds

  Until tree seedlings are well established, they are at risk from weeds that compete for water, nutrients and light (Graham et al. 2009; Singh et al. 2010). Weeds are generally invasive species, and traits that promote invasiveness also predispose them to rapid response to climate change (Kriticos et al. 2003; Kriticos et al. 2010). For example, many weed species can thrive with water and nutrient limitations, making them strong competitors for resources in less vigorous plantations. As climate changes, the geographic range of many weed species are expected to change, with range expansions to higher latitudes and elevations as rising temperatures relax cold range boundaries (e.g. Lantana, McFayen 2008). Indeed, many of Australia’s worse weeds benefit from extreme events, and there is a huge pool of invasive plants available to colonise bare spaces left by drought, fire and storm damage, and wind and flooding waters help spread weeds (e.g. Low 2008).

  There may also be increased dispersal and pollination of weeds due to climate change impacts on animals (e.g. Gallagher et al. 2006). As invasive animals move into new areas in response to climate change, they may also contribute to increased spread of weeds and/or create disturbance advantage for weeds. Higher temperatures may increase insects’ breeding cycles and provide more weed pollination.

  Given weed control is one of the key influences on the cost of establishment of new tree plantings in Australia (Summers et al. 2015), any changes in the vigour of weeds may impact on the economic viability of establishing new carbon plantings. Moreover, weed management is doubly important in such projects because the removal and suppression of weeds are potential sources of emissions (Singh et al. 2010).

- Frost

  Although frost damage can impact mature trees, new growth on young tree plantings are particularly susceptible to frost damage, especially for frost-sensitive species such as spotted gum (Reid 2020). Trees affected by frost may be killed outright or become predisposed to lower growth rates due to leaf death (when water inside cells freezes, expands and bursts plant cells) and/or increased susceptibility of frost-affected leaves to insect or fungal attack (Inouye, 2000).

  The risks of frost damage may decrease with climate change. This is because the number of frost days (below 0^{o}C) are expected to decrease across the NRM clusters where new planting projects are most likely to be established, with this decrease being most pronounced in the Central Slopes and Murray Basin (median decline of about 6 to 8%). However, a caveat to this assumption of decrease frost damage is that there is also an increasing trend of dryness, and there is evidence that the extent frost damage increases with dryness (e.g. Zohar et al. 1981). Moreover, there is also evidence of reduced frost hardening with warmer temperatures (Woldendorp et al. 2008), and that increasing atmospheric CO_2 may increase frost sensitivity in eucalypts (Barker et al. 2005), with impacts being severe for eucalypt seedling (Lutze et al. 1998).

- Browsing damage

  Browsing damage can be a problem from the time seedlings go into the ground or germinate, until they have reached about 1 to 2 m in height (Close and Davison 2003; PFT 2017). Rabbits, hares, deer, kangaroos and wallabies are common browsers of young trees (Reid 2020). Climate change will have an impact on survival of young trees via influencing the population of these browsers. Rabbits, for example, are predicted to retreat to regions with cooler climates (Low 2008). Given browsers favour certain trees, they may also impact the species composition of new plantings (Close and Davison 2003).

- Pests and diseases

  A number of pests and diseases can reduce establishment and survival of newly planted sites, including leaf chewers, sap suckers and leaf pathogens (e.g. Carnegie and Angel 2005; Pegg et al. 2009; Loch and Matsuki 2009; Matsuki and Tovar 2012; Walker and Allen 2013). While some target young plants, many can affect both establishment success and later age growth. The implications of climate change for pests and diseases is discussed in detail below.

Factors affecting longer-term vegetation growth rates

Below we describe three key factors that may impact the longer-term rates of carbon storage in live woody biomass of new tree plantings. However, the impacts on carbon storage in wood products and debris is not always directly related to increases in carbon stored in live woody biomass. These nuances are also discussed below.

- Persistent increase in mean annual temperature

  As described above, mean annual temperature is expected to increase in all NRM clusters where new plantings are expected to predominate. How changes in temperature impacts trees will depend on the change with respect to the optimum range for plant performance (e.g. Cunningham and Read 2006). If mean annual temperature increase *beyond* a tree species climate envelope (which may extend beyond the current natural distribution), this will restrict the long-term growth (Booth and Jovanovic 2002, 2005). Conversely, if temperature increases (particularly in winter) still remain *within* this range, growth may be promoted through increases in the length of the growing season (Ayres and Lombardero 2000; Booth et al. 2015) and higher rates of photosynthesis (Hyvonen et al. 2007), and may advance the timing of the spring growth flush. Indirect changes in soil nutrient cycling processes may also be a contributor to these effects (Battaglia et al. 2009; Kirschbaum 2004).

However, increasing dryness may also interact with the optimum range for plant growth. For example, the critical temperature for respiration (Tmax) of *Eucalyptus globulus* increased from 53.5 °C for well-watered plants to 59 °C when plants were water stressed (Gauthier et al. 2014), but the respiration rate at Tmax of water stressed plants was more than double that of well-watered plants. Moreover, for a range of species, Tmax is on average 10°C greater than the high temperature threshold of Photosystem II, meaning that photosynthesis stops earlier than respiration. Given that respiration releases 6 – 8 times more CO_2 into the atmosphere than does the burning of fossil fuels, with half coming from leaves, even small fractional changes in leaf respiration can have a large impact on ecosystem C cycling (Atkin et al. 2007; Canadell et al. 2007).

Where temperature increases associated with climate change alter rates of growth, changes in carbon stored in wood products is not directly proportion to changes in carbon stored in biomass (Pinkard and Bruce 2011). This is because the basic density of wood commonly decreases as growth rate increases (Downes et al. 1997; Drew et al. 2009). Similarly, where temperature increases enhance rates of growth, this does not directly result in increased carbon stored in litter and coarse woody debris. This is because the rates of litter and CWD standing will depend not only on the rates of litter production (and hence, biomass), but also the rates of decomposition. The rates of litter decomposition may also increase within rising temperatures- at least where there is adequate moisture (Shalin and Qiang 2002; Liski et al. 2003).

- Persistent increase in water stress

  The two most established plantation and farm forestry species (blue gum and radiata pine) respond to water stress by reducing photosynthesis and stomatal conductance (Thompson and Wheeler 1992; Pinkard et al. 2011; White et al. 2009) and allocation of biomass (Raison et al. 1992; Pinkard et al. 2011), with these changes resulting in slower rates of growth than occur when water is non-limiting (Benson et al. 1992). Such species are well adapted to short periods of water stress but are vulnerable to persistent water stress (White et al. 2009; ABARES 2011). Persistent water stress not only affects growth rates, but also the length of the growing season, with well-watered trees maintaining growth throughout winter, unlike drought-affected trees where growth was curtailed (Benson et al. 1992).

  Decreasing rainfall and increasing potential evapotranspiration will increase water stress, and this will supress the productivity of many tree plantings (Battaglia et al. 2009). As described above, there is projected to be a decline in dry season rainfall in the NRM clusters where new plantings predominantly occur. A projected increase in potential evapotranspiration was also clear. The median projected increases in potential evapotranspiration were generally between about 4 and 8%. Although highly uncertain, most of these increases are expected in the winter months, particularly in the Southern Slopes (all) and Murray Basin, were median increases reached between about 7 to 10% for those months. Consistent with the rise in potential evapotranspiration, there was a general (albeit small) decline in relative humidity projected across all clusters.

Modelling climate change impacts on percentage changes in forest growth rate in different regions of Australia, ABARES (2011) showed that even within a given region, the predicted impacts varied between species. For example, in the areas simulated within the SouthWest Flatlands West and East Coast South and Murray Basin all key species planted (hardwoods and softwoods) were predicted to decrease growth rates, whereas in the Southern Slopes Tasmania (East and West) East Coast North, the impacts are less severe for most commonly established species (with the exception of radiata pine and flooded gum).

The extent of mortality associated with persistent water stress will be highly influenced by the stocking rate (stems per hectare) at which trees are established (e.g. Singh et al. 2010; Summers et al. 2015). Project proponents planting trees such as mallee eucalypts in the Southern and SouthWest Flatlands West have found that, regardless of the stocking densities used at establishment, trees self-thinned over time to be stocked at about 200-300 sph (Fitzgerald, pers. Com. 2020). Similarly, others have found there is relatively little loss in growth rates when stocking rates are decreased (e.g. from 1200 to 600 stems/ha for blue gum) in areas subject to persistent water stress (White et al. 2009). Given costs of mechanical and manual tree plantings are heavily influenced by the stocking rate used (Summers et al. 2015), to ensure projects are as cost effective as possible in the face of continuing dryness, new plantings should only be established at stocking rates that minimise mortality from inter-tree competition for resources, and thus, optimise the carbon sequestration potential based on the sites future carrying capacity. A caveat to this is that in some regions severely impacted by weeds, low stocking rates at establishment may require longer periods of weed control.

Thinning tree plantings can also increase growth rates in the face of climate change by reducing water stress of remaining trees. Thinning residues left on the ground will decay, however, producing emissions as well as increasing soil carbon storage (Singh et al. 2010).

In addition to stocking rates, the extent of mortality associated with persistent water stress will also be influenced by planting configuration. Compared to block planting, linear belts have a larger perimeter to area ratio, resulting in less competition for resources such as water (Paul et al., 2016), and hence several studies have shown linear plantings increase above ground biomass (i.e. carbon sequestration) compared with block planting (Henskens et al., 2001; Paul et al., 2015, 2016).

- Heat stress

  Tissue damage and tree mortality can occur following exposure to temperatures above upper thermal limits, and high temperature has been implicated as a contributing factor in a number of global forest mortality events (Matusick et al. 2013; Mitchell et al. 2014; Allen et al. 2015). Extreme heat may limit tree growth in summer, as observed in European forests by Angert et al. (2005) and Ciais et al. (2005). As noted in Sections 3.3.1 and 3.3.2, in addition to increasing mortality, heat stress may also decrease long-term carbon storage due to the diversion of resources away from growth to heat shock proteins (Bita and Gerats 2013; Teskey et al. 2015), particularly when the frequency of heat stress is relatively high compared to the time required for tissue recovery (Curtis et al. 2014).

Plants have the capacity to acclimate to varying temperatures, as illustrated by seasonal variation in thermal limits (Battaglia et al. 1996; O'Sullivan et al. 2013). This 'hardening' to seasonal temperature changes may be enhanced by short periods of exposure to non-optimal temperatures that elicit a range of enduring physiological responses that benefit plants when more extreme conditions occur (Hoffmann et al. 2013; Walter et al. 2013). Irrespective of changes in mean annual temperatures, the increases in the frequency and severity of high temperature weather events to which plants have no time to acclimate have a strong influence on species survival and growth, particularly if combined with soil water limitations (Allen et al. 2009; Ögren 1994). High temperatures combined with drought have been implicated in mortality of both blue gum and radiata pine plantations (Butcher 1976; Ogren and Evans 1992). Species such as blue gum can be damaged or killed by short term exposure to temperatures between 40 – 50 °C, and by longer-term exposure to temperatures as low as 35 – 40 °C, and with little photosynthesis occurring at leaf temperatures more than 30 °C, where leaf temperature can be as much as 10℃ higher than air temperature (Macfarlane 1998).

In terms of heatwaves (number of days about 35 ºC), all cluster areas had an increase, although this was about 10% for Southern Slopes (all sub-clusters). The clusters with the largest increases in these heatwaves was clearly the Central Slopes, Murray Basin, East Coast (North) and Southern and South Western Flatlands (West) where the median increases were about 10 to 25%.

Pests and diseases

Pest and disease can also have significant effects on productivity of tree plantings (Carnegie and Ades 2002; Pinkard et al. 2006b; Rapley et al. 2009; Wardlaw 2001). Pest risk is a function of the vigour of the trees, the capacity of the trees to defend themselves against attack, and the abundance of the pest (Pinkard and Bruce 2011). These three aspects are discussed in turn below.

- Vigour of the trees and stand

  The sorts of impacts of climate change on plantation productivity described above suggest that in many locations host vigour may decline in response to climate change-induced physiological stress. For example, in a modelling exercise Pinkard et al. (2008) predicted that the impact of a given level of pest damage would increase under future climates for both blue gum and radiata pine, particularly at lower fertility sites or where water was limiting growth of the host.

  For reforestation projects that establish a mix of species, there will be much diversity in species when compared to plantings of a single tree species. This increased diversity of species within a stand provides resistance to pests and diseases (Old & Stone 2005; Singh et al. 2010).

- Defence mechanisms

  Plants rely on physical barriers and chemical defence mechanisms to reduce their vulnerability to insects and disease. Specific leaf area, the ratio of leaf area:dry mass, can enhance defence responses to leaf diseases (Smith et al. 2006), and can reduce damage from leaf chewing insects (Steinbauer 2001). This leaf attribute has been found to decrease in response to elevated CO_2 (Ayres et al. 2004) and water stress (Geiger and Thomas 2002), which may reduce pest damage to trees.

There are also interactions between the various risks associated with climate change. For example, fire-damaged or dead trees often become more susceptible to wood-decay fungi and attacks by pests and diseases (see earlier sections), which releases additional greenhouse gases, including methane (Singh et al. 2010).

Reductions in foliar nitrogen concentrations have been observed experimentally at higher atmospheric CO_2 concentrations (Ayres and Lombardero 2000; Hunter 2000), and are likely to decrease the survival and fecundity of the insects (Lawler et al. 1997), and also result in an increase in carbon-rich defence chemicals that may reduce insect damage (Ayres et al. 2004). However, the positive impacts of increasing temperature on pest may be negated by the negative impacts of persistent water stress. Persistent water stress: (i) decreases the concentrations of defence compounds (Ayres and Lombardero 2000; Kainulainen et al. 1998); (ii) increases concentrations of compounds such as glucose that favour fungal development (Desprez-Loustau et al. 2006), and; (iii) changes concentrations of chemical compounds in the stem (Desprez-Loustau et al. 2006; Kainulainen et al. 1998), and facilitates bark and cambial cracks (Pook and Forrester 1984) that increases the susceptibility of plantations to damage from stem borers and bark beetles (Old and Stone 2005).

- Abundance of the pest

  As mean temperatures rise (and particularly where this increases the length of the plantation growing season), many insect species are expected to respond by increasing their number of generations per year and the duration of feeding over the growing season (Ohmart and Edwards 1991; Ayres and Lombardero 2000). For example, increased summer temperatures are likely to accelerate the development rate and reproductive potential of insect pests, while warmer winters will increase over-winter survival (Old & Stone 2005). However, while increasing winter temperatures may facilitate range expansions of many pests (e.g. to higher altitudes and latitudes), increasing heatwaves in other regions may also limit the species' ranges (Burdon et al. 2006). The projected warmer and drier climatic conditions in southern Australia are expected to increase the distribution and activity of pine aphid, *Essigella californica* (Essig); leaf skeletoniser, *Uraba lugens* Walker; and eucalypt weevil (*Gonipterus scutellatus* (Gyllenhal) (Pinkard et al., 2008). Warmer climatic conditions are expected to favour reproduction and survival of autumn gum moth, *Mnesampela innamo* (Guenáa) but drier conditions would decrease the undesirable activities of this pest (Pinkard et al., 2008).

  The reductions in foliar nitrogen concentrations anticipated with higher atmospheric CO2 concentrations (Ayres and Lombardero 2000; Hunter 2000) may have differing impacts on pests and disease. It may decrease the survival and fecundity of the insects (Lawler et al. 1997), However, the resultant change in C:N ratio may result in increased foliage consumption by some pest species tolerant of low N availability, while others will be inhibited (Old & Stone 2005).

  In terms of diseases, changes in temperature, rainfall, soil moisture and relative humidity, as well as variability in these factors, all influence spore release and infection processes (e.g. Chakraborty et al. 1998). For example, in southern Australia, increased frequency of extreme wet and dry periods may increase incidence of the root rot pathogen *Phytophthora cinnamomic*. Persistent water stress increases concentrations of compounds such as glucose that favour fungal development (Desprez-Loustau et al. 2006). Also, for any diseases where cool winter temperatures restrict development, increases in survival during those periods because of increasing mean annual temperatures may result in more rapid disease development at the start of the host growing season (Ayres et al. 2004).

Diseased trees will not only sequester less carbon because of a reduction in biomass production, but they are likely to release greenhouse gases (e.g. methane) due to any increase in activity of decay causing microorganisms such as *Armillaria* spp., *Ganoderma* spp., *Phelinus* spp. And *Phytophthora* spp., and stem-rots and butt-rots (Tainter & Baker, 1996; Singh et al. 2010).

Fire

High-intensity wildfires consume large amounts of biomass, leading to large losses of carbon to the atmosphere (e.g. Bradshaw et al. 2013). Although this carbon may be re-sequestered via post-fire regrowth, burning biomass produces large quantities of potent greenhouse gases such as methane and nitrous oxides (with global warming potentials about 21–25 and 298 times that of CO_2 over 100 years, respectively). Hence, wildfires pose a significant risk to abatement in new tree plantings, particularly larger plantings that are not dispersed across the landscape (Jenkins et al. 2019). Reducing fire risk will be affected by climate change via its effect on not just weather, but also fuel load. These three factors are discussed in turn below.

- Fire weather

  Reduced rainfall, warmer temperatures and increased incidence of high temperature events are projected to increase forest fire weather risk over much of Australia (Booth 2009; Hennessy et al. 2005; Nicholls and Lucas 2007; Pitman et al. 2007). Indeed the increase in average fire danger index, or days/year FFDI > High, were generally consistent with increases in projected temperatures, with increases in all cluster areas, but the largest increases being projected in the Central Slopes where the projected increases in temperatures were the greatest. Similarly, the smallest increases were projected for the Southern Slopes Tasmania (East and West) where the projected increases in temperatures were the smallest.

  Higher temperatures, reduced rainfall and increased vapour pressure deficit are also likely to result in drier fuel (Hennessy et al. 2005; Matthews et al. 2011). Matthews et al. (2011) suggested that this, combined with an increase in the number of days of high fire danger, may increase the length and severity of the fire season and reduce the window for managers of new plantings to use prescribed burning to mitigate the risks from wildfires. Moreover, projected increases in frequency of lower rainfall, and hence, increased frequency of dry lightning in some regions may result in increased natural ignition (Steffen 2009; Dowdy 2020).

- Fuel load

  As described above, climate change may influence the productivity of new plantings. This will in turn impact fuel load given rates of litterfall and production of litter and CWD are directly related to the productive of the (Paul and Polglase 2004).

  In addition to influencing the rates of inputs of carbon into the fuel pools, climate change may also influence the rate of loss of carbon from fuel. The increases in leaf C:N ratio that have been observed in a number of species in response to elevated atmospheric CO_2 concentrations (Ayres and Lombardero 2000; Lawler et al. 1997) may influence litter decomposition rates.

While decomposition of both leaf litter and woody debris is faster at warmer temperatures provided there is adequate moisture (Hyvonen et al. 2008; Mackensen et al. 2003), increased C:N ratios have been shown to decrease litter decomposition rates (Hyvonen et al. 2008). This may further exacerbate fuel build-up.

Plantations with high risk of fire damage will be those that are older given they have a greater build-up of debris (Pinkard et al. 2010), with a woody weed understorey (Geddes 2006). Although even young plantations are also vulnerable where thinning debris is present.

For plantations and farm forestry plantings of relatively high value (e.g. due to wood production), residues produced post-pruning, thinning or harvesting may be burnt by land managers to reduce the risk of high-intensity wildfires (Forestry Plantations Queensland 2009; Singh et al. 2010). While planned fires (prescribed burning or hazard reduction burning) emit carbon they can be used to reduce the risk of more intense fires (e.g. Attiwill & Adams, 2008). However, questions remain as to whether planned fires results in an overall decrease in emissions (Bradstock et al. 2012; Volkova et al. 2014)

Drought

Although some species (e.g. sugar gum; *Eucalyptus cladocalyx*) have relatively high drought tolerance, many (e.g. blue gums) are suspectable to drought, with severe water stress resulting in premature leaf senescence and xylem embolism that can then result in tree mortality (Dutkowski 1995; White et al. 2009).

Droughts (% change in time in drought, or change in droughts/20yrs, or extreme drought duration) were projected to increase across all clusters when considering median changes to 2050, with the most pronounced increases projected for the South Western Flatlands (East, and particularly West). Apart from these clusters, most other clusters had some chance of droughts decreasing (albeit relatively small compared to the change of increase)- particularly in the Central Slopes and East Coast (North and South).

Impacts of drought on productivity of tree plantings can be exacerbated by warmer temperatures and heat stress. A number of mortality events in forests have been linked to drought stress combined with a period of hot weather (Groom et al. 2004; Mitchell et al. 2014). The projected increases in drought conditions and heatwaves suggest that there will be an increased risk of mortality in Australia's plantations under future climatic conditions.

Flooding

Flood damage can influence the long-term viability of new plantings in riparian zones. This may include damage to fences around the plantings, and/or burial of seedlings by sediment (Wedd and Erskine 2003). It may also facilitate increased soil erosion.

In terms of flooding potential (number of days per year > 99.9th percentile rainfall), there was a generally projected increase across all clusters. The largest increases (median 0.4-0.5 days) was fond in the Southern Slopes Tas (West), and the smallest increases (median <0.1 days) was found in the Southern and South Western Flatlands (West).

Storm Damage

Strong wind events can result in extensive damage to tree plantings, including stem breakage and uprooting (Wood et al. 2008). Plantations are particularly vulnerable to wind damage following thinning (Wood et al. 2008). As well as direct damage, there can be indirect effects such as damage to surrounding trees and pest incursions associated with that damage.

In the NRM cluster areas where new plantings are expected, projected changes in mean annual windspeed are relatively small (median change < about ±2%). The only clear projections in windspeed were found in Southern Slopes Tas (East and West) where windspeed was projected to increase (median increase of about 2 to 4%).

Although windspeed may not substantially increase by 2050, nevertheless, elevated CO_2 studies suggest that forests of the future may have larger crowns, greater leaf mass and reduced coarse root biomass than now (Ainsworth and Long 2005; Long et al. 2004), as well as lower-density wood (Yazaki et al. 2005). These changes may increase vulnerability of new tree plantings to wind damage.

Other carbon pools

The soil organic carbon (SOC) pools are not accounted for in any of the ERF methodologies for new forests. Nevertheless, SOC is an important component of the global carbon cycle since it represents twice the amount of carbon found in the atmosphere and about 75 % of the total terrestrial organic carbon pool (Prentice 2001). We know that SOC stocks increase following the establishment of new trees on ex-agricultural land, with average rates of sequestration between 0.02-1.8 Mg C ha^{-1} yr^{-1}, depending on the region (Paul et al. 2018), and tended to be highest in regions of relatively high rainfall, particularly on ex-cropland (England et al. 2016).

The storage of carbon in soil depends on the balance between gains and losses of carbon. Changes in climate are likely to impact the SOC pools via changes in carbon gains associated with changes in tree productivity and fires, and also changes in losses associated with changed rates of decomposition attributable to the balance between increases from increased temperature, and decreases from decreased rainfall and increased potential evapotranspiration (Albaladejo et al. 2013).

Viscarra Rossel et al. (2019) identified the relatively productive temperate climatic regions in southern Australia as potentially more vulnerable to losses of SOC in response to climate change as these regions tend to be relatively productive, thereby having more SOC (particularly the faster-turning POC pool) available to lose. The soil in these regions is most strongly influenced by climate (Viscarra Rossel et al. 2019). With hotter temperatures, the addition of fresh inputs into the faster-turning POC might also accelerate its rates of decomposition through biological priming mechanisms (Kuzyakov et al. 2000). This may result in additional losses of mineral-associated C from the more stable C fractions (Lajtha et al. 2014). The implication is that amplified rates of decomposition will reduce the ability of the soil in these regions to act as a sink for CO_2, leading to a more substantial net release to the atmosphere and a positive feedback effect (Jenkinson et al. 1991).

Most of the studies related with the controlling factors of SOC have been restricted to the surface soil horizon and only a few include the total soil profile. However, more than 50 % of the total SOC is stored below 20 cm depth (Batjes 1996). Jobbágy and Jackson (2000) reported that in temperate grasslands, 59 % of SOC is located between 20 and 100 cm depth. Consequently, minor shifts in these subsoil stocks of organic C will have considerable impact on the entire C balance (Don et al. 2007).

Summary

The majority of risks outlined in Table 13 are risks to accumulation. The main risks for maintaining abatement include the threats resulting from disturbance events such as heat-stress, pest/disease, fires and drought. In terms of risks to the portfolio, the main concerns relate to persistent increases in temperature, persistent increases in water stress, and disturbances from heat-stress and droughts. However, the only risks we have medium to high confidence in are those associated with persistent increases in temperature, heat-stress and fires.

Overall risk ratings were judged to be low for most risks influencing establishment of new trees, with only a decline in the storage of soil moisture at planting judged to be of medium risk. The overall risk ratings were generally judged to be higher with respect to impacts on long-term growth. The highest-ranking risks were from the persistent increases in water stress.

Table 13. Risk assessment for the Planting of New Forest activities.

Climate impacts (risk to establishment failure)	Science confidence in projection				Portfolio-level risks?	Risk to accumulation	Risk to maintenance
Heat-stress limiting plant growth and increasing mortality rates	High	Likely	Moderate	Medium	X	X	X
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium	Likely	Major	High	X	X	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Likely	Major	High	X	X	
Changes in timing/occurrence of suitable conditions for tree and crop establishment	Medium	Likely	Moderate	Medium		X	X
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening	High	About as likely as not	Minor	?		X	
Decreased frost days with implications for increased seed dormancy and reduced germination rates	High	About as likely as not	Minor	?		X	
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	Low	About as likely as not	Insignificant	Low		X	
Mechanical damage from wind and storms	Low	About as likely as not	Minor	Low		X	X
Direct impacts via secondary climate change variables							
Drought-induced plant mortality, with possibility of recruitment failure.	Medium	Likely	Moderate	Medium	X	X	X
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Low	Likely	Moderate	Medium		X	X
Indirect impacts via climate change impacts on weeds, pests and diseases							
Increase in invasive weeds	Low	Likely	Minor	Low		X	
Increase in browsing by feral animals	Low	Likely	Minor	Low		X	
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	Low	Likely	Moderate	Medium		X	X

3.3.4 Savanna fire management

Embedded Methodologies

SAVANNA FIRE MANAGEMENT - EMISSIONS AVOIDANCE (2015)
SAVANNA FIRE MANAGEMENT – SEQUESTRATION AND EMISSIONS AVOIDANCE (2018)

Savanna Fire Management projects currently comprise about 6.3% of contracted abatement under the ERF scheme (Table 8). In these projects, strategic burning is carried out with the intention of reducing large high intensity late dry season fires through increasing the prevalence of cooler early dry season fires. Planned burning occurs primarily in the early dry season and may include igniting fires from aircraft, from vehicles along the sides of roads and tracks, from boats on waterways, or by walking across country. Other fire management activities include burning firebreaks to prevent the spread of unplanned fire or undertaking fire suppression in the late dry season. The specific type and timing of fire management depends upon landscape features within the project area and local weather conditions.

Savanna fire management results in two potential sources of abatement. The first results from emissions avoidance, whereby abatement occurs through reductions in the non-CO_2 greenhouse gases methane and nitrous oxide. A second source of abatement is via an increase in carbon being sequestered in dead organic matter in response to fire management.

Proponents only wishing to participate in emissions avoidance activities can use the Emissions Avoidance (2015) methodology. Because this is an avoidance activity there is no sequestration, thus no associated permanence obligations. The second source of abatement that is recognised is the resulting increase in sequestration in dead organic matter, which is included in the Savanna Fire Management Sequestration and Emissions Avoidance (2018) methodology, which includes both avoidance and sequestration (although excluding sequestration in live biomass and standing dead pools). If electing to include sequestration, there are permanence obligations of at least 25 years. Only the sequestration component is considered in the risk assessments below.

Abatement calculations for the Savanna Fire Management Sequestration and Emissions Avoidance (2018) methodology can be conducted using the Savanna Burning Abatement Tool (SavBAT v3.0) which integrates all of the required historical spatial fire data with the required data on the spatial distribution of eligible vegetation, and calculates abatement using the formulae as specified by the method.

Spatial domain

There is currently 24,765,597 ha of savanna fire management projects across northern Australia. These are mostly distributed in the Monsoonal North (West) and Wet Tropics NRM cluster region, but with some projects also in the Monsoonal North (East) cluster region. Very few of these projects, however, have elected to include sequestration as an abatement option.

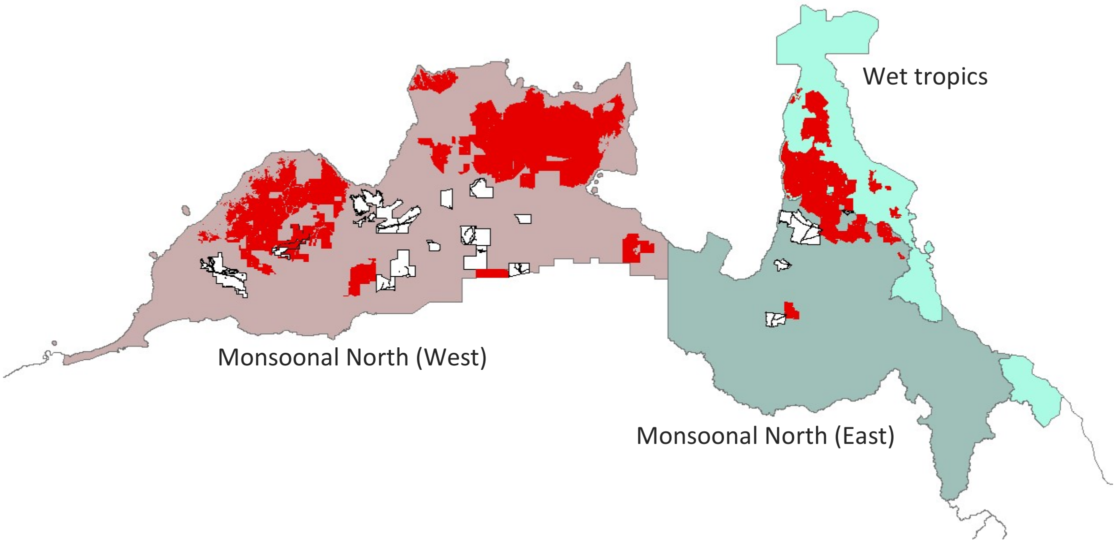

Figure 10. Sub-clusters containing existing ERF projects undertaking savanna burning projects. Red areas are existing projects undertaking emissions avoidance activities. Hollow areas are revoked projects.

These regions are dominated by tropical savannas (mostly woodlands) and constitute the most fire-prone landscapes in Australia. On an average year, more than two-thirds of fires observed across Australia occurred in these regions (Russell-Smith et al. 2007). As outlined by Russell-Smith and Whitehead (2015), in these monsoonal regions of northern Australia, intense bursts of high summer rainfall are separated by an extended annual dry season (southern winter and spring) ‘drought’. This drives an annual cycle of elevated fire risk alternating with periods of little or no fire risk. Therefore, a predominance of fires occurring in the latter part of the dry season, typically under severe fire weather conditions (periodically strong south-easterly winds, high temperatures, low humidity, fully cured fuels). Fire regimes dominated by frequent, large, late dry season fires are commonplace in many regions of northern Australia, especially the higher rainfall regions of Monsoonal North (West) (e.g. Kimberley region and the Top End) and the Wet Tropics (e.g. western Cape York Peninsula).

Land use is predominantly extensive beef cattle pastoralism, although this is economically marginal in frequently burnt, higher rainfall northern regions of the Monsoonal North (West) and Wet Tropics regions (Russell-Smith and Whitehead 2015). Therefore, much of the northern parts of Monsoonal North (West) and the Wet Tropics remain relatively intact and spared from land clearing or modification post European settlement (Lesslie et al. 2010). Much of this area is therefore National Parks, reserves, and Indigenous protected areas.

The carbon storage potential for tropical savannas in Australia is relatively low, with the maximum above-ground biomass typically being <40 Mg C ha^{-1} (Roxburgh et al. 2019), which is less than other tropical biomes (Grace et al., 2006; Murphy et al. 2014). This is partly because savannas are characterized by frequent fires that cause much of the carbon captured by vegetation to be released back to the atmosphere. Moreover, tropical savanna regions have a relatively short and variable growing season, with evaporation rates greatly exceeding rainfall for most of the year, and the timing of the onset and cessation of the seasonal monsoon is highly unpredictable (Russell-Smith and Whitehead 2015). Also, soils are often of low fertility or low water-holding capacity (Woinarski and Dawson 2002).

Specific changes in the climatic conditions impacting the vulnerability of savanna fire management projects are discussed in detail in the next section. However in general terms, future climatic projections up to 2050 suggest the Monsoonal North (West and East) and the Wet Tropics will have some of the highest increases in mean annual temperature of all NRM cluster regions across Australia- especially when considering the RCP8.5 scenario. For the RCP4.5 and RCP8.5 scenarios, the median increase of mean annual temperatures are projected to be between 1 and 1.8 ^{o}C by 2050, with this extent of increase consistent for both the wet and dry seasons.

There are contrasting changes projected for rainfall in the wet and dry seasons. Projections for the RCP4.5 and RCP8.5 scenarios up to 2050 suggest there will be negligible change in the median rainfall during the wet season (summer and autumn). However in the dry season (winter and spring) the median rainfall is projected to decline by between about 5 and 15%, although this is highly uncertain, with some models predicting significant increases in dry season rainfall, particularly in the Wet Tropics under the RCP8.5 scenario where increases of about 60% are considered possible.

Risk assessment against identified climate impact factors

Factors affecting the seasonality and severity of fires

There is projected to be an increase in both the average cumulative forest fire danger index and number of days per year where FFDI exceeds high. Moreover, the decline in rainfall is projected to be most pronounced in the dry season, thereby resulting in increased seasonal drought and thus, presumably increasing curing of grasses and drying of the fuel (e.g. Beringer et al. 2015). These projections all suggest that the frequency of fires of relatively high intensity may increase.

An increased frequency of high intensity fires may result in increased burn areas in the baseline over time, and thus, a greater potential for abatement from savanna fire management projects. However, with increasing frequencies of fires of high intensities, the risk that a late dry season fire will occur despite fire management is increased. When this occurs, project proponents are 'set-back' as there will be no opportunity to manage fire with an early dry season burn until fuel loads recover again post the late dry season burn. Hence, climate change may decrease the window available to conduct relatively cool early-season burns, thereby posing a risk to this methodology.

Factors affecting the maximum biomass potential of woody vegetation

The impact of fire management on live woody biomass is not accounted for in the savanna fire management methodologies. Nevertheless, any changes in the live biomass will directly impact rates of litterfall. This may require changes to the default assumptions for prediction of rates of fuel accumulation currently applied in SavBAT. There are two key factors likely to impact that maximum biomass potential of woody vegetation in tropical savannas, and these are discussed in turn below.

- Increased woodiness due to elevated atmospheric CO_2

  As described above for HIR/NfMR projects in the rangeland NRM cluster regions, the global phenomena of increased woodiness also seems to be relatively pronounced in Australia within the tropical savanna regions in the Monsoonal North (West and East) and Wet Tropics NRM cluster regions where a weak positive upward trend of woodiness has been monitored (e.g.

Burrows et al., 2002; Lehmann et al., 2009; Bond & Midgley, 2012; Murphy et al. 2014). All of these regions have in common water limitations supressing growth. Hence, the increased woodiness in these regions has been at least partly attributed to the increase in water use efficiency of photosynthesis with elevated atmospheric CO_2 concentrations (e.g. Donohue et al. 2013; Scheiter et al. 2014). Considering range of climate change simulations in Australian savannas, Beringer et al. (2015) predicted that tree biomass will increase with climate change, with this increase being primarily attributable to elevated atmospheric CO_2.

- Persistent increase in water stress

  As described above, mean annual rainfall is expected to decrease in the Monsoonal North (West and East) and Wet Tropics regions. A projected increase in potential evapotranspiration was also clear, although this was relatively consistent across both wet and dry seasons. The median projected increases in potential evapotranspiration were generally between bout 3 and 7%. Consistent with the rise in potential evapotranspiration, there was a general (albeit small) decline in relative humidity projected across all clusters. All of these changes in climatic conditions point to a persistent increase in water stress.

  A persistent increase in water stress is predicted to result in a decrease in carbon storage in Australian savannas (e.g. Scheiter et al. 2014), with clear evidence that basal area (or carbon storage) of Australian savannas (and savannas globally) increases with increasing mean annual rainfall (Lehmann et al. 2014). Indeed, there are clear differences in savanna fire management projects between the two key rainfall zones in Australian savannas. The default parameters applied in SavBAT differ for projects for the high rainfall zone (HRZ; > 1000 mm yr^{-1}) and low rainfall zone (LRZ; 600-1000 mm yr^{-1}). Thus, if the area of the HRZ was to decrease in size due to climate change, many projects within this zone may not attained the abatement anticipated, with abatement likely to become more representative of the LRZ.

  Moreover, even within the HRZ and LRZ, there may be shifts in the ecosystem in response to a persistent increase in water stress. For example, savanna open forest may shift to savanna woodlands when a critical threshold in water stress is exceeded (Hirota et al., 2011; Staver et al., 2011). Such changes will have implications on the woody:grass ratio, which in turn, has implications for the fuel loads (Paul and Roxburgh 2020).

Factors affecting post-fire recovery of woody vegetation

The capacity for vegetative regeneration post-fire is well developed in virtually all woody species in Australian savannas (e.g. Lacey 1974), and so although a savanna fire event may top-kill trees or shrubs, they typically survive (Williams et al. 1998; Liedloft and Cook 2007). This is attributable to a combination of re-sprout from epicormic buds and/or regrowth of saplings (Bond et al. 2012). Again, although the impact of fire management on live woody biomass is not accounted for in the savanna fire management methodologies, any changes to the rate of post-fire recovery of live biomass will not only impact the long-term average live biomass carbon stocks, but also directly impact rates of litterfall. This may require changes to the default assumptions for prediction of rates of fuel accumulation currently applied in SavBAT. Here we discuss risks imposed by climate change to these rates of recovery post-fire, and thus, the sensitivity of savannas to changes in fire regimes.

- Heat stress

  Even though tropical savannas are acclimatised to high temperatures, the Monsoonal North (East and West) regions are projected to be the areas of Australia that will have highest increases in heatwaves (or the number of days per year above 35°C). The number of heatwaves in the Monsoonal North was projected to increase by between about 35 and 65% by 2050; much more than any other region. Indeed, the Wet Tropics region was projected to have an increase in heatwaves of only < 10%. With increased frequency of heatwaves in savannas, we may anticipate increases the mortality of newly germinating seedling (e.g. Good et al. 2014), and so the rates of post-fire recovery may decline.

- Drought

  There is much evidence of tree die-back associated with severe drought periods in Australian savannas (Fensham and Holman, 1999, Fensham and Fairfax, 2007, Fensham et al., 2009). Kanniah et al. (2013) used satellite data to show that carbon uptake and carbon fluxes in Australian savanna systems were correlated to precipitation patterns.

  Given there are projected increases in the Monsoonal North (West and East) and Wet Tropics regions in the percentage of time in drought, the change in frequency of extreme droughts, and the duration of these extreme droughts, it may be anticipated that rates of post-fire recovery may decline.

Factors affecting fuel loads

There are five key factors directly influencing fuel loads that may be impacted by climate change. These are discussed in turn below.

- Inputs from biomass

  An increase in biomass will generally result in increased turnover and thus, fuel loads (Russell-Smith et al. 2009; Yates et al. 2015). Considering range of climate change simulations, Beringer et al. (2015) predicted that grass biomass in Australian savannas will increase with climate change, with this increase being primarily attributable to a persistent increase in temperate.

  Nevertheless, the impact of climate change on biomass is unclear as although it may decline with increasing water stress and slower recovery rates post-fire, this may be negated by increased water use efficiency with elevated CO_2 (see above two sections).

  Decomposition

  In addition to changes in the rates of input to fuel with climate change, there are also likely to be changes to the rates of loss due to decomposition. Rates of decomposition may also increase within rising temperatures- at least where there is adequate moisture (Shalin and Qiang 2002; Liski et al. 2003).

- Seasonality of turnover

  In Australian savannas, litterfall and the production of coarse woody debris is highly seasonal, with most inputs to fuel occurring during the seasonal drought (Williams et al. 1997; Cook 2003; Cuff and Brocklehurst 2015). Therefore, as the rainfall declines in the dry season, the seasonality of these inputs to fuel is anticipated to increase.

- Storm events and cyclone intensities

  In the Monsoonal North (East and West) and Wet Tropics, there is an increase projected for the number of days per year where the rainfall will exceed the 99.9th percentile. Although there is no evidence that the number of tropical cyclones will increase in Australia (and in fact they may decrease in numbers), there is some evidence to suggest that maximum tropical cyclone intensities (i.e. wind speeds) are likely to increase (Walsh et al. 2004; App 2012). This observation was consistent with the projection of increasing windspeeds during the summer months (when cyclones may occur), particularly in the Wet Tropics.

  There is evidence in Australian savannas that lightning strike and windthrow associated with storms may contribute to mortality, and hence, fuel loads (e.g. Lonsdale and Braithwaite, 1991). Hence, an increase in storm events and cyclone intensities may result in increased inputs to fuels.

- Weeds

  The ongoing and rapid spread of exotic gamba grass (*Andropogon gayanus*) across northern Australia’s mesic savannas has the potential to transform fire regimes in coming decades, dramatically increasing typical fire intensities (Setterfield et al., 2010) and reducing tree biomass. There are also similar threats from the flammable weedy mission grass (*Pennisetum polystachion*) (Csurhes 2005). These weeds have been shown to increase the frequency and intensity of land dry season fires. The increasing temperatures is expected to cause a southern shift in the distribution of gamba grass (Csurhes and Hanna-Jones 2016).

Other carbon pools

As mentioned above, the live biomass pool is currently not considered in the savanna fire management methods, yet climate change is likely to impact fuel accumulation rates via its impact on live biomass. Therefore changes to SavBAT default parameters will be required to ensure the methodology maintains accurate predictions of the impact of fire management on carbon sequestration in these fuels.

There is also some evidence that increasing woody biomass in savanna systems is paralleled by increasing soil carbon stocks (Coetsee et al. 2010; Murphy et al. 2014); however, the generality of such an effect is highly uncertain. Despite this uncertainty, changes in soil carbon stocks are likely to be very important, given that soil organic carbon is by far the largest pool in these savannas, representing about 75% of ecosystem carbon (Chen et al., 2003).

Chen et al. (2003) estimated that 74% of the carbon in a northern Australian savanna system is stored in soil organic matter and only 24% is stored in live biomass. How soil carbon stocks respond to fire or climate change is still uncertain. Richards et al. (2011) showed in a modelling study that soil carbon storage increased when fire return intervals increased from 1 to 5 yr but slightly decreased for less frequent fires. This implies that carbon storage in savanna ecosystems is maximized when fire return intervals are long. By contrast, field experiments show only weak impacts of fire on soil carbon (Beyer et al., 2011). Conversely, fires create resistant soil carbon in the form of charcoal-like substances, which are resistant to further decay and thus, over time, can accumulate.

Summary

Given savanna fire management projects have abatement calculated with respect to a baseline period that changes over time to ensure the most recent years are included in the baseline calculation, the risks will differ between existing projects and new projects. Unlike existing projects, in new projects going forward the baseline will be impacted by climate change.

A persistent increase in water stress was judged to be a high risk to both accumulation and maintenance. This is because a decrease in water availability will result in a decline in rates of fuel accumulation due to a decline in live woody biomass, and the rate of post-fire recovery of this live biomass. Under the current methodology, these changes would require updates to SavBAT defaults for litterfall, and hence, assumed rates of fuel accumulation for different vegetation types. With slower rates of fuel accumulation, there will be less abatement from fire management.

Of all the regions in Australia, the increases in temperature are projected to be the highest in the regions where savanna fire management projects occur. It is also a region that experiences cyclones, and these are projected to intensify. It is therefore likely that savanna vegetation will have increasing mortality rates associated with heat stress and cyclones. Increased rates of mortality will increase the fuel and thus, increase the abatement potential from fire management. However, this will be partly negated by increased temperatures resulting in increased rates of decomposition. With higher rates of decomposition, fuel loads will decline and the abatement potential from fire management will be less. Again, for the currently methodology to account for these changes, updates to SavBAT default assumptions of inputs and outputs to fuels will be required.

Fire intensity and fire weather is projected to increase, and this will increase the potential abatement from fire management. However, this will only be possible where project managers can manage fires carefully to minimise the chance of a late dry season fire accidentally occurring during the period of the project.

Table 14. Risk assessment for the Savanna Fire Management activities.

Direct impacts via primary climate change variables	Science confidence in projection	likelihood	Consequence	Risk rating	Portfolio-level risks?	Risk to accumulation	Risk to maintenance
Heat-stress limiting plant growth and increasing mortality rates	High	Likely	Moderate	Medium	X	X	
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium	Likely	Moderate/ Major	Medium/ High	X	X	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Likely	Moderate	Medium	X	X	
Mechanical damage from wind and storms	Low	Likely	Insignificant	Low		X	X
Direct impacts via secondary climate change variables							
Drought-induced plant mortality, with possibility of recruitment failure.	Medium	likely	Moderate	Medium	X	X	X
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Low	Likely	Moderate	Medium	X		X
Indirect impacts via climate change impacts on weeds, pests and diseases							
Increase in invasive weeds	Low	Likely	Moderate	Medium			X

3.3.5 Management of Intertidal Ecosystems (Blue Carbon)

Embedded Methodologies

METHODOLOGY UNDER CONSIDERATION

Blue carbon ecosystems include mangroves, tidal marshes and seagrass beds. Globally, the capacity of blue carbon ecosystems to sequester carbon and mitigate climate change is receiving increasing interest (O'Connor et al. 2020), based on relatively rapid rates of sequestration, and high levels of organic carbon below-ground, especially in soil organic matter. From their global analysis, O'Connor et al. (2020) identified restoration of degraded ecosystems to be the most promising management intervention, with indications of significant increases in carbon storage after four years, and suggestions ecosystem carbon stocks could recover to those of undisturbed systems in less than 20 years.

Kelleway et al. (2017), in their review of opportunities for including blue carbon in the Emissions Reduction Fund, identified the introduction (or re-introduction) of tidal flows to restore mangrove and tidal marsh ecosystems as the most promising intervention on which to base a future ERF methodology. This conclusion was based on an assessment against the ERF criteria for new methodology development, and the availability of suitable sites across Australia (Commonwealth of Australia 2019). Other management options that were considered, but were deemed unsuitable for further method development at this time, included avoided clearing (of mangroves) and avoided soil disturbance, land-use planning changes to facilitate mangrove and tidal marsh migration, restoration of seagrass ecosystems, avoidance of seagrass loss, and seagrass re-establishment.

Tidal marshes are coastal, saline ecosystems comprising a diversity of grasses, rushes, and herbs (and are often referred to colloquially as saltmarshes). They occur in the intertidal to supratidal zones of Australia's estuaries and sheltered coasts, and historically have been degraded or lost through land reclamation for infrastructure or agricultural use. For example, in SE Queensland mapping has shown that just 36% of the 1955 extent of tidal marshes remains today (Accad et al. 2016, cited in Kelleway et al. 2017). Mangrove ecosystems are comprised of trees and shrubs that are adapted to live in the saline intertidal zone of low-energy coastlines, with Australia having the third largest area of mangroves globally, occurring throughout the tropical north of the country, but also extending through the subtropical and temperate coasts of Australia's mainland. Extensive mangrove loss has occurred in areas of intensive coastal development (Kelleway et al. 2017).

The proposed activities associated with tidal marsh and mangrove restoration involve the re-introduction of tidal flows to promote the recovery of vegetation and associated re-sequestration of carbon into vegetation and the soil. Typical scenarios might include where tidal flow has been disconnected or restricted, e.g. through the building of levees, roads and sea walls, and where removing the barrier and reintroducing flow leads to subsequent re-sequestration in vegetation and the soil.

In both mangrove and tidal marsh ecosystems the majority of stored carbon is in the soil, with Kelleway et al. (2017) reviewing the literature and concluding approximately 90% of total carbon in tidal marshes resides in the soil, and approximately 75% for mangrove ecosystems. In mangroves the sequestration in woody biomass is also likely material, and thus it is proposed both above- and below-ground biomass, as well as soil carbon, be included as mandatory pools for accounting for mangrove ecosystems (Commonwealth of Australia 2019). In tidal marshes the biomass comprises predominantly herbaceous vegetation, and therefore reporting of biomass carbon is suggested to be optional (Commonwealth of Australia 2019). The potential for substantial loss of soil carbon from environmental disturbance is therefore a key risk for blue carbon activities. This includes both losses through direct soil disturbance, as well as losses over time due to reduced rates of organic matter input from reduced vegetation growth or mortality. In some instances, it may also be possible to claim for emissions avoidance, where the introduction of tidal flows inhibits or reduces the emissions of greenhouses gasses from the existing land (principally nitrous oxide and methane). The focus here, however, is solely on sequestration.

Spatial domain

There are relatively large areas of mangroves across northern Australia (Figure 11), although the vast majority of these occur in relatively isolated areas with little anthropogenic disturbance. Because the proposed methodology requires a change in current tidal management to re-introduce tidal flows, potential areas are therefore limited to those where previous developments for infrastructure or agriculture have taken place. Data on the extent of suitable areas is limited, though the area available for individual interventions is likely restricted. Kelleway et al. (2017) provided estimates of up to 35,000 ha of tidal marsh replaced by ponded pastures in Queensland, 62,000 ha of drained coastal wetlands in northern NSW (inclusive of both mangroves and tidal marshes), and several locations in South Australia where salt production ponds were developed, from as early as the 19th century. The potential domain is therefore spatially extensive across the coastal catchments of the continent where anthropogenic development has taken place (Figure 11).

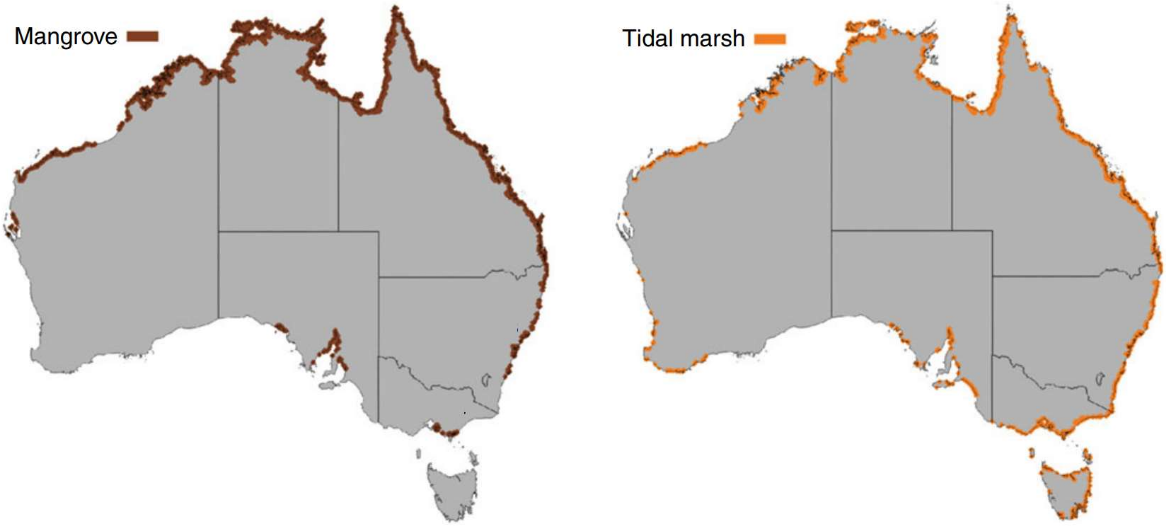

Figure 11. Spatial distribution of Australian mangrove and tidal marsh ecosystems. Re-drawn from Serrano et al. (2019)

Risk assessment against identified climate impact factors

For the Management of Intertidal Ecosystems (Blue Carbon) activity the distinction between disturbance impacts, and factors that impact on vegetation growth and ecosystem functioning, are less clearly separated than when dealing with terrestrial ecosystems. For example, a freshwater inundation event may induce physiological stress and impact growth rates over the long term (with implications for rates of accumulation), or if the disturbance persists, it may lead to mortality, and abatement losses. Lovelock et al. (2017) have developed a risk assessment framework for blue carbon ecosystems similar to that presented in Section 2.1, which combines likelihoods with various categories of consequence, with consequence quantified as being proportional to the soil carbon stock (on the basis the more there is to start with, the higher the potential loss). Although Lovelock et al. (2017) have identified a number of generic risk factors, and formulated a conceptual model of different pathways to emission due to direct and indirect disturbance impacts, no formal risk assessment was undertaken.

Factors affecting vegetation growth

Factors affecting soil respiration and soil microbial processes

There are two main mechanisms by which introducing (or re-introducing) tidal flows increase carbon sequestration. These are:

- Re-invigoration of native intertidal vegetation that leads to (a) higher above- and below-ground biomass, and (b) higher rates of turnover into the soil pool, leading to increased sequestration.
- Increased re-distribution of organic matter, either from within or external to the site, leading to enhanced build-up of carbon-rich sediments.

The opportunity for sequestration arises from the historical loss of biomass and/or soil carbon following the original intervention that impeded the tidal flow. For example, in tropical monsoon areas structures such as artificial levees have been used to create ‘ponded pastures’, which support pasture rather than tidal marsh or mangrove. In such systems soil organic carbon losses are accelerated as the soils dry and become more aerobic (Bu et al. 2015), with the removal and/or death of mangrove trees leading to significant losses of biomass carbon. Similarly, subtropical and temperate estuaries have been modified using levees or floodgates, to promote draining for agricultural use. In their conceptual model of risks to blue carbon, Lovelock et al. (2017) identified disturbance to the soil matrix, and disturbance to the primary producers, as the two primary pathways for loss. This distinction is also adopted here, but extended to include non-disturbance-related impacts of climate change factors on soil respiration, and on net photosynthesis.

The factors that reduce plant productivity, thereby reducing the rates of both biomass and soil carbon accumulation, are similar to those for terrestrial vegetation, primarily involving the potential for heat- and water-stress induced limitations to plant growth. However, precisely how such changes might affect carbon sequestration is difficult to predict (McLeod et al. 2011). For example, whilst increasing atmospheric CO_2 concentrations combined with a moderate increase in temperature might increase overall productivity, increasing temperatures are also expected to increase rates of soil respiration. The net effect on the total ecosystem is therefore difficult to predict, particularly as there are many additional factors in blue carbon ecosystems that can influence soil respiration, such as variability in the level of inundation, exposure to currents, and the presence of bioturbating organisms such as crabs (Lovelock et al. 2017). At the biogeographic scale mangrove distribution is controlled by temperature, with many species being frost sensitive, and with the latitudinal limit coinciding with the 20°C sea surface temperature (Asbridge et al.

2016). An overall increase in average temperature (Appendix B, Figure B1(a)) and a reduction in frost days (Appendix B, Figure B1(m)) is therefore expected to result in climate-induced latitudinal shifts to mangrove distribution.

A change in climatic extremes, particularly heatwaves and extreme temperature days, has the potential to disrupt growth, and potentially cause mortality. Across the nine sub-clusters that contain significant blue carbon ecosystems the change in the number of days year^{-1} expected to be greater than 35°C is projected to increase by approximately 50% (minimum 30%; maximum 76%; Appendix B, Figure B1(n)). This suggests extreme heat days are likely to be more common across the extent of potential project areas, though care needs to be taken with this interpretation given coastal environments can be quite different climatically than those inland. A recent example of the potential impact of extreme heat days is the mass mortality along approximately 1000 km of mangrove ecosystems in the Gulf of Carpentaria in 2015-2016 (Duke et al. 2017), where extreme temperatures (combined with drought conditions and a temporary drop in sea level) have been implicated in the event. This is discussed further under 'Combined Disturbance Impacts' below.

There is little consensus amongst climate models regarding the direction or magnitude of changes in average rainfall (Appendix B, Figure B1(d)), however there are implications for long-term changes in the exposure to fresh water for blue carbon ecosystems, particularly mangroves. Over the long-term gradual changes in rainfall are expected to influence mangrove distributions, for example through reductions in sediment salinity that facilitates faster growth, higher biomass, and lateral dispersal (Asbridge et al. 2015). Conversely, increasing aridity is expected to lead to reduced growth and spatial contraction. However, over the 2050 timeframe considered here, gradual changes in precipitation are expected to be secondary to changes in extreme rainfall events and drought. These factors are also discussed under 'Combined Disturbance Impacts' below.

Whilst changes in average temperature and associated variables such as evapotranspiration and relative humidity are likely to occur by 2050 and beyond (with overall *high* to *very high confidence*), the consequences for rates of carbon sequestration, and associated risks to abatement accumulation, are too uncertain to determine at this stage (Adam 2020). Of greater significance are losses associated with disturbances, which have implications for both abatement accumulation and maintenance.

Pest/Diseases

There is little current knowledge regarding the pests and diseases of tidal marshes. Adam (2002) in an extensive review of the structure, function and threats to tidal marshes globally did not list pests and diseases as a significant threat, though susceptibility to invasive plants was noted. For mangroves heavy infestations of insects leading to defoliation have been suggested[10], but hard evidence for this is elusive. Burrows (2003) made the observation that, traditionally, insect herbivory on mangroves was assumed to be low due to a depauperate specialised herbivore fauna, and that mangrove leaves are less palatable and less nutritious than leaves of other tree species. However, in a detailed exploration of herbivory rates in mangroves in Queensland,

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[10] https://wetlandinfo.des.qld.gov.au/wetlands/ecology/components/flora/mangroves/mangrove-dieback.html

Burrows (2003) concluded that rates of insect herbivory were similar to terrestrial forests, with mangroves supporting a diverse assemblage of insect herbivores. Herbivory impacts were particularly apparent on young and developing leaves, with leaf loss rates in the order of 7-36%, reducing average leaf longevity by 4-13%. The potential for extensive insect outbreaks, either under current climatic conditions or into the future, remains an open question (Cannicci et al. 2008).

Fungal diseases have been recorded in mangroves (Osorio et al. 2016, 2017), leading to mortality, such as reported for a community of river mangroves (*Aegiceras*) in Brisbane during the summer of 2006; and in the late 1970s, a soil fungus, *Halophytophthora* sp., caused large areas of dieback through leaf loss and trunk rot around Gladstone, central Queensland (Pegg et al. 1980). Interestingly, out of approximately 12 species of mangrove within the affected area, only one species was impacted. As for the potential for mass mangrove dieback from disease to significantly impact sequestration accumulation or maintenance, there is currently insufficient information on which to base an assessment.

Invasive plant species have been noted as a potential threat to tidal marshes. Adam (2002) reports several instances where the common reed (*Phragmites australis*) and *Typha* sp. Have invaded tidal marshes in urbanised areas subject to stormwater discharge, where a lowering of salinity and increase in nutrients has facilitated been observed to invade saltmarshes. Although unlikely to be of widespread concern, any proposed activity where such threats are possible should include a contingency plan for managing these invasive weeds. Tidal marshes are also susceptible to invasion by mangroves (Adam 2002; Asbridge et al. 2015), though in the context of the activities under consideration here such an outcome might be considered favourable – on the assumption the tidal flow intervention was not linked to conservation outcomes related specifically to tidal marsh restoration.

In summary, the likelihoods and consequences of pests and diseases to risks to accumulation and maintenance for blue carbon projects remains uncertain at this time.

Combined Disturbance Impacts

CHANGES IN SEA LEVEL
STORMS/FLOODING
DROUGHT/HEATWAVES

The spatial distribution of mangroves is inherently dynamic, with historical records showing significant fluctuations in expansion and retraction of Australian mangrove forests over time and over large expanses of coastline (10s – 1000s km), with associated waves of mortality and regeneration (Saintilan and Williams 2001; Asbridge et al. 2015). Similar, though more localised, changes to tidal marsh distribution have also been reported (Adam 2002). A combination of factors have been implicated in these changes, including fluctuations in sea level, drought and flood events, extreme temperatures, and changes to the rates of sedimentation. Because of the interactions amongst these factors, they are here treated together.

A reduction in sea level has been heavily implicated in the significant northern Australia mangrove die-back event in 2015-2016 (Duke et al. 2017, Lovelock et al. 2017). A drop in average sea level of approximately 20cm over the period arose from a persistent El Niño event that during strong years commonly leads to sea level declines in the western Pacific (and increases in the eastern Pacific). This correlated with the majority of the mortality occurring at the shoreline, with plants that maintained access to groundwater being less affected. Coincident with the event was a period of extreme drought and extreme high temperatures, placing plants further under stress and potentially contributing to mortality.

In contrast to El Niño-driven declines in sea level, sea levels are expected to rise on average over the long term. This is consistent with recent history, with increases of 1.5-2.0mm yr^{-1} from the mid-1800s to 1993, 2.8 to 3.6mm yr^{-1} between 1993 and 2010, and approximately 3.1mm yr^{-1} since. Projections are for sea levels to continue rising in the future, with Australia projected to experience an increase of approximately 0.12m up to 2030 (Figure 12), and up to approximately 0.45m by 2090. A simplistic scenario is that sea level rise will lead to landward expansion, where the seaward edge becomes inundated and plants die, but recruitment occurs as new land becomes increasingly intertidal, and this has indeed been observed (Asbridge et al. 2015). Saintilan et al. (2020) suggest mangroves would not be able to adapt to rates of sea level rise higher than 7mm yr^{-1}. However, predicting the overall response across different sites is complex, as the impact will also be mediated by the size and shape of estuaries and associated topography, water circulation patterns, freshwater and groundwater inputs, and climatic conditions (Asbridge et al. 2015). For example, mangroves can maintain position if rates of sediment accumulation increase proportionally to increased sea level rise, and increased precipitation and freshwater runoff can help promote establishment through making conditions more favourable to growth, through an influx of nutrient and through reducing salinity.

As the intensity and/or frequency of rainfall increases, then there can also be negative impacts, due to persistent inundation leading to ‘drowning’, and the burial of pneumatophores (‘air-breathing roots’) by increased rates of sediment deposition (conversely, increased erosion from flooding has also been observed). Studies of mangrove physiology have suggested long-term inundation by flooding will lead to reduced assimilation, and thus productivity; such impacts would also be expected in tidal marsh communities. Associated with more intense and frequent rainfall is the potential for increased cyclone and storm activity, which can lead to mortality through windthrow, losses in productivity due to leaf loss, and losses of soil organic carbon from increased current flow and subsequent erosion and sediment redistribution (Asbridge et al. 2015).

Under drought conditions salinity can increase leading to reductions in growth and limitations to regeneration, and as noted above, when combined with extreme heat events and reduced sea levels mass mortality can occur. As Asbridge et al. (2015) conclude, “If climate change predictions are realised, mangroves in some regions could soon be experiencing widespread mortality and losses to productivity due to significant reductions in photosynthesis and metabolism.” The same conclusion could undoubtedly be made for tidal marshes.

The key drivers included in the above discussion are all features of the current climate, and all are expected to intensify under climate change. The projected changes in extreme temperatures were summarised in the previous section, and extreme drought frequency and extreme drought duration are both projected to increase across the regions supporting blue carbon ecosystems (Appendix B, Figure B1(t,u)). By 2050, extreme drought frequency is projected to increase by 0.4 – 1.5 days per 20 years, and extreme drought duration to increase by 1 to 11 months. Although tropical cyclones are projected to become less frequent across the Monsoonal North, Wet Tropics and East Coast sub-clusters, the proportion of the most intense storms is projected to increase (*medium confidence*). Across all regions the expectation is for 13-75% increase in the number of intense rainfall days.

Mangroves and tidal marshes exist in high-energy environments, under conditions that are challenging for plant growth, and where plant growth is the primary mechanism by which these ecosystems are able to sequester high amounts of organic matter in the substrate (through increased biomass, sediment capture, and inputs from plant turnover). It is therefore understandable that these ecosystems are subject to several disturbance impacts than can, and do, lead to significant impacts on carbon storage. Lovelock et al (2017) in their in their conceptual model of blue carbon risk dynamics specifically include erosion and changes to sedimentation rates as an important risk factor for carbon loss, and in the Australian context Kelleway et al. (2017) discuss sedimentation rates as a mechanism for both the sequestration and loss of blue carbon. On face value it would appear the risk consequences for carbon, arising from either reduced rates of accumulation or losses, would therefore be high. However, much of the evidence for climatic impacts reviewed above comes from blue carbon ecosystems in environments that are have not been heavily impacted by anthropogenic activity. The basis of the proposed methodology is the restoration of tidal flows following previous management, through modification of existing infrastructure, such as levees or other barriers. It is therefore likely such areas will be at least partially protected from the worse impacts of storm surges and other direct mechanical disturbance. The major risks are therefore likely to come from combinations of changing drought, flooding, and changes in sea level. Because these factors can cause both accretion and loss of carbon, the magnitude and direction of change in carbon storage is uncertain. Given this uncertainty the combined risk rating is therefore deemed to be medium, arising a likelihood that such change will eventuate (‘Likely’), and that the worst impacts are likely to be moderated by existing site infrastructure, with a ‘Medium’ consequence. Overall, however, the confidence is *low*, given the uncertainty surrounding precisely where, and under what conditions, particulars site might either benefit or suffer growth declines or direct losses to stored carbon.

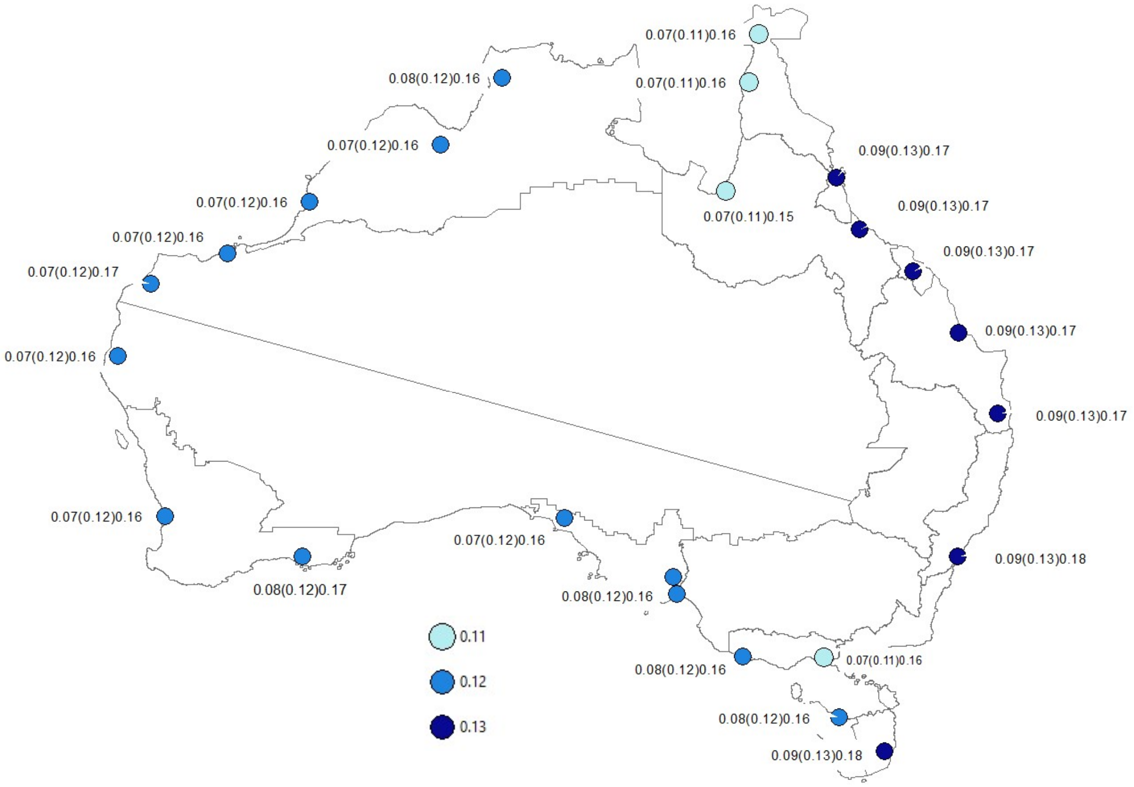

Figure 12. Projected 2030 sea level rise (m). Trends for 2090 are similar, with a range 0.44 – 0.48m.

Fire

Fire has been used in the control of invasive grasses in tidal marshes, and some Queensland tidal marshes have been historically burnt to encourage 'green pick' regrowth for grazing (Adam 2002). However, in general, the risk to loss of carbon sequestration due to fire is considered negligible.

Other carbon pools

Ecosystem-level carbon accounting under the proposed methodology is comprehensive. For mangrove systems the proposal is to include above-and below-ground living and dead biomass carbon, as well as soil organic carbon. For tidal marsh ecosystems the proposal is the same, although with the reporting of biomass carbon optional, given it forms only a small proportion of the total ecosystem carbon (Commonwealth of Australia 2019).

Summary

There are risks to both accumulation and maintenance for sequestration activities in Blue carbon ecosystems, however the primary drivers are connected and interacting, involving changes to sea levels (both short-term declines and long-term increases), drought, flooding and storm impacts, extreme temperatures, and impacts to rates of sedimentation and erosion. Because these factors can cause either accretion or loss of carbon, the magnitude and direction of change in carbon storage is uncertain, and hence identifying where and under what conditions particular sites might be at risk requires further detailed analysis. Despite this uncertainty, Blue Carbon ecosystems have historically shown dynamism in patterns of regrowth and mortality, and such changes are expected to continue into the future. An important question is how much protection projects might be afforded by existing infrastructure, such as levees and embankments, and how modifications to these structures to promote increased tidal flows can be undertaken in such a way as to not leave the regenerating systems vulnerable to some of the identified risk factors, particularly tidal surges and storm damage.

Table 15. Risk assessment for the proposed Management of Intertidal Ecosystems (Blue Carbon) activities.

Direct impacts via primary climate change variables	**Science confidence in projection**	**likelihood**	**Consequence**	**Risk rating**	**Portfolio-level risks?**	**Risk to accumulation**	**Risk to maintenance**
Heat-stress limiting plant growth and increasing mortality rates	High	Likely	Minor	Low		X	X
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Likely	Minor	Low	X	X	X
Changes to soil respiration and soil microbial processes	High	Likely	Minor	Low	X	X	X
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	Low	About as likely as not	Moderate	Medium		X	X
Flood-related soil erosion and deposition	High	About as likely as not	Moderate	Medium		X	X
Mechanical damage from wind and storms	Low	Likely	Minor	Medium		X	X
Coastal storm surges with implications for blue carbon stability	Medium	Likely	Moderate	Medium		X	X
Direct impacts via secondary climate change variables							
Sea level change, with implications for blue carbon stability	High	Likely	Moderate	Medium		X	X
Drought-induced plant mortality, with possibility of recruitment failure.	Medium	Likely	Moderate	Medium	X?	X	X
Indirect impacts via climate change impacts on weeds, pests and diseases							
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	?	?	?		X	X

3.3.6 Management of Agricultural Soils

Embedded Methodologies

MEASUREMENT OF SOIL CARBON SEQUESTRATION IN AGRICULTURAL SYSTEMS (2018)
ESTIMATING SEQUESTRATION OF CARBON IN SOIL USING DEFAULT VALUES (2015)

The basis of soil carbon sequestration is a change in land management that either increases the rate at which carbon is accumulated into the soil, or decreases the rate at which soil carbon is lost from the soil, or both. There are currently two available methodologies. The 'Estimating Sequestration of Carbon in Soil Using Default Values' calculates abatement through the use of lookup tables of sequestration rates under different activities and in different regions. It does not have any registered or contracted projects. The revoked 'Sequestering carbon in soils in grazing systems method (2014)' methodology has been replaced by the 'Measurement of soil carbon sequestration in agricultural systems' methodology, which requires the field-based measurement of sequestration, and compared to the 2014 methodology, broadens the list of eligible farming systems to include cropping, grazing and horticulture, and provides for additional measurement options to take advantage of the latest technologies for in-field and laboratory sensing to estimate carbon. It is receiving increasing interest with 50 registered and 11 contracted projects (as at May 2020), and a total contracted abatement of nearly 14 Million tonnes.

There are eleven allowable activities that can be applied under the 2018 methodology to build soil organic carbon, ranging from altering stocking rates and grazing management, through to stubble management and pasture improvement.

- Applying nutrients to the land in the form of synthetic or non-synthetic fertiliser to address a material deficiency
- Applying lime to remediate acid soils
- Applying gypsum to remediate sodic or magnesic soils
- Undertaking new irrigation
- Re-establishing or rejuvenating a pasture by seeding
- Establishing and permanently maintaining a pasture where there was previously no pasture, such as cropland or bare fallow
- Altering the stocking rate, duration or intensity of grazing
- Retaining stubble after a crop is harvested
- Converting from intensive tillage practices to reduced or no-till practices
- Modifying landscape or landform features to remediate land
- Using mechanical means to add or redistribute soil through the soil profile

Although this list represents a wide range of activities, across a potentially wide spatial domain, the common aim across all options is to increase the storage of soil organic carbon (SOC) in agricultural soils in a form that is persistent over the long term. The key risk factors are therefore those that impact on the rates at which that carbon in incorporated into the soil (principally through plant growth), and the rates of loss back to the atmosphere (principally through soil respiration, but also potentially direct disturbance, including erosion).

Spatial domain

The spatial domain for analysis includes six agricultural land-use classes extracted from the Land Use of Australia 2010-2011 coverage (ABARES 2016): grazed modified pastures, dryland cropping, dryland horticulture, irrigated pastures, irrigated cropping and irrigated horticulture (Figure 13). Agricultural activity occurs within all sub-clusters, concentrated within the Southern Slopes and South Western Flatlands, Murray Basin, Central Slopes and East Coast sub-clusters.

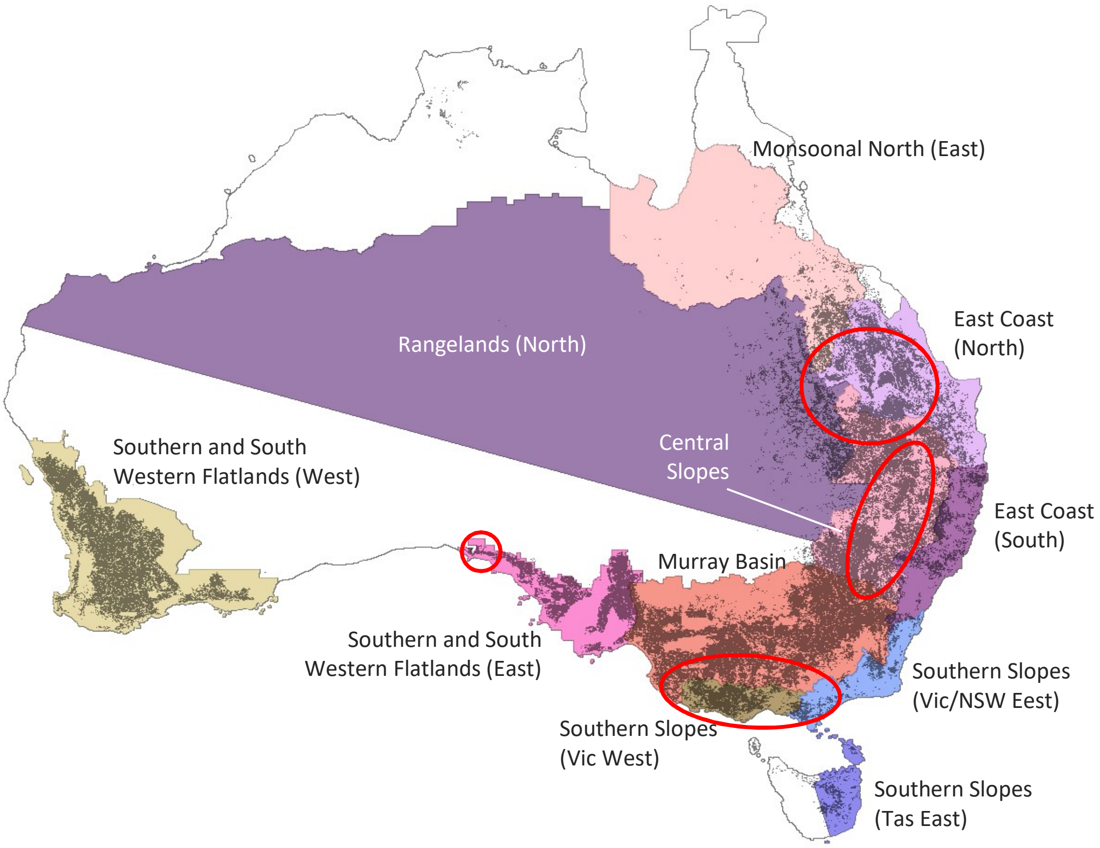

Figure 13. Spatial domain for the Management of Agricultural Soils activity. Grey area shows the distribution of Agricultural land use across Australia. Existing registered and contracted projects are located approximately within the red boundaries.

Risk assessment against identified climate impact factors

Soil carbon sequestration is widely regarded as a viable and enduring option for greenhouse gas mitigation, as evidenced by the ‘4 per mille Soils for Food Security and Climate’ goal announced at the COP21 UNFCC conference of the parties that produced the Paris Climate Agreement (Minasny et al. 2017). This equates to approximately 2-3 Gt C yr^{-1}, or approximately 20-35% of global anthropogenic emissions annually. However, significant social and economic barriers to achieving this goal have been recognised (Amundson and Biardeau 2018; Demenois et al. 2020). Increasing soil organic carbon also poses practical difficulties, such as the potential for reversal, and accounting for the many interacting factors, that vary spatially and temporally, that control rates of organic matter input and SOC losses through decomposition and erosion (Meyer et al. 2018).

These two controlling processes, organic matter input and loss, can respond differentially to a given set of climate change factors. For example, the expected plant growth response to increasing atmospheric CO_2 concentration, temperature and rainfall is an increase in plant production, and hence an increase in the rate of organic matter input. However, these same factors may also be expected to stimulate microbial activity in the soil, leading to increased decomposition. Whilst overly simplistic, this scenario illustrates the net effect on soil carbon storage to any given set of forcing variables may be uncertain. In general, factors affecting organic matter input and decomposition are expected to have implications for both risks to accumulation and maintenance; although losses are likely to occur over extended timeframes compared to, for example, instantaneous losses of biomass carbon from wildfire.

Climate change factors affecting rates of organic matter input and decomposition

- *Increasing atmospheric CO_2 concentration*
- *Increasing average temperatures*
- *Changes in rainfall and drought*

The main risk factors influencing rates of organic matter input are those that affect crop and pasture productivity, such as changes in atmospheric CO_2 concentration (with implications for growth and water use efficiency), temperature, and precipitation. There is a vast literature on the potential impacts of climate change on crop and pasture production, and a complete review is well beyond the scope of this report. Here we summarise the primary crop and pasture responses, with particular reference to Australia's main agricultural regions.

Elevated CO_2 has been observed to increase crop biomass and product yields across numerous experimental studies, although it is recognised responses in actual field settings may be lower than observed under idealised experimental conditions, where plants are unstressed and have access to plentiful resources (Tubiello et al. 2007). Positive growth responses to CO_2 fertilisation can be further moderated by changes in temperature and precipitation, for example increased temperatures with associated increases in potential evapotranspiration can increase demand for water. Differences in photosynthetic pathway are another factor, with C3 species generally considered to be more responsive to CO_2 compared to C4 species, though with C4 species relatively more responsive to temperature increase. The net response to increasing atmospheric CO_2 is therefore difficult to predict.

Studies that have simultaneously investigated temperature, precipitation and CO_2 fertilisation on crop and pasture growth have suggested some consistency in predicted plant responses. Phelan et al. (2014) investigated projected changes in temperature, CO_2 and precipitation across five sites in Tasmania, covering rainfed pastoral and wheat cropping agricultural systems. Increasing mean temperatures combined with an assumed slight increase in mean precipitation led to overall predictions if increased plant productivity. A key caveat to these conclusions is the assumption that patterns of rainfall do not change significantly. Across Tasmania mean temperature by 2050 is projected to increase 0.64(0.95)1.5 °C (*very high confidence*), although with a wide range of predicted outcomes for annual average precipitation change, from a -8.5% to a 4.4% increase by

2050. In a study of wheat yields at the continental scale, Ghahramani et al. (2015) compared current yields to those projected at 2030, and concluded little substantial change compared to the baseline with current management practices. Furthermore, they suggested possible yield increases might be possible applying currently available management options take advantage of moderate elevated atmospheric CO_2 concentrations and associated expected increases in water use efficiency.

In southeast Australia Cullen et al. (2012) investigated the response of pasture production to changes in temperature, precipitation and CO_2, across a range of sites that varied from Tasmania through to southern New South Wales. Little change or higher productivity was predicted across all sites with 1°C warming; whereas at 2°C degrees warming the C4-dominated site in New South Wales experienced growth gains, and growth at the other sites were stable or declined. As with the study of Phelan et al. (2014) rainfall variability and extreme events were not considered. The overall findings are consistent with the review of Lee et al. (2013) on climate change responses to pastures in southeast Australia, with a general tendency for growth increases under 2050 predictions of changes to temperature and precipitation, and with variability in rainfall likely to be the major driver of variability in pasture production. Across the two main cropping sub-clusters in southeast Australia (Murray Basin and Central Slopes) the predicted change in temperature are 0.9(1.3)1.7 °C and 1.4(1.0)1.2 °C, respectively (*very high confidence*). The range in predicted rainfall was -12.5(-1.0)6.5 % and -12.7(6.0)7.1 % for the Murray Basin and Central Slopes sub-clusters, respectively.

Whilst changes in average rainfall are generally variable between GCMs across the continent, with the direction of predicted change ranging from increase to decrease, for the Southern and South West Flatlands – West (FL-West) and – East (FL-East) sub-clusters there is a strong and consistent prediction of a decrease in winter rainfall (*high confidence*), of -18.0(-8.7)1.1 % and -16.8(-4.2)2.4 %, respectively. In Western Australia this represents a continuation of an historical trend for reduced rainfall since approximately the mid-1970s. Significant reductions in rainfall are expected to be reflected in reduced crop and pasture growth, and this is what has been observed. Scanlon and Doncon (2020) reported rainfall declines across the western Australian wheatbelt, during the peak growing months of April-October, of 14%-20%, coincident with reductions in wheat yield of 10-14%. In a modelling study Ghahramani and Moore (2016) explored a range of crops, locations (within Western Australia) and climate change scenarios, concluding crop yields are most likely to decline under the most feasible range of climate projections studies.

Although there have been many studies considering the gradual change over time in climate factors such as CO_2 concentration, temperature and precipitation, it is recognised that extreme events have the potential to significantly affect crop and pasture productivity (Tubiello et al. 2007; Sippel et al. 2018). However, few studies have specifically investigated the response of crop and pasture productivity to extreme events. An exception is Harrison et al. (2016) who undertook parallel climate scenario analyses in dairy pastures of southeast Australia, with one set of scenarios applying averaged climate change factors, and the other maintaining the same average, but adding variability to simulate extreme events (in terms of heatwaves, drought duration, and more extreme rainfall events). Overall, the scenarios embedding extreme event variability resulted in lower annual pasture growth, with up to 50% lower standing biomass by the end of the growth season. With respect to extreme events, all of the sub-clusters within which agricultural activity occurs in Australia (Figure 13) are projected to experience an increase in the number of days greater than 35°C (median increase 43%; range 17-71%); an increase in the number of days exceeding the 99th percentile rainfall (median increase 43%; range 14-76%); and variability in the change in extreme drought duration (minimum -0.36 months for Murray Basin; maximum 10.9 months (Southern and South Western Flatlands (West)).

Climate change factors affecting rates of soil organic carbon (SOC) loss

- *Increasing atmospheric CO_2 concentration*
- *Increasing average temperatures*
- *Changes in rainfall and drought*

Organic carbon inputs to the soil come from either the deposition of above-ground biomass components on the soil surface, or within the soil through root turnover, residues and exudates. Although the majority of incoming organic carbon will decompose over short timeframes and return to the atmosphere as CO_2, the components that are resistant to decomposition may be retained in the soil matrix through chemical recalcitrance, assimilated into decomposer tissues, or become bound to soil minerals (Baldock et al. 2012). Over time even these more biologically stable forms of SOC decompose with the carbon returning to the atmosphere. Building and retaining SOC therefore requires not simply increasing the rates of organic matter production, but also the retention of the more stabilised forms in order to balance the continuous SOC decomposition losses. Knowledge of the chemical composition of the soil is therefore critical to understanding the long-term stability, and the shorter term vulnerability. Three SOC fractions are commonly recognised: particulate organic carbon (POC; residency time ~7 years) which is relatively ephemeral, and thus at risk from loss; humic material (HOC; residency time ~50 years), which is relatively more stabilised; and resistant organic carbon (ROC; residency time >100 years), which is resistant to decomposition, and include charcoal and charcoal-related compounds.

Viscarra-Rossel (2019) mapped POC, HOC and ROC at the continental scale, and calculated the vulnerability of SOC to loss as the proportion of POC to (HOC+ROC)(Figure 14). This simply is the ratio of the mass of carbon most susceptible to loss (POC) to more stabilised forms (HOC + ROC). Summarising the distribution of vulnerability across the agricultural land within each sub-cluster suggests the areas most likely to support SOC management are those with medium to high vulnerability (Figure 14).

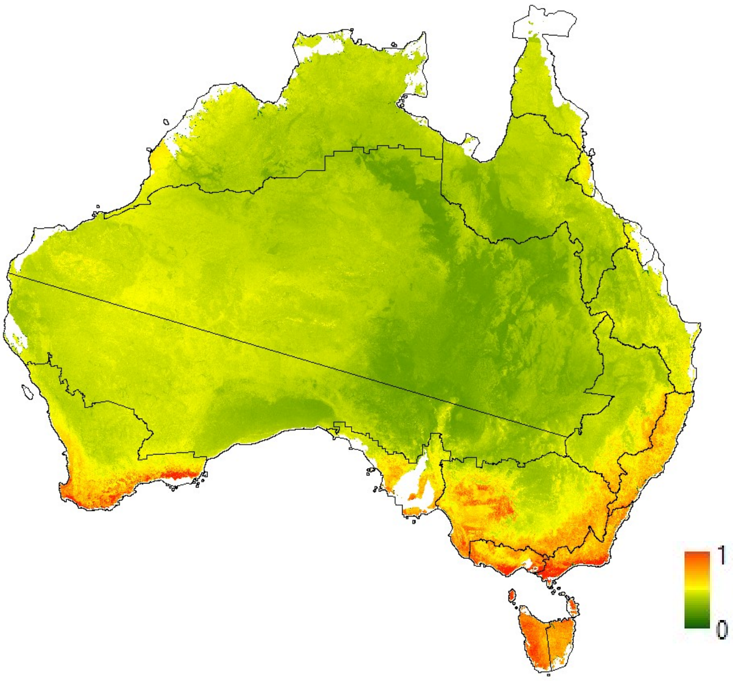

Figure 14. The soil carbon vulnerability index (POC / (HOC + ROC)) of Viscarra-Rossel et al. (2019).

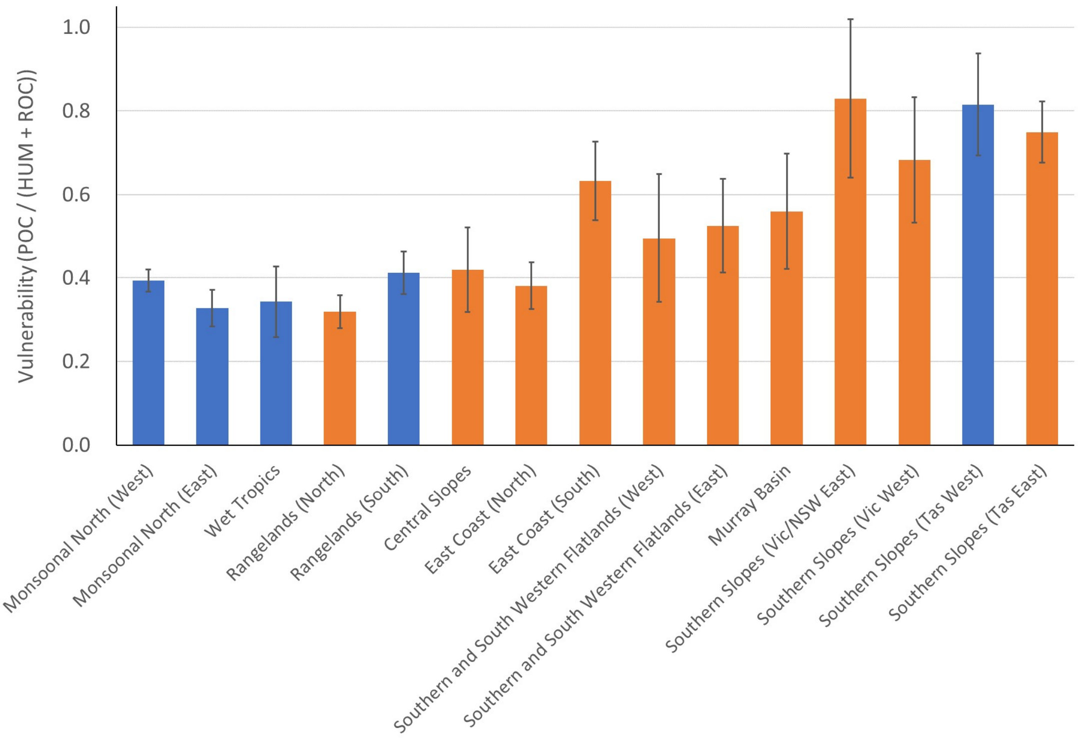

Figure 15. Soil carbon vulnerability of each NRM sub-cluster (mean and standard deviation). Orange bars are sub-clusters with agricultural activity.

The degree of vulnerability of SOC is a function of (a) the chemical composition of the organic matter, with the more labile POC fraction comprising more recent and readily decomposable plant matter, and the more stable fractions comprising organic matter that has been increasingly depolymerised (Conant et al. 2011), and (b) the degree of protection the material has from decomposition processes, such as binding to clay and other soil minerals.

Much research effort has been devoted to studying the response of soil carbon losses to increasing temperature, driven by a concern that anthropogenic warming could trigger the release of stored soil carbon globally, leading to a positive warming feedback with the atmosphere (Schlesinger and Andrews 2000). The ubiquity of increased soil respiration with increasing temperature has been confirmed across numerous laboratory experiments globally, where the temperature sensitivity factor Q_{10}, calculated as the rate of change of respiration with a temperature change of 10°C, has been reported with values for terrestrial soils in the range 1.3-3.3 (Oertel et al. 2016), and with a global average of 2.4 (Wang et al. 2018a). Under field conditions, however, other factors such as water stress can reduce the direst effects of temperature, for example by reducing the availability of nutrients to the microbial population.

To overcome the uncertainties of extrapolating laboratory experiments to real ecosystems, field manipulations are required. In their review of results from 49 globally distributed field experiments where artificial warming had been applied, Crowther et al. (2016) concluded strong empirical support for increased SOC loss as global temperatures increased, with the greatest losses in those soils with initially the highest stores of carbon. One of the major limitations of the analysis is that the studies did not include the feedback between rates of SOC loss, and impacts on rates of input (reviewed above). Indeed, the linkage between changes to rates of input via plant growth and loss rates remains one of the key knowledge gaps in carbon cycling research. For example, it has been hypothesised that simply increasing the rate of organic matter input to the soil may stimulate microbial activity, leading to compensatory losses due to enhanced soil respiration (the 'priming' hypothesis: Fontaine et al. 2007; Chen et al. 2019).

Gray and Bishop (2019) investigated the potential change in soil carbon due to combined changes in temperature and rainfall, using climate projections corresponding to ~2070. The study area included all of New South Wales and Victoria, and approximately half of South Australia and Queensland. Overall, SOC stocks were predicted to decline, although with marked spatial variability corresponding approximately to average annual rainfall, and hence plant productivity. In the most productive regions SOC stocks were projected to decline up to 10-20%, but in the less productive areas, including the major cropping areas, declines were in the order 2.5 to 5.0 %. It is important to note that the modelling did not consider the interactions with possible changes to plant productivity.

In a study of the response of soil carbon to climate change (to year 2070) under a range of cropping management practices across the entire cropping lands of Australia, Luo et al. (2019a) found, at the national level, a relatively small net emission from rainfed cropping soils. At a regional scale, and taking into account uncertainty in the model projections, Queensland cropping zones were consistently a net source of carbon from the soil, with up to a 20 tC ha^{-1} loss predicted. In temperate regions the results ranged from a net loss to a net gain, with an average suggesting a slight positive increase. This study included both the responses of plant production to climate factors, as well as direct impacts to soil respiration, and therefore represents one of the few attempts to integrate both the input and loss sides to understanding SOC dynamics.

Impacts of drought on soil respiration have also been widely investigated. In a global review Wang et al. (2014) concluded drought stress consistently impacts the main components of soil respiration (root respiration, microbial respiration and heterotrophic respiration (SOC decomposition)), and also leads to a de-coupling of above- and below-ground processes. Because the different components of respiration can respond differentially to different climate drivers, the impacts of drought stress can vary across different ecosystems, although the general tendency is for reduced rates of SOC loss with increasing drought intensity. In a study of change in SOC across 10 farms in New South Wales, Singh and Whelan (2020) recorded significant declines in SOC due to drought. Similarly, Meyer et al. (2018) in their exploration of the implications of both wet and dry future climate scenarios on SOC across western Victoria, found that under the more productive, wetter conditions SOC increased, but decreased under dryer conditions. This study, like that of Luo et al. (2019a), simultaneously included both changes to plant inputs to the soil, as well as decomposition losses. Karunaratne et al. (2014), also in New South Wales, reported a decline in SOC following drought.

There are two studies that have explicitly investigated SOC sequestration with respect to activities allowable under the ‘Measurement of soil carbon sequestration in agricultural systems’ methodology. In the first, Badgery et al. (2020a) tracked SOC changes following management change over 16 years at a site in Condobolin, New South Wales. The management changes included a control treatment (conventional tillage), and three manipulations (reduced tillage, no till and establishment of perennial pasture). In all manipulations SOC increased over the first 12 years, but then reversed such that at year 16 SOC levels were the same as at the start of the experiment. SOC measurements included the POC, HOC and ROC fractions, and in all cases the initial increase was predominantly in the more vulnerable POC fraction. The subsequent observed loss across all treatment is an important indicator of the likely variability in SOC over timeframes commensurate with those of a typical ERF project. Although there were no obvious temperature or precipitation drivers to explain these results, given the trends in SOC were common to all management interventions suggested the variability observed was not strongly related to management, with suggestions from the measurement of soil nitrogen that shifts in microbial activity associated with increased rates of nutrient harvesting may be implicated in the loss of SOC via respiration. Rabbi et al. (2015) similarly concluded that climate and soil related variables (such as clay content and pH) were the dominant drivers of the spatial variability of SOC across 1482 sites in eastern Australia (explaining 64% of the variability), compared to management practice, which explained just 1.4% of the variation. And across 615 sites in Victoria, Robertson et al. (2016) found 80% of the variation in SOC stock could be related to annual rainfall and humidity, and after accounting for climate variability, differences in SOC between different management types contributed minimally to explaining the residual variation, with changes in SOC not significantly related to management practice.

In the second study Badgery et al. (2020b) report results from a 5-year study of ten farms across central west New South Wales where a wide range of allowable activities under the methodology had been applied. Farms were chosen with low current carbon stocks (relative to the region) to maximise the chances of sequestration. After five years, increases in SOC were observed for all 10 farms, and statistically significantly so for 6 of the 10. Overall, an increase of approximately 0.25 to

1.8 tC ha^{-1} yr^{-1} was measured across different activities, with the highest rates associated with sowing perennial pasture with organic amendments. A control property, with no management change implemented, showed a slight decline in SOC over the same period. Two key caveats of this study are that additional emissions were not accounted for (e.g. due to additional fertiliser addition or changes to stock numbers), and that, because of the sensitivity of SOC to climate variability, the observed SOC stocks may not be able to be maintained, particular as the study period included only the initial responses of the treatments.

Pest/Diseases

The literature on the potential for climate change to alter pests and diseases dynamics in pasture cropping systems is voluminous, driven by the significant implications for human food production (Prakash et al. 2014). However, the overall impact of climate change can be either positive or negative depending on the nature of the pest or disease, and the host species. For example, elevated CO_2 can increase palatability by changing the chemical composition of leaves, such as a decreasing nitrogen content, which can increase insect damage through greater consumption to meet dietary needs. Higher temperatures may also mean more numbers of pests survive the winter season, and on larger scales a poleward spread of many pest and diseases has been documented. Conversely, beneficial effects of climate change are possible. For example, Wang et al. (2019b) concluded that seasonal outbreaks of the Australian plague locust are likely to decline across all seasons, due to a shift to unfavourable climatic conditions for the species.

Other Disturbances

FIRE

STORMS/FLOODING

Because SOC is, by definition, stored below ground, this affords some protection from many environmental disturbances such as high winds, storm damage and fire (excluding secondary losses through subsequent erosion). Extreme climatic events and droughts were discussed earlier in this section, in relation to impacts on plant growth and SOC decay. Other disturbances that could impact the sequestration of SOC are flood events, and fire. The primary pathway for fire to impact SOC in agricultural settings is via burning of stubble, undertaken to facilitate crop re-planting and to help control pests and diseases. The removal of fresh organic matter through fire reduces the amount available to enter the soil matrix, and fire can also affect soil quality such as a reduction in macro-aggregate stability (Chan et al. 2006). Because stubble burning is implemented as part of farm management, it is not considered a risk factor for SOC sequestration under the ERF methodologies. Wildfires are also possible in agricultural landscapes, for example up to 20 fires were started by lightening strikes in Western Australia's wheatbelt in 2018, with the largest burning approximately 3000 ha[11]; and in 2015 approximately 85,000 of cropping land was burnt in South Australia[12]. Although fire danger weather is expected to incease over the coming decades across Australia's agricultral areas (Appendix B, Figure B1(q,r)), which may see an increase in such

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[11] https://www.abc.net.au/news/2018-11-16/fires-damages-millions-of-dollars-worth-of-wa-crops/10504886

[12] https://www.abc.net.au/news/2015-12-01/farmers-hit-by-sa-bushfires-face-years-of-land-rehabilitation/6991176?nw=0

events in the future, direct risks to soil carbon sequestration are considered low (with a likelihood category of ‘likely’, and a consequence of ‘Insignificant’).

Flooding of agricultural soils can lead to both short-term and long-term effects on SOC, and the projections across Australia’s agricultural zone is for increases in both the frequency and intensity of extreme rainfall (Appendix B, Figure B1(o)), increasing the probability of flooding – although the confidence in timing and location of such events is low, given the high uncertainty in modelled rainfall projections. Flooding can have two impacts on stored soil carbon. First, there is the potential for erosion and topsoil loss. Second, if flooding is prolonged then roots can become starved of oxygen leading to plant death (Piao et al. 2019), and soil respiration. Long-term impacts of flood events on SOC are largely unknown.

Other carbon pools

The soil organic carbon pool is the only pool required to be measured within the ‘Measurement of soil carbon sequestration in agricultural systems’ methodology, with no requirement to account for changes in living biomass or debris. However, emissions of other greenhouse gasses must be accounted for, that are associated with the imposed management change, such as N_2O release following fertiliser addition, and CH_4 emissions from any increase in animal stocking rates. Such holistic accounting is important. For example Meier et al. (2020) demonstrated that gains in SOC associated with the replacement of cropland by permanent pastures were offset by increased emissions from livestock, although Badgery et al. (2020a) as part of their broader study reported one site where the replacement of cropping with sheep grazing did not lead to a net increase in emissions.

Summary

Given the range of potential responses of crop and pasture growth to climate change, it is difficult to generalise what the risks might be to reduced rates of organic matter input to the soil, with both positive and negative growth responses possible depending on circumstances. Because the choice of timing and species selection for crop establishment is under management control, and because pastures are herbaceous with a strong capacity to recover both vegetatively and from seed, there is potential for growth to be maintained over the short term. However, the long-term implications of a gradual change in climatic conditions on crop and pasture growth are uncertain, and in part are subject to adaptive management interventions such as shifts in the timing of crop establishment, and choice of crop species/cultivar. A review of the potential responses of SOC decomposition to climate change indicated a consistent prediction of increased rates of SOC loss under a range of factors, particularly temperature and rainfall. However, disentangling the relative balance between organic matter input and decomposition loss is a difficult task empirically, and in most studies it is the net change in SOC that is reported.

A number of modelling studies had suggested variability in climatic conditions and soil properties is the primary driver of variability in SOC, with management changes only playing a minor role (e.g. Rabbi et al. 2015; Robertson et al. 2016). Furthermore, the importance of understanding what SOC pool fractions are being modified was bought into sharp focus by Badgery et al. (2020a), discussed above. In that study the management changes that were implemented across 10 sites all resulted in an increase of the faster turnover POC pool. Because this pool is most vulnerable to loss

(Viscarra-Rossel et al. 2019), then the risks to maintenance and/or accumulation are significantly greater if it is this pool that increases the most following a change in management. This was borne out by the Badgery et al. (2020a) results that showed a complete reversal of all SOC gains, across all 10 sites, over a 16 year period, and where the majority of gains were in the POC pool. Moreover, because the pattern of change was similar across contrasting management interventions, this further supports the contention that it is climate and other non-management-related factors that are the primary drivers of SOC dynamics. The likelihoods of the various climatic changes can all be considered 'likely', and given the evidence that gains and losses of SOC are strongly affected by climate and other non-management related factors, and that direct observations based on activities consistent with the ERF methodology showed reversal under current climatic conditions, the consequences are considered 'Moderate/Major', yielding a risk rating of 'Medium/High'.

Table 16. Risk assessment for the Management of Agricultural Soils activities.

Direct impacts via primary climate change variables	**Science confidence in projections**	**likelihood**	**Consequence**	**Risk rating**	**Portfolio-level risks?**	**Risk to accumulation**	**Risk to maintenance**
Heat-stress limiting plant growth and increasing mortality rates	High	Likely	Moderate/ Major	Medium/ High		X	X
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium	Likely	Moderate/ Major	Medium/ High		X	X
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Likely	Moderate/ Major	Medium/ High		X	X
Changes in timing/occurrence of suitable conditions for tree and crop establishment	High	Likely	Insignificant	Medium		X	X
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	High	Likely	?	?		X	X
Decreased frost days with implications for increased seed dormancy and reduced germination rates	High	Likely	?	?		X	X
Changes to soil respiration and soil microbial processes	High	Likely	Moderate/ Major	Medium/ High		X	X
Changes to timing/seasonality of crop growth.	High	Likely	Moderate/ Major	Medium/ High		X	X
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	High	Likely	Minor	Low		X	X
Flood-related soil erosion and deposition	High	Likely	Minor	Low		X	X
Direct impacts via secondary climate change variables							
Drought-induced plant mortality, with possibility of recruitment failure.	Medium	About as likely as not	Minor	Medium		X	X
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Low	Likely	Insignificant	Low		X	X
Indirect impacts via climate change impacts on weeds, pests and diseases							
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	?	?	?		X	X

3.4 Long-term (2090) outlook

The aim of this study was assess the potential impacts of climate change and associated disturbances on risks to sequestration in ERF projects, to approximately 2050, commensurate with the conclusion of a single crediting period from the present time. It is however instructive to look at how those risk factors might evolve towards the end of the century. Because this review was primarily qualitative, the relative importance of changes in the quantitative estimates of change between 2050 and 2090 are difficult to assess. For example, under the RCP4.5 scenario the change in continental mean annual temperature is expected to increase from approximately 1.0-1.5°C in 2050, to 1.3-2.0°C in 2090. Just how this increase will interact with other climate change factors (such as changes to rainfall) to affect, for example, plant growth rates or soil respiration, is difficult to quantify without the aid of process-based models, and more extensive analyses.

What is of interest in the context of this review is the consistency in the trends over the next approximately 100 years, and whether the conclusions based on the 2050 projections will generally hold for the end-of-century. Table 17 summarises the predicted trends in the 21 climate factors listed in Table 7 between 2050 and 2090. Red cells in the table indicate that the climate factor is projected to increase both in 2050 and in 2090, with a black up arrow indicating an intensification of the trend, and a red down arrow indicating a weakening of the trend. Blue cells in the table indicate that the climate factor is projected to decrease both in 2050 and in 2090, with a black up arrow indicating an intensification of the trend, and a red down arrow indicating a weakening of the trend. White cells indicate either no change relative to baseline, or a change in sign of the indicator between 2050 and 2090. Across the 21 variables x 15 sub-clusters 21/315 or approximately 7% of cells in the table indicate a weakening in the trend, predominantly associated with changes in the projections of the wettest day. Approximately 10% (30/315) of cells in the table indicate either no change relative to baseline, or a change in sign of the indicator between 2050 and 2090. The vast majority (84%) of climate factor x sub-cluster combinations therefore indicate a continuation and further intensification of current trends. This suggests the conclusions based on projections to year 2050 will be generally applicable towards the end of the century, although the actual consequences are difficult to determine given uncertainty in the model projections increases over time, and given the qualitative basis on which the 2050 conclusions were conducted.

Table 17. Climate Indicator comparison of 2050 and 2090 projections relative to the baseline years 1986-2005 (median projected change across global circulation models). Red cells indicate a predicted increase in the indicator for both 2050 and 2090 relative to baseline. Blue cells indicate a predicted decrease in the indicator for both 2050 and 2090 relative to baseline. White cells indicate either no change relative to baseline, or a change in sign of the indicator. Up arrows indicate a strengthening of the trend between 2050 and 2090. Down arrows indicate a weakening of the trend between 2050 and 2090. * = data unavailable.

Climate change factor		Monsoonal North (West)	Monsoonal North (East)	Wet Tropics	Rangelands (North)	Rangelands (South)	Central Slopes	East Coast (North)	East Coast (South)	Southern and South Western Flatlands (West)	Southern and South Western Flatlands (East)	Murray Basin	Southern Slopes (Vic/NSW East)	Southern Slopes (Vic West)	Southern Slopes (Tas West)	Southern Slopes (Tas East)
Mean temperature change (°C)	2050	1.3	1.3	1.0	1.5	1.5	1.4	1.3	1.2	1.2	1.1	1.3	1.3	1.0	0.9	1.0
	2090	1.8⬆	1.9⬆	1.4⬆	2.1⬆	2.0⬆	2.1⬆	1.8⬆	1.8⬆	1.7⬆	1.5⬆	1.8⬆	1.7⬆	1.5⬆	1.3⬆	1.4⬆
Maximum temperature change (°C)	2050	1.3	1.3	1.0	1.6	1.6	1.4	1.3	1.3	1.3	1.2	1.4	1.4	1.1	0.9	1.0
	2090	1.8⬆	2.0⬆	1.4⬆	2.3⬆	2.2⬆	2.2⬆	1.9⬆	2.0⬆	1.8⬆	1.7⬆	2.0⬆	1.8⬆	1.7⬆	1.4⬆	1.5⬆
Minimum temperature change (°C)	2050	1.3	1.3	1.0	1.4	1.3	1.3	1.3	1.3	1.1	1.0	1.2	1.2	1.0	0.9	1.0
	2090	1.9⬆	1.9⬆	1.4⬆	2.0⬆	1.8⬆	1.9⬆	1.8⬆	1.7⬆	1.6⬆	1.4⬆	1.7⬆	1.6⬆	1.3⬆	1.3⬆	1.4⬆
Precipitation change (%)	2050	0.1	-0.1	0.7	-0.5	-3.8	0.6	-2.0	0.5	-8.7	-4.2	-1.0	-0.7	-3.3	-1.5	-1.8
	2090	-0.7	-4.3⬆	-1.6	-4.6⬆	-4.8⬆	-4.2	-8.6⬆	-2.3	-11.5⬆	-6.7⬆	-5.7⬆	-5.0⬆	-7.2⬆	-1.6⬆	-0.8⬇
Shortwave radiation change (%)	2050	-0.1	0.0	0.0	0.0	0.3	0.5	0.4	0.6	0.6	0.7	1.1	1.4	1.5	1.2	1.3
	2090	-0.2	0.2⬆	0.1⬆	0.0	0.4⬆	1.3⬆	1.1⬆	1.5⬆	1.0⬆	1.1⬆	1.5⬆	2.2⬆	2.0⬆	1.6⬆	1.7⬆
Potential-evapotranspiration change (%)	2050	4.3	4.2	3.7	4.5	3.8	4.9	4.4	5.4	3.9	3.8	4.2	4.8	4.5	4.2	4.8
	2090	6.8⬆	6.4⬆	5.1⬆	5.1⬆	4.7⬆	6.8⬆	7.4⬆	7.8⬆	5.4⬆	5.1⬆	5.4⬆	7.5⬆	6.5⬆	5.6⬆	6.4⬆
Windspeed change (%)	2050	-0.1	0.0	0.3	-0.4	0.0	-0.5	-0.4	-1.3	-0.2	-1.0	-0.8	-0.4	-0.7	0.0	0.3
	2090	-0.9⬆	0.5⬆	1.0⬆	-0.5⬆	-0.4	-0.7⬆	0.5	-1.0⬇	-0.3⬆	-1.4⬆	-1.3⬆	-0.6⬆	-1.1⬆	0.2⬆	0.2⬇
Relative humidity change (%)	2050	-0.4	0.1	0.0	-0.5	-1.2	-0.7	0.1	-0.4	-0.9	-0.5	-0.8	-0.5	-0.5	-0.4	-0.4
	2090	-0.7⬆	-0.8	0.0	-1.1⬆	-1.6⬆	-1.6⬆	-0.9	-1.0⬆	-1.2⬆	-0.8⬆	-1.6⬆	-1.1⬆	-0.9⬆	-0.4	-0.5⬆
Coldest night change (°C)	2050	1.4	1.4	1.2	1.3	1.2	1.2	1.4	1.2	0.9	1.0	1.0	1.1	1.0	1.1	1.1
	2090	2.3⬆	2.3⬆	1.8⬆	1.8⬆	1.6⬆	1.6⬆	2.0⬆	1.5⬆	1.3⬆	1.3⬆	1.2⬆	1.4⬆	1.3⬆	1.3⬆	1.4⬆
Hottest day change (°C)	2050	1.5	1.5	1.2	1.7	1.7	1.7	1.4	1.8	1.5	1.4	1.7	1.8	1.4	1.2	1.5
	2090	2.0⬆	2.1⬆	1.7⬆	2.5⬆	2.6⬆	2.4⬆	1.9⬆	2.3⬆	2.0⬆	2.0⬆	2.4⬆	2.5⬆	1.9⬆	1.8⬆	1.8⬆
Wettest day change (%)	2050	7.9	9.6	10.8	3.5	2.8	6.3	1.7	4.4	3.6	5.4	7.1	5.5	11.2	4.6	7.5
	2090	12.2⬆	7.1⬇	11.6⬆	3.3⬇	5.3⬆	8.7⬆	0.7⬆	7.2⬆	6.2⬆	6.9⬆	4.5⬇	4.2⬇	7.6⬇	8.2⬆	6.5⬇
Wettest 1-in-20 year change (%)	2050	9.0	11.7	17.0	6.8	6.6	13.6	9.0	9.8	8.5	11.8	8.8	8.0	12.1	11.1	6.5
	2090	13.9⬆	10.0⬇	10.6⬇	10.7⬆	8.6⬆	18.1⬆	8.6⬇	15.8⬆	9.7⬆	9.1⬇	7.4⬇	4.9⬇	14.6⬆	11.0⬇	6.1⬇

Table 17. Continued.

Climate change factor		Monsoonal North (West)	Monsoonal North (East)	Wet Tropics	Rangelands (North)	Rangelands (South)	Central Slopes	East Coast (North)	East Coast (South)	Southern and South Western Flatlands (West)	Southern and South Western Flatlands (East)	Murray Basin	Southern Slopes (Vic/NSW East)	Southern Slopes (Vic West)	Southern Slopes (Tas West)	Southern Slopes (Tas East)
Change in number of days/year below 0 degrees (days)	2050	0	0	0	-0.1	-1.0	-6.9	-0.1	-0.2	-0.1	-0.7	-4.9	-0.6	-0.2	-1.3	-3.8
	2090	0	0	0	-0.2⬆	-1.2⬆	-9.7⬆	-0.1	-0.2	-0.1	-0.7	-6.3⬆	0.0	-0.2	-1.4⬆	-3.7⬇
Change in number of days/year above 35 degrees (days)	2050	49.3	36.7	5.3	29.8	16.2	15.2	11.9	2.8	10.6	7.5	10.4	2.1	3.7	0.0	0.6
	2090	71.9⬆	56.6⬆	9.0⬆	45.0⬆	24.0⬆	24.6⬆	20.3⬆	5.7⬆	14.3⬆	12.5⬆	17.1⬆	3.0⬆	6.0⬆	0.0	1.0⬆
Change in days/year > 99.9th percentile rainfall (days)	2050	0.2	0.3	0.3	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.3	0.1	0.3	0.5	0.2
	2090	0.3⬆	0.3	0.4⬆	0.1⬇	0.1	0.2	0.1	0.1	0.1	0.1⬇	0.2⬇	0.1	0.3	0.5	0.2
Change in number months/year <10th percentile rainfall (days)	2050	0.0	0.0	0.1	0.0	0.1	0.1	0.2	0.1	0.6	0.2	0.1	0.1	0.2	0.1	0.1
	2090	0.0	0.0	0.2⬆	0.0	0.1	0.2⬆	0.2	0.2⬆	0.6	0.2	0.1	0.2⬆	0.2	0.1	0.1
Change in annual average cumulative forest fire danger index	2050	57	1	38	469	625	339	145	107	248	303	288	75	320	*	50
	2090	210⬆	440⬆	81⬆	617⬆	823⬆	631⬆	267⬆	258⬆	370⬆	442⬆	471⬆	203⬆	396⬆		130⬆
Change in number days/year with FFDI > High (days)	2050	3.6	4.3	2.6	9.5	18.5	17.7	7.1	5.8	7.5	11.8	10.3	3.2	10.7	*	1.7
	2090	9.4⬆	31.0⬆	3.0⬆	13.3⬆	23.2⬆	28.0⬆	15.5⬆	8.0⬆	12.8⬆	14.1⬆	15.1⬆	7.2⬆	13.4⬆		4.2⬆
Change in time in drought (%)	2050	-0.8	-0.8	1.1	3.9	3.9	0.5	0.2	0.2	21.0	8.6.0	0.1	-1.7	-1.7	-1.7	-1.7
	2090	7.6	7.6	5.1⬆	10.5⬆	10.5⬆	11.0⬆	13.2⬆	13.2⬆	27.5⬆	18.5⬆	14.2⬆	9.8	9.8	9.8	9.8
Change in extreme drought frequency (droughts/20 years)	2050	0.4	0.4	0.7	0.3	0.3	0.3	0.4	0.4	1.5	1.5	0.0	0.6	0.6	0.6	0.6
	2090	0.7⬆	0.7⬆	0.4⬆	0.7⬆	0.7⬆	0.6⬆	0.7⬆	0.7⬆	1.7⬆	1.7⬆	0.8⬆	0.8⬆	0.8⬆	0.8⬆	0.8⬆
Change in extreme drought duration (months)	2050	1.1	1.1	1.1	*	*	0.2	2.9	2.9	10.9	1.8	-0.4	4.6	4.6	4.6	4.6
	2090	5.4⬆	5.4⬆	7.9⬆			5.5⬆	8.9⬆	8.9⬆	14.6⬆	6.1⬆	6.1	7.0⬆	7.0⬆	7.0⬆	7.0⬆

4 Whole-of-scheme mechanisms for mitigating risk

This section briefly reviews the main ERF mechanisms that are designed to mitigate risk and to provide flexibility for proponents to help manage climate related and other physical risks to sequestration. Note these whole-of-scheme mechanisms were not taken into account in the risk assessments in Section 3, nor in the development of the associated risk ratings.

4.1 Risk of reversal buffer

The risk of reversal buffer applies to all sequestration projects, reducing the carbon abatement issued by 5 per cent. It is simply a ‘flat tax’ that is applied to all carbon payments. The intent of the buffer is to protect the ERF (as a scheme as a whole) against short-term losses of sequestered carbon due to e.g. losses from fire disturbances, and to provide additional protection over and above other methodology-specific measures designed to reduce risks and ensure permanence. It is important to note the risk of reversal buffer does not confer any protection to individual projects, and at the project-level it remains the proponent’s responsibility to ensure any lost sequestration is re-established. Under the legislation there is scope to adjust this buffer as required, for example if this risk profile to projects changes appreciably. To date no significant sequestration losses have been reported, suggesting that the current buffer of 5% is set at an appropriate level. However, the results of this review may be a reflection that the two activities facing the greatest potential risks under current and future climate change (Planting of native forests, Management of agricultural soils) are those that have had relatively limited uptake, and thus relatively limited exposure to date. A thorough assessment of the most appropriate level for the risk of reversal buffer would require a numerical analysis of the likelihoods and consequences of the different risk factors identified in this report, to facilitate the calculation of the probabilities of reduced rates of sequestration accumulation and losses across under different activities, and in different locations nationally.

4.2 Permanence requirements

As noted in the introduction, activities that sequester carbon have permanence obligations to ensure that stored carbon remains locked up for a period sufficient to ensure greenhouse gas benefits have been realised. For projects that have a sequestration component, permanence is either 25 years or 100 years, elected by the proponent. If a 25 year permanence period is elected, then, in addition to ACCU payments being reduced by the 5% risk of reversal buffer, they are also reduced by a further 20% (or 25% in the case of short-rotation plantation forestry projects). For projects that elect a 100 year permanence period, only the risk of reversal buffer is applied.

Adopting a 25 year permanence period significantly reduces the exposure to risks from climatic variability and losses to disturbance, especially as, beyond the 25-year timeframe, projections of climate change factors from the global circulation models become increasingly uncertain.

Across the portfolio (Table 18) approximately 50% of projects that include a sequestration component have elected a 25 year permanence period, and 50% a 100 year permanence period. There are, however, marked differences between the different activity categories. Within the 'Protection of existing forests' category 92.4% of projects elected the 100 year permanence period. The majority of 'Planting of new forests' projects also elected a 100 year permanence period (60.9%), and the split for the 're-establishment of forest cover' activity was 45.8% with a 100 year permanence, and 54.2% with a 25 year permanence. In contrast, only 5.1% of the 'management of agricultural soils' projects have elected a 100 year permanence period. The single Savanna fire management project that has elected to include sequestration as part of reportable abatement has elected a 25 year permanence period.

It is interesting to note that the patterns of elected permanence period in Table 18 match the rankings of risk derived in Section 3.3, which indicated the lowest risks were associated with protecting existing forests (which have 92% of projects with 100 year permanence), activities with intermediate risks (planting of new forests and re-establishing native forests) had 61 and 46% of projects with 100 year permanence periods, and the activity with the highest risk profile (management of agricultural soils) has just 5.1 % of projects with 100 year permanence. Although the assumption proponents are selecting shorter permanence periods based on higher perceived risk needs testing, it is a feasible hypothesis given most ERF activity is mediated by a relatively small number of service providers, who collectively have both a deep knowledge of land based carbon sequestration, but also of the potential risk factors involved. It is also likely the risks on which proponents are basing decisions extend beyond physical risks to the abatement, such as a desire to maintain flexibility for land use options into the future.

Table 18. Summary of elected permanence periods across all projects listed in the ERF Projects register[1] (9 August 2020 update, including revoked projects).

Activity category	Number of registered projects	Number (%) with 25 year permanence	Number (%) with 100 year permanence
Re-establishment of native forest cover	345	187 (54.2)	158 (45.8)
Planting of new forests	156	61 (39.1)	95 (60.9)
Protection of existing forests	66	5 (7.6)	61 (92.4)
Management of agricultural soils	59	56 (94.9)	3 (5.1)
Savanna fire management	1	1 (100.0)	0 (0.0)
Management of intertidal ecosystems	NA	NA	NA
	627	(49.4)	(50.6)

[1] http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register

If fire or other environmental disturbance leads to a loss of sequestration, then the onus is on landowners to take actions to re-establish the carbon stores, and further ACCUs will generally not be awarded until the previous level of sequestration is restored. Alternatively, ACCUs equivalent to the lost carbon can be relinquished. In a previous review of the ERF scheme the Climate Change Authority noted the importance of permanence, and the risks to national GHG targets arising if carbon is lost and not replaced, with one possible outcome being the need for the government to purchase additional credits to meet the shortfall (Commonwealth of Australia 2017). To help guard against such outcomes there is therefore a need for effective enforcement of permanence obligations. This is achieved through a number of reporting and notification requirements, which in the case of those electing 100 year permanence, extend well beyond the 25 year project crediting period.

4.3 Flexibility to source ACCUs from the secondary market

When proponents enter into a fixed contract to deliver ACCUs under the current ERF reverse auction purchasing mechanism, there is no requirement that the ACCUs delivered to satisfy the contracted abatement come from the contracted project; any shortfall can be made up from purchases on the secondary market, or from other projects within the proponents portfolio, and where the secondary market facilitates the sale and purchase of ACCUs that are generated outside of those contracted with the Government. There are a number of possible sources for ACCUs to supply the secondary market, including projects that are out of contract but still within the crediting period and are still creating abatement, and projects that were registered but not contracted under auction.

4.4 Options contracts

The Clean Energy Regulator has recently introduced a new form of contract, the Options contract[13], which allows contract holders to better manage both their price and supply risks. Options contracts provide the proponent with the right, but not the obligation, to sell ACCUs to the Commonwealth. Although any abatement generated under an options contract must be tied to a single project (thus precluding the use of the secondary market to meet any shortfall, as described in Section 4.3 above), if anticipated abatement is not achieved, then the proponent may reduce (or cease deliveries) to the Commonwealth without penalty.

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[13] http://www.cleanenergyregulator.gov.au/DocumentAssets/Documents/Auction%20Guidelines%20-%20Option%20to%20Deliver.pdf

5 Potential for ERF activities to mitigate risk and contribute to farm-level resilience

5.1 Co-benefits

Environmental, biodiversity, cultural and social co-benefits associated with ERF projects have the potential to incentivise landholders to maintain (and hence secure) carbon stores in the land sector. For example, a management change that simultaneously increases soil organic carbon whilst at the same time increases farm profitability is likely to endure; whereas an activity of limited profitability focussing solely on carbon is likely to be seen as expendable.

Many land-based options for carbon sequestration additionally provide co-benefits in terms of food security, environmental sustainability and/or farm profitability. In this context, co-benefits are added positive benefits associated with GHG reduction and improved carbon management in farms. Co-benefits are well established in the agricultural literature, both in agronomic terms and from social, environmental, economic and policy perspectives (e.g. Bustamante et al. 2014; Fleming et al. 2019). Examples include enhanced biodiversity, improved soil health and productivity, and improved water holding capacity and management of erosion and salinity and improved livestock productivity gains. While each of these examples are benefits, it is important to recognise that trade-offs associated with on-farm GHG abatement projects are possible, such as the potential for decreased catchment runoff with extensive reforestation (Table 19). Understanding the complete range of co-benefits and trade-offs is an expanding area of research.

Although a number of land management options for sequestration also have the potential to increase overall profitability, to date, reliance on carbon price alone has been insufficient to drive broad scale adoption of carbon farming projects in the agricultural sector in Australia, due in part to high transaction costs, high opportunity costs associated with land use change, and a carbon price that is insufficient to compensate (Fleming et al. 2019; Sanderson and Reeson 2019). The notable exceptions are projects that involve avoided deforestation, management of regrowth, and savanna burning. These activities are concentrated in the semi-arid areas of NSW and Queensland, and Northern Australia, with their economic viability relying on large spatial scales of application, on lands with low or nil opportunity costs. Additional barriers that have been identified include lack of information and/or understanding by landholders on potential opportunities, and a perceived (or possibly real) lack of options suitable to their particular enterprises (Climate Change Authority 2018).

Recent research suggests that re-framing opportunities with increased attention to co-benefits and broader economic incentives, in addition to potential financial opportunities, could re-invigorate how carbon farming is perceived and adopted in the Australian agricultural sector (Fleming et al. 2019). Table 19 provides a summary of five broad categories of co-benefits for land sector carbon sequestration: Farm productivity, Soil health, Biodiversity & conservation, Water quality and quantity, and Socio-economic. These categories reflect a range of values and motivations that are relevant to how land is managed and can be used to better evaluate which abatement methods have the most economic value as well as the best outcomes across a range of non-GHG values.

Co-benefits that a common across many methodologies include improved and diversified income streams, increased soil health and reduced erosion, and improved biodiversity and conservation outcomes. Methodologies that have a spatially extensive footprint (savanna fire management and human induced regeneration) also tend to have the strongest benefits in the socio-economic category, particularly around poverty alleviation and employment, industry expansion, and improved recognition and respect of indigenous culture. Consistent dis-benefits include the potential for impacts on catchment water flows associated with widespread revegetation (although revegetation can also lead to hydrological benefits through e.g. the local redistribution of surface flows; Bennett et al. 2014), and the potential for conflict with other land uses.

Table 19. Matrix of co-benefits and dis-benefits associated with ERF methodologies.

		Activity										
	Co-benefit / dis-benefit	Measurement of soil carbon sequestration in agricultural systems	Savanna fire management	Human induced regeneration	Native Forests from managed regrowth	Reforestation by enviuronmental or mallee plantings	Reforestation and afforestation	Measurement-bsed methods for new farm forestry plantations	Plantation forestry	Avoided deforestation	Avoided clearing of native regrowth	Blue carbon
Farm productivity	Improved crop / pasture yields & farm productivity	🟩				▨	▨	▨				
	Improved / diversified income streams	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Improved animal welfare (e.g. shelter, reduced stress)					▨	▨	▨				
Soil health	Improved soil health via increased SOC	🟩										
	Increased soil stability / reduced soil surface erosion	🟩	▨	▨	▨	🟩	🟩	🟩	🟩	🟩	🟩	
	Mediation of dryland salinity				▨	🟩	▨	▨		▨	▨	
Biodiversity / conservation	Increased biodiversity & ecosystem function/resilience	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩
	Reduced biodiversity e.g. monocultures / homogenisation								▩			
	Improved conservation outcomes	▨	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩
Water quality / quantity	Reduced nitrogen / phosphorus / pesticide leakage	🟩			▨	▨	▨	▨	▨	▨	▨	
	Reduced water yields				▩	▩	▩	▩	▩	▩	▩	
	Improved water quality	▨			▨	▨	▨	▨	▨	▨	▨	▨
Socio-economic	Conflict / competition with other land uses				▩	▩	▩	▩	▩	▩	▩	▩
	Emissions offsetting (e.g. bioenergy, product substitution)						▨	▨	🟩			
	Reduced air pollution (e.g. particulates)		🟩	🟩								
	Employment creation		🟩	🟩					▨			
	Poverty alleviation		🟩	🟩								
	Introduction of new/diversified products to market					▨	▨	▨	▨			
	Promotion of new technical innovations	▨	▨	▨								
	Promotion / enhancement / expansion of an industry		🟩	🟩								
	Harminisation / improved efficiency of land use	▨			▨	▨	▨	▨	▨	▨	▨	
	Recognition / assimilation / respect of local/Indigenous knowledge		🟩	🟩								
	Promotion of equity in access to land, decision-making, knowledge		🟩	🟩								
	Increased community resilience		🟩	🟩								
	Enhanced capacity for indigenous commuinities to meet land stweardship obligations		🟩									
	Improved or clarified land tenure / use rights for local communities		▨	▨								

Legend

🟩 Strong co-benefit

▨ Marginal/potential co-benefit

▩ Marginal/potential dis-benefit

5.2 Long-term carbon security

The security of carbon sequestered by ERF activities is influenced by both gradual changes in mean climatic conditions and the associated increases in the frequency, severity and duration of extreme climatic events such as droughts and heatwaves. Unprecedented climatic conditions are already being experienced across Australia, such as the high temperature events recorded in southern Australia in the summer of 2013/14 and the unprecedented severity of the 1998-2009 drought in SE Australia CSIRO (2016). A key tipping point will be when ERF activities fall outside the current known range of suitable climatic conditions for the target species (Booth et al. 2014).

Adapting management practices has the potential to modify the risks of climate change for carbon security. Figure 16 illustrates the relationship between increasingly extreme climate change and the cost, complexity and risk associated with adapting to that change. The figure describes three levels of adaptation related to the degree of climate change that has occurred, that define the sorts of responses that will be required. The more the climate changes, the more complex and potentially costly, risky and disruptive are the management changes required (Stafford Smith et al. 2011).

In Zone 1, incremental changes in climate mean that conditions will mostly fall within the climate envelopes of the target species. Incremental changes in management will generally be adequate to manage the increased risk, with little change from current practices required. An example would be changing plant spacings in environmental or commercial plantings (Mendham et al. 2007). As climate change becomes more extreme, there will be a threshold above which these types of changes in management will become ineffective, and a new level of response will be required (Zone 2). Changing species or genotypes, or implementing different establishment techniques, are examples of this level of management change. As with Zone 1, these types of strategies will become ineffective as climate change becomes more extreme, requiring transformational change in management (Zone 3), for example a change in land use away from ERF activities.

The climate change scenarios described in this report suggest that, in the short term, Zone 1 and 2 strategies will be sufficient in most cases for adaptation. The more extreme climate changes projected for later in the century may require transformational change. Detailed modelling and scenario analysis are required to identify where, and under what climatic conditions, various adaptation strategies may be effective. This approach has been demonstrated for the plantation forestry sector, where models were used to identify the conditions under which thinning activities would reduce risk of drought mortality under future climate change scenarios (Battaglia and Bruce 2017).

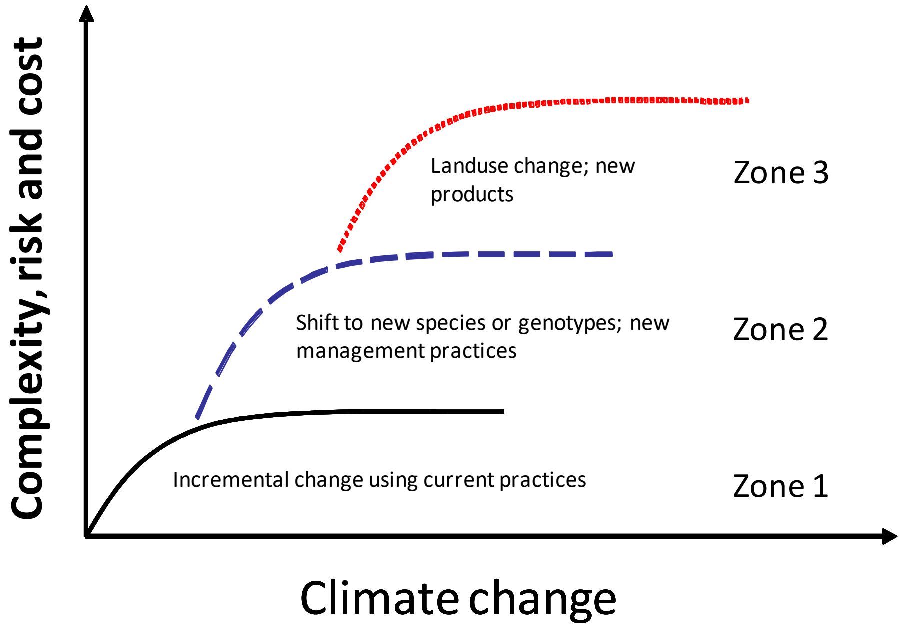


Figure 16. Relationship between climate change impacts, adaptation responses and the potential benefits from (or success of) adaptation (after Howden et al. 2010)

The following focuses on strategies for managing climate change impacts, from the perspective of managing exposure to climate change and sensitivity of species to those changes (Figure 17). We identify where possible the strategies relevant to zones 1 – 3 in Figure 16, for each of the six thematic areas.

Exposure refers to the direct and indirect climatic effects that can affect establishment, growth and survival within ERF activities. Heatwaves, frosts, drought and storms are examples of direct climatic effects; pests, weeds and fire are examples of indirect climatic effects.

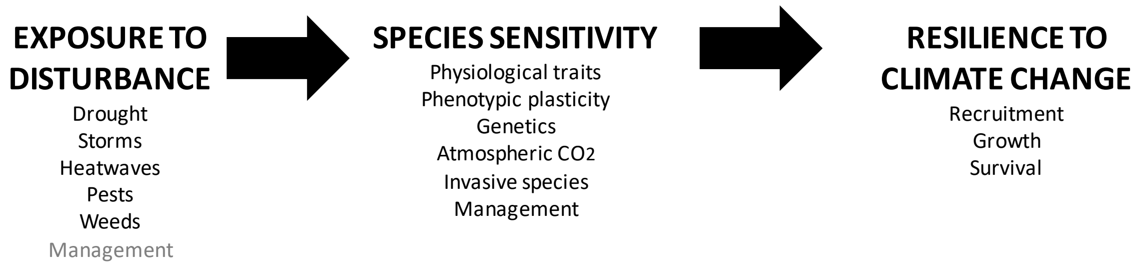


Figure 17. Conceptual overview linking exposure, sensitivity and resilience within the context of biotic responses to climate change.

Sensitivity refers to physiological and phenotypic traits, genetics, and external influences that affect physiological function such as atmospheric CO_2 concentrations. In reality, exposure and sensitivity interact to determine resilience to climate change. This is illustrated in Figure 18, which shows the mean annual temperature and mean maximum temperature in February for a site in eastern Australia, projected assuming moderate emissions and warming scenarios. Over the period 1990 – 2090, mean daily temperature is projected to increase from 14 – 26℃ at this site, and mean daily maximum temperature from 28 – 41℃. Leaf temperatures 10℃ warmer than air temperature are possible McFarlane (2004). Assuming a mean critical temperature for photosystem II of 45℃ (O’Sullivan et al. 2013), leaf temperatures may be significantly affecting carbon uptake by 2050 at this site. This analysis relies on a number of assumptions, and highlights a dearth of research on temperature thresholds for physiological processes. There is good evidence however of some capacity for plants to moderate their sensitivity to temperature through acclimation (Hoffmann et al. 2013), and of genetic variation within and between species in temperature sensitivity (Battaglia et al. 1996).

Another example revolves around plant strategies for water use. There is a gradient of species responses to water stress, from profligate water use up until a threshold is reached and hydraulic failure occurs, to a more conservative approach where stomata are shut at relatively low water stress and plants are reliant on stored C for survival (Mencuccini et al. 2015). Profligate water users tend to be fast-growing species, but under conditions of more frequent or intense drought, will be at greater risk of mortality than species using a more conservative approach. The capacity of woody plants to survive and recover from drought is related to their embolism resistance, which is described by the relationship between xylem pressure and the loss of hydraulic conductivity due to embolism (Choat et al 2012). Despite the variation observed in embolism resistance across rainfall gradients, Choat et al. (2012) found that most species across all forest biomes operated with a narrow safety margin, making them vulnerable to drought.

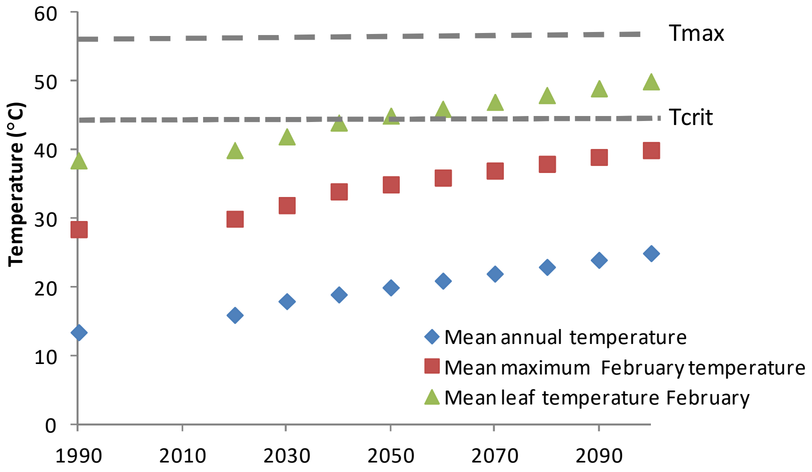


Figure 18. Projected temperature for a site in eastern Australia (32.24°S, 148.61°E), showing mean annual temperature, the mean maximum temperature in February, and the mean maximum leaf temperature in February (assuming leaf temperature is 10 °C higher than air temperature). Base climate data is for the period 1961 – 1990 (BOM). Climate projections used the CSIRO 3.5 GCM, with an A1FI emissions scenario, and assumed a moderate rate of global warming (www.csiro.ozclim). Heatwave conditions are not considered. T_{max} is the mean heat tolerance of dark respiration and T_{crit} is the mean heat tolerance of Photosystem II (O'Sullivan et al. 2013).

5.2.1 Strategies for improving long-term carbon security

The timeframe over which management decisions are made influences which management responses will be most appropriate. This is related to the degree of uncertainty about how the climate is likely to change (Stafford Smith et al. 2011).

Global circulation models are reasonably consistent in projections of climate change in the short term. Uncertainty increases with time, related to uncertainty about emissions scenarios and human responses to climate change. With short decision timeframes, there is more certainty about how the climate might change, and identifying appropriate management strategies is more straightforward. With increasing uncertainty (and timeframes), a range of possible futures needs to be considered, meaning that scenario analysis becomes an important tool.

Hallegate (2009) suggests four possible strategic and operational approaches that may be beneficial when dealing with longer timeframes. All aim to improve the robustness of decision-making in the light of uncertainty:

1. Apply 'no regrets' strategies that yield benefit even in the absence of climate change. An example might be the use in environmental plantings of genotypes more adapted to warmer and drier conditions;
2. Select reversible strategies that limit the cost of making the wrong management decision. For example, a decision could be made not to proceed with an ERF activity in an area considered to have high climate risk. If the climate changes are less extreme than predicted, then the decision could be reversed;
3. Add safety margins into management strategies to reduce vulnerability, such as making the decision to establish new plantings at a lower stocking density to manage water stress;
4. Reduce decision timeframes so there is more certainty around climatic conditions. Instead of producing sawlogs on a long rotation, for example, the decision could be made to produce engineered wood products that can utilise smaller diameter logs while still meeting the ERF requirements for rotation length.

Table 20 provides an overview of common approaches to climate adaptation applicable to land-based sequestration. The literature is strongly skewed to commercial plantations, reflecting the focus of the industry on understanding its risk and adaptation options in recent years. Many of the strategies will not be applicable to all of the ERF methodologies under consideration in this report – the following section focuses on identifying activity-specific strategies.

Most of the strategies identified are classified as Zone 1, or incremental strategies (Figure 16), that may be effective under low – moderate levels of climate change. In order to better understand the sorts of conditions under which these strategies might be effective, and the frequency of occurrence of above-threshold climate events that are likely to occur within a given period of time (e.g. number of mortality-inducing droughts per 20 years). This is beyond the scope of the present study.

Table 20. Summary of the sorts of adaptation strategies that may be applicable to manage climate risk for ERF activities. Application time refers to whether they are relevant at establishment or post-establishment. The climate risk addressed relates back to Figure 17 (exposure, sensitivity). Zone refers to those identified in Figure 16.

Adaptation strategy	Application time	Climate risk addressed	Zone*	Description	References
	Estab, Post-estab (E, P)	Exposure, sensitivity (E, S)			
Project location	E	E	3	Selecting sites with more favourable climatic conditions for ERF activities, and avoiding those with greater risk profiles. This could involve risk mapping for specific activities and zones. For SOC projects, establish in areas not prone to flooding.	Pinkard et al. (2014) Battaglia et al. (2009) Wood et al. (2008) Select Carbon (2012)
Land use change	E	E	3	Relevant to the plantation forestry methodology, involving relocation away from riskier sites at the end of a rotation	Pinkard et al. (2014) Battaglia et al. (2009) Joyce et al. (2009)
Species/genotype selection	E	S	2	Selecting species and genotypes with physiological and morphological attributes that make them less sensitive to climatic conditions in specific locations e.g. frost, drought, heatwaves	Warren and Adams (2000) Gauthier et al. (2014) Rezende et al. (2014) Choat et al. (2012) Dutkowski (1995) Close et al. (2000)
Increased species/genetic diversity	E, P	S	2	The role of species and genetic diversity in spreading risks and providing ecosystem-level insurance associated with disturbance events and climate change	Matais et al. (2013) Loreau (2010)
Planting design	E	E	2	Managing water availability through planting design e.g. linear vs block plantings.	Henskens et al. (2001)

Feral animal management	E	E	1	Managing exotic and native animal browsing pressure to facilitate vegetation establishment	
Weed management	E, P	E, S	1	Weed control to reduce competition for resources (water, nutrients, light)	Baker et al. (1988)
Integrated pest management	E, P	E	1	Control insect and fungal pests when they reach threshold levels	Pinkard et al. (2013)
Fuel management	P	E	2	Reduce fuel loads, either using mechanical methods or fire. Note that for some ERF methodologies, emissions resulting from fire need to be captured	Cheney (1985) Cheney and Richmond (1980) Lacey (2008)
Fire management	P	S	1	Fire planning including fire breaks and fuel management to reduce risk of fire damage	CFA (2011) Lacey (2008)
Plant spacing	E	E	1	Establish new plantings at wider spacing to reduce competition for resources particularly water. This may be a short-term solution requiring further density manipulation once plantings have reached full site occupancy	Mendham et al. (2007)
Thinning	P	E	2	Reduce stand density to manage water stress as stands reach full site occupancy; rule of thumb for commercial plantations is 800 mm rainfall can support 800 stems/ha	White et al. (2009)
Fertilising	E, P	S	1	Can be used to rebuild crowns following defoliation from pests or storms, although may interact with water stress	Wardlaw et al. (2005)
Civil engineering	E	E	1	Considered design landscape re-construction for tidal flow for blue carbon projects, to enhance protection from storms and tidal surges.	
Plant breeding	E	S	2	Crop breeding programs for adaptation to drought and heat stress, and pests and diseases	Chapman et al. (2012).

5.3 Assessment of adaptation options against methodology categories

Re-establishment of native forest cover

These methodologies rely on regeneration, and management methods to support regeneration. There has been little specific consideration of strategies for adapting these to climate change. Options predominantly fall into the Zone 3 category (Figure 16, Table 20), based around redefining locations suitable for these activities where risk ratings are high. Zone 1-2 strategies, such as feral animal control (when it is additional to the specified management intervention) may be cost-prohibitive for these activities, particularly in light of the low risk rating for fire. Other Zone 1 adaptation responses include fuel management to reduce the likelihood of fire, management of any planned grazing to protect the vegetation when it is most vulnerable (for example during drought or after fire), and site selection protocols to ensure adequate propagules are present to support regeneration towards the required 20% canopy cover. This could involve ensuring adequate seedlings or vegetative reproduction on-site, or proximity to existing seed sources from adjacent forest stands (Nolan et al. 2019).

The requirement for this activity to demonstrate existing regeneration, and to monitor progress towards attaining forest canopy cover (20%) helps to inform outcomes and to manage risk. The requirement to demonstrate existing forest potential, in particular, provides significant mitigation against risks associated with mortality during the early vulnerable stages of regeneration.

Potential adaptation strategies to reduce exposure and/or sensitivity to climate change for this activity are given in Table 21.

Protection of existing forests

Activities in this category revolve around avoided deforestation and clearing of existing forests, meaning that establishment is not a consideration. As for the re-establishment of native forest cover activities, there are limited adaptation strategies available for protection of existing forests activities (Table 22). Zone 1-2 strategies such as fuel and fire management, while relevant, may be cost prohibitive, particularly in light of the low risk rating for this category of disturbance.

Inherent in this activity is the requirement to start with intact forest, which avoids any risks associated with establishment.

Planting of new forests

Methods in this category involve establishment of new plantings, with a range of planting width, tree density and configurations, and conversion of short-rotation plantation forests to long-rotation. Of all the methodologies, this category has the most options for adaptation. Adaptation strategies falling into Zone 1 – 3 categories (Figure 16) are relevant. The adaptation strategies listed below (Table 23) are most likely to be cost-effective for plantation-based activities.

A common climate adaptation strategy for commercial forests is to reduce the length of the growth cycle, so that alternative germplasm more adapted to emerging climatic conditions can be planted (Joyce et al. 2009). This may be incompatible with the Plantation methodology, that allows conversion from short to long rotation management, without other adaptation strategies such as modified spacing or some form of thinning. It is incompatible with the environmental planting methodologies due to permanency requirements. Applying wider spacings to plantings in lower rainfall areas has been demonstrated to improve survival and growth at least until there is full site occupancy (Mendham et al. 2007). Weed control may be required for a longer duration using this approach, which will affect establishment costs. Additional thinning may also be required once full site occupancy has been reached, to manage water stress.

Fertilising post-pest/disease damage can promote crown recovery (Wardlaw et al. 2005), although in low rainfall areas this may result in increased risk of water stress associated with drought (Ward et al. (2005)).

Management of agricultural soils

Soil carbon sequestration ERF activities rely on additions of carbon in biomass into the soil via crop growth and turnover, but the same climate factors that impact rates of plant growth and turnover also affect losses of soil carbon from microbial-mediated soil respiration. The net sequestration outcome is therefore a balance between the rates of organic matter input, and losses from respiration. Climate adaptation strategies revolve around Zone 1 activities to limit reductions in the rates of organic matter production, such as pest control to reduce biomass losses to pest damage, growth reductions or plant mortality; Zone 2 activities such as selecting, or breeding for, species and genotypes more tolerant of climate extremes; and Zone 3 activities such as selecting sites projected to have less extreme climate. Warmer winters and associated impacts on seed dormancy, may necessitate sowing treated seed to boost recruitment. Luo et al. (2019b) noted SOC in the subsoil (i.e. below 30cm depth) generally exists in more stabilised forms, and hence would be expected to be less vulnerable to loss. Activities that target subsoil carbon might therefore be expected to be less susceptible to subsequent loss. There are, in general, few actions that can be currently undertaken to directly manage respiratory losses of soil carbon, although manipulation of microbial function to enhance soil carbon sequestration is an active area of research (Kellenbach et al. 2019).

Savanna fire management

Strategies for climate change adaptation for savanna fire management for sequestration have received very little attention in the literature, with the focus being almost exclusively on climate change impacts. Some climate changes may reduce biomass accumulation and fuel loads, and hence the risk of high intensity late season fires. Control of gamba grass may be an important adaptation strategy for managing fuel loads. Table 25 provides examples of possible adaptation strategies for this activity.

Management of intertidal ecosystems

There are limited adaptation strategies applicable to this activity, due to the focus on improving C sequestration of existing and rehabilitating mangrove and saltmarsh systems (Table 26). The consequences of storm surges and sea level change may be managed using engineering approaches. The sensitivity of vegetation to changing climate is less easy to manage, with the main strategy revolving around regular evaluation of where the vegetation is at greatest risk, and hence where this ERF activity may not be appropriate in the future.

Table 21. Examples of climate adaptation strategies that may be effective for ERF methodologies focused on re-establishment of native forest cover.

Direct impacts via primary climate change variables	**Risk rating**	**Adaptation strategy**	**Notes**
Heat-stress limiting plant growth and increasing mortality rates	Medium	Select alternative sites with less climate risk	
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium	Select alternative sites with less climate risk	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	Medium	Select alternative sites with less climate risk	
Changes in timing/occurrence of suitable conditions for tree and crop establishment	Medium	Select alternative sites with less climate risk	Climate risk modelling can assist in identifying locations with more acceptable risk profiles, or where risk may be effectively managed using the strategies outlined above
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	?	Select alternative sites with less climate risk	
Decreased frost days with implications for increased seed dormancy and reduced germination rates	?	Select alternative sites with less climate risk	
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	Low	Select alternative sites with less flood risk	
Flood-related soil erosion and deposition	Low		
Mechanical damage from wind and storms	Low		
Direct impacts via secondary climate change variables			
Drought-induced mortality in crops and trees, with possibility of recruitment failure.	Low/ Medium	Select alternative sites with less climate risk	
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk;	Low	Fuel and fire management	The target tree species for these activities are well-adapted to fire. Identifying changes in fuel load related to buffel grass incursion will help to identify where fuel loads may require management. Mapping changing fire danger for specific locations may be advantageous in better quantifying risk
Indirect impacts via climate change impacts on weeds, pests and diseases			
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	Feral animal management	Projected increases in browsing pressure from feral animals suggests that this strategy may be important to ensure adequate levels of regeneration are achieved. Costs may preclude this as a strategy

Table 22 Examples of climate adaptation strategies that may be effective for ERF methodologies focused on protecting existing forests

Direct impacts via primary climate change variables	Risk rating	Adaptation strategy	Notes
Heat-stress limiting plant growth and increasing mortality rates	Low	Select alternative sites with less climate risk	
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Low	Select alternative sites with less climate risk	Climate risk modelling can assist in identifying locations with more acceptable risk profiles, or where risk may be effectively managed using the strategies outlined above
Persistent increase in temperature, exceeding species climate envelope for optimal growth	Low	Select alternative sites with less climate risk	
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	Low	Select alternative sites with less flood risk	
Mechanical damage from wind and storms	Low		
Direct impacts via secondary climate change variables			
Drought-induced plant mortality, with possibility of recruitment failure.	Low/ Medium	Select alternative sites with less climate risk	
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Low	Fuel and fire management	The target tree species for these activities are well-adapted to fire. Identifying changes in fuel load related to buffel grass incursion will help to identify where fuel loads may require management. Mapping changing fire danger for specific locations may be advantageous in better quantifying risk.
Indirect impacts via climate change impacts on weeds, pests and diseases			
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	Select alternative sites with less climate risk	

Table 23 Examples of climate adaptation strategies that may be effective for ERF methodologies focused on planting of new forests.

Heat-stress limiting growth and increasing mortality of trees	Medium	Plant breeding, species/genotype selection; select alternative sites with less climate risk. Establishment of species/genetically diverse plantings.	Selecting species/genotypes with higher heat tolerance may improve rates of carbon sequestration. Under more extreme climatic conditions, a shift in land use away from these ERF activities may be required
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	High	Initial spacing; planting design.	Appropriate for all activities involving new plantings. Weed control may be required for a longer period following establishment related to a longer period for canopy closure. Row rather than block plantings may improve water availability
Persistent increase in temperature, exceeding species climate envelope for optimal growth	High	Plant breeding, species/genotype selection; select alternative sites with less climate risk. Establishment of species/genetically diverse plantings.	Selecting species/genotypes with greater tolerance to warmer temperatures may improve rates of carbon sequestration. Under more extreme climatic conditions, a shift in land use away from these ERF activities may be required
Changes in timing/occurrence of suitable conditions for tree and crop establishment	Medium	Site preparation	Areas identified as at risk can be managed to improve establishment through practices such as soil ripping and mounding to improve water infiltration, and weed control to reduce early competition for water. Under more extreme climatic conditions a shift in land use away from these ERF activities may be required
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening	?	Species/genotype selection; select alternative sites with less climate risk. Establishment of species/genetically diverse plantings.	Selecting species/genotypes with greater tolerance to unseasonal frosts may improve establishment rates. Under more extreme climatic conditions, a shift in land use away from these ERF activities may be required
Decreased frost days with implications for increased seed dormancy and reduced germination rates	?		
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	Low	Site preparation	Areas identified as at risk of flooding can be managed to improve establishment through practices such as soil ripping and mounding
Mechanical damage from wind and storms	Low	-	-

Table 23 Contd.

Direct impacts via secondary climate change variables

Drought-induced plant mortality, with possibility of recruitment failure.	Medium	Initial spacing; thinning; land use change	At sites identified as having a high risk of drought, reducing initial spacing may be effective in managing water stress. Where unexpected drought is stressing plantings, thinning can be used to reduce competition for water. Under more extreme climatic conditions, a shift in land use away from these ERF activities may be required
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Medium		

Indirect impacts via climate change impacts on weeds, pests and diseases

Increase in invasive weeds	Low	Weed management	Chemical and mechanical methods can be applied
Increase in browsing by feral animals	Low	Browsing animal control	Fencing, chemical or physical controls are possible; state-level controls on use of chemical and physical methods may apply
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	Medium	Integrated pest management	On-site debris and weeds can provide over-wintering sites for insects and pathogens, and removal may reduce early-season pest/disease build-ups. Integrated pest management can guide where and when pest management strategies will be effective

Table 24. Examples of climate adaptation strategies that may be effective for ERF methodologies focused management of agricultural soils. All identified strategies focus on the management of rates of soil organic input into the soil from crop residues and plant turnover, to either ensure plant productivity is maintained, or that plant productivity is not compromised. Practical management options for directly manipulating rates of soil carbon loss from respiration are currently limited (Kellenbach et al. 2019).

	Risk rating	**Adaptation strategy**	**Notes**
Heat-stress limiting plant growth and increasing mortality rates	Medium/ High	Select alternative sites with less climate risk; Select alternative species/ genotypes Plant breeding	Select or breed genotypes that are tolerant of heat stress and can survive particularly during the establishment phase. Under more extreme climatic conditions, a shift to alternative land use may be required
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium/ High	Select alternative sites with less climate risk	Under more extreme climatic conditions, a shift to alternative land use may be required
Persistent increase in temperature, exceeding species climate envelope for optimal growth	Medium/ High	Select alternative sites with less climate risk	Under more extreme climatic conditions, a shift to alternative land use may be required
Changes in timing/occurrence of suitable conditions for tree and crop establishment	low	Select alternative sites with less climate risk	Under more extreme climatic conditions, a shift to alternative land use may be required
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	?	Select alternative species/genotypes Plant breeding	Select species/genotypes more tolerant of out of season frosts
Decreased frost days with implications for seed dormancy and reduced germination rates	?	Sow seed	Sow pre-treated seed where recruitment rates are expected to be poor due to dormancy issues
Changes to soil respiration and soil microbial processes	Medium/ High	-	-
Changes to timing/seasonality of crop growth.	Low	Select alternative sites with less climate risk; Select alternative species/ genotypes Plant breeding	Select species/genotypes with growth cycles more aligned to changed seasonal conditions. Under more extreme climatic conditions, a shift to alternative land use may be required
Increased flooding, with implications for establishing crops and trees, and greater susceptibility to some pests and diseases	Low	Select alternative sites with less climate risk	Under more extreme climatic conditions, a shift to alternative land use may be required
Flood-related soil erosion and deposition	Low	Select alternative sites with less climate risk	Under more extreme climatic conditions, a shift to alternative land use may be required

Table 24 Contd.

Direct impacts via secondary climate change variables			
Drought-induced plant mortality, with possibility of recruitment failure.	Low	Species/genotype selection Plant breeding Select alternative sites with less climate risk	Select species/genotypes more tolerant of water stress. Under more extreme climatic conditions, a shift to alternative land use may be required
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk;	Low	Fire management	Activities such as fire breaks may reduce fire movement in the landscape.
Indirect impacts via climate change impacts on weeds, pests and diseases			
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	Integrated pest management Species/genotype selection Plant breeding	Strategic use of chemicals to control pests/diseases. Use of species/genotypes more resistant to pest attack

Table 25. Examples of climate adaptation strategies that may be effective for ERF methodologies focused on savanna fire management

	Risk rating	Adaptation strategy	Notes
Heat-stress limiting plant growth and increasing mortality rates	Medium		Under more extreme climatic conditions, a shift to alternative land use may be required
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	Medium/ High		
Persistent increase in temperature, exceeding species climate envelope for optimal growth	Medium		
Mechanical damage from wind and storms	Low		
Direct impacts via secondary climate change variables			
Drought-induced plant mortality, with possibility of recruitment failure.	Medium		
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	Medium	Fire management	Adaptive timing and application of fire in the landscape
Indirect impacts via climate change impacts on weeds, pests and diseases			
Increase in invasive weeds	Medium	Weed management	Control gamba grass to help reduce risk of late season high intensity fires

Table 26. Examples of climate adaptation strategies that may be effective for ERF methodologies focused on management of intertidal ecosystems

	Risk rating	Adaptation strategy	Notes
Heat-stress limiting plant growth and increasing mortality rates	Low	Select alternative sites with less climate risk	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	🟨	Select alternative sites with less climate risk	
Changes to soil respiration and soil microbial processes	Low	Select alternative sites with less climate risk	
Increased flooding, with implications for establishing crops and trees in terms of growth and survival, and greater susceptibility to some pests and diseases	Medium		
Flood-related soil erosion and deposition	🟧	Civil engineering	Explore options for managing tidal flow to enhance protection from storms and tidal surges.
Mechanical damage from wind and storms	🟧		
Coastal storm surges with implications for blue carbon stability	🟧	Civil engineering	Managing tidal flow to enhance protection from storms and tidal surges.
Direct impacts via secondary climate change variables			
Sea level change, with implications for blue carbon stability	🟧	Civil engineering	Managing tidal flow to enhance protection from storms and tidal surges.
Drought-induced mortality in crops and trees, with possibility of recruitment failure.	🟧	Select alternative sites with less climate risk	Under more extreme climatic conditions, a shift in land use away from these ERF activities may be required
Indirect impacts via climate change impacts on weeds, pests and diseases			
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?		

6 Summary

For each of the 18 identified risk factors in Table 10 an assessment was made of the level of overall risk associated with each class of activity, based on a combination of a review of the current literature, a review of projected changes in the underlying climate variables, and expert opinion (Table 27). The classification was separated into risks to maintenance and accumulation, and overall risk. There was marked variability across the risk profiles, with some activity classes being most sensitive to changes in disturbance regimes (Management of intertidal ecosystems); some activity classes being most sensitive to changes in climate change factors (Management of agricultural soils; Planting of new forests); and some activities indicating relatively even sensitivity to both factors (Re-establish native forest cover; Protect existing forests; Savanna fire management). The maximum risk rating allocated was 'High' corresponding to a likelihood of the risk factor recurring into the future, and a potential consequence of 'Major', nominally tagged as either a loss of up to 50-80% of the stored carbon (or reduced accumulation of up to 20-50% of that expected).

Of the identified risk factors drought-induced stress, heat stress, and increased aridity/reduced soil water availability were the most prevalent. Changes to fire regimes were also a commonly identified risk factor, although only for Planting of new forests and Savanna fire management were the risks considered to be higher than 'Low'. Risk factors associated with the potential impacts of pests and diseases, and changes to exposure to frost, were generally uncertain and are marked in the table with question marks. These can be considered gaps requiring further research.

Some identified climate factors might be expected to have a positive impact on carbon sequestration in ecosystems, such as via the increasing atmospheric CO_2 concentration that has been implicated in increasing woodiness across arid Australia, and changes in rainfall patterns that might increase rates of tree and grass production. Such climate-driven changes in carbon storage interact with, and potentially enhance, the outcomes of changes in land management, and hence may have implications for the additionality requirements under the ERF.

To integrate the findings across all risk factors a simple index was formulated that summed up, for each class of activity, the risk ratings. Risk ratings of 'Low' were assigned a value of 1; risk ratings of 'Low/Medium' or 'Medium' were assigned a values of 3; and risk ratings of 'Medium/High' or 'High' were assigned a values of 6. Risk ratings marked as uncertain were excluded, and hence had a value 0. Because a simple and transparent index was desired, there was no further attempt to weight the risk factors by uncertainty. This index therefore combines a measure of both how many risk factors were identified for each class of activity, and the relative magnitude of those factors (Figure 19).

The index suggests Management of agricultural soils and Planting of new forests have the highest composite risk rating. This is followed by Savanna fire management, Management of intertidal ecosystems and Re-establishment of native forest cover, which have intermediate values. Protection of existing forests has the lowest risk profile. The index also shows the different methodology categories have different risk profiles with respect to accumulation risks and maintenance risks (Figure 19). For the activities involving soil carbon sequestration (management of agricultural soils and management of intertidal ecosystems) the risks are evenly split, with all risk factors identified as having potential impacts on both accumulation and maintenance. This is because changes in soil carbon are driven by changes in the rates organic matter input, as well as losses of soil carbon from respiration, and the impacts of climate change can effect both pathways. Further work is required to tease apart the relative sensitivities to soil carbon loss and gain for each climate impact factor. For the Planting of new forests, Savanna fire management and Re-establishment of native forest cover categories risks to the accumulation of carbon were greater than risks to the maintenance of that carbon, mostly arising from potential impacts to plant growth and decomposition processes. For the protection of existing forests category, only maintenance risks are significant, given the carbon store is present at the start of the project.

Although the index cannot be used as a basis for quantifying potential carbon losses, in conjunction with the more detailed information in Table 27 this ranking could be used as a basis for prioritising attention on the methodologies and associated risk factors that are suggested to be most vulnerable. This could include further investigation of the policy settings underlying each methodology to determine if they could be modified further to alleviate exposure to carbon loss, and to prioritise further research effort on those sectors and activities deemed to be most at risk.

Table 27. Risk assessment summary. Risk assessments are shown for each combination of impact factor and activity category, separated by maintenance, accumulation and combined risks. Note each impact factor can contribute to both maintenance and accumulation risk. Overall rating is based on a simple weighted sum across all risk factors to give a composite score for each activity category and risk type. The weightings were: Not rated = 0; Low risk = 1; Medium risk = 3; High risk = 6.

	Combined risk						Maintenance risk						Accumulation risk					
	Manage agricultural soils	Planting new forests	Savanna fire management	Intertidal ecosystems	Re-establish native forest cover	Protect existing forests	Manage agricultural soils	Planting new forests	Savanna fire management	Intertidal ecosystems	Re-establish native forest cover	Protect existing forests	Manage agricultural soils	Planting new forests	Savanna fire management	Intertidal ecosystems	Re-establish native forest cover	Protect existing forests
Direct impacts via primary climate change variables																		
Heat-stress limiting plant growth and increasing mortality rates	🟥	🟧	🟧	🟨	🟧	🟨	🟥	🟧		🟨		🟨	🟥	🟧	🟧	🟨	🟧	
Reduced soil water availability, leading to reduced crop and tree growth and greater potential for plant stress.	🟥	🟥	🟥		🟧	🟨	🟥					🟨	🟥	🟥	🟥		🟧	
Persistent increase in temperature, exceeding species climate envelope for optimal growth	🟥	🟥	🟧	🟨	🟧	🟨	🟥			🟨		🟨	🟥	🟥	🟧	🟨	🟧	
Changes in timing/occurrence of suitable conditions for tree and crop establishment	🟧	🟧			🟧		🟧	🟨					🟧	🟧			🟧	
Increased frost damage associated with increased dryness / reduced opportunities for frost hardening.	?	?			?		?						?	?			?	
Decreased frost days with implications for increased seed dormancy and reduced germination rates	?	?			?		?						?	?			?	
Changes to soil respiration and soil microbial processes	🟥			🟨			🟥			🟨			🟥			🟨		
Changes to timing/seasonality of crop growth	🟥						🟥						🟥					
Increased flooding, with implications for establishing crops and trees; greater susceptibility to pests and diseases	🟨	🟨		🟧	🟨	🟨	🟨			🟧		🟨	🟨	🟨		🟧	🟨	
Flood-related soil erosion and deposition	🟨			🟧	🟨		🟨			🟧			🟨			🟧	🟨	
Mechanical damage from wind and storms		🟨	🟨	🟧	🟨	🟨		🟨	🟨	🟧	🟨	🟨		🟨	🟨	🟧	🟨	
Coastal storm surges with implications for blue carbon stability				🟧						🟧						🟧		
Direct impacts via secondary climate change variables																		
Sea level change, with implications for blue carbon stability				🟧						🟧						🟧		
Drought-induced plant mortality, with possibility of recruitment failure.	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
Increased fire danger weather; Decreased landscape moisture content, with implications for fire risk	🟨	🟧	🟧		🟨	🟨	🟨	🟧	🟧		🟨	🟨	🟨	🟧			🟨	
Indirect impacts via climate change impacts on weeds, pests and diseases																		
Increase in invasive weeds		🟨	🟧						🟧					🟨				
Increase in browsing by feral animals		🟨												🟨				
Extended range of pests/diseases; Increased over-wintering resulting in faster build-up in the growing season	?	🟧		?	?	?	?	🟧		?	?	?	?	🟧		?	?	
Overall rating	39	31	22	21	19	9	39	14	10	21	5	9	39	31	16	21	19	0

Individual risk rating

?	Not rated (0)
🟨	Low (1)
🟧	Medium (3)
🟥	High (6)

Composite risk score

🟦	≤10
🟦	11-20
🟦	21-30
🟦	>30

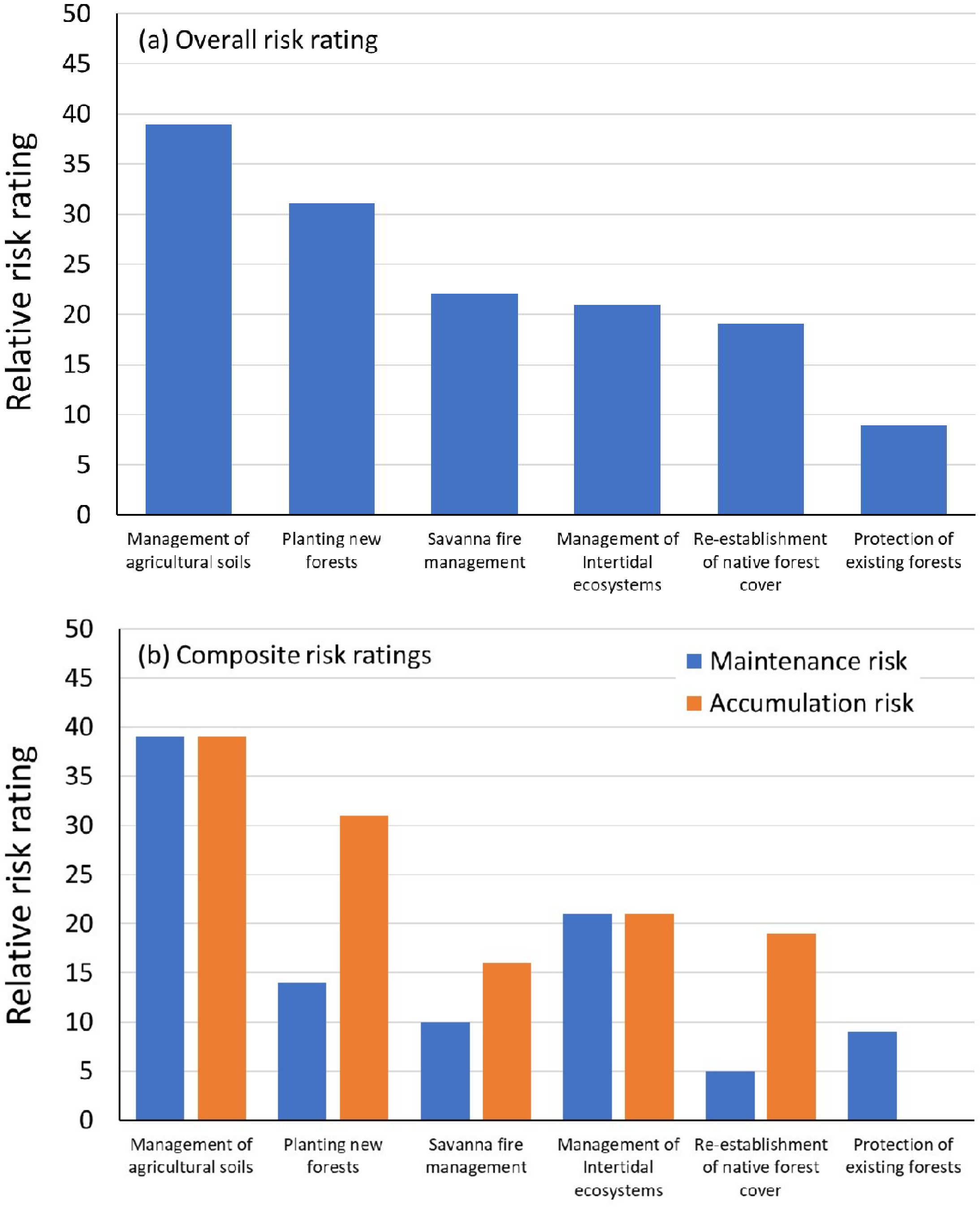


Figure 19. Composite relative risk rating for each activity category. (a) Overall risk rating. (b) Separation of risks into maintenance and accumulation. See text for details.

Activity-specific findings

MANAGEMENT OF AGRICULTURAL SOILS

The dominant risks to sequestration for the Management of agricultural soil activity were associated with climate change impacts on the rates of organic matter input to soil, and the rates of loss through changes to soil respiration and the microbial biota. Based on the qualitative review undertaken here it was not possible to quantify relative differences in risks between accumulation and maintenance – for example a reduction in plant growth can simultaneously reduce the rate of input (accumulation risk), and by doing so also indirectly increase soil carbon loss (maintenance risk) through changing the balance between the rates of organic matter accumulation and soil respiration. The vulnerability of soil organic carbon (SOC) to loss has been recently highlighted by a number of studies suggesting the majority of the spatial and temporal variability observed in SOC can be attributed to non-management related factors. For example, Badgery et al. (2020b) showed, across 10 locations in NSW and over a 16 year period, that all of the SOC gains made over the early years following changes in management, designed specifically to build SOC, were lost by year 16. Moreover, the SOC that did accumulate following management change was predominantly Particulate Organic Carbon (POC), which has a fast turnover rate and this thus most vulnerable to loss. Finally, the patterns of subsequent reversal of the sequestration were similar over widely differing management interventions, suggesting the primary factor controlling the reversal was not solely related to management. The associated risks therefore apply at the portfolio-level, as well as individual projects. Although the soil measurement methodologies only require the measurement and reporting of total organic carbon, information on the composition of different soil carbon fractions (such as POC) would provide valuable additional information for understanding the potential future vulnerability of the sequestered carbon. Zone 1 adaptive measures focus on actions to enhance or maintain rates of organic matter input to the soil, such as pest control, and adjusting the timing of crop establishment. Zone 2 measures involve selecting, or breeding for, species/genotypes more tolerant of extreme climate. Although a number of adaptation options were identified, their effectiveness in helping to secure SOC over the long term remains untested. No specific actions were identified that could be currently undertaken to directly manage respiratory losses of soil carbon, although manipulation of microbial function to enhance soil carbon sequestration is an active area of research.

PLANTING OF NEW FORESTS

The majority of risks identified for the Planting of new forests activity were associated with risks of under delivery, arising from reductions in tree growth (and hence sequestration rates) from persistent increases in temperature, persistent increases in water stress, and disturbances from heat-stress and droughts. The greatest risk period is soon after planting or germination, when plants are young and more vulnerable to climatic stress. Wildfires were also identified as a particular risk factor, associated with risks to maintenance of stored carbon, but predominantly at the project level. Of all the activity categories Planting of new forests has the widest range of opportunities for adaptation, many of these involving incremental Zone 1 responses. Examples include varying planting species and genetic stock, altering planting configuration to reduce risks of resource limitations, careful site preparation and timing of establishment, and fire risk reduction management (Zone 2). Selective breeding for genotypes that confer increased resilience to climate extremes is a Zone 2 response option. Many of the adaptive measures are currently applied in the context of plantation forestry, but could also be modified for environmental plantings.

SAVANNA FIRE MANAGEMENT

A persistent increase in water stress was judged to be a high risk to both accumulation and maintenance for the sequestration component of the Savanna fire management activity. This is because a decrease in water availability will lead to a decline in maximum biomass potential, and thus, the potential for sequestration with fire management. For example, it has been shown that savanna vegetation types with relatively high maximum biomass potential have a much greater the potential for sequestration with fire management when compared to savanna vegetation types with relatively low maximum biomass potential. However, this will be partly negated by increases in water stress also resulting in slower rates of post-fire recovery and increased seasonality of turnover. These two factors will both increase the extent of abatement potential from fire management when compared to a baseline that has higher fuel accumulation in the late dry season and slow recovery of biomass post-fire. Of all the regions in Australia, the increases in temperature are projected to be the highest in the regions where savanna fire management projects occur. It is also a region that experiences cyclones, and these are projected to intensify. There are several factors that can interactive either lead to increased or decreased opportunities for sequestration, leading to an intermediate-level overall risk rating (Figure S1). Savanna burning projects have an extensive history of delivering co-benefits, particularly with respect to indigenous livelihoods and biodiversity outcomes. However, given the large spatial extent of most projects, and the ubiquitous nature of the risk factors (e.g. temperature increase; cyclone activity) relatively few adaptation opportunities were identified that have the potential to significantly mitigate the identified risks. Control of gamba grass was identified as a key risk mitigation strategy.

MANAGEMENT OF INTERTIDAL ECOSYSTEMS (BLUE CARBON)

Given a Blue Carbon methodology is currently being designed, undertaking an initial assessment of potential risk is timely. Intertidal ecosystems can be considered ’high energy’, in that they are subject to regular and profound environmental perturbations, from the daily tidal cycle through to flooding and freshwater inundation. There are risks to both accumulation and maintenance for sequestration activities in Blue carbon ecosystems, however the primary drivers are connected and interacting, involving changes to sea levels (both short-term declines and long-term increases), drought, flooding and storm impacts, extreme temperatures, and impacts to rates of sedimentation and erosion. Because these factors can cause either accretion or loss of carbon, the magnitude and direction of change in carbon storage is uncertain, and hence identifying where and under what conditions particular sites might be at risk requires further detailed analysis. Because the primary management intervention involves the re-introduction of tidal flows to restore mangrove and tidal marsh ecosystems, this implies candidate project areas will be relatively close to human occupation (compared to the vast expanses of mangrove forest in Northern Australia), and that the management interventions are likely to include modification of existing infrastructure, such as levees and embankments. Because of this level of control in how projects are designed and implemented, it is possible this could provide Zone 1 opportunities to mitigate against some of the major risk factors, such as carefully designed engineering to simultaneously promote increased tidal flows, but also provide protection to the regenerating systems from disturbances such as tidal surges and storm damage. Adaptive responses to address risks associated with the sensitivity of vegetation to a changing climate are difficult to identify, and may have to rely in the first instance on regular evaluation to assess where vegetation might be at greatest risk, to help inform where the activity should be best targeted in the future.

RE-ESTABLISHMENT OF NATIVE FOREST COVER

This activity includes the Human Induced Regeneration (HIR) methodology that significantly contributes to the current ERF portfolio, in addition to the Native Forest from Managed Regrowth methodology. From the perspective of abatement accumulation, the main risks are associated with changes in the climate that affect the survivorship of young regenerating stands, and the growth rates of mature stands. The main drivers were identified to be changes in average and maximum temperature, and the associated variables potential evapotranspiration and relative humidity, which have the potential to reduce net primary productivity, and hence rates of carbon sequestration. Regarding risks to abatement maintenance, the main factor identified was from mortality associated with extreme drought, although the ultimate consequences for carbon abatement are uncertain as they are a function of the combined rates of subsequent debris decay and other losses (such as from termites), and rates of post-drought recovery. The drought risk is exacerbated through the regional concentration of projects in north west New South Wales, and south west Queensland. Because fire is not a major feature in the areas where these activities have been established, or are likely to be established in the future, it was not considered a significant risk factor, although fire does occur within the region, and hence individual project should have in place appropriate fire management plans. The key stage of vulnerability for these projects is during the establishment and early years of growth. The embedded methodological requirements of having to demonstrate a potential for forest cover to be achieved (through e.g. evidence of seedlings or young regrowth), and for having to demonstrate advancement of the vegetation towards forest cover over time, provides strong mitigation against the impacts of climate change on the vulnerable early stages of regeneration. Other Zone 1 and 2 adaptation responses include fuel management to reduce the likelihood of fire, management of any grazing to protect the vegetation when it is most vulnerable (for example during drought or after fire), and site selection protocols to ensure adequate propagules are present to support regeneration towards the required 20% canopy cover. These could involve ensuring adequate seedlings or vegetative reproduction on-site, or proximity to existing seed sources from adjacent forest stands.

PROTECTION OF EXISTING FORESTS

Because both the Avoided Deforestation and Avoided Clearing methodologies within this activity class involve the protection of existing forests, the question of risks to accumulation are not relevant, and risks associated with initial forest regeneration are avoided. The main risks are therefore associated with the maintenance of abatement, which were identified to be mortality associated with extreme drought, although as noted the ultimate consequences for carbon abatement are uncertain as they are a function of the combined rates of subsequent debris decay and other losses (such as from termites), and rates of post-drought recovery. Because of the potentially broad spatial scale of drought events, and given the concentration of current projects geographically, there are implications at both the whole portfolio level, as well as the individual project level. Opportunities mitigating these risks are limited, but include control of invasive weeds (an existing requirement of the methodology), which also helps mitigate against risks from wildfire – although for Avoided Deforestation, fire risks were assessed to be low, similar to the Re-establishment of native forest cover class, and individual project should also have in place appropriate fire management plans. In the areas most suited to the Avoided Clearing methodology the fire risk is relatively higher, due to higher productivity and greater contiguity of ground fuels. Zones 1-2 adaptation responses therefore include fuel management to reduce the likelihood of fire, and management of any grazing to protect the vegetation when it is most vulnerable (for example following severe drought, or after fire disturbance).

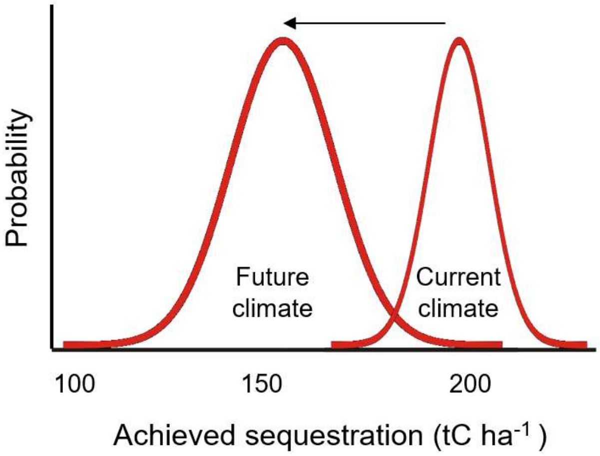
Next steps

The qualitative risk assessments undertaken in this study, based on literature review, likely trends in future climate, and expert opinion, provide a starting point for more detailed analysis that could provide more specific, and quantitative, information on the potential losses of abatement under various scenarios of climate, disturbance regimes, and abatement activity. Although the risk rankings developed here cannot be used for quantitative analysis, they could be used as a basis for prioritising attention on the activities within the methodologies that were identified to be most at risk. This could include deeper investigation of current and future policy settings on risk mitigation, and the prioritisation of further research effort on those sectors and activities deemed to be most at risk. The current risk assessments could also be used as a basis to fill knowledge gaps with research, in particular gaps in knowledge around climate change impacts. For example, future impacts associated with changing frost days and pests and diseases were note as particular areas requiring further investigation.

A logical extension of the work presented here is to embed the risk analysis framework developed in the project within a process-based modelling environment capable of simulating changes in plant growth and decomposition, soil organic carbon dynamics, and disturbance regimes, all linked to the key climate drivers. This would allow actual estimates of carbon reversal loss and reduced accumulation to made, e.g. in units Mt CO_2e yr^{-1}, and would facilitate more informed decision making from both project proponents, and policy. The component models for undertaking such an assessment currently exist, but the challenge would be in bringing them together within the one analysis framework. This involves linking together models that predict plant growth (as a function of CO2, temperature, rainfall etc.) and litterfall with the turnover of soil carbon (including the POC, HOC and ROC fractions to allow simulation of realistic rates of decay, and climate vulnerability). Other modules, such as topographically-defined flooding extents and fire spread and intensity models, could then be added to provide an integrated description of the key carbon pools and their drivers.

An idealised output from such an analysis is shown in Figure 20. The red distributions summarise the range of expected outcomes under a given climate scenario, inclusive of between-GCM variability, and other uncertainties that can be estimated. Comparisons between scenarios can then be made to quantify the magnitude of carbon stock change (or emissions implications), together with an estimate of the certainty of those changes occurring.

Figure 20. Idealised outputs from a numerical risk assessment, illustrating a range of possible outcomes under current and future climates (the red probability distributions) reflecting both variability and uncertainty, with the risk quantified as the difference in the two distributions (denoted by the arrow).



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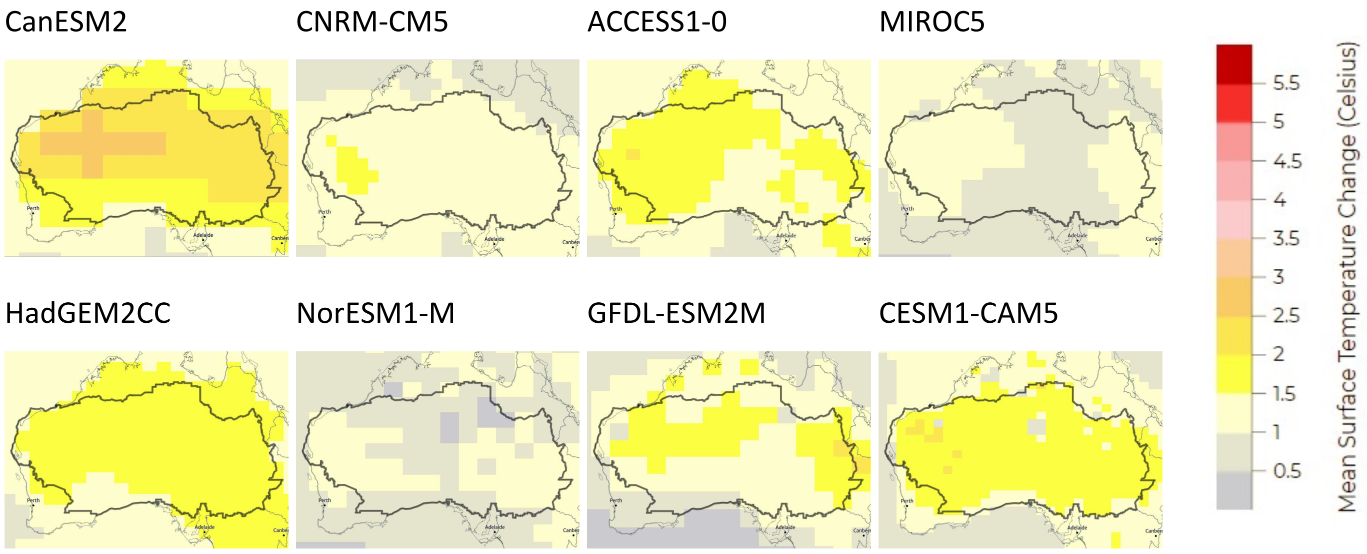
Appendices

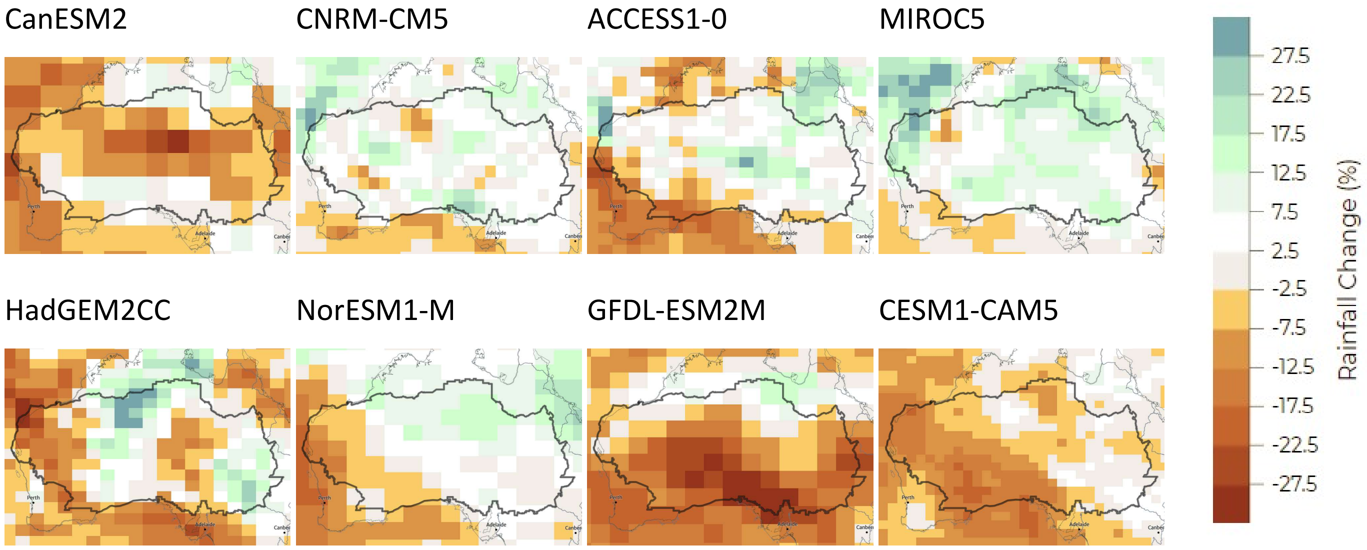
A. Inter-model and spatial variability in Global Circulation Model predictions

Figure A.1. Example global circulation model outputs for eight representative models, showing the predicted change (relative to 1986-2005) in (a) annual average surface temperature, (b) rainfall and (c) evapotranspiration for the year (2050). The eight models provide a representative coverage of the annual and seasonal range in projections across all Australia. The highlighted region is the 'Rangelands' NRM super-cluster (https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/regional-climate-change-explorer/super-clusters/?current=RA&popup=true&tooltip=true).

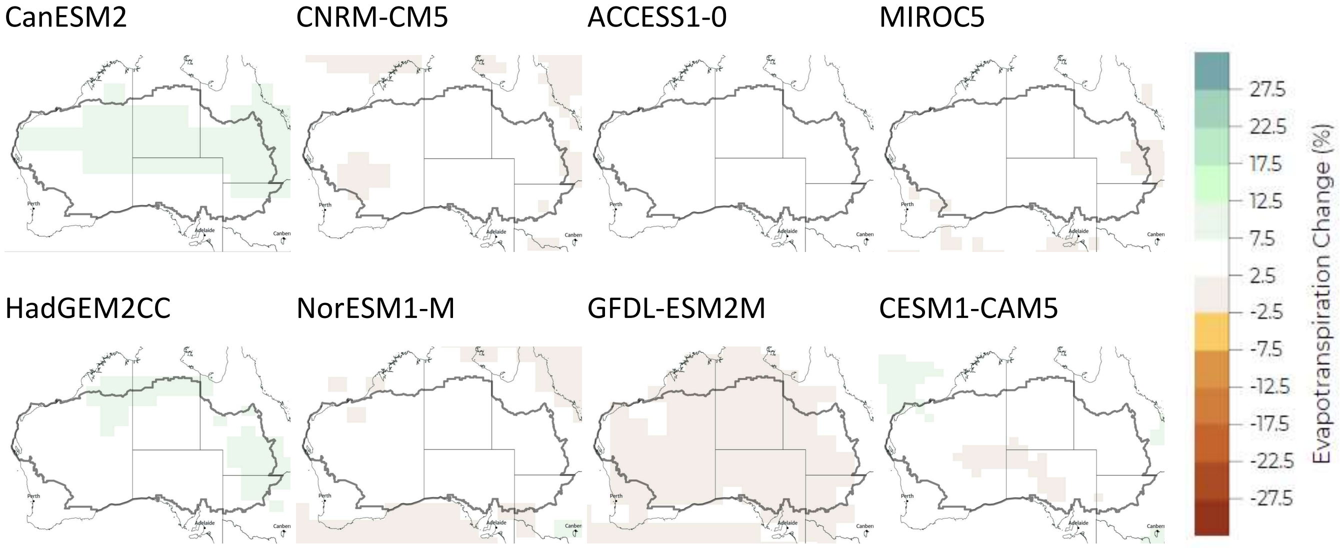
(a) Mean annual surface temperature change (degrees) (2050)



(b) Annual rainfall change (%) (2050)



(c) Mean annual evapotranspiration change (%) (2050)

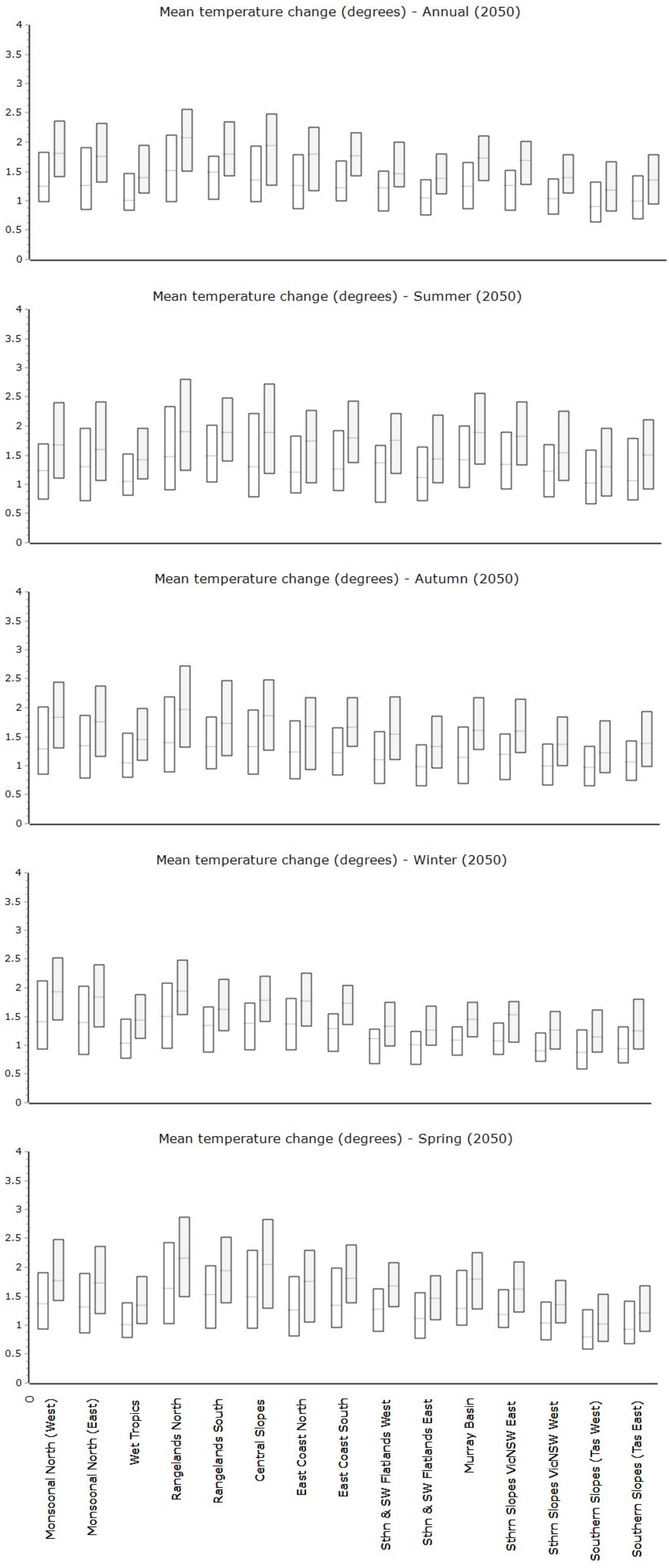


B. NRM zone climate change projections

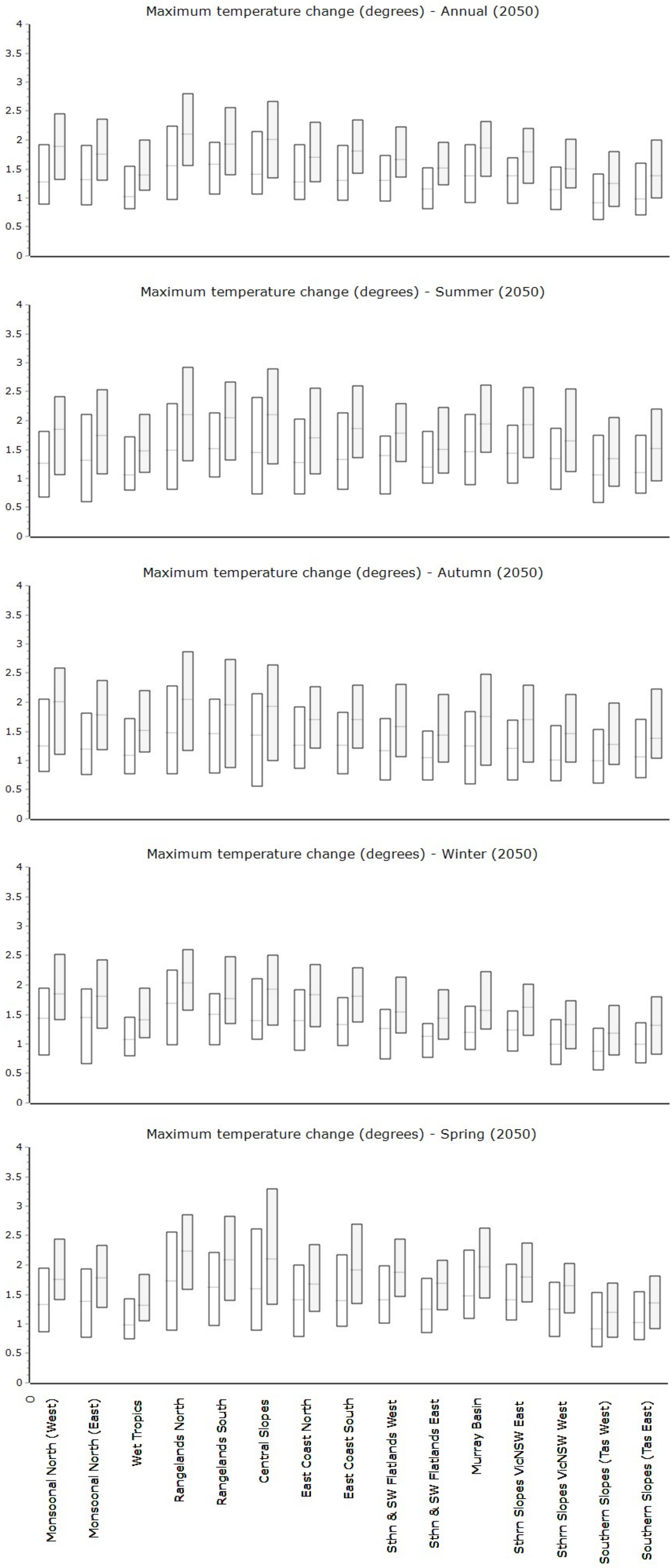
Figure B.1. Climate change factor summaries for 2050 for each NRM sub cluster and for each of 21 factors listed in Table 6. White bars = RCP4.5; Grey bars = RCP8.5. Bars denote the median and 10th and 90th percentile projections across up to 40 global circulation models. Values in x-axis labels for factors (m) – (u) are current (1986 - 2005) average conditions.

(a) Mean temperature change
(b) Maximum temperature change
(c) Minimum temperature change
(d) Precipitation change
(e) Shortwave radiation change
(f) Potential-evapotranspiration change
(g) Windspeed change
(h) Relative humidity change
(i) Coldest night change
(j) Hottest day change
(k) Wettest day change
(l) Wettest 1-in-20 year change
(m) Change in number of days/year below 0 degrees
(n) Change in number of days/year above 35 degrees
(o) Change in days/year > 99.9th percentile rainfall
(p) Change in number months/year < 10th percentile rainfall
(q) Change in annual average cumulative forest fire danger index
(r) Change in number days/year with FFDI > High
(s) Change in time in drought
(t) Change in extreme drought frequency
(u) Change in extreme drought duration

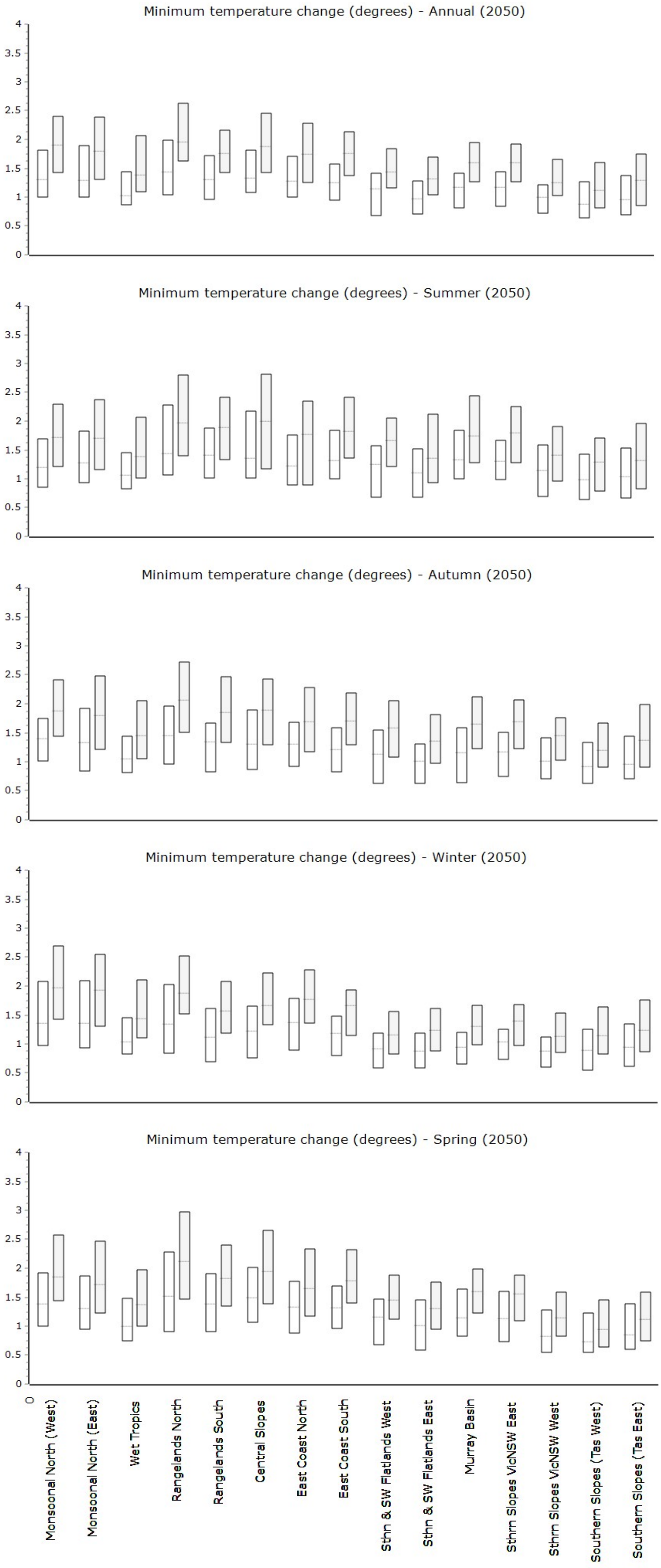
(a)


Mean temperature change (degrees) - Annual (2050)
Mean temperature change (degrees) - Summer (2050)
Mean temperature change (degrees) - Autumn (2050)
Mean temperature change (degrees) - Winter (2050)
Mean temperature change (degrees) - Spring (2050)
0
0.5
1
1.5
2
2.5
3
3.5
4
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

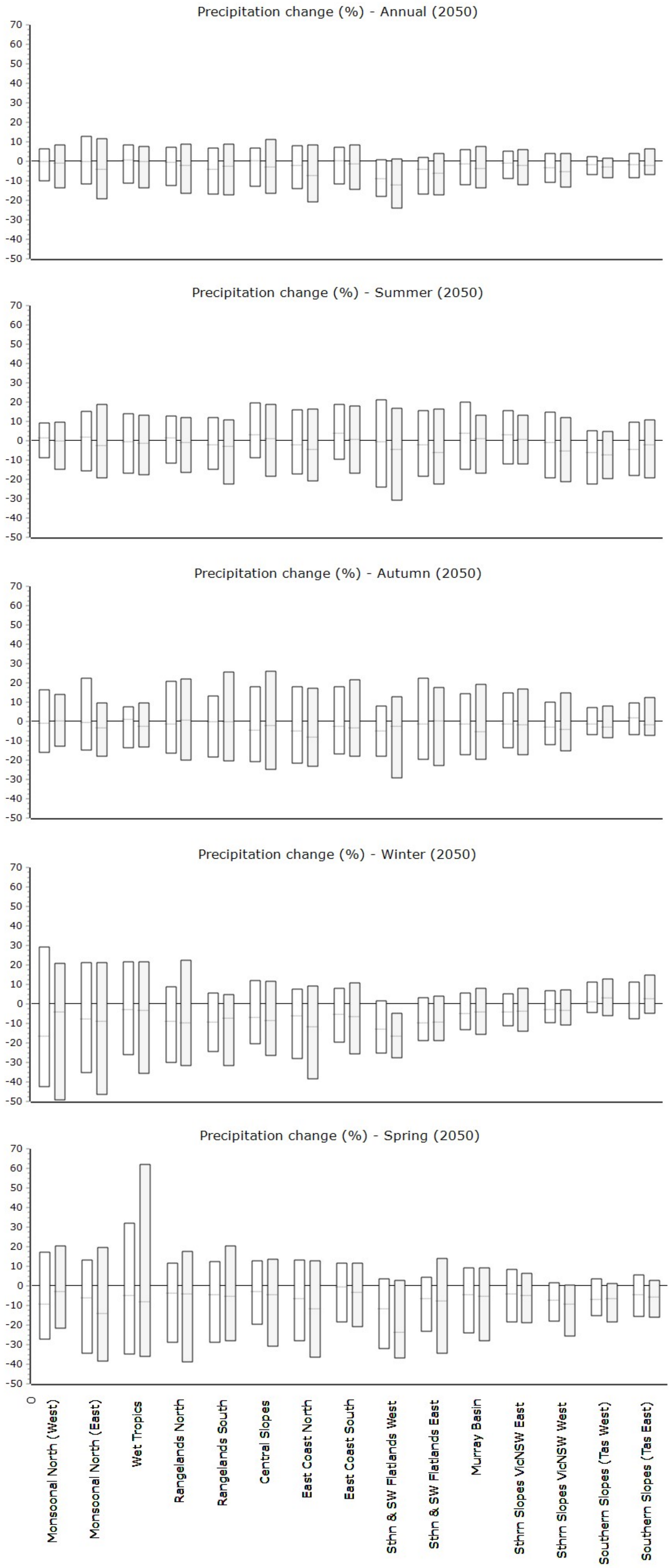
(b)


Maximum temperature change (degrees) - Annual (2050)
Maximum temperature change (degrees) - Summer (2050)
Maximum temperature change (degrees) - Autumn (2050)
Maximum temperature change (degrees) - Winter (2050)
Maximum temperature change (degrees) - Spring (2050)
0
0.5
1
1.5
2
2.5
3
3.5
4
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

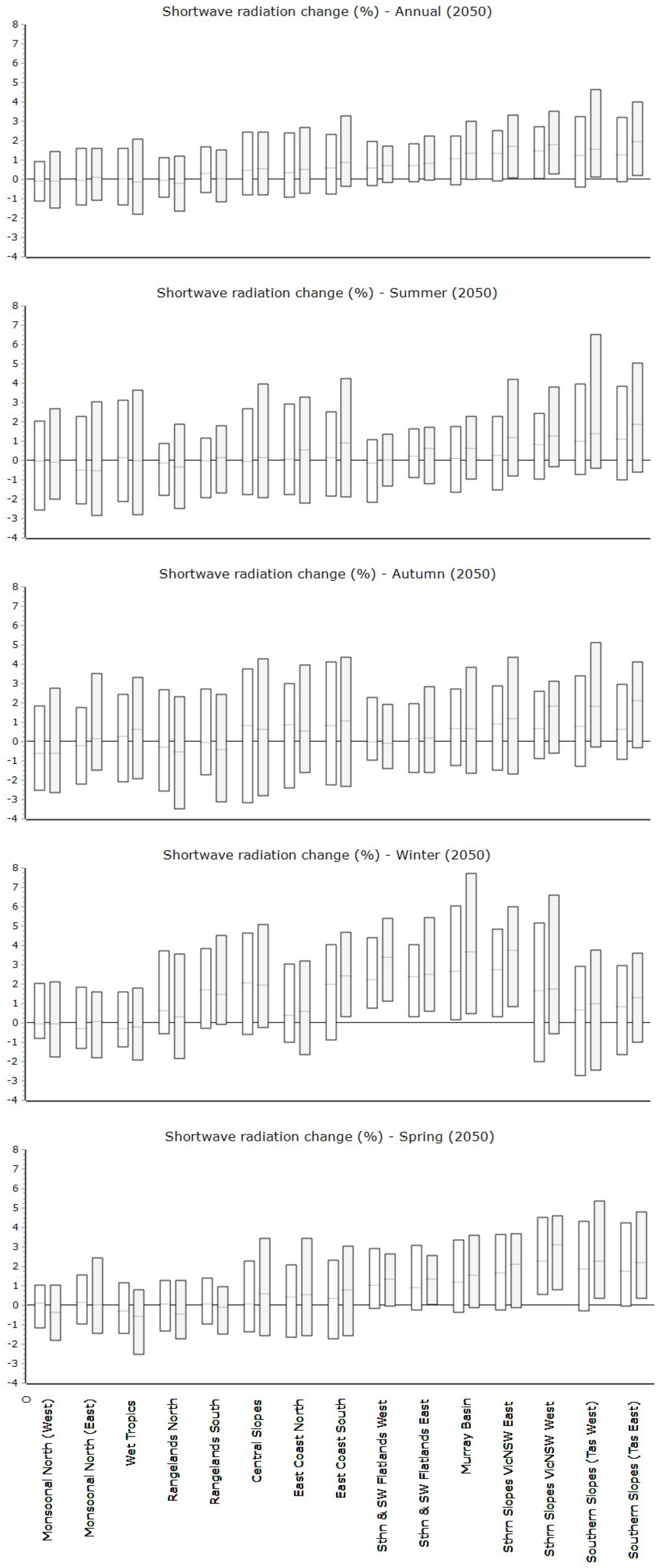
(c)


Minimum temperature change (degrees) - Annual (2050)
Minimum temperature change (degrees) - Summer (2050)
Minimum temperature change (degrees) - Autumn (2050)
Minimum temperature change (degrees) - Winter (2050)
Minimum temperature change (degrees) - Spring (2050)
0
0.5
1
1.5
2
2.5
3
3.5
4
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

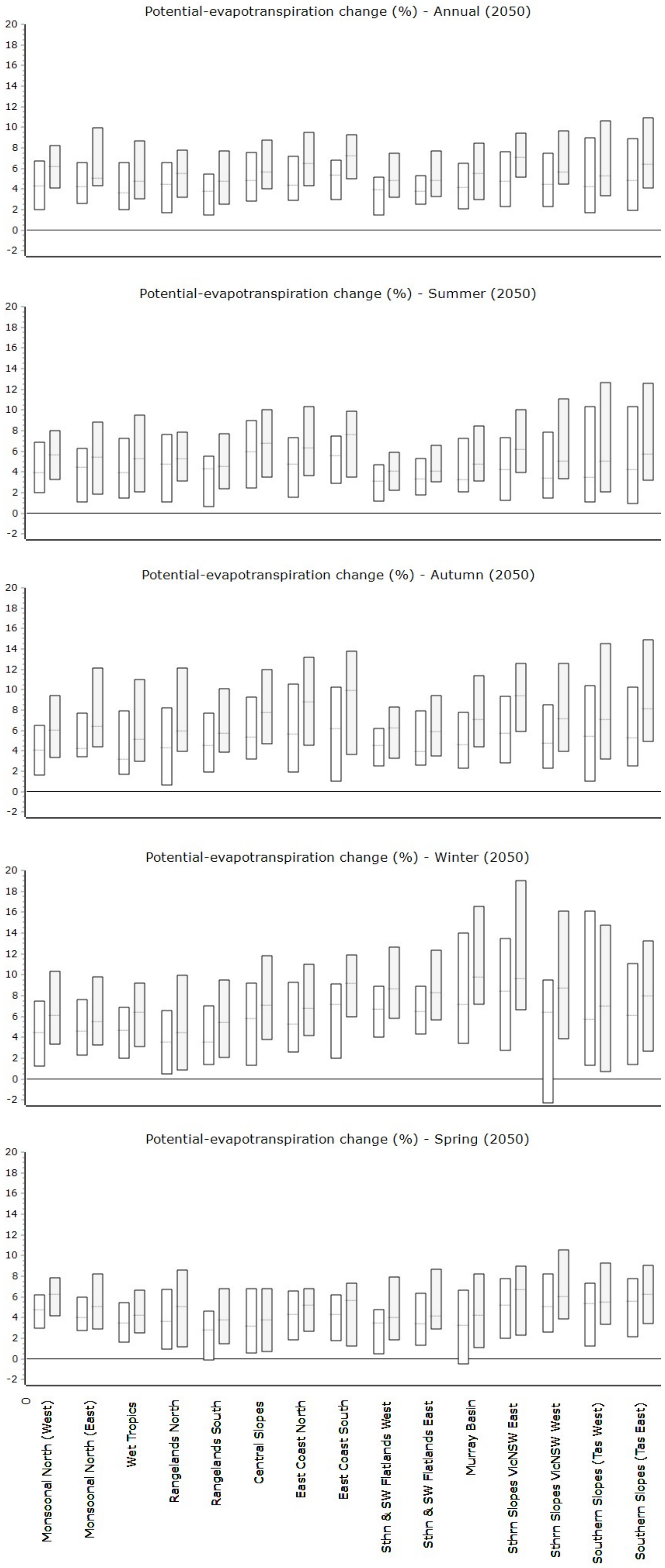
(d)


Precipitation change (%) - Annual (2050)
Precipitation change (%) - Summer (2050)
Precipitation change (%) - Autumn (2050)
Precipitation change (%) - Winter (2050)
Precipitation change (%) - Spring (2050)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

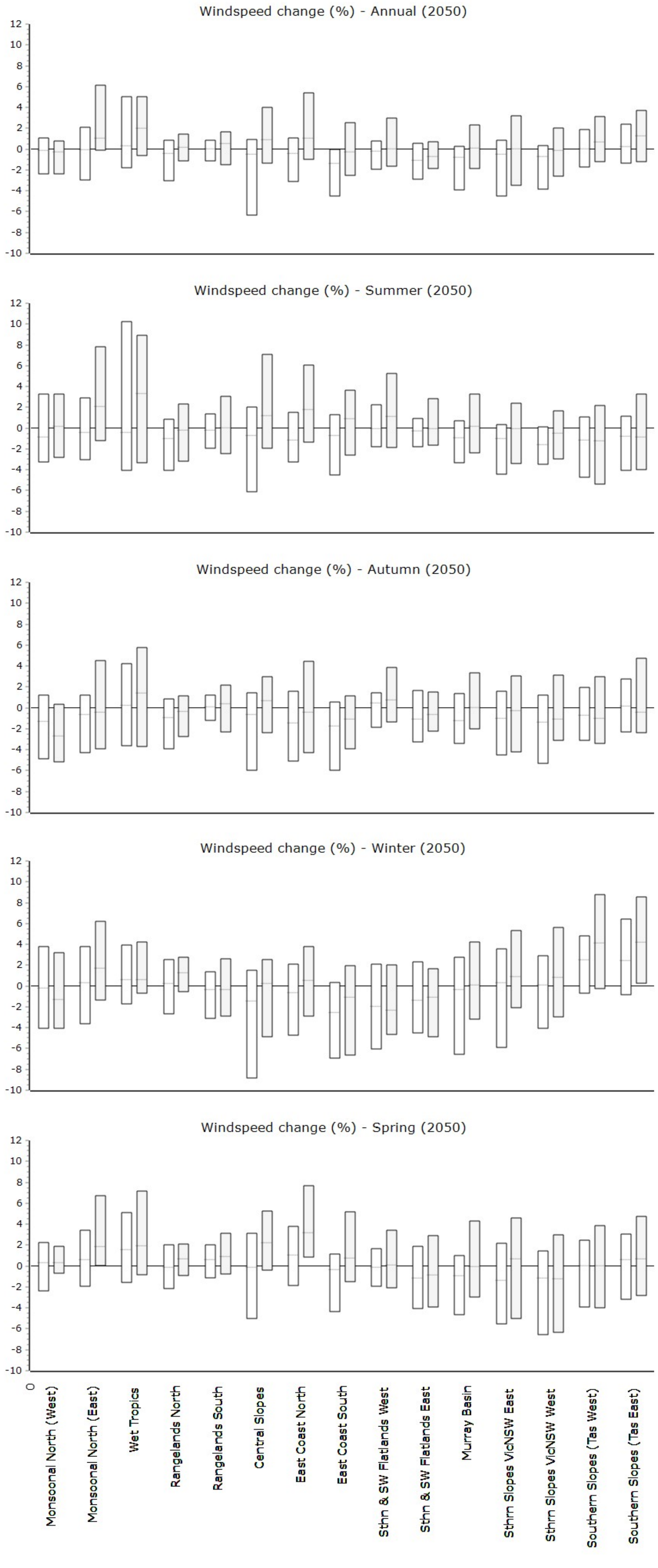
(e)


Shortwave radiation change (%) - Annual (2050)
Shortwave radiation change (%) - Summer (2050)
Shortwave radiation change (%) - Autumn (2050)
Shortwave radiation change (%) - Winter (2050)
Shortwave radiation change (%) - Spring (2050)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

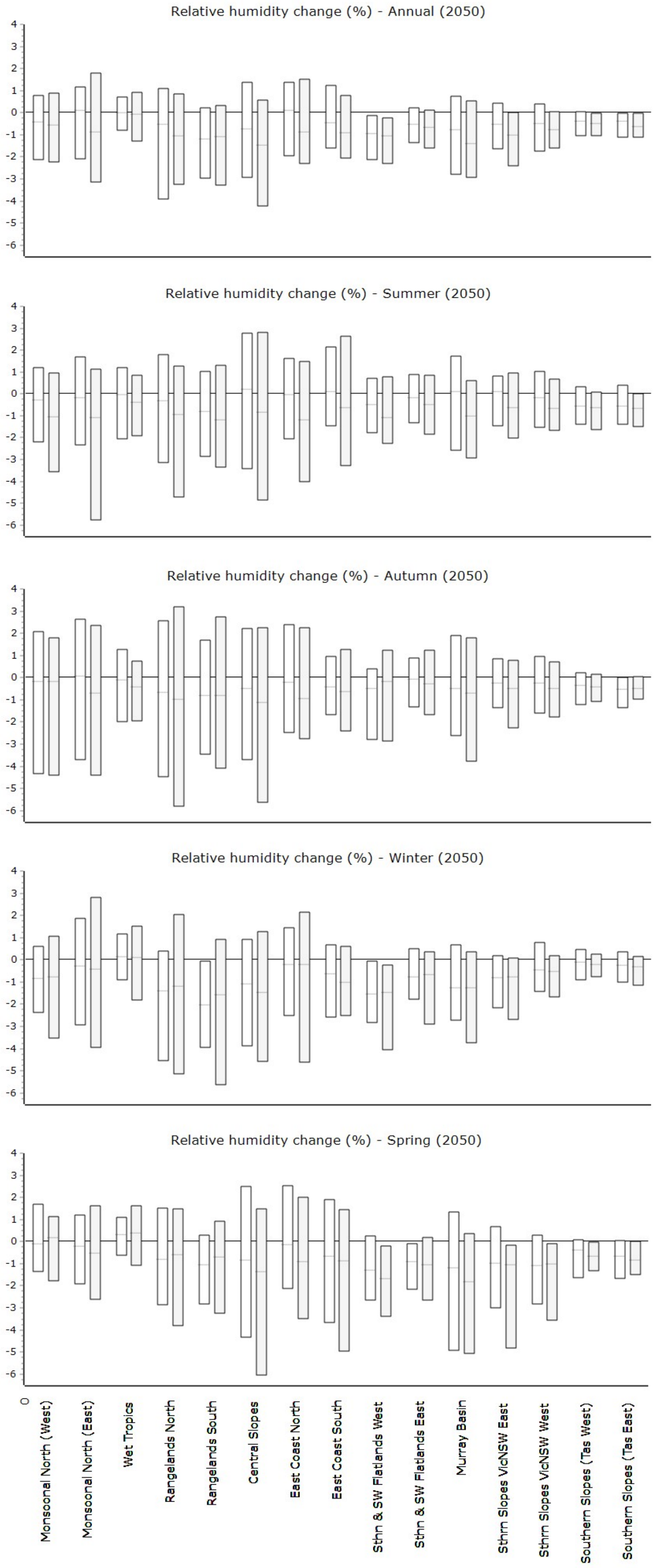
(f)


Potential-evapotranspiration change (%) - Annual (2050)
Potential-evapotranspiration change (%) - Summer (2050)
Potential-evapotranspiration change (%) - Autumn (2050)
Potential-evapotranspiration change (%) - Winter (2050)
Potential-evapotranspiration change (%) - Spring (2050)
20
18
16
14
12
10
8
6
4
2
0
-2
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

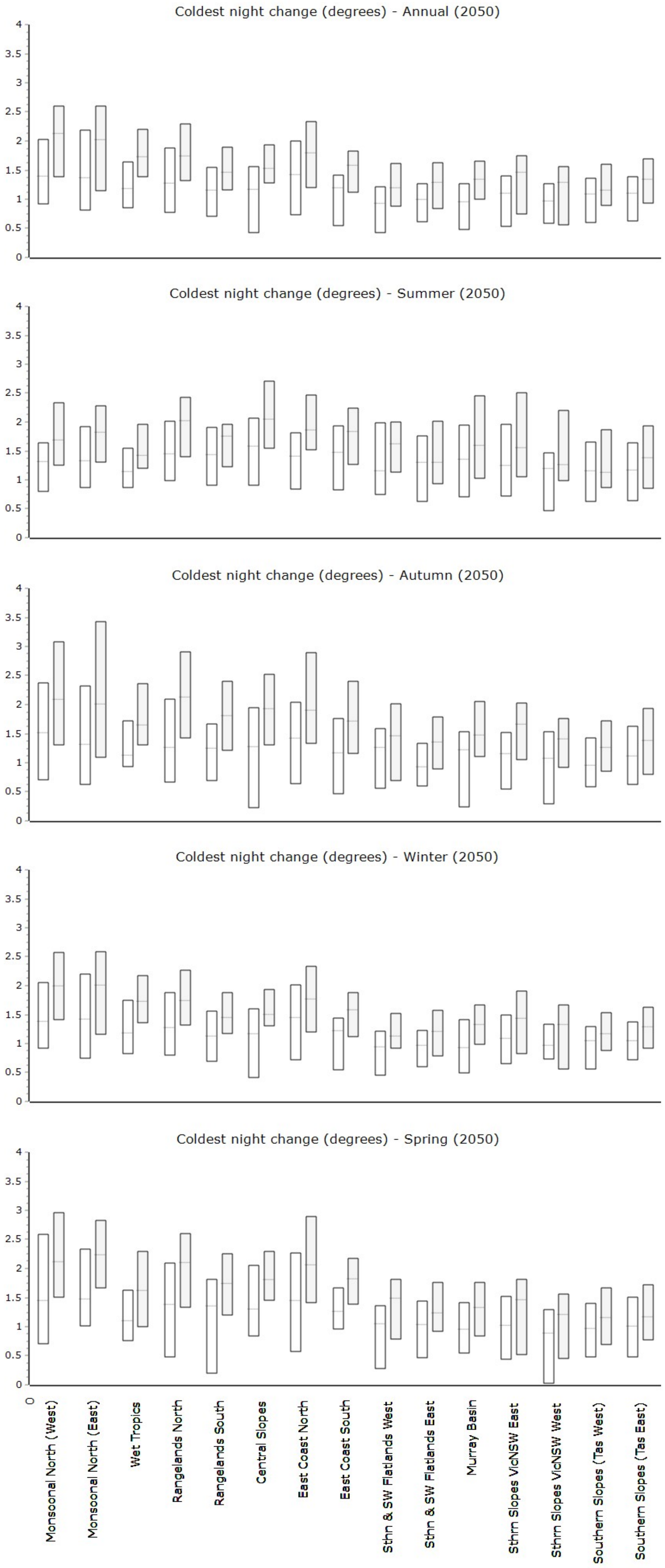
(g)


Windspeed change (%) - Annual (2050)
Windspeed change (%) - Summer (2050)
Windspeed change (%) - Autumn (2050)
Windspeed change (%) - Winter (2050)
Windspeed change (%) - Spring (2050)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

(h)


Relative humidity change (%) - Annual (2050)
Relative humidity change (%) - Summer (2050)
Relative humidity change (%) - Autumn (2050)
Relative humidity change (%) - Winter (2050)
Relative humidity change (%) - Spring (2050)
4
3
2
1
0
-1
-2
-3
-4
-5
-6
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

(i)



Coldest night change (degrees) - Annual (2050)

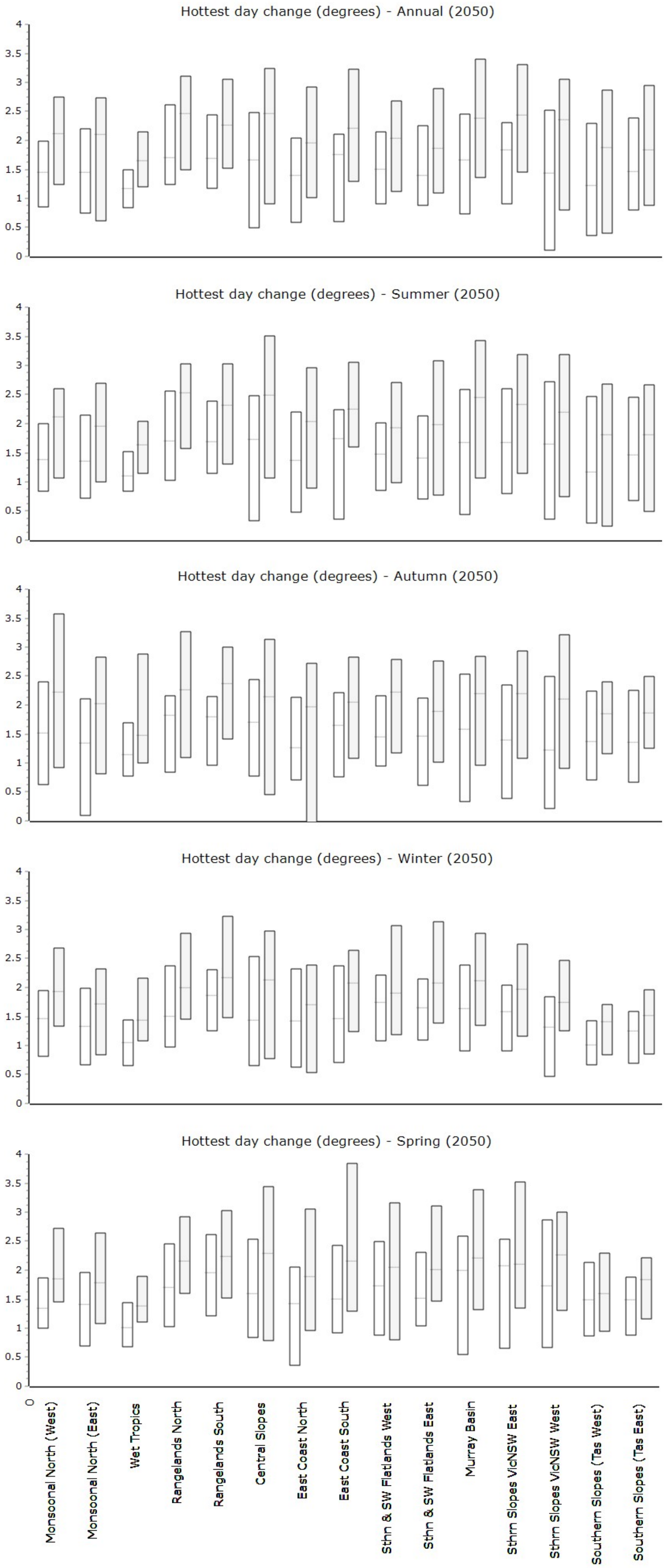
Coldest night change (degrees) - Summer (2050)

Coldest night change (degrees) - Autumn (2050)

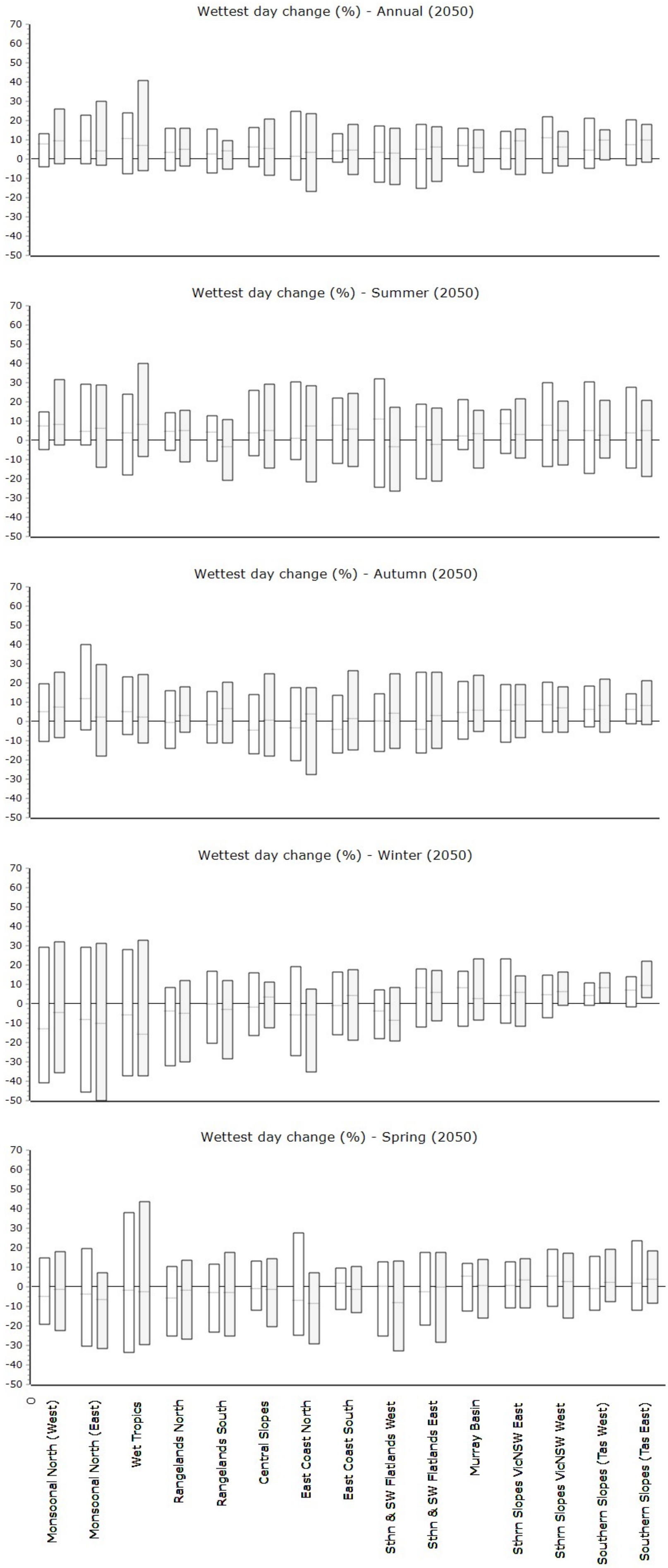
Coldest night change (degrees) - Winter (2050)

Coldest night change (degrees) - Spring (2050)

(j)


Hottest day change (degrees) - Annual (2050)
Hottest day change (degrees) - Summer (2050)
Hottest day change (degrees) - Autumn (2050)
Hottest day change (degrees) - Winter (2050)
Hottest day change (degrees) - Spring (2050)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

(k)



Wettest day change (%) - Annual (2050)

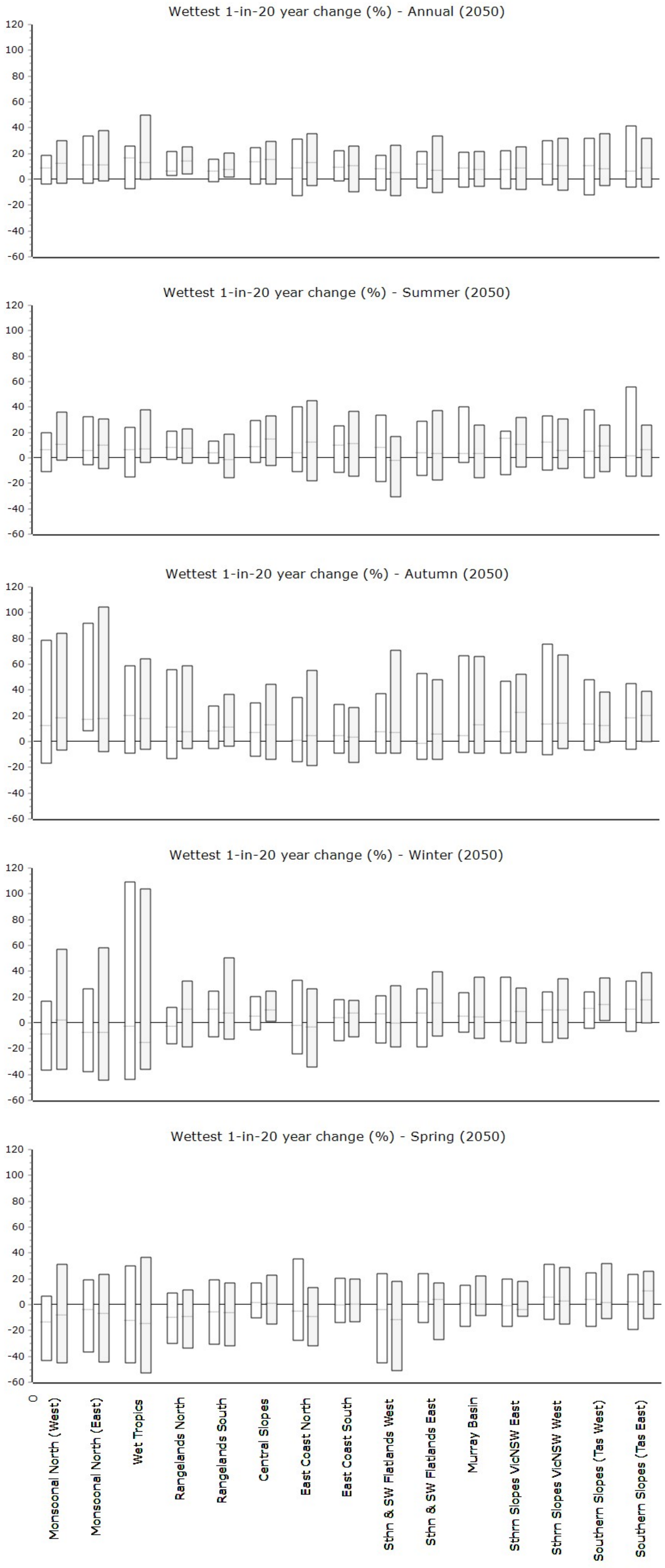
Wettest day change (%) - Summer (2050)

Wettest day change (%) - Autumn (2050)

Wettest day change (%) - Winter (2050)

Wettest day change (%) - Spring (2050)

(l)


Wettest 1-in-20 year change (%) - Annual (2050)

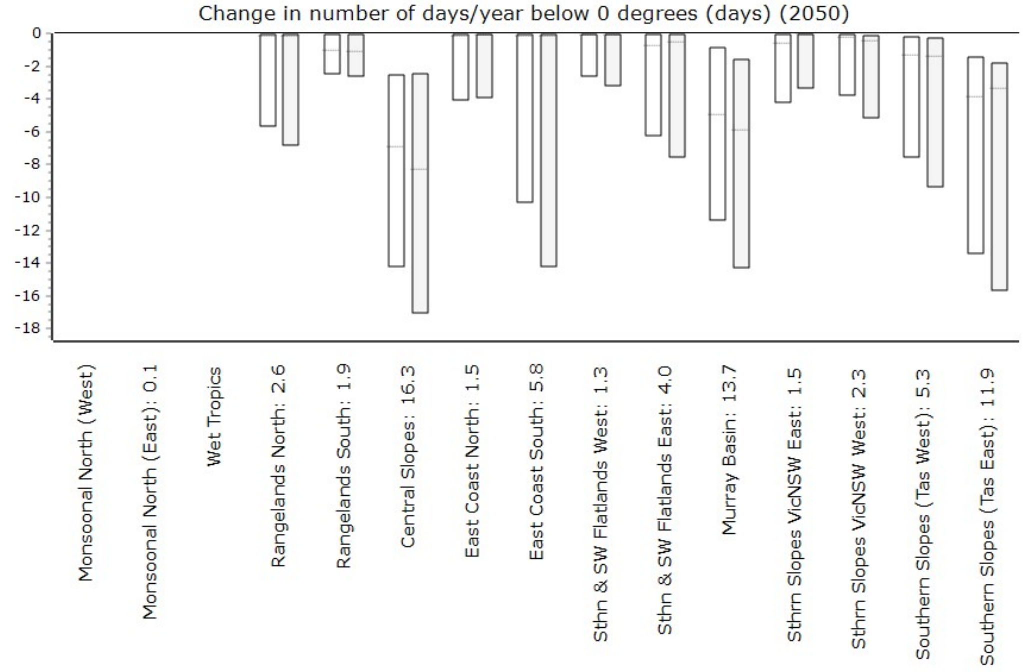
Wettest 1-in-20 year change (%) - Summer (2050)

Wettest 1-in-20 year change (%) - Autumn (2050)

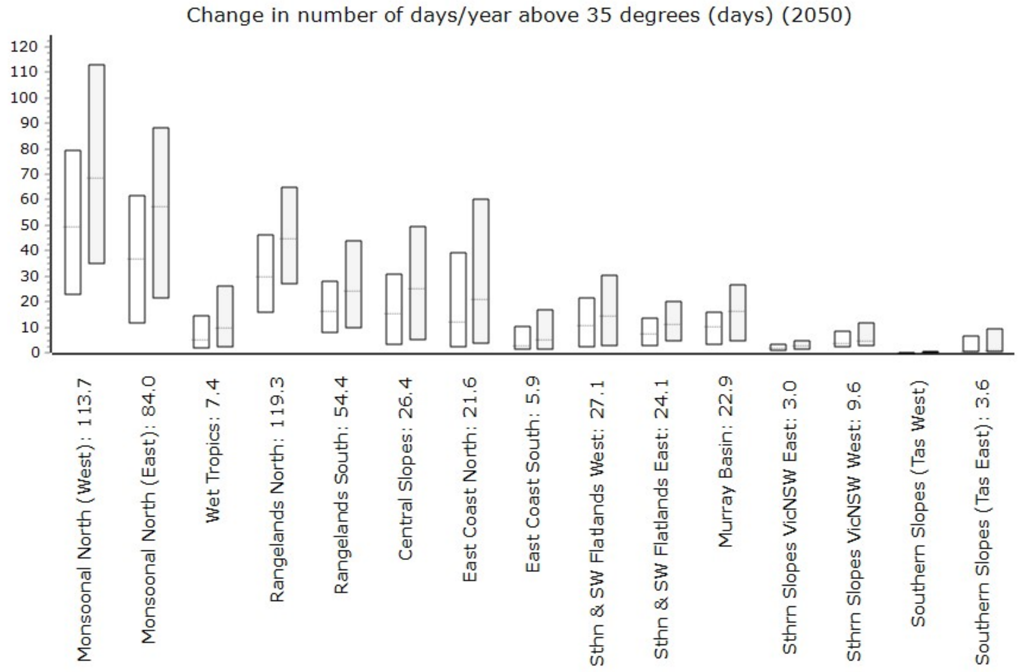
Wettest 1-in-20 year change (%) - Winter (2050)

Wettest 1-in-20 year change (%) - Spring (2050)

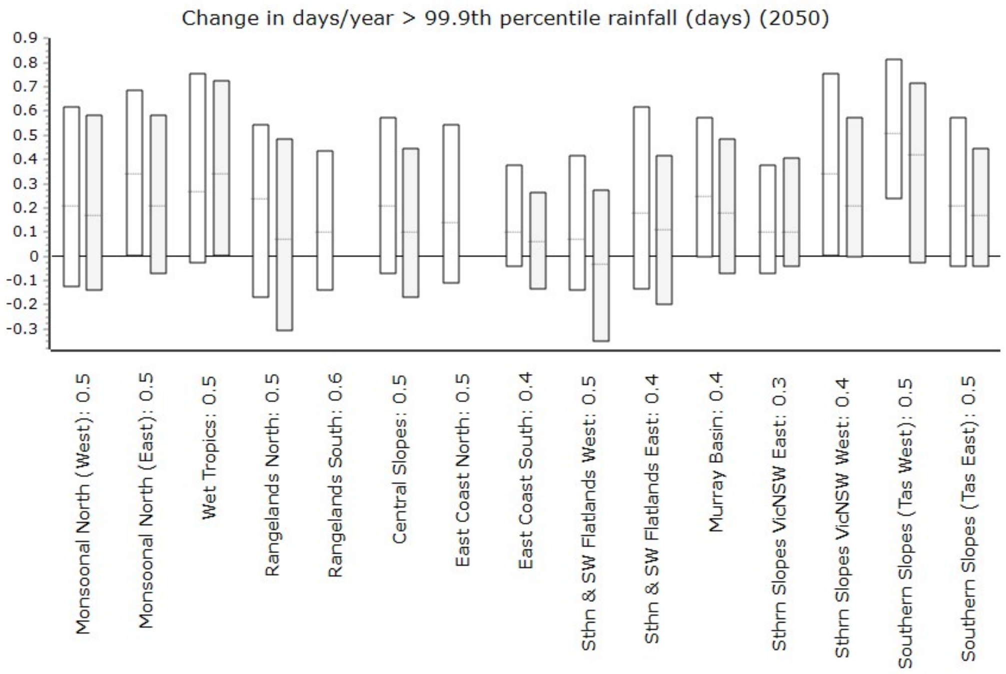
(m)


Change in number of days/year below 0 degrees (days) (2050)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Monsoonal North (West)
Monsoonal North (East): 0.1
Wet Tropics
Rangelands North: 2.6
Rangelands South: 1.9
Central Slopes: 16.3
East Coast North: 1.5
East Coast South: 5.8
Sthn & SW Flatlands West: 1.3
Sthn & SW Flatlands East: 4.0
Murray Basin: 13.7
Sthrn Slopes VicNSW East: 1.5
Sthrn Slopes VicNSW West: 2.3
Southern Slopes (Tas West): 5.3
Southern Slopes (Tas East): 11.9

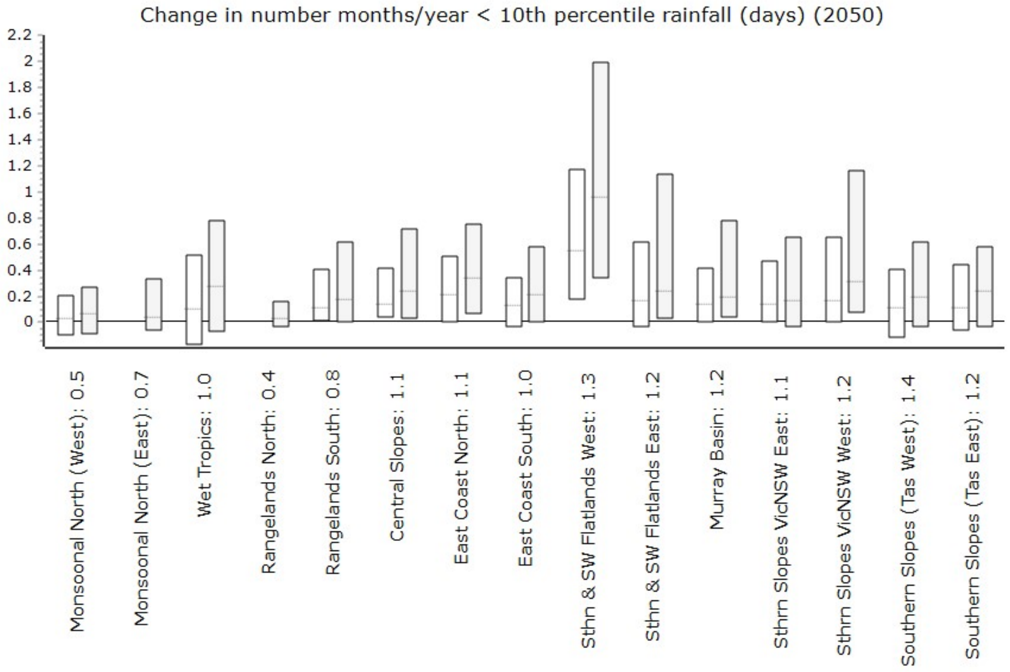
(n)


Change in number of days/year above 35 degrees (days) (2050)
120
110
100
90
80
70
60
50
40
30
20
10
0
Monsoonal North (West): 113.7
Monsoonal North (East): 84.0
Wet Tropics: 7.4
Rangelands North: 119.3
Rangelands South: 54.4
Central Slopes: 26.4
East Coast North: 21.6
East Coast South: 5.9
Sthn & SW Flatlands West: 27.1
Sthn & SW Flatlands East: 24.1
Murray Basin: 22.9
Sthrn Slopes VicNSW East: 3.0
Sthrn Slopes VicNSW West: 9.6
Southern Slopes (Tas West)
Southern Slopes (Tas East): 3.6

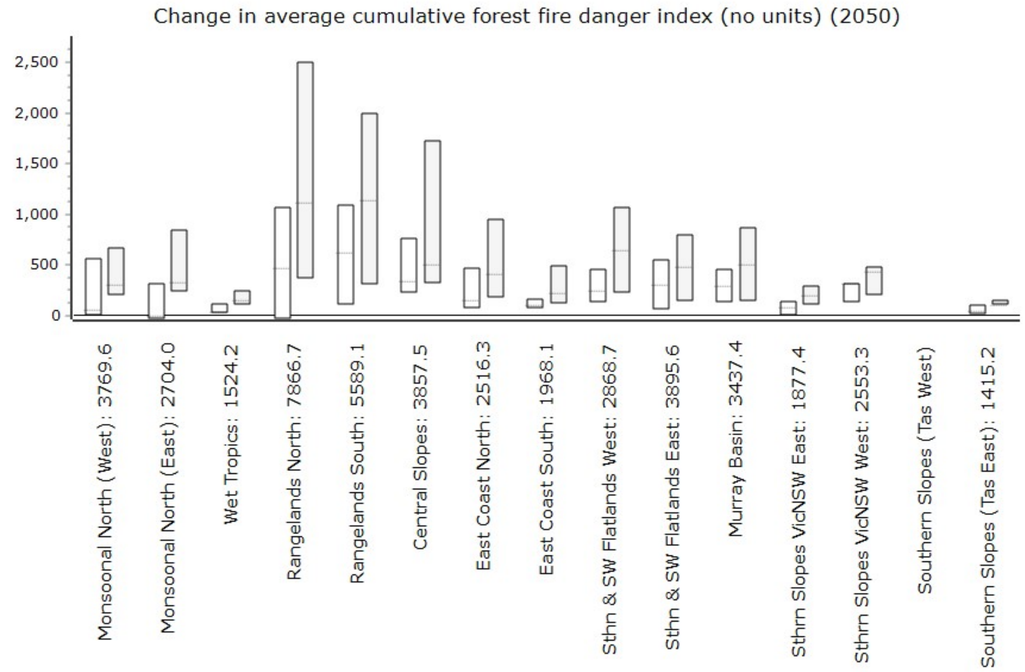
(o)


Change in days/year > 99.9th percentile rainfall (days) (2050)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Monsoonal North (West): 0.5
Monsoonal North (East): 0.5
Wet Tropics: 0.5
Rangelands North: 0.5
Rangelands South: 0.6
Central Slopes: 0.5
East Coast North: 0.5
East Coast South: 0.4
Sthn & SW Flatlands West: 0.5
Sthn & SW Flatlands East: 0.4
Murray Basin: 0.4
Sthrn Slopes VicNSW East: 0.3
Sthrn Slopes VicNSW West: 0.4
Southern Slopes (Tas West): 0.5
Southern Slopes (Tas East): 0.5

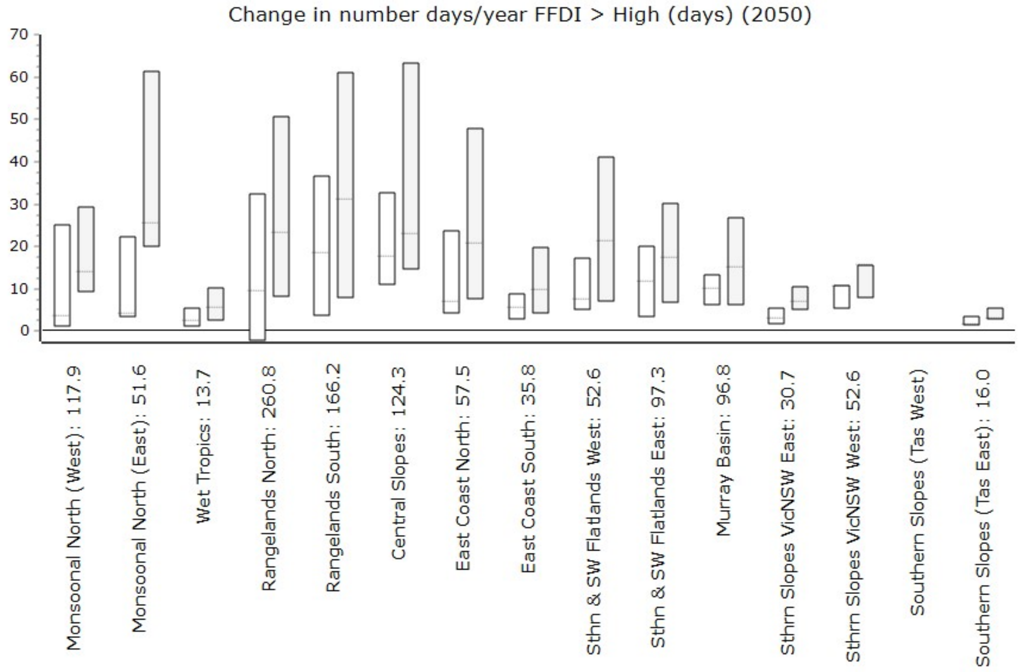
(p)


Change in number months/year < 10th percentile rainfall (days) (2050)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Monsoonal North (West): 0.5
Monsoonal North (East): 0.7
Wet Tropics: 1.0
Rangelands North: 0.4
Rangelands South: 0.8
Central Slopes: 1.1
East Coast North: 1.1
East Coast South: 1.0
Sthn & SW Flatlands West: 1.3
Sthn & SW Flatlands East: 1.2
Murray Basin: 1.2
Sthrn Slopes VicNSW East: 1.1
Sthrn Slopes VicNSW West: 1.2
Southern Slopes (Tas West): 1.4
Southern Slopes (Tas East): 1.2

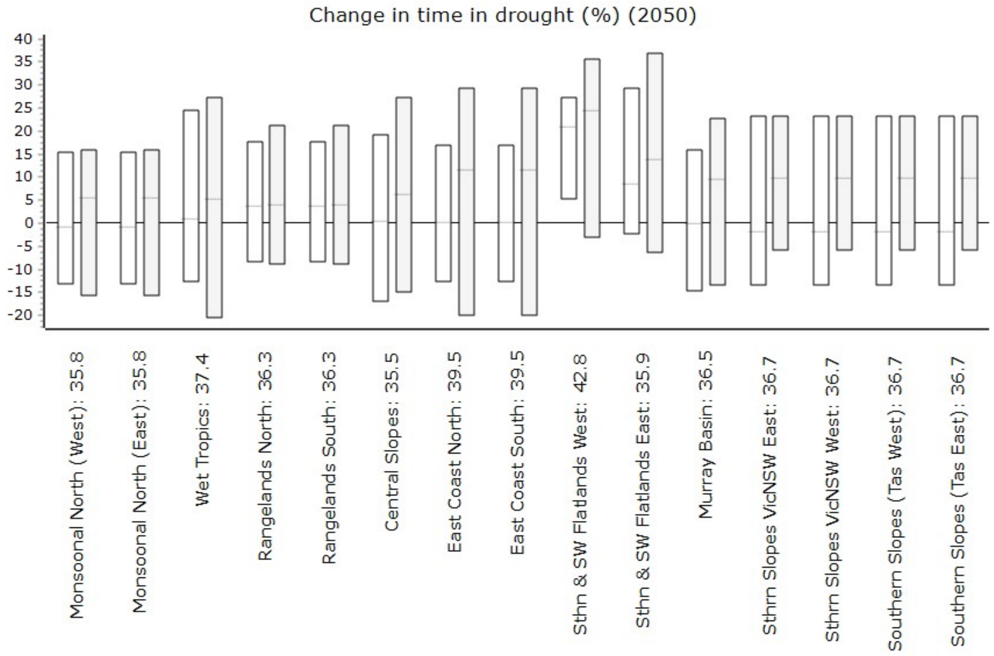
(q)


Change in average cumulative forest fire danger index (no units) (2050)
2,500
2,000
1,500
1,000
500
0
Monsoonal North (West): 3769.6
Monsoonal North (East): 2704.0
Wet Tropics: 1524.2
Rangelands North: 7866.7
Rangelands South: 5589.1
Central Slopes: 3857.5
East Coast North: 2516.3
East Coast South: 1968.1
Sthn & SW Flatlands West: 2868.7
Sthn & SW Flatlands East: 3895.6
Murray Basin: 3437.4
Sthrn Slopes VicNSW East: 1877.4
Sthrn Slopes VicNSW West: 2553.3
Southern Slopes (Tas West)
Southern Slopes (Tas East): 1415.2

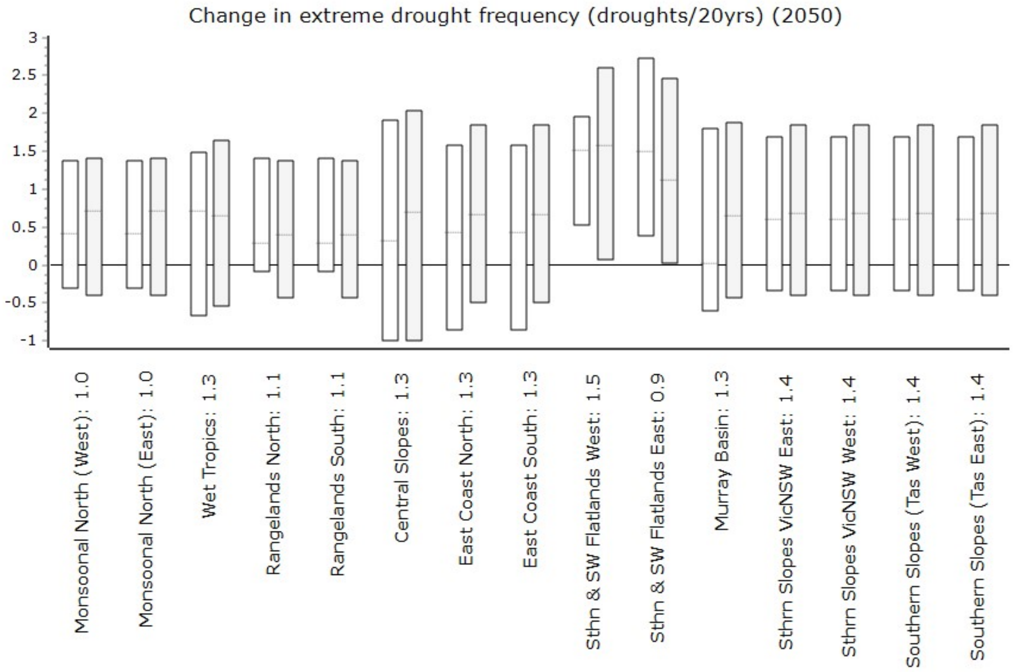
(r)


Change in number days/year FFDI > High (days) (2050)
70
60
50
40
30
20
10
0
Monsoonal North (West): 117.9
Monsoonal North (East): 51.6
Wet Tropics: 13.7
Rangelands North: 260.8
Rangelands South: 166.2
Central Slopes: 124.3
East Coast North: 57.5
East Coast South: 35.8
Sthn & SW Flatlands West: 52.6
Sthn & SW Flatlands East: 97.3
Murray Basin: 96.8
Sthrn Slopes VicNSW East: 30.7
Sthrn Slopes VicNSW West: 52.6
Southern Slopes (Tas West)
Southern Slopes (Tas East): 16.0

(s)


Change in time in drought (%) (2050)
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
Monsoonal North (West): 35.8
Monsoonal North (East): 35.8
Wet Tropics: 37.4
Rangelands North: 36.3
Rangelands South: 36.3
Central Slopes: 35.5
East Coast North: 39.5
East Coast South: 39.5
Sthn & SW Flatlands West: 42.8
Sthn & SW Flatlands East: 35.9
Murray Basin: 36.5
Sthrn Slopes VicNSW East: 36.7
Sthrn Slopes VicNSW West: 36.7
Southern Slopes (Tas West): 36.7
Southern Slopes (Tas East): 36.7

(t)


Change in extreme drought frequency (droughts/20yrs) (2050)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Monsoonal North (West): 1.0
Monsoonal North (East): 1.0
Wet Tropics: 1.3
Rangelands North: 1.1
Rangelands South: 1.1
Central Slopes: 1.3
East Coast North: 1.3
East Coast South: 1.3
Sthn & SW Flatlands West: 1.5
Sthn & SW Flatlands East: 0.9
Murray Basin: 1.3
Sthrn Slopes VicNSW East: 1.4
Sthrn Slopes VicNSW West: 1.4
Southern Slopes (Tas West): 1.4
Southern Slopes (Tas East): 1.4

(u)

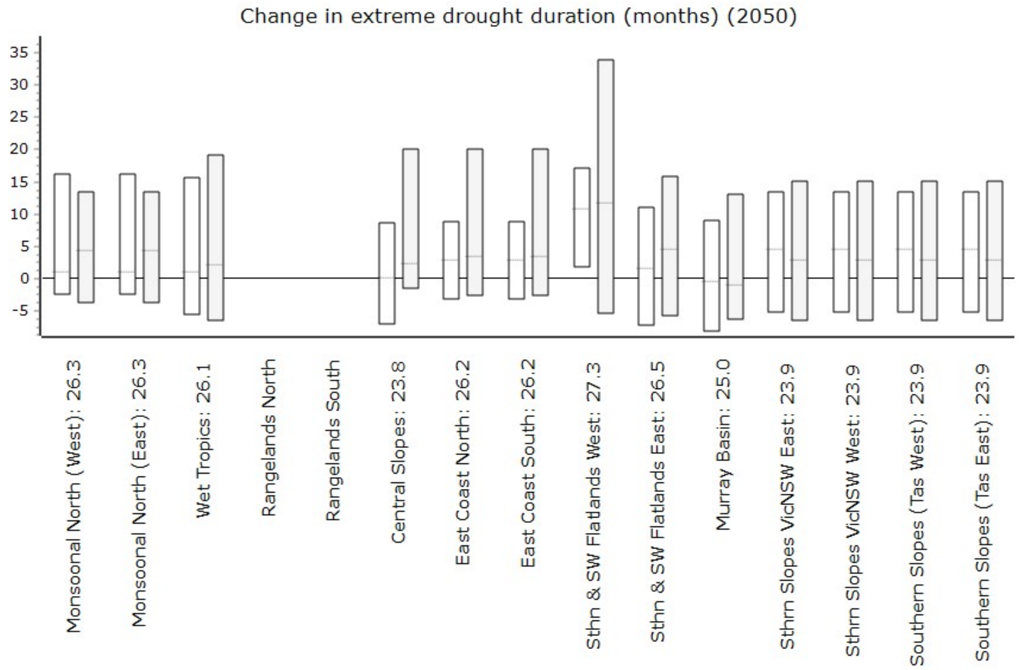
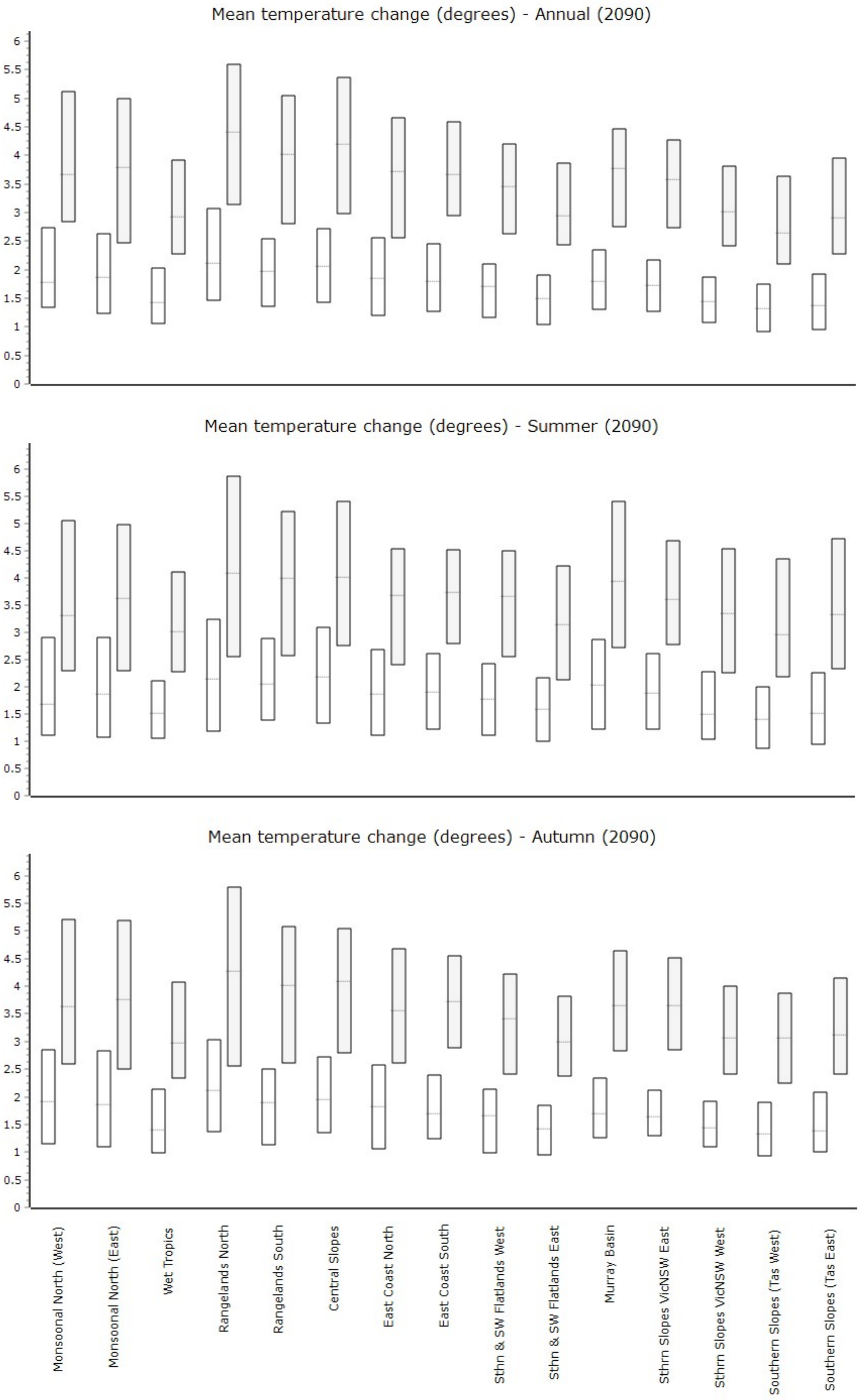

Change in extreme drought duration (months) (2050)
35
30
25
20
15
10
5
0
-5
Monsoonal North (West): 26.3
Monsoonal North (East): 26.3
Wet Tropics: 26.1
Rangelands North
Rangelands South
Central Slopes: 23.8
East Coast North: 26.2
East Coast South: 26.2
Sthn & SW Flatlands West: 27.3
Sthn & SW Flatlands East: 26.5
Murray Basin: 25.0
Sthrn Slopes VicNSW East: 23.9
Sthrn Slopes VicNSW West: 23.9
Southern Slopes (Tas West): 23.9
Southern Slopes (Tas East): 23.9

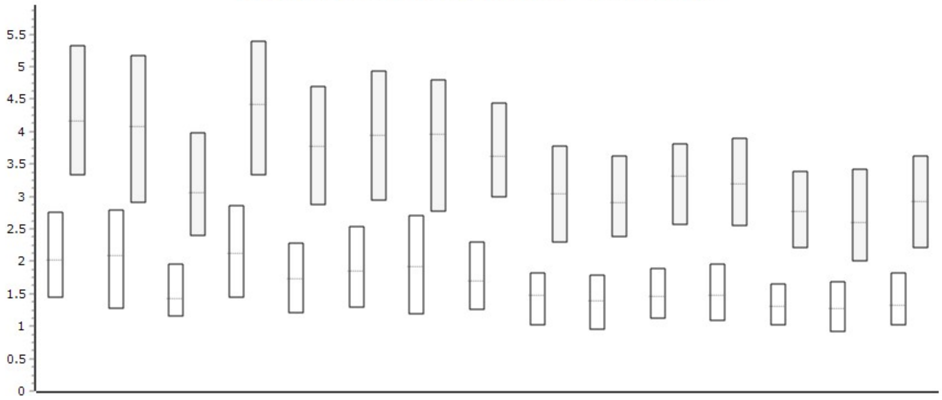
Figure B.2. Climate change factor summaries for 2090 for each NRM sub cluster and for each of 21 factors listed in Table 6. White bars = RCP4.5; Grey bars = RCP8.5. Bars denote the median and 10th and 90th percentile projections across up to 40 global circulation models. Values in x-axis labels for factors (m) – (u) are current (1986 - 2005) average conditions.

(a) Mean temperature change
(b) Maximum temperature change
(c) Minimum temperature change
(d) Precipitation change
(e) Shortwave radiation change
(f) Potential-evapotranspiration change
(g) Windspeed change
(h) Relative humidity change
(i) Coldest night change
(j) Hottest day change
(k) Wettest day change
(l) Wettest 1-in-20 year change
(m) Change in number of days/year below 0 degrees
(n) Change in number of days/year above 35 degrees
(o) Change in days/year > 99.9th percentile rainfall
(p) Change in number months/year < 10th percentile rainfall
(q) Change in annual average cumulative forest fire danger index
(r) Change in number days/year with FFDI > High
(s) Change in time in drought
(t) Change in extreme drought frequency
(u) Change in extreme drought duration

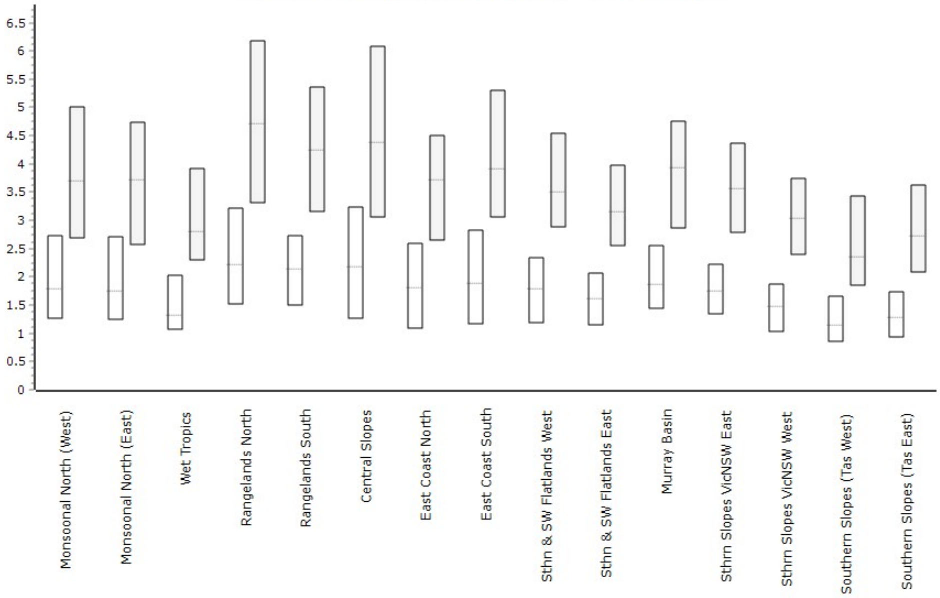
(a)


Mean temperature change (degrees) - Annual (2090)
Mean temperature change (degrees) - Summer (2090)
Mean temperature change (degrees) - Autumn (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

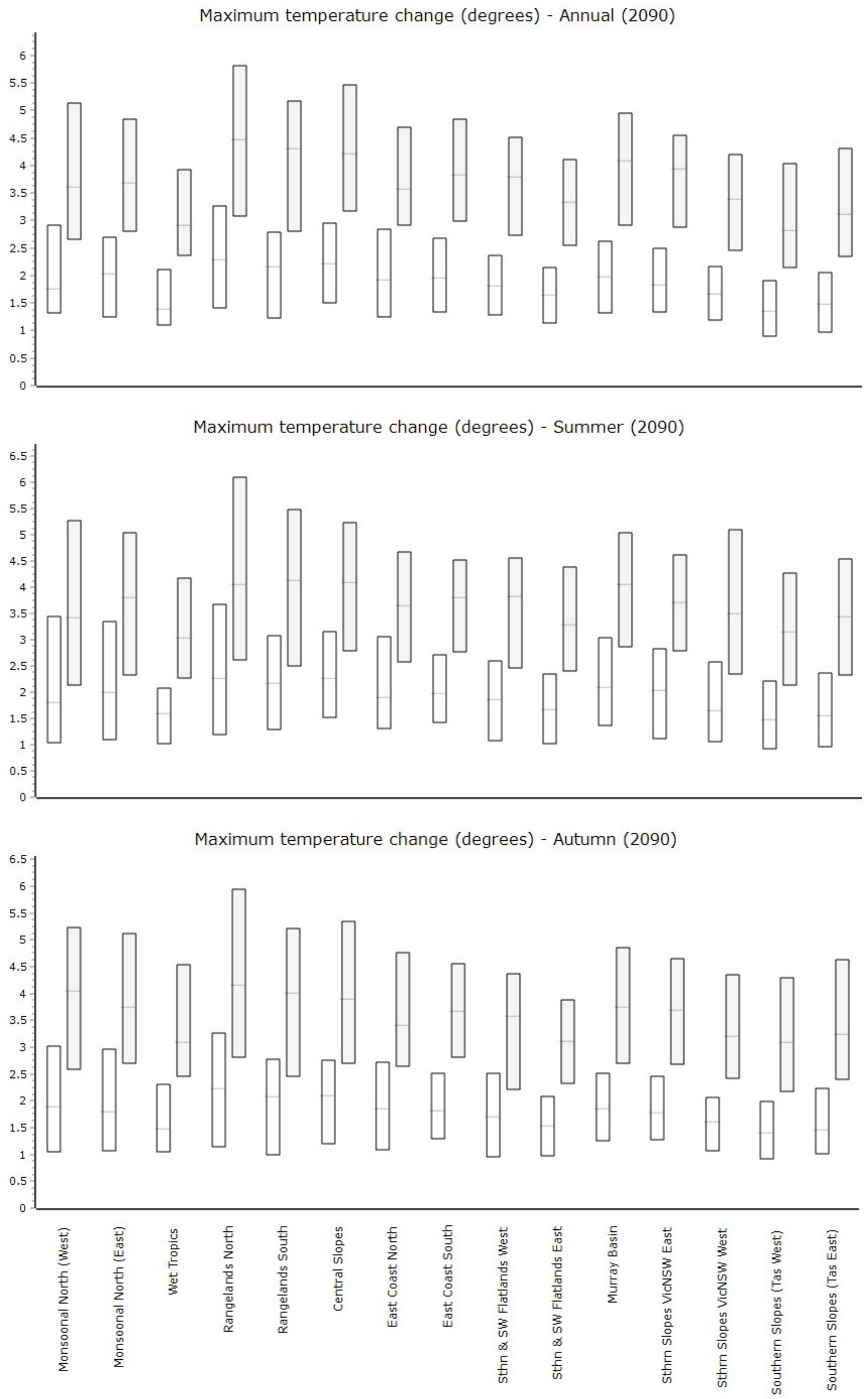
Mean temperature change (degrees) - Winter (2090)

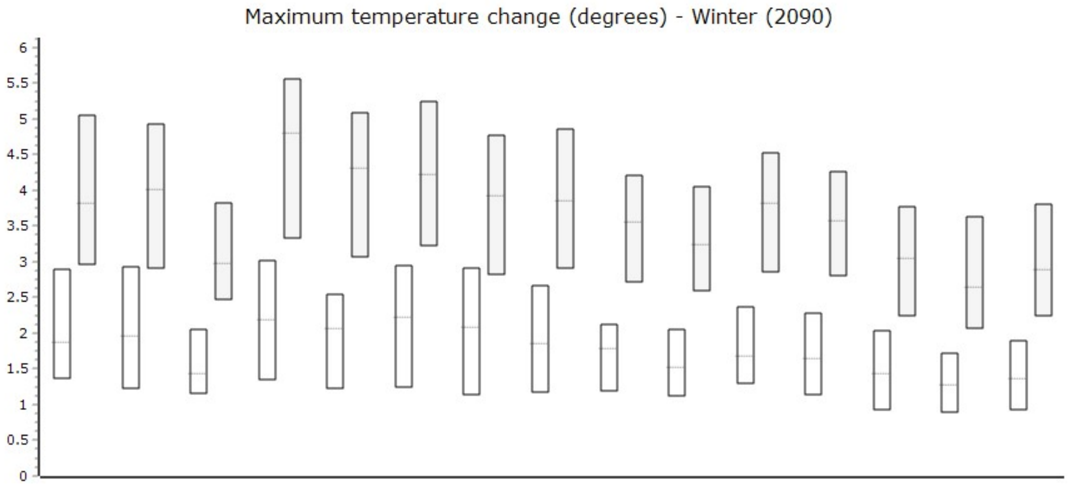


Mean temperature change (degrees) - Spring (2090)

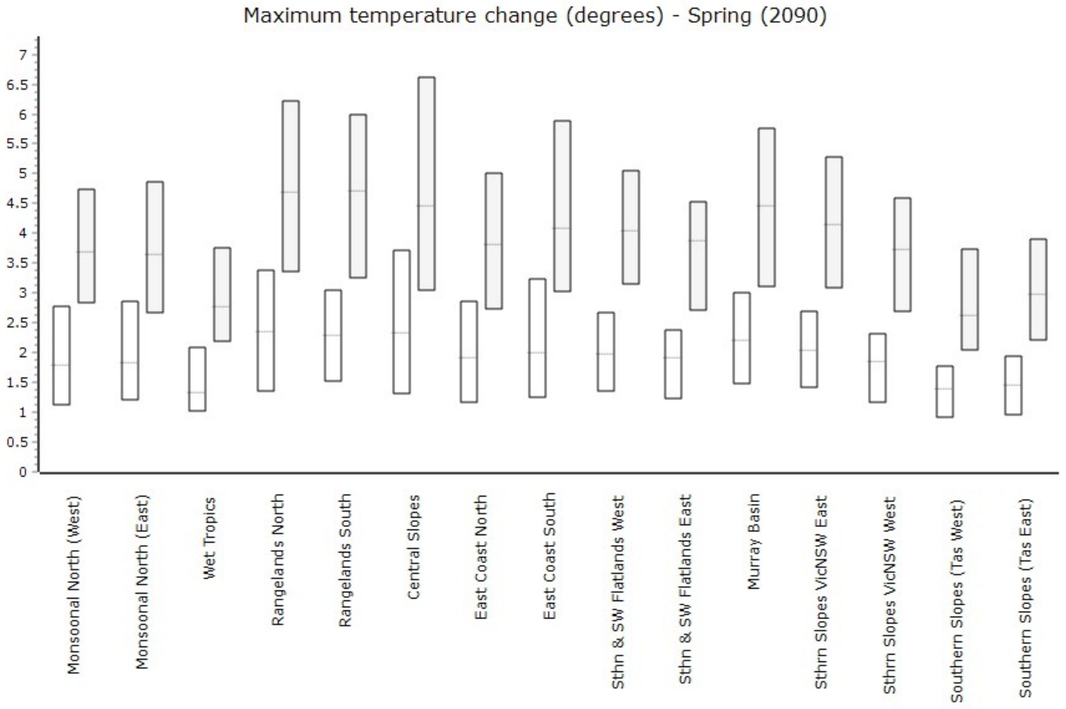


(b)


Maximum temperature change (degrees) - Annual (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Maximum temperature change (degrees) - Summer (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
Maximum temperature change (degrees) - Autumn (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

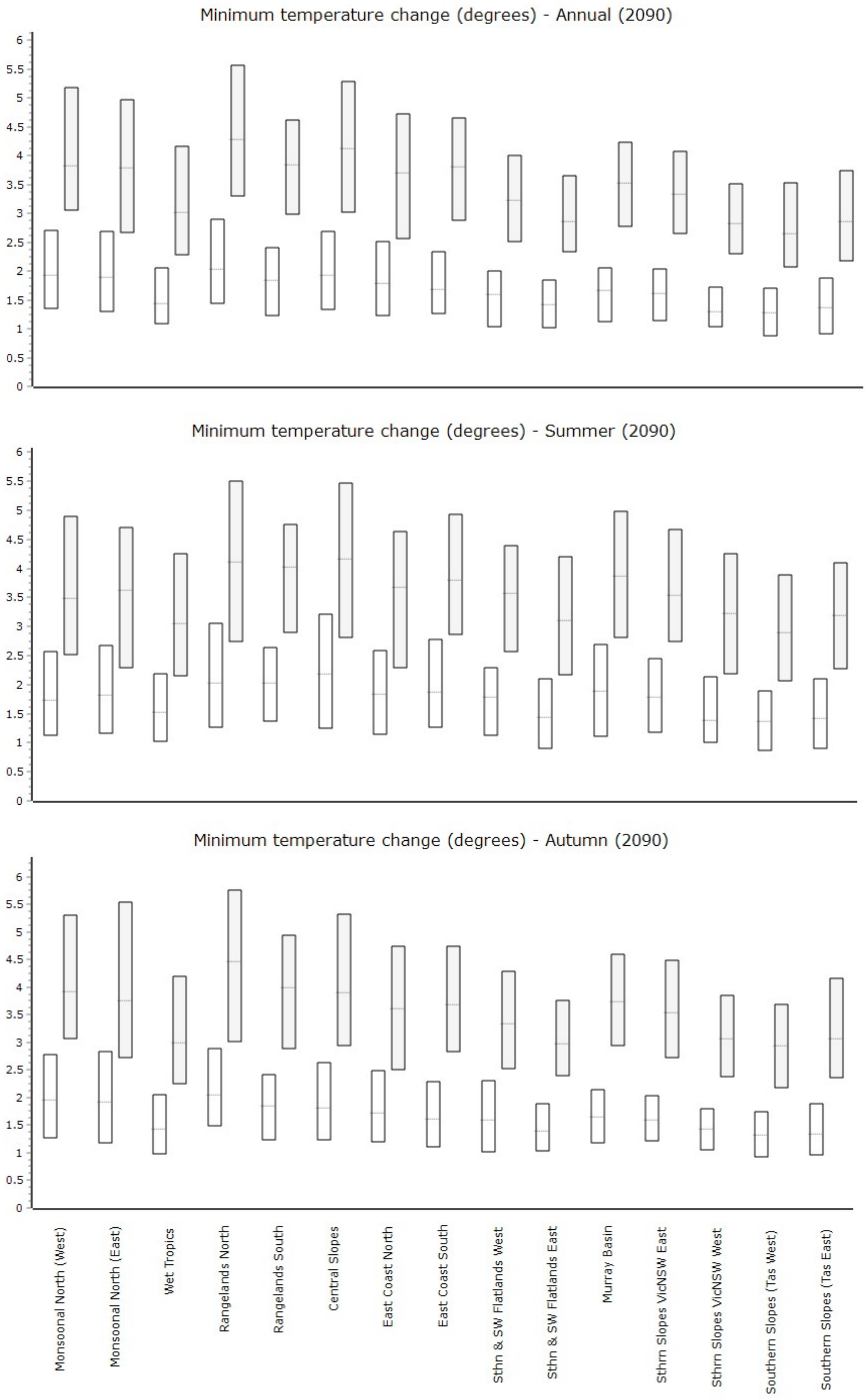


Maximum temperature change (degrees) - Winter (2090)



Maximum temperature change (degrees) - Spring (2090)

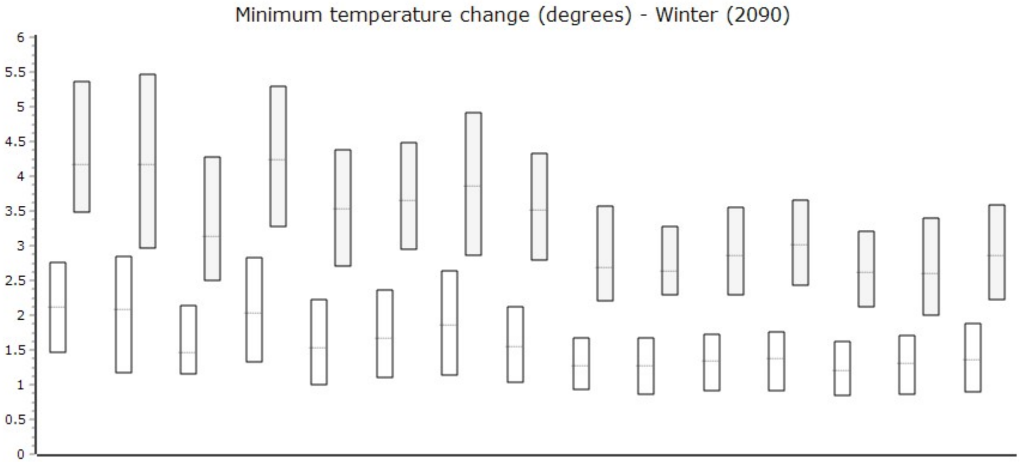
(c)

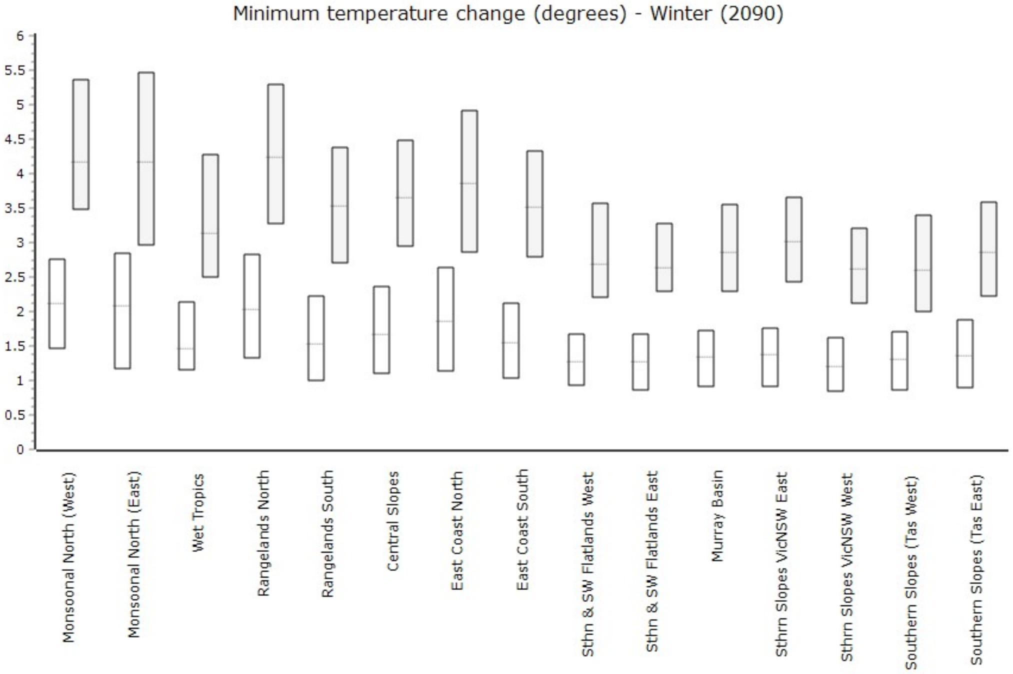


Minimum temperature change (degrees) - Annual (2090)

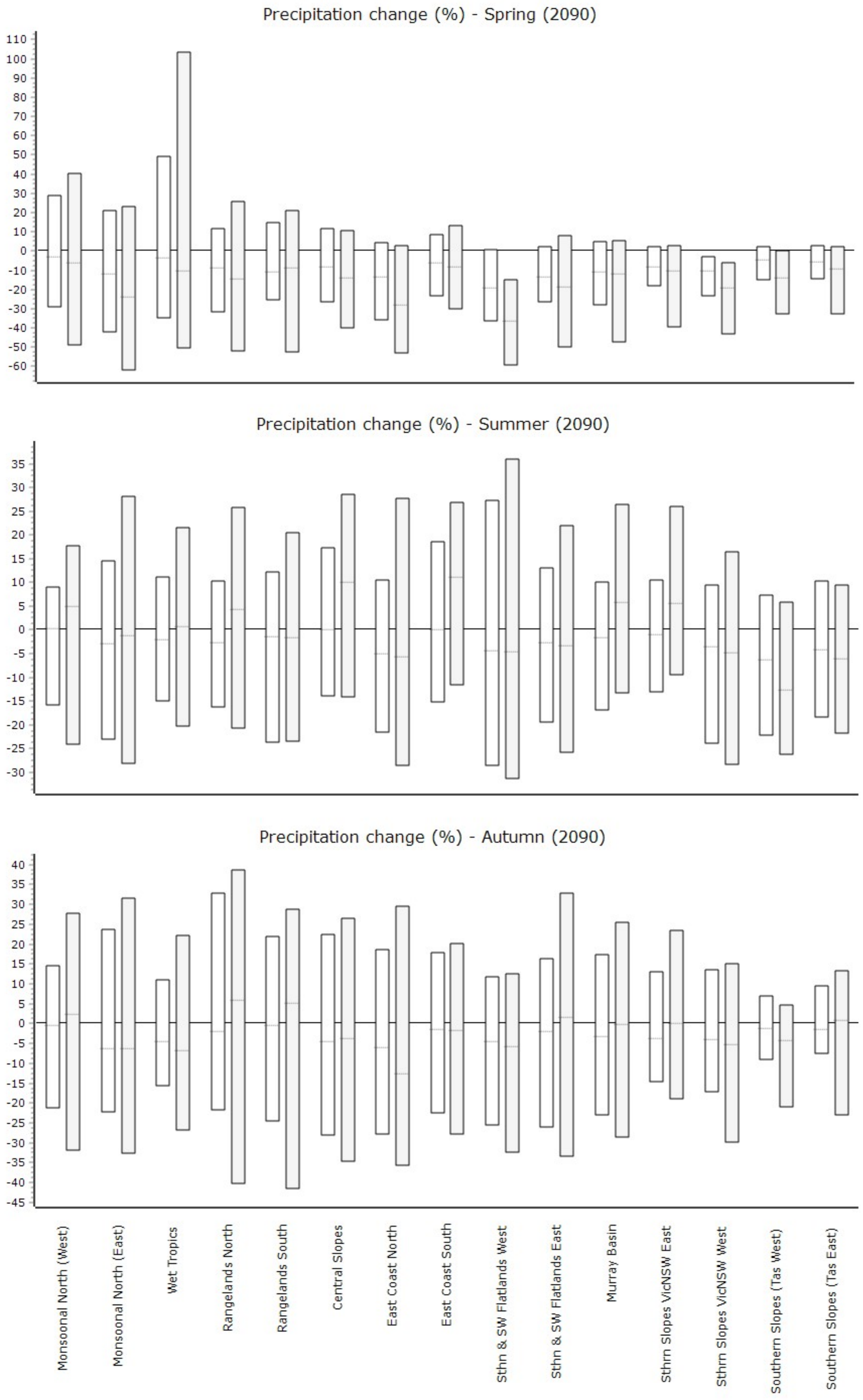
Minimum temperature change (degrees) - Summer (2090)

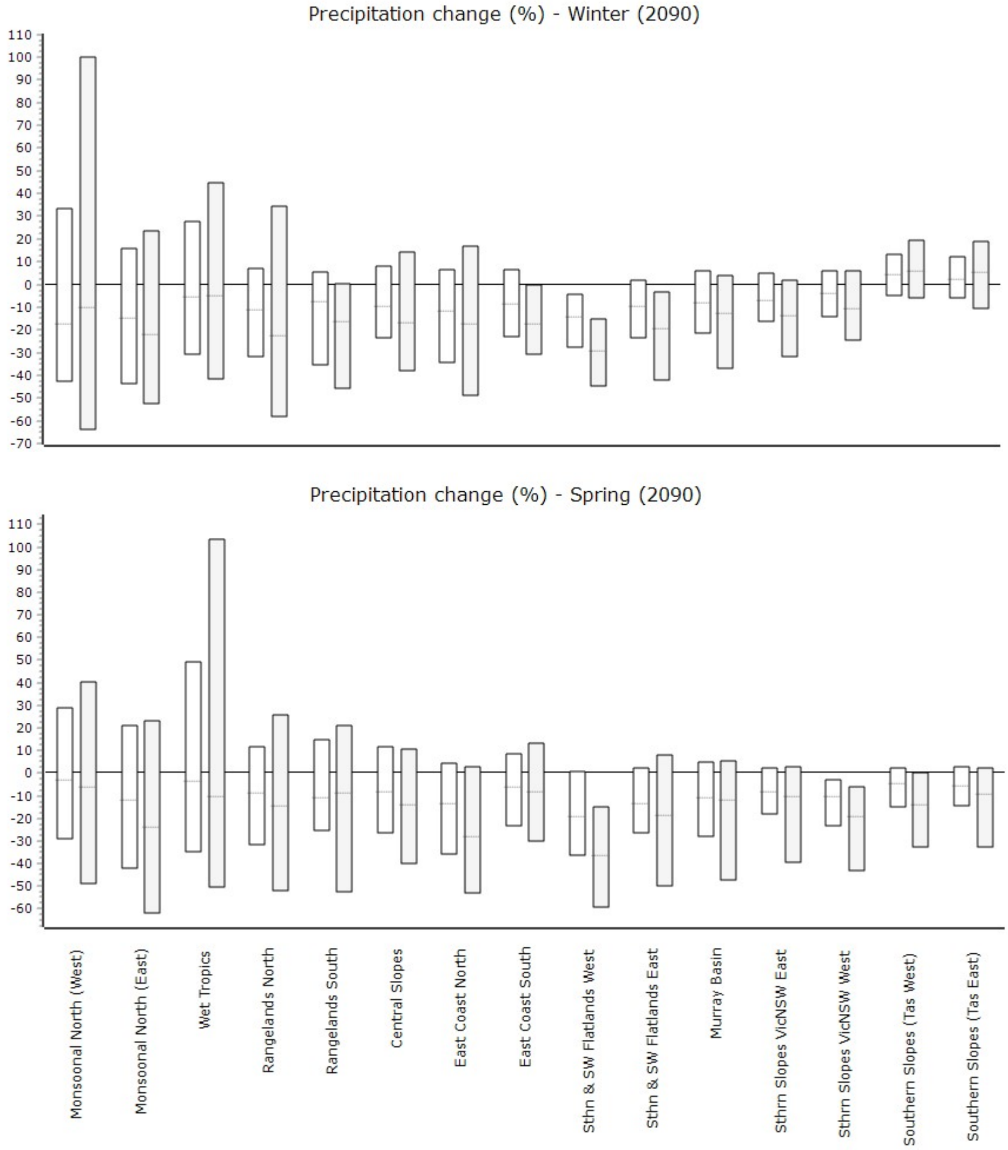
Minimum temperature change (degrees) - Autumn (2090)


Minimum temperature change (degrees) - Winter (2090)

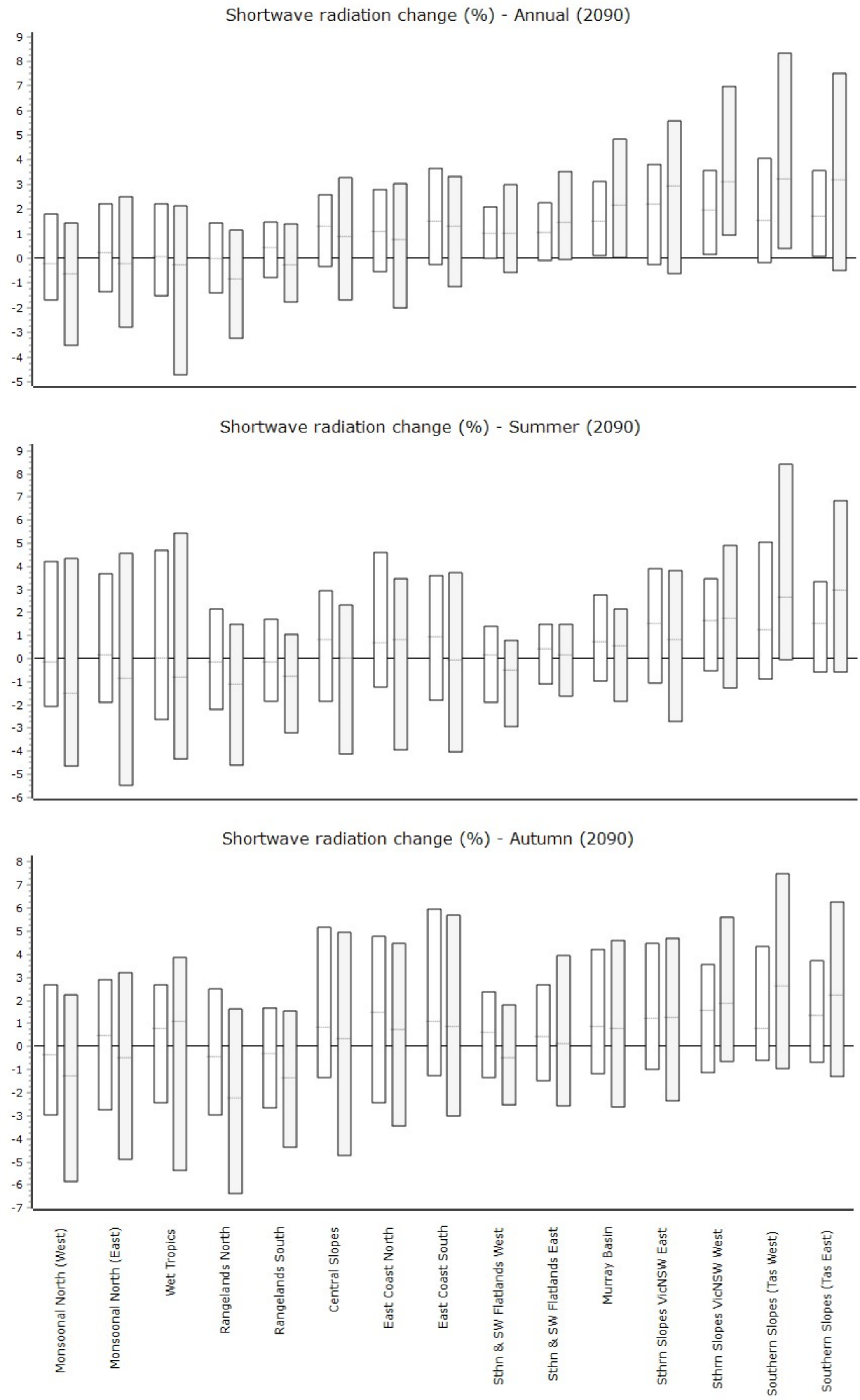

Minimum temperature change (degrees) - Winter (2090)

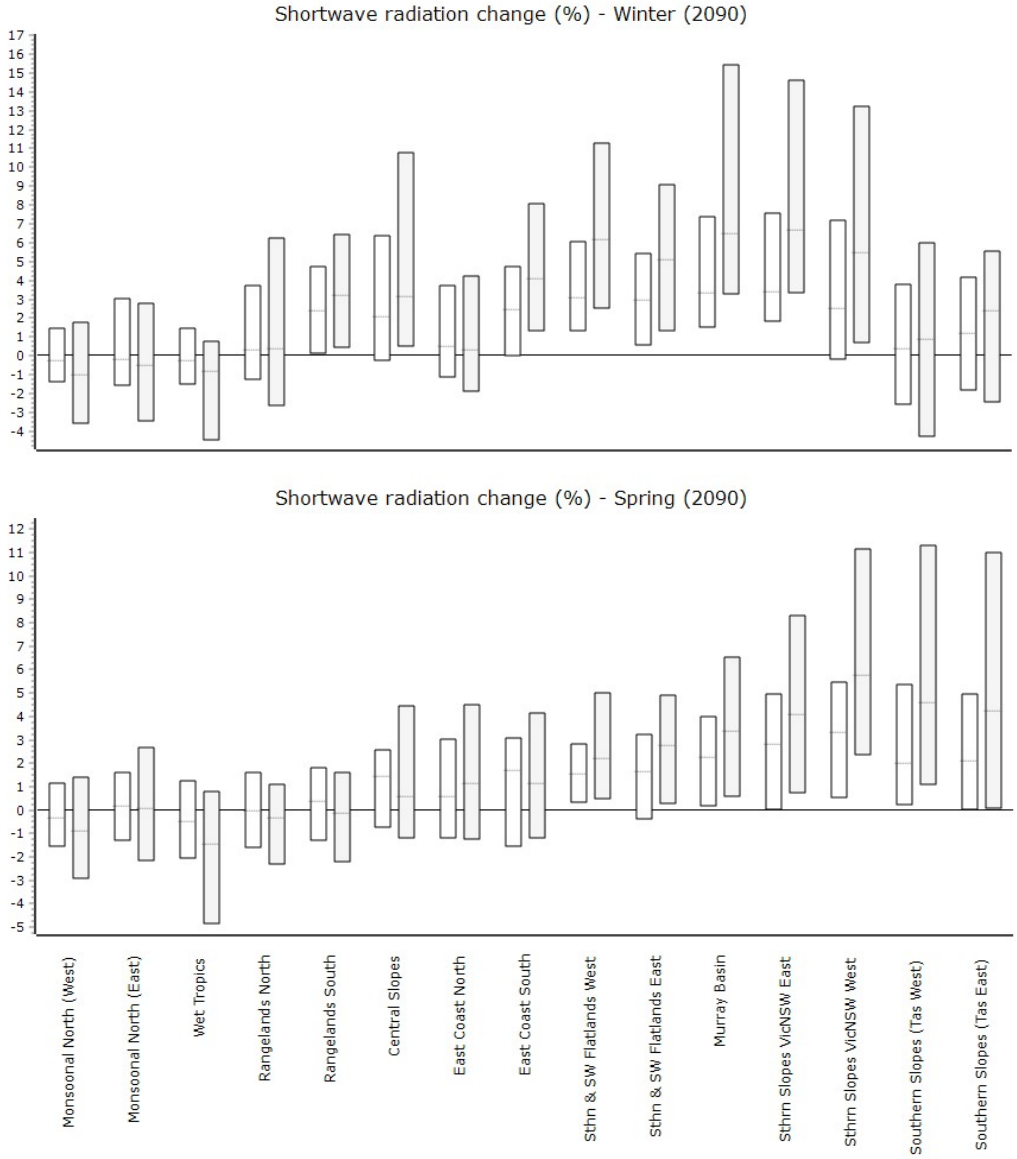
(d)


Precipitation change (%) - Spring (2090)
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Precipitation change (%) - Summer (2090)
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Precipitation change (%) - Autumn (2090)
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)


Precipitation change (%) - Winter (2090)
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Precipitation change (%) - Spring (2090)
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

(e)

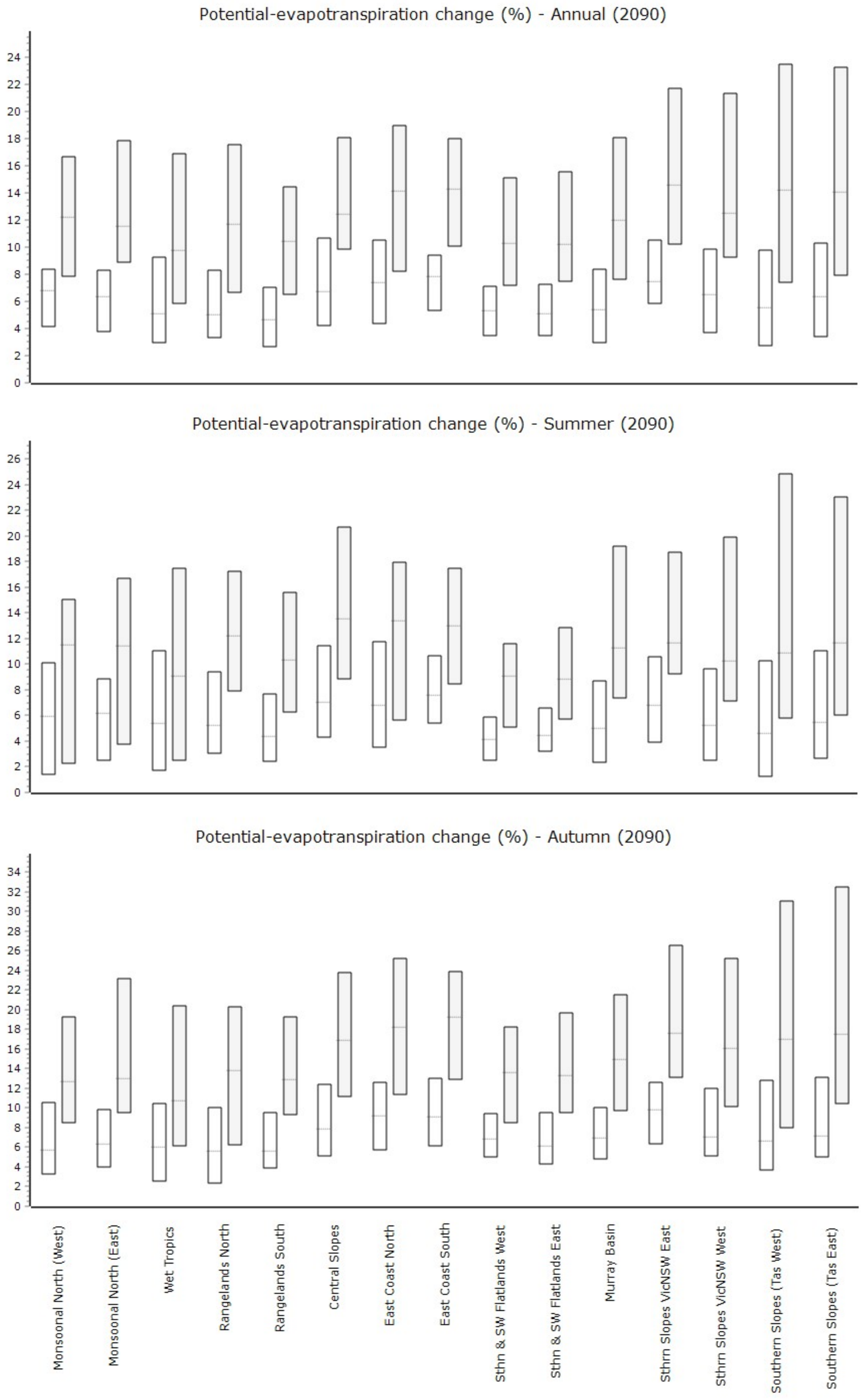

Shortwave radiation change (%) - Annual (2090)
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
Shortwave radiation change (%) - Summer (2090)
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
Shortwave radiation change (%) - Autumn (2090)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)



Shortwave radiation change (%) - Winter (2090)

Shortwave radiation change (%) - Spring (2090)

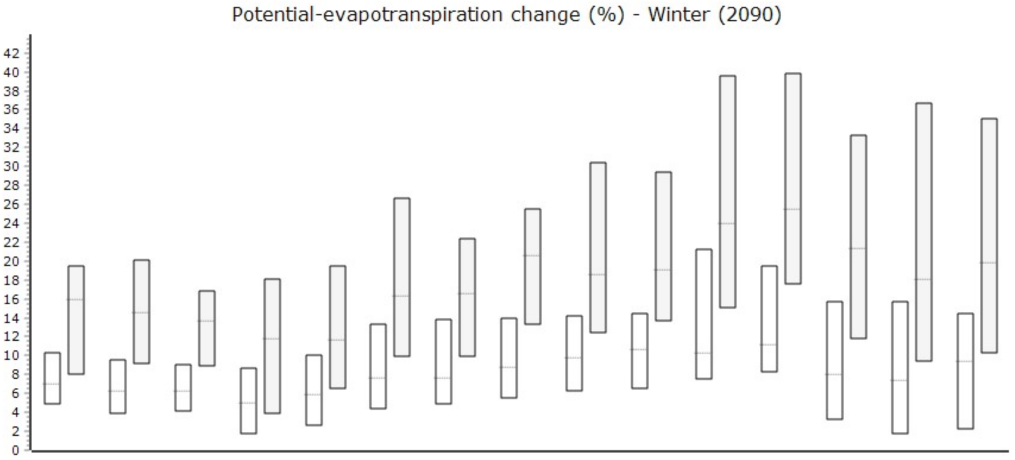
(f)

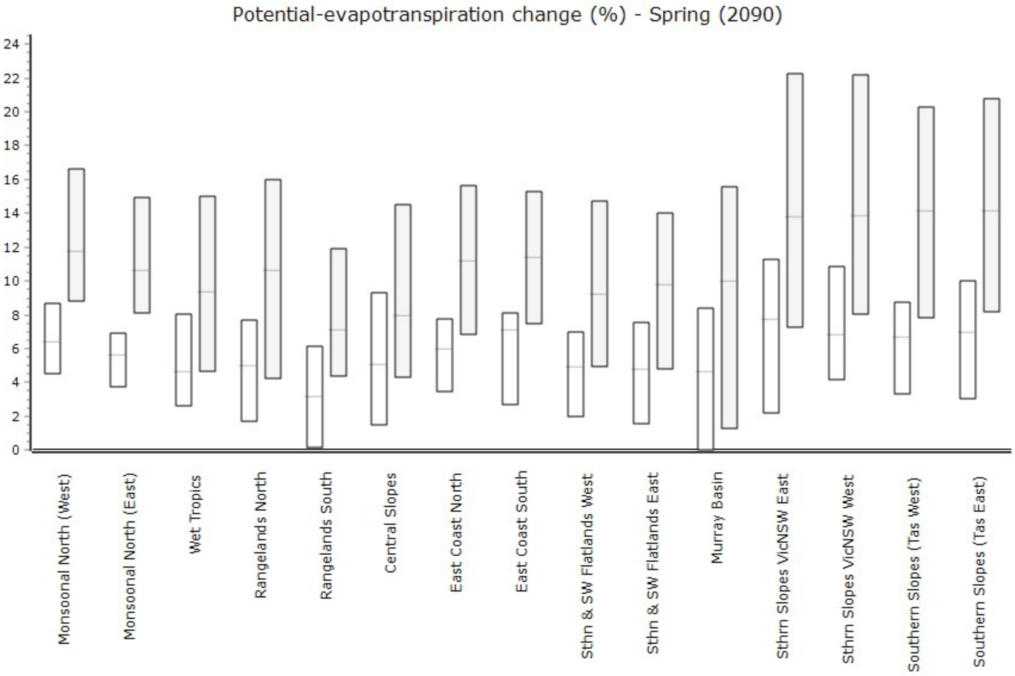


Potential-evapotranspiration change (%) - Annual (2090)

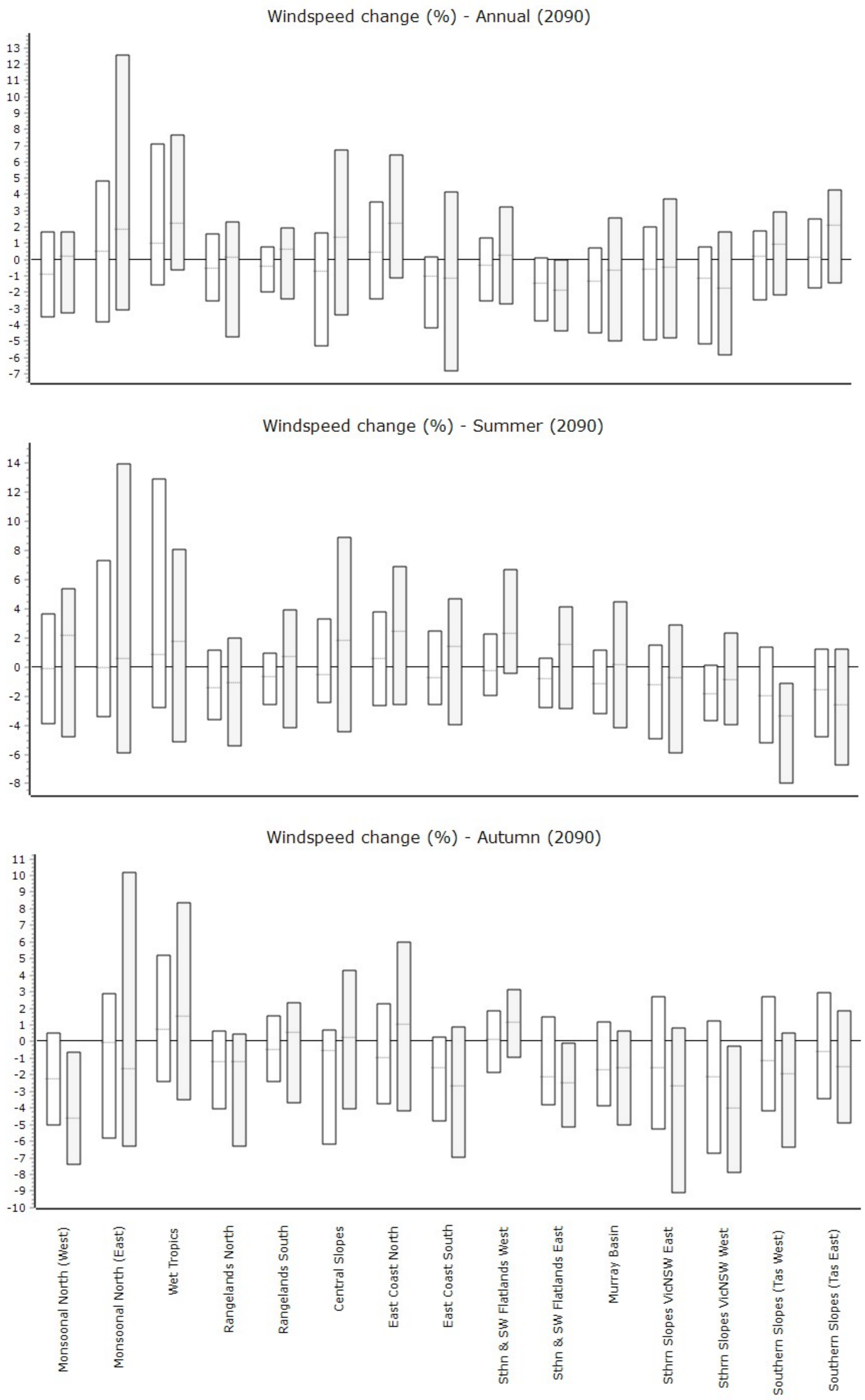
Potential-evapotranspiration change (%) - Summer (2090)

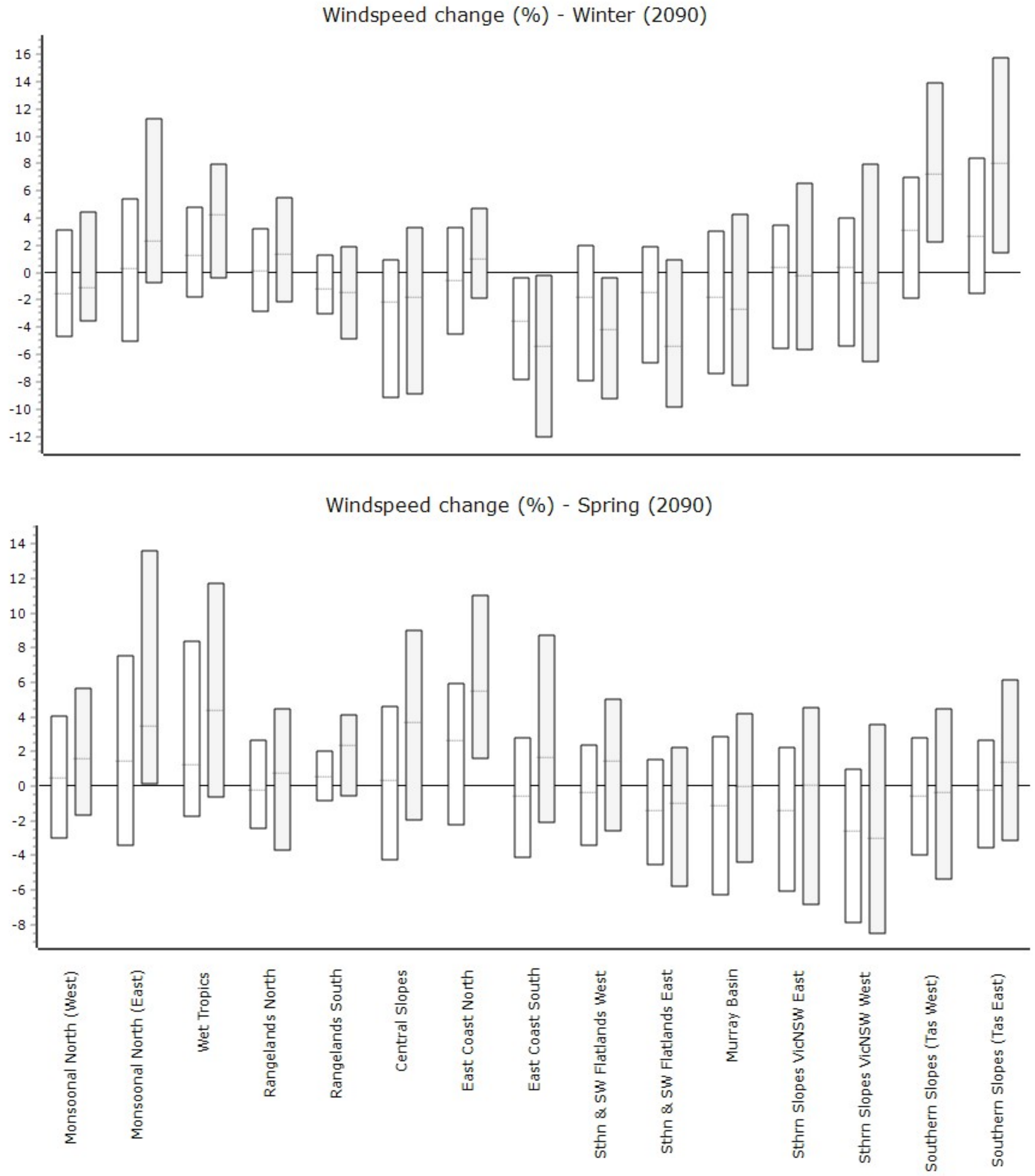
Potential-evapotranspiration change (%) - Autumn (2090)


Potential-evapotranspiration change (%) - Winter (2090)


Potential-evapotranspiration change (%) - Spring (2090)

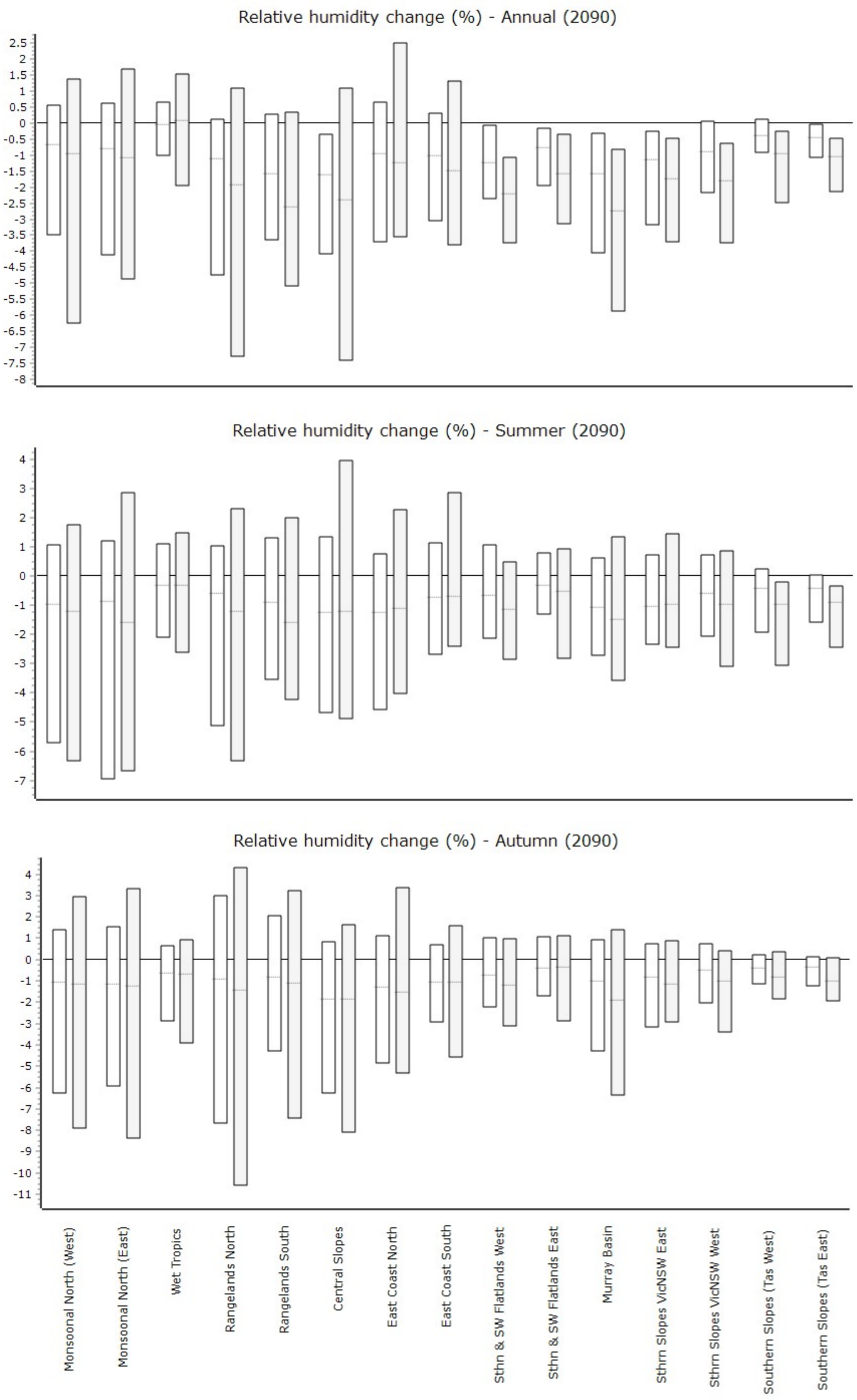
(g)

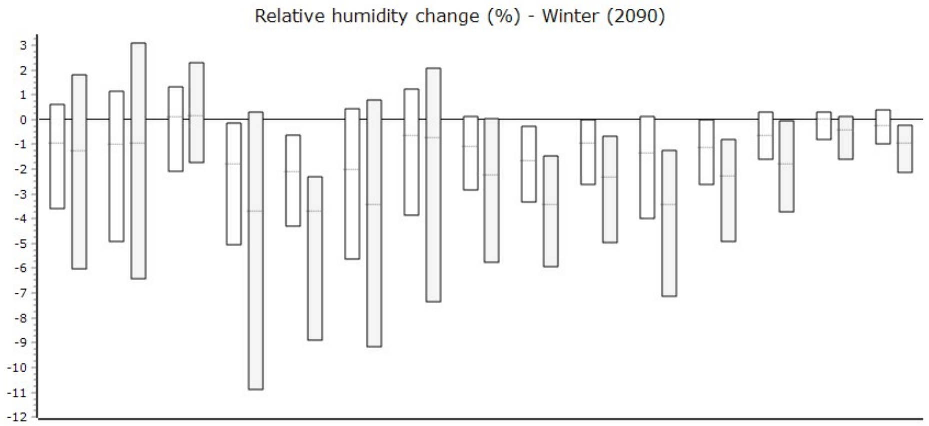

Windspeed change (%) - Annual (2090)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
Windspeed change (%) - Summer (2090)
14
12
10
8
6
4
2
0
-2
-4
-6
-8
Windspeed change (%) - Autumn (2090)
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

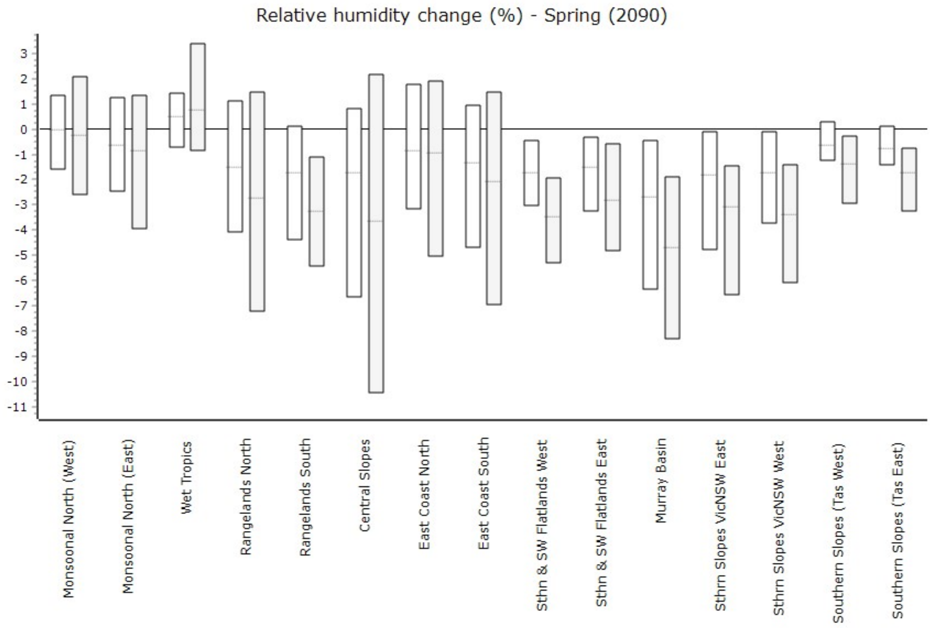

Windspeed change (%) - Winter (2090)

Windspeed change (%) - Spring (2090)

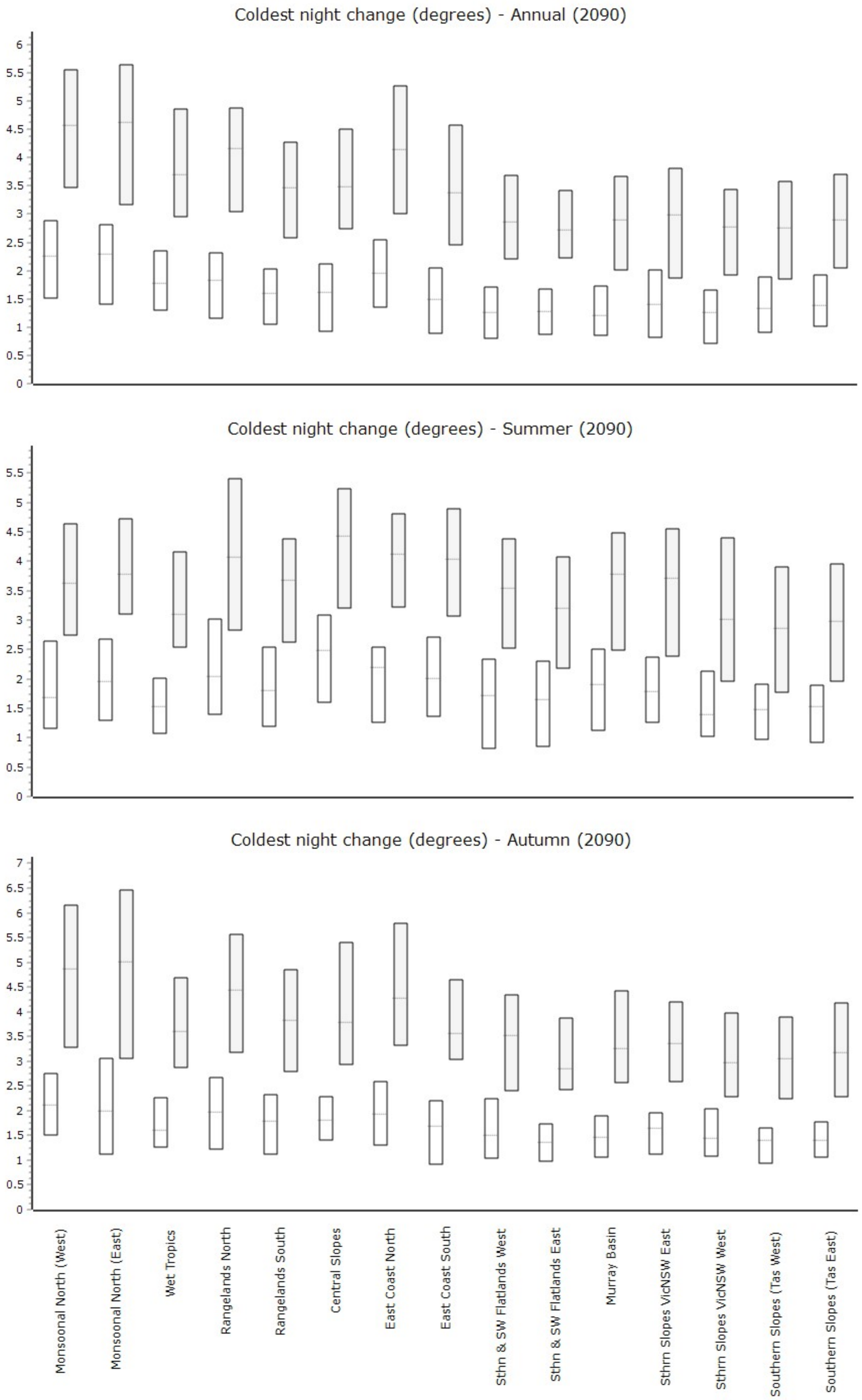
(h)


Relative humidity change (%) - Annual (2090)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8
Relative humidity change (%) - Summer (2090)
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
Relative humidity change (%) - Autumn (2090)
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)


Relative humidity change (%) - Winter (2090)


Relative humidity change (%) - Spring (2090)

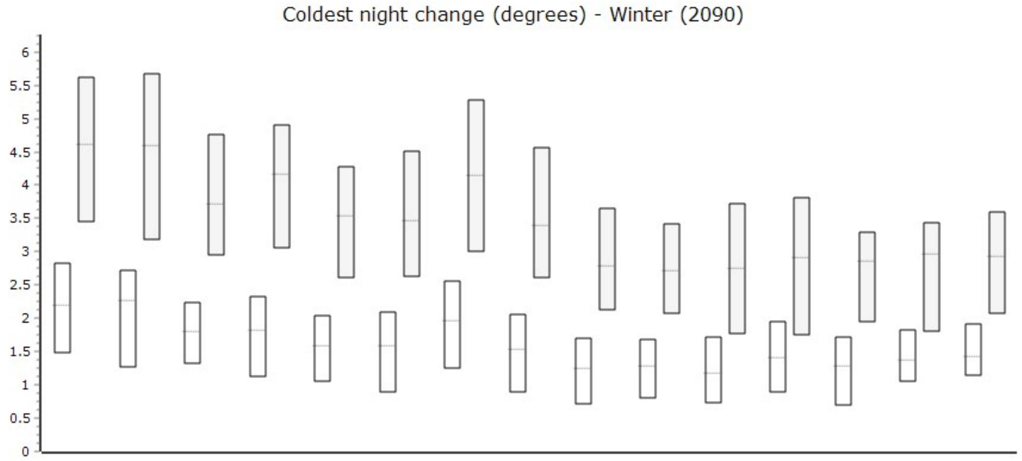
(i)

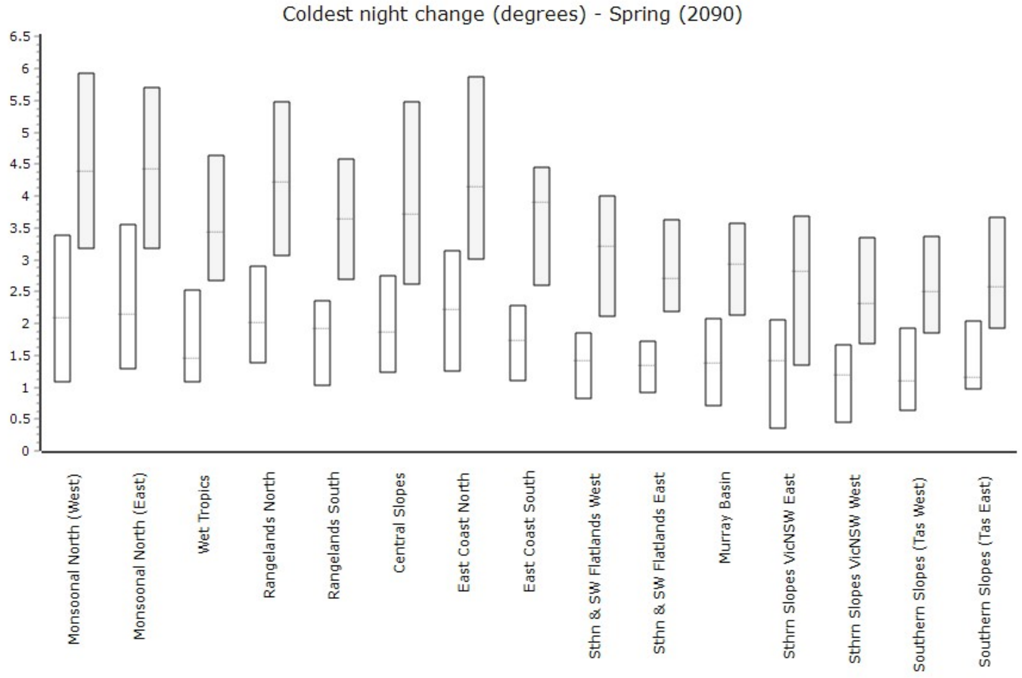


Coldest night change (degrees) - Annual (2090)

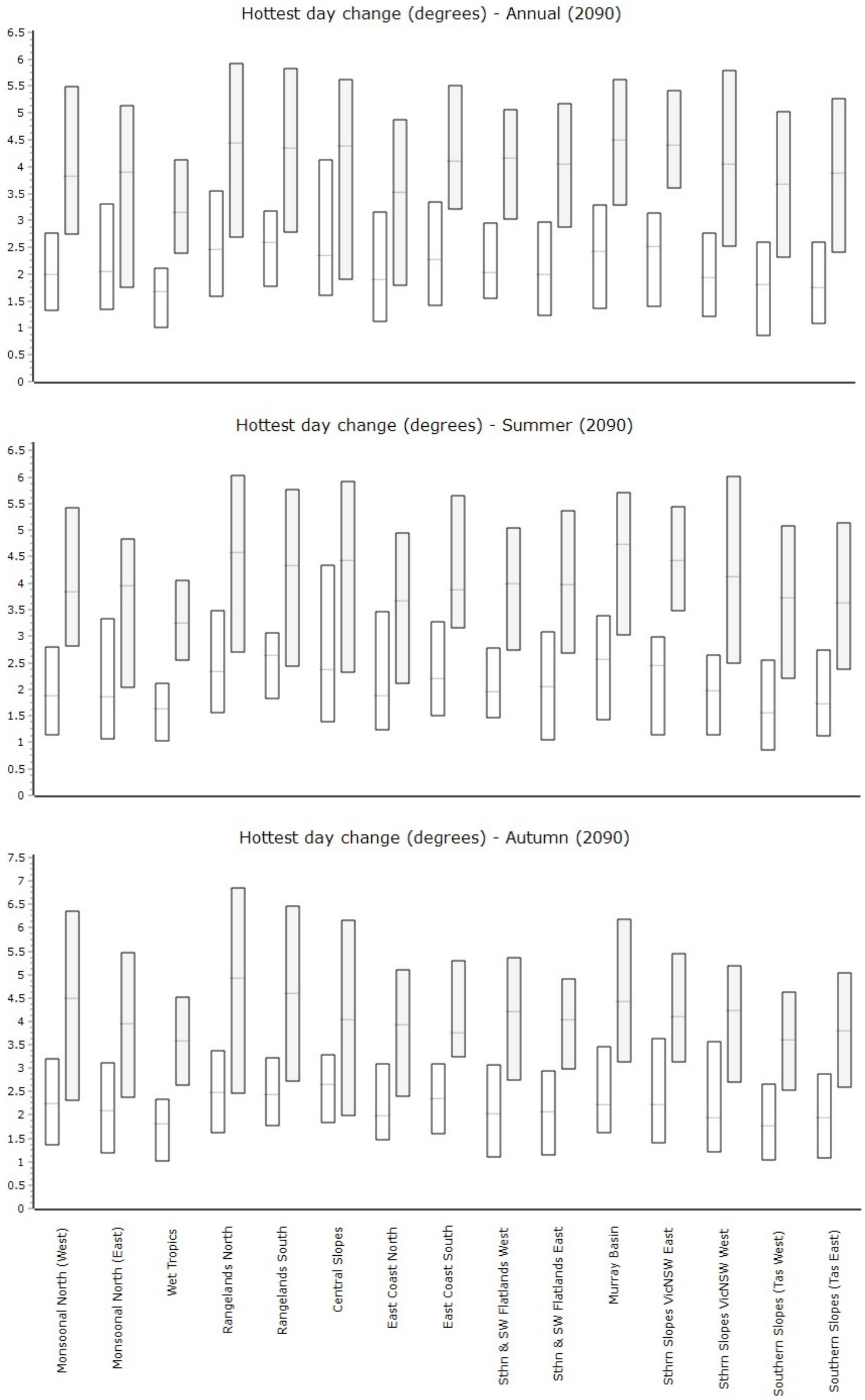
Coldest night change (degrees) - Summer (2090)

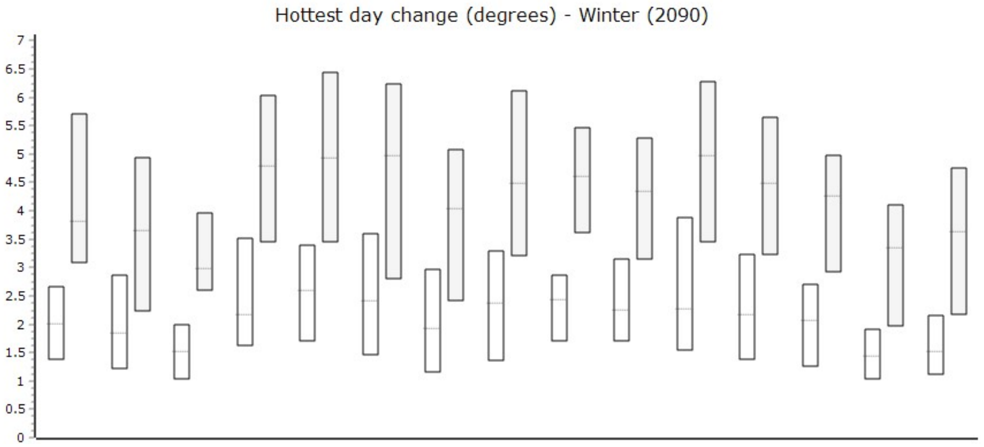
Coldest night change (degrees) - Autumn (2090)

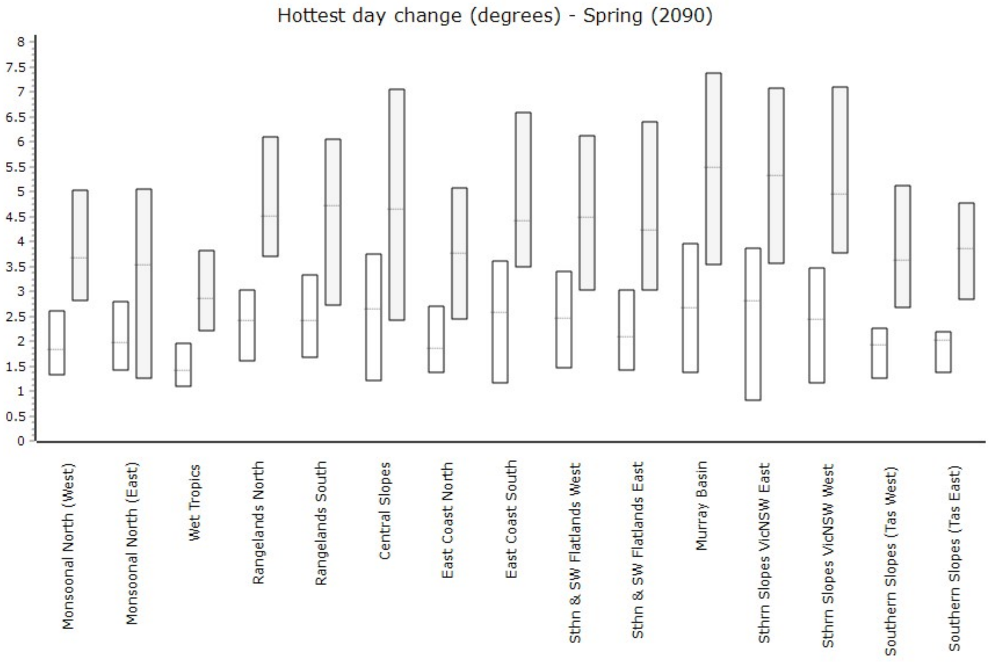

Coldest night change (degrees) - Winter (2090)


Coldest night change (degrees) - Spring (2090)

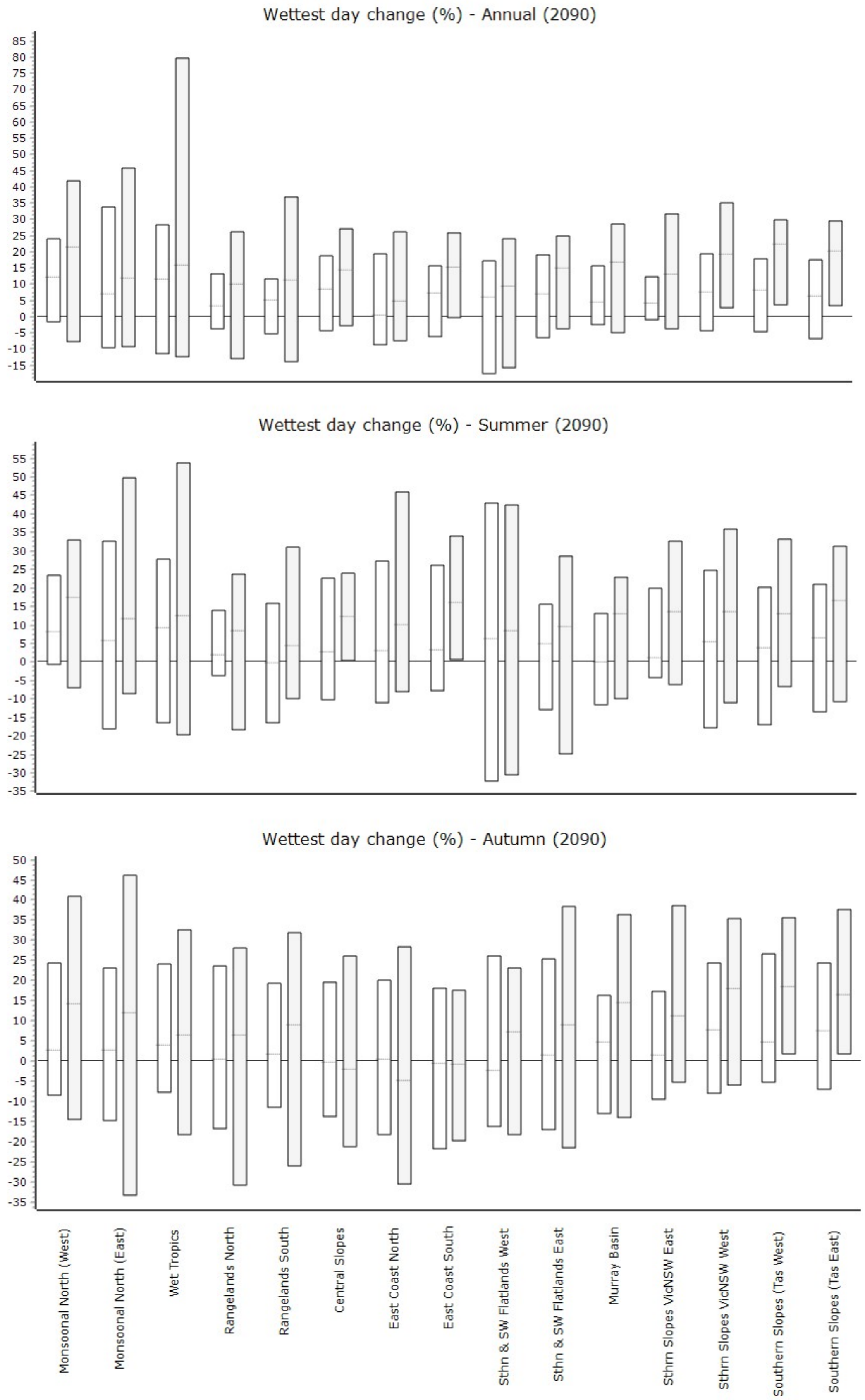
(j)

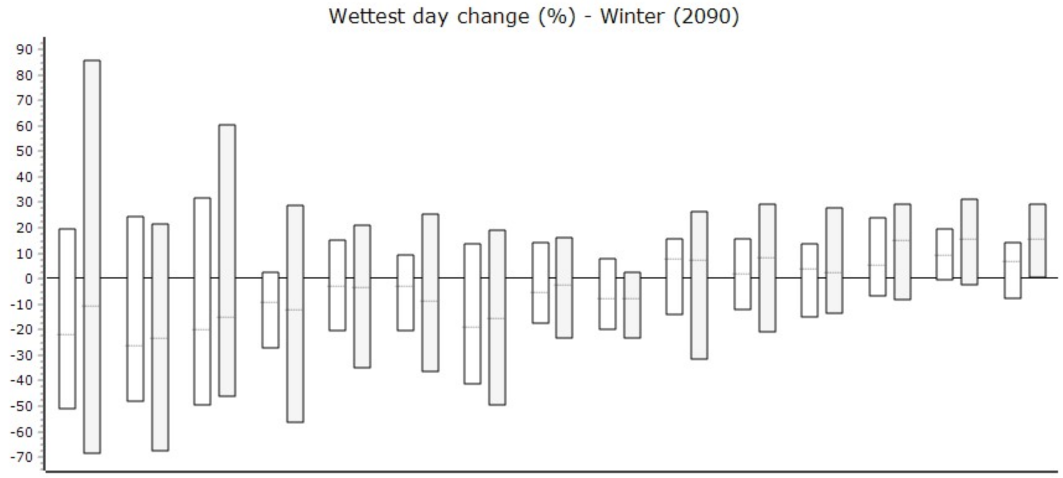

Hottest day change (degrees) - Annual (2090)
Hottest day change (degrees) - Summer (2090)
Hottest day change (degrees) - Autumn (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

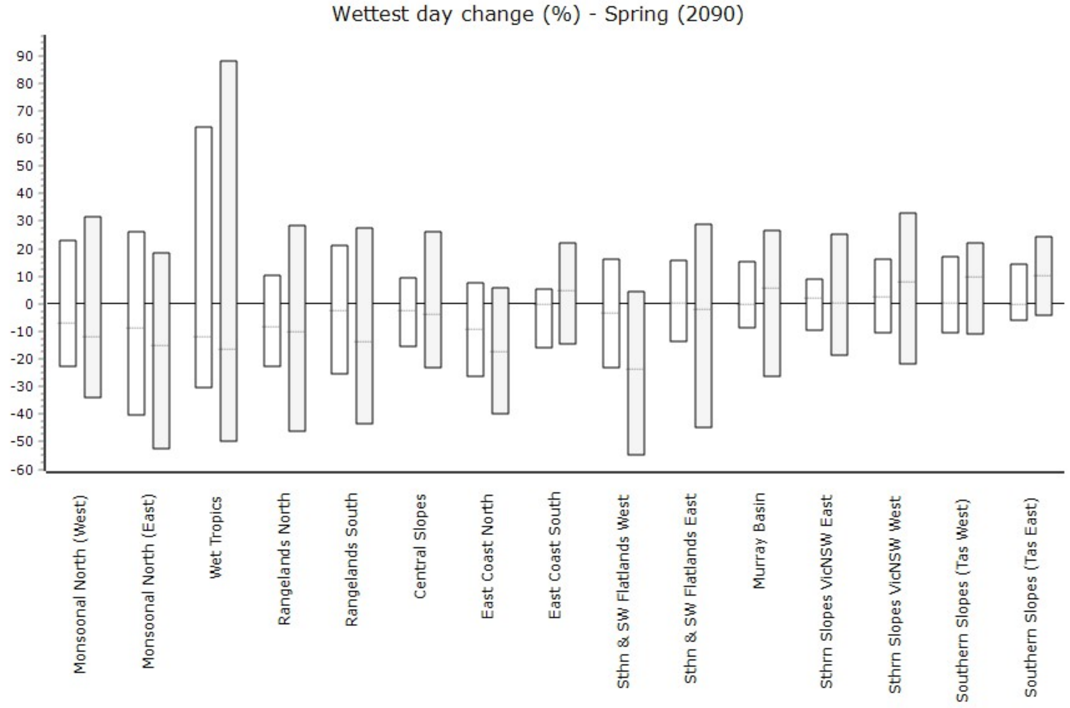

Hottest day change (degrees) - Winter (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7


Hottest day change (degrees) - Spring (2090)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

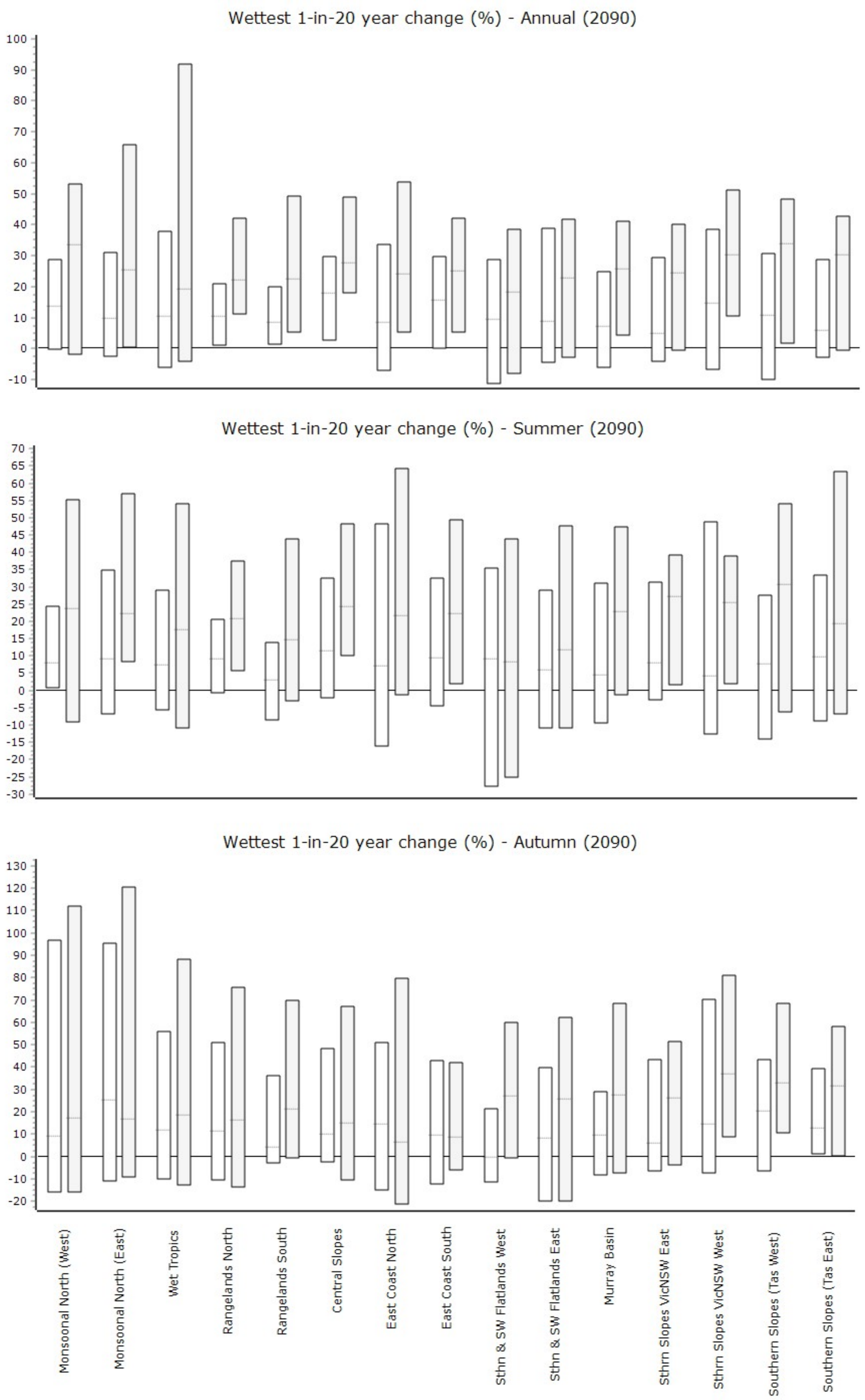
(k)

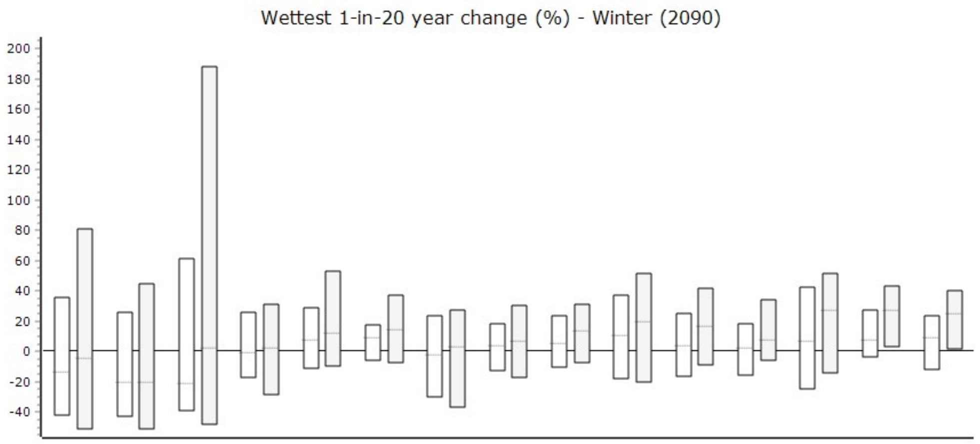

Wettest day change (%) - Annual (2090)
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
Wettest day change (%) - Summer (2090)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
Wettest day change (%) - Autumn (2090)
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

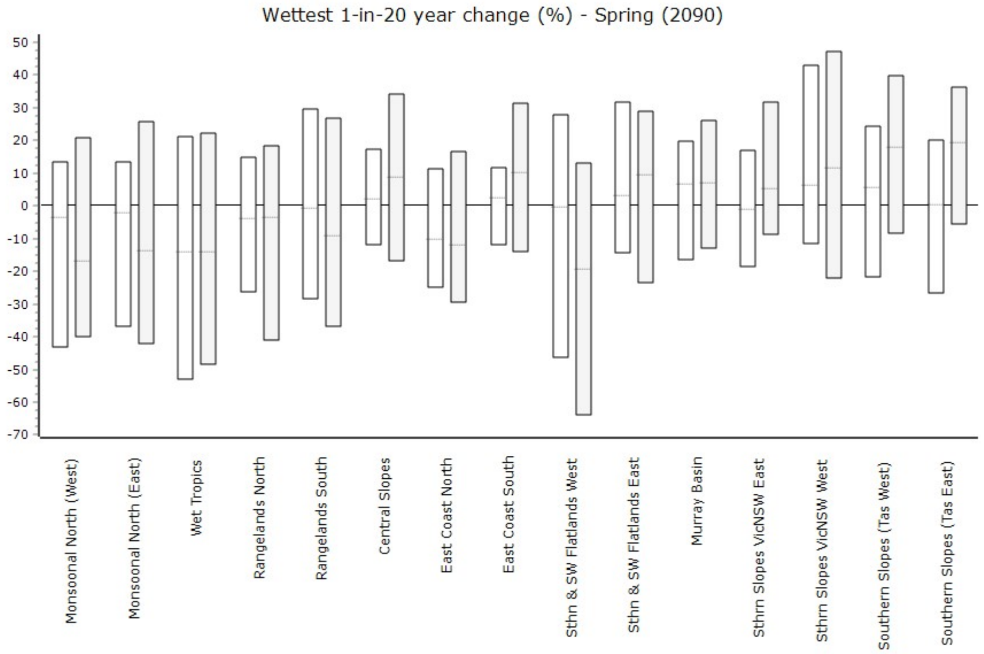

Wettest day change (%) - Winter (2090)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70


Wettest day change (%) - Spring (2090)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

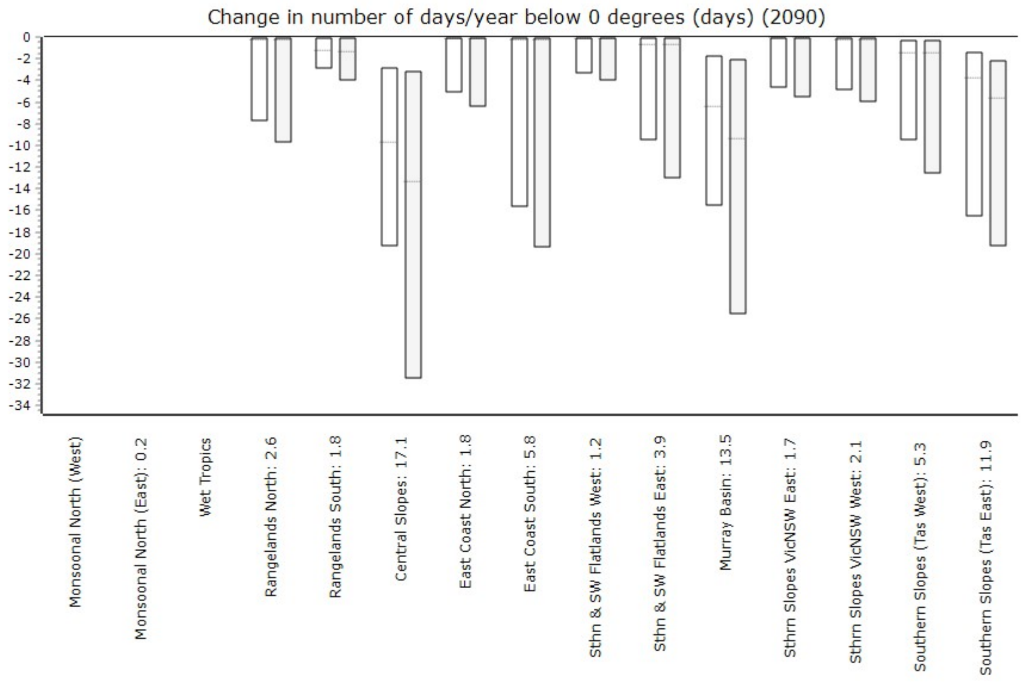
(l)


Wettest 1-in-20 year change (%) - Annual (2090)
100
90
80
70
60
50
40
30
20
10
0
-10
Wettest 1-in-20 year change (%) - Summer (2090)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Wettest 1-in-20 year change (%) - Autumn (2090)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

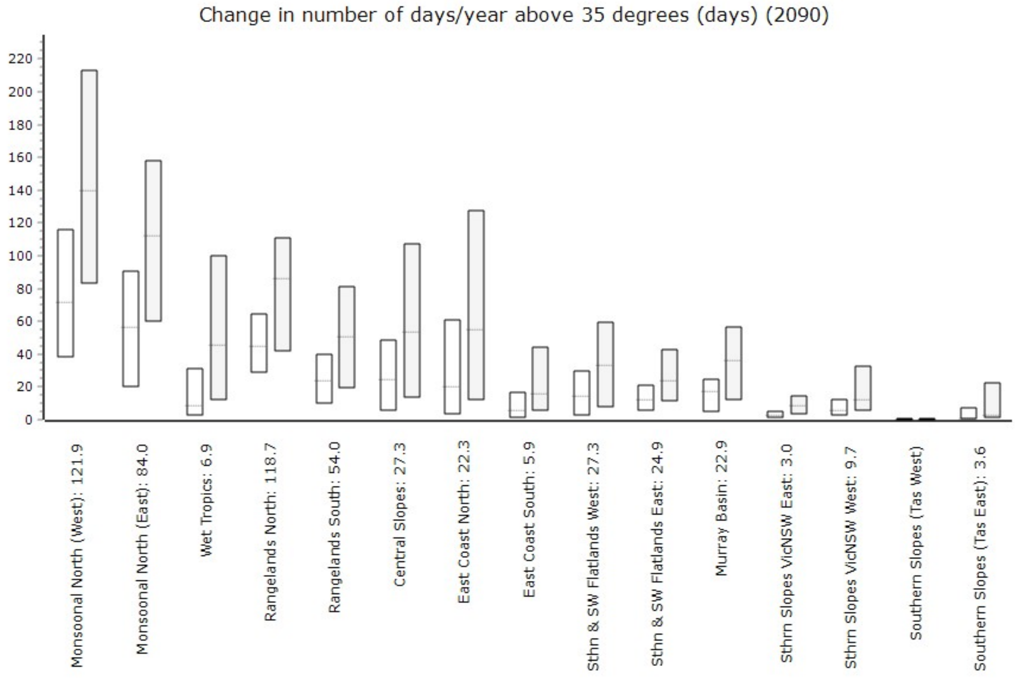

Wettest 1-in-20 year change (%) - Winter (2090)
200
180
160
140
120
100
80
60
40
20
0
-20
-40


Wettest 1-in-20 year change (%) - Spring (2090)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

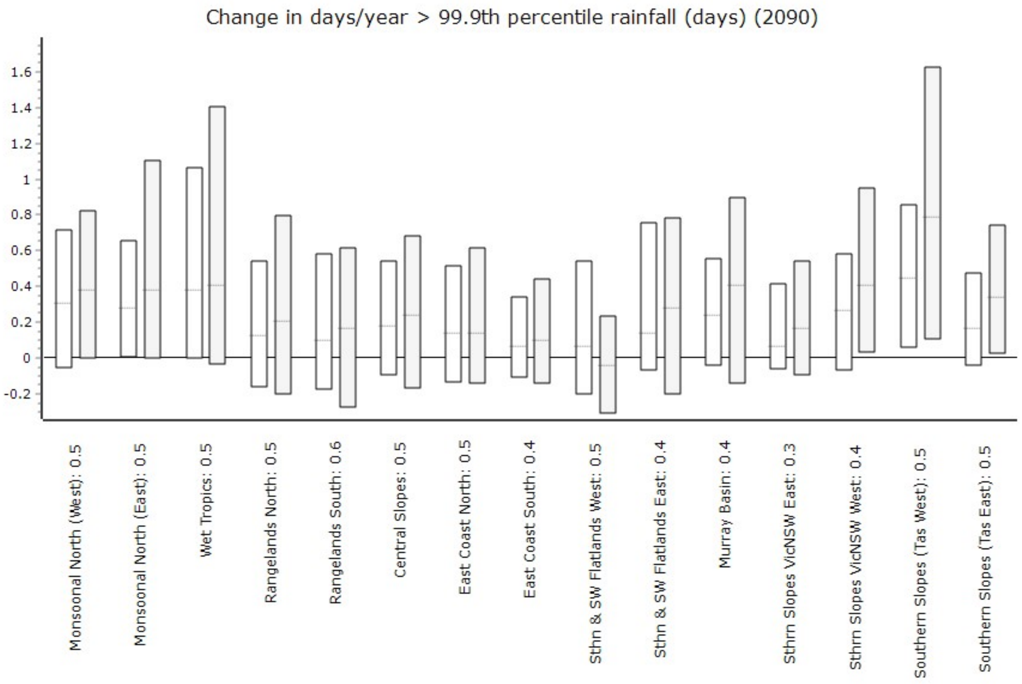
(m)


Change in number of days/year below 0 degrees (days) (2090)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
Monsoonal North (West)
Monsoonal North (East): 0.2
Wet Tropics
Rangelands North: 2.6
Rangelands South: 1.8
Central Slopes: 17.1
East Coast North: 1.8
East Coast South: 5.8
Sthn & SW Flatlands West: 1.2
Sthn & SW Flatlands East: 3.9
Murray Basin: 13.5
Sthrn Slopes VicNSW East: 1.7
Sthrn Slopes VicNSW West: 2.1
Southern Slopes (Tas West): 5.3
Southern Slopes (Tas East): 11.9

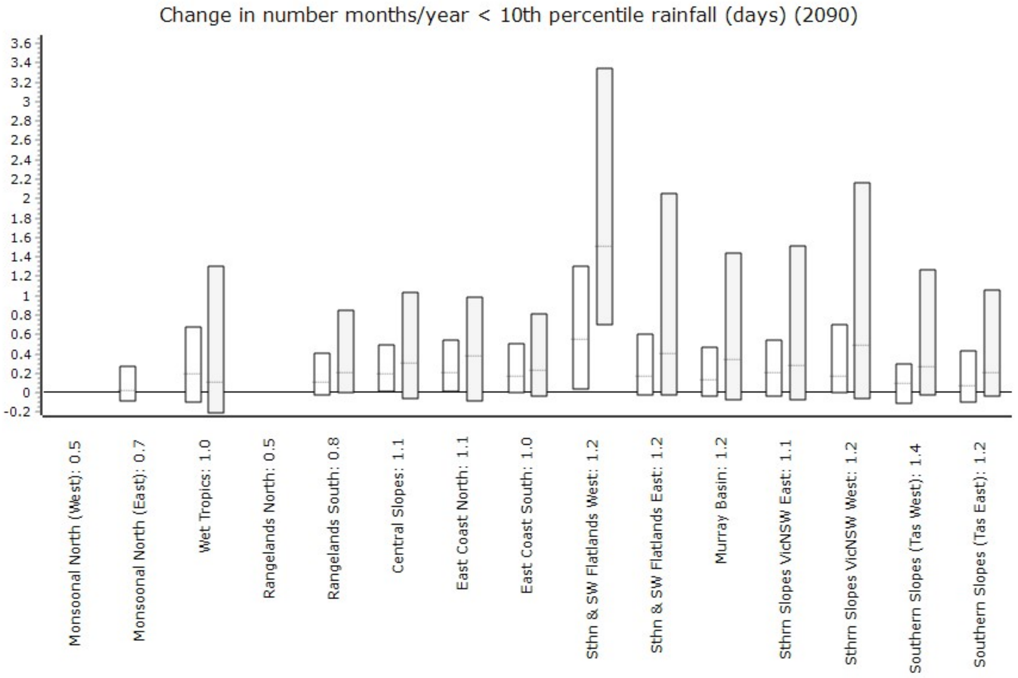
(n)


Change in number of days/year above 35 degrees (days) (2090)
220
200
180
160
140
120
100
80
60
40
20
0
Monsoonal North (West): 121.9
Monsoonal North (East): 84.0
Wet Tropics: 6.9
Rangelands North: 118.7
Rangelands South: 54.0
Central Slopes: 27.3
East Coast North: 22.3
East Coast South: 5.9
Sthn & SW Flatlands West: 27.3
Sthn & SW Flatlands East: 24.9
Murray Basin: 22.9
Sthrn Slopes VicNSW East: 3.0
Sthrn Slopes VicNSW West: 9.7
Southern Slopes (Tas West)
Southern Slopes (Tas East): 3.6

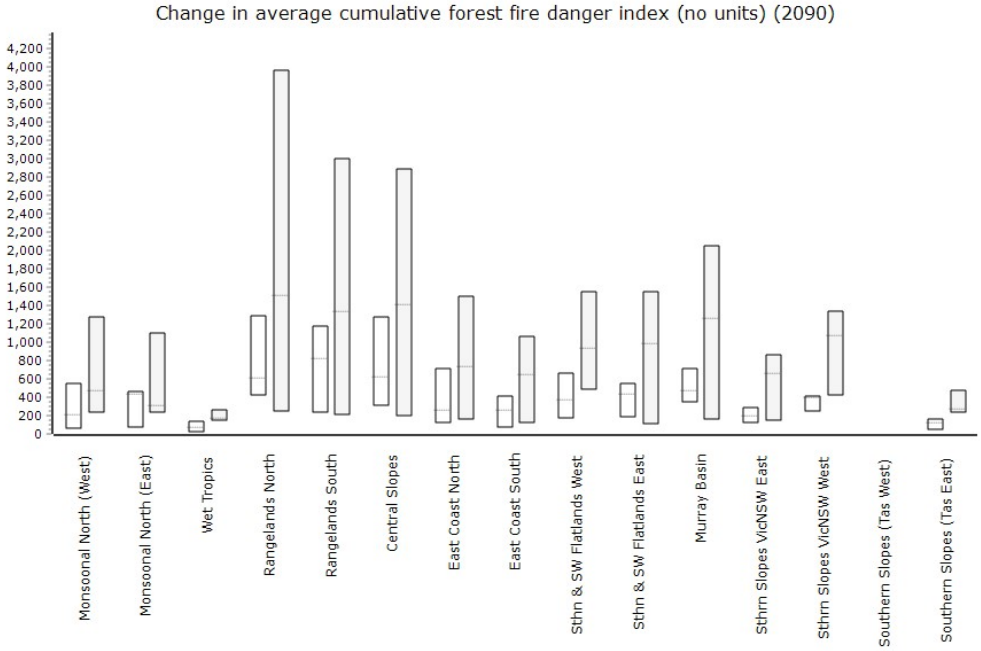
(o)


Change in days/year > 99.9th percentile rainfall (days) (2090)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Monsoonal North (West): 0.5
Monsoonal North (East): 0.5
Wet Tropics: 0.5
Rangelands North: 0.5
Rangelands South: 0.6
Central Slopes: 0.5
East Coast North: 0.5
East Coast South: 0.4
Sthn & SW Flatlands West: 0.5
Sthn & SW Flatlands East: 0.4
Murray Basin: 0.4
Sthrn Slopes VicNSW East: 0.3
Sthrn Slopes VicNSW West: 0.4
Southern Slopes (Tas West): 0.5
Southern Slopes (Tas East): 0.5

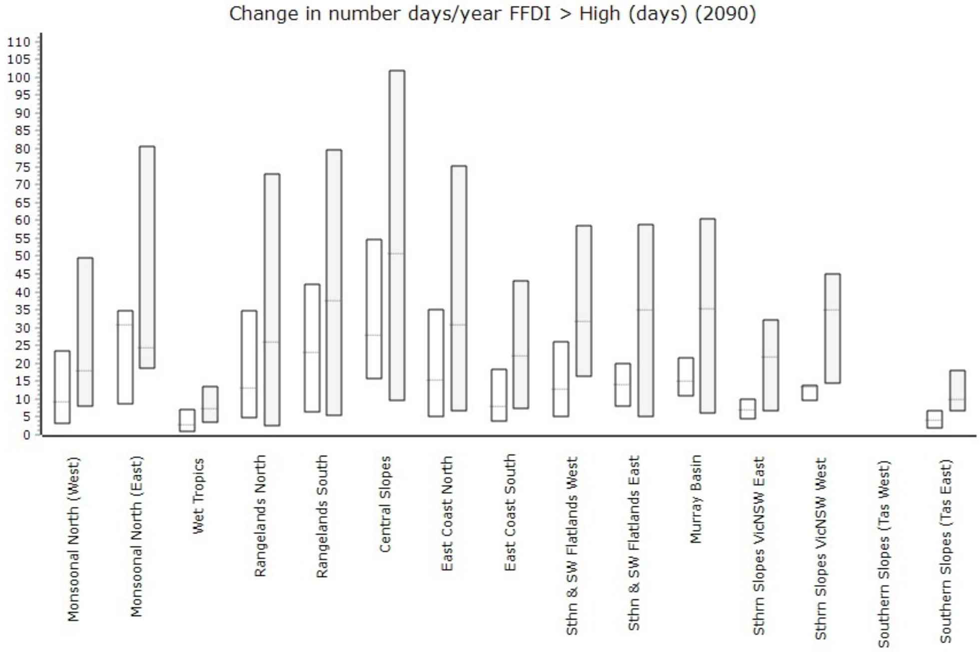
(p)


Change in number months/year < 10th percentile rainfall (days) (2090)
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Monsoonal North (West): 0.5
Monsoonal North (East): 0.7
Wet Tropics: 1.0
Rangelands North: 0.5
Rangelands South: 0.8
Central Slopes: 1.1
East Coast North: 1.1
East Coast South: 1.0
Sthn & SW Flatlands West: 1.2
Sthn & SW Flatlands East: 1.2
Murray Basin: 1.2
Sthrn Slopes VicNSW East: 1.1
Sthrn Slopes VicNSW West: 1.2
Southern Slopes (Tas West): 1.4
Southern Slopes (Tas East): 1.2

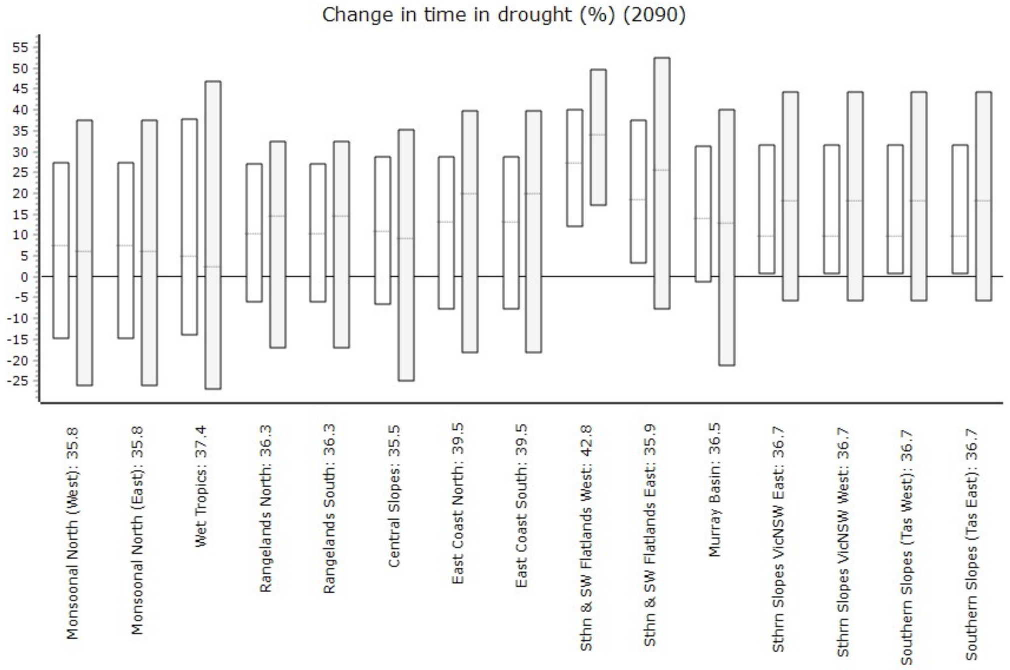
(q)


Change in average cumulative forest fire danger index (no units) (2090)
4,200
4,000
3,800
3,600
3,400
3,200
3,000
2,800
2,600
2,400
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

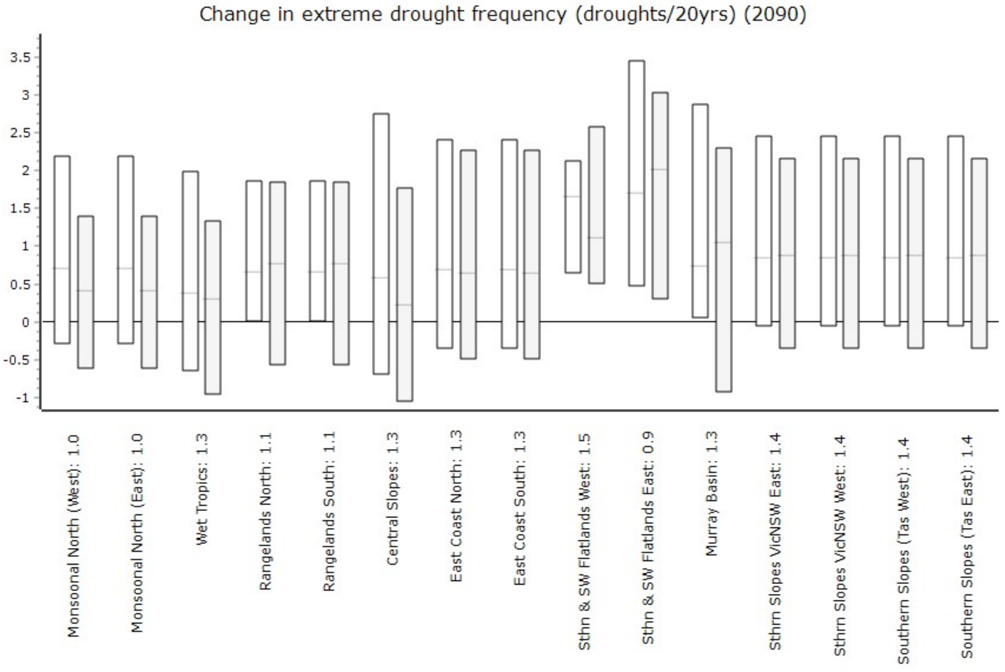
(r)


Change in number days/year FFDI > High (days) (2090)
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

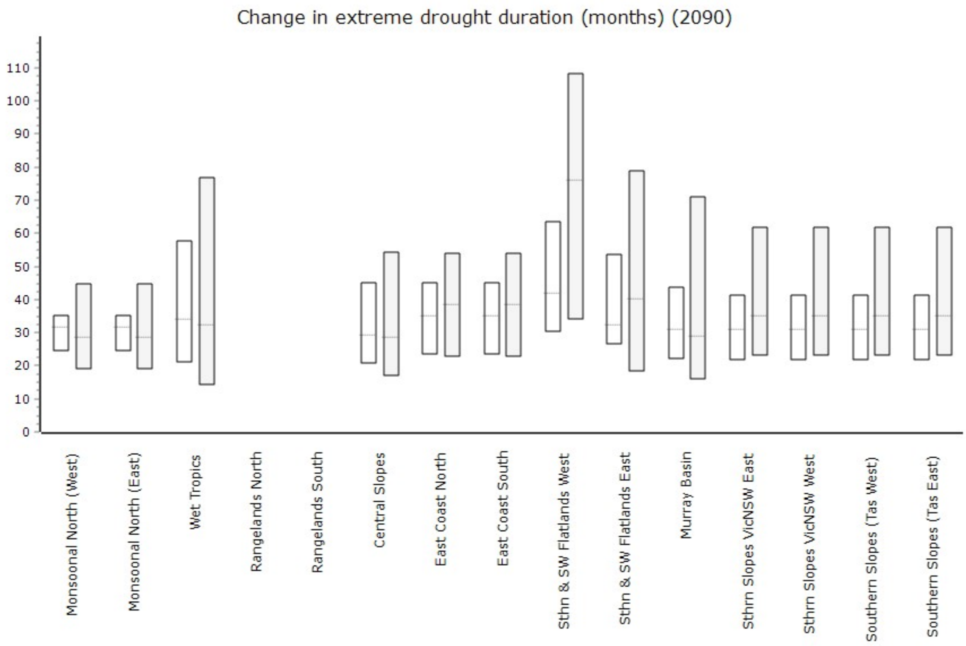
(s)


Change in time in drought (%) (2090)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
Monsoonal North (West): 35.8
Monsoonal North (East): 35.8
Wet Tropics: 37.4
Rangelands North: 36.3
Rangelands South: 36.3
Central Slopes: 35.5
East Coast North: 39.5
East Coast South: 39.5
Sthn & SW Flatlands West: 42.8
Sthn & SW Flatlands East: 35.9
Murray Basin: 36.5
Sthrn Slopes VicNSW East: 36.7
Sthrn Slopes VicNSW West: 36.7
Southern Slopes (Tas West): 36.7
Southern Slopes (Tas East): 36.7

(t)


Change in extreme drought frequency (droughts/20yrs) (2090)
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Monsoonal North (West): 1.0
Monsoonal North (East): 1.0
Wet Tropics: 1.3
Rangelands North: 1.1
Rangelands South: 1.1
Central Slopes: 1.3
East Coast North: 1.3
East Coast South: 1.3
Sthn & SW Flatlands West: 1.5
Sthn & SW Flatlands East: 0.9
Murray Basin: 1.3
Sthrn Slopes VicNSW East: 1.4
Sthrn Slopes VicNSW West: 1.4
Southern Slopes (Tas West): 1.4
Southern Slopes (Tas East): 1.4

(u)


Change in extreme drought duration (months) (2090)
110
100
90
80
70
60
50
40
30
20
10
0
Monsoonal North (West)
Monsoonal North (East)
Wet Tropics
Rangelands North
Rangelands South
Central Slopes
East Coast North
East Coast South
Sthn & SW Flatlands West
Sthn & SW Flatlands East
Murray Basin
Sthrn Slopes VicNSW East
Sthrn Slopes VicNSW West
Southern Slopes (Tas West)
Southern Slopes (Tas East)

C. NRM zone climate change projection consensus summaries

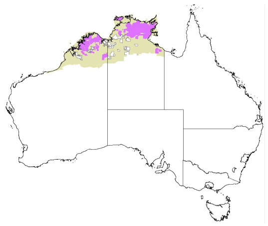
In each table below, for each of the 15 NRM sub-clusters, is given the following information:

- Map showing sub-region location
- Summary of currently registered ERF projects within the region (number of projects, and total project area, as of as of 3 June 2020). Revoked projects have been excluded.
- Summary of climate change projections, with an estimate of the confidence of each projected change (as a consensus across approximately 40 global circulation models). Confidence is ranked as *Low*, *Medium*, *High*, and *Very High*.
- Timeseries charts showing historical trends in average annual temperature and rainfall (1950-present, blue lines), together with the range of model predictions (10th and 90th percentiles) across all available CMIP5 simulations (up to 2100).

For all regions, on an annual and decadal basis, natural variability in the climate system can act to either mask or enhance any long-term human induced trend, particularly in the next 20 years and for rainfall.

Climate change projection data and summaries obtained from published reports and data downloads from: https://www.climatechangeinaustralia.gov.au/en/climate-projections/about/.

Monsoonal North (West)

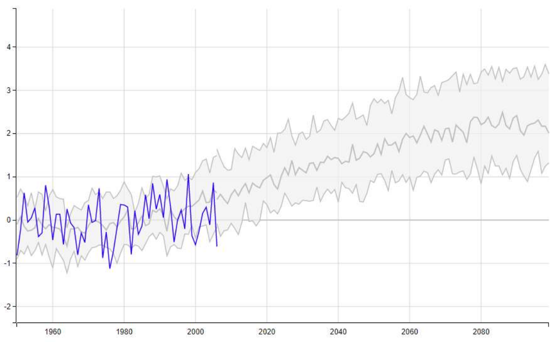


ERF Activity	n projects	Area (ha)
Savanna fire management	99	21,933,335

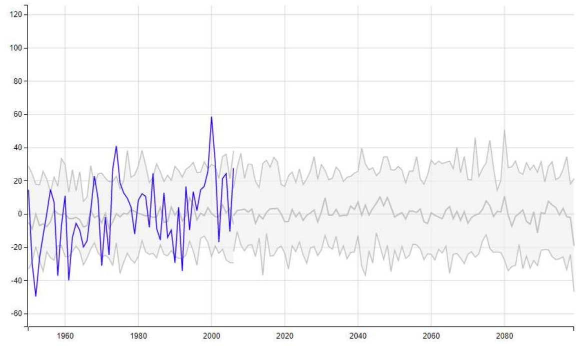
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.5 to 1.4 °C above the climate of 1986 – 2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.8 to 5.1 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.3 to 2.8 °C.
- More hot days and warm spells are projected with *very high confidence*. Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Changes to rainfall are possible but unclear. Providing confident rainfall projections for the Monsoonal North cluster is difficult because global climate models offer diverse results, and models have shortcomings in resolving some tropical processes. Natural climate variability is projected to remain the major driver of rainfall changes in the next few decades. By late in the century, potential summer rainfall changes are approximately -15 to +10 per cent under an intermediate emission scenario (RCP4.5) and approximately -25 to +20 per cent under a high scenario (RCP8.5). Per cent changes are much larger in winter in some models, but these changes are less reliable because average winter rainfall is very low.
- Increased intensity of extreme rainfall events is projected, with *high confidence*. However, the magnitude of the increases cannot be confidently projected.
- Drought will continue to be a feature of the regional climate variability, but projected changes are uncertain.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase (*medium confidence*).
- Potential evapotranspiration is projected to increase in all seasons as warming progresses (*high confidence*), though the magnitude is known only with *medium confidence.* Projected changes for autumn, winter and spring for 2030 are around 2 to 6 % (about 1 to 5 % for summer) and for 2090 are about 5 to 10 % (about 2 to 10 % for summer) for RCP4.5 and 10 to 20% (about 5 to 15 % for summer) for RCP8.5.
- There is little change projected in relative humidity until later in the century under a high emission scenario (RCP8.5), where a decrease in relative humidity is projected (*medium confidence*), with projected ranges of -6 to +1 % under RCP4.5 and -8 to +3 % under RCP8.5.
- Annual changes in soil moisture for RCP8.5 by 2090 range from around −13 % to +4 % with medium model agreement on substantial decrease. The percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the strong increase in potential evapotranspiration. Given the potential limitations of the underlying methods, there is only medium confidence that soil moisture will decline.
- Runoff could increase or decrease under RCP4.5 and RCP8.5 in 2090, though the majority of models suggest decrease. The confidence in these projections is *low* because the method used is not able to consider changes to rainfall intensity, seasonality and changes in vegetation characteristics.
- In regions where abundant rain falls (Top End and the Kimberley), climate change is not expected to change the frequency of fire (*high confidence*). In more southerly locations, changes to future rainfall will be the determining factor of change to fire frequency. When fire does occur, there is high confidence that fire behaviour will be more extreme.

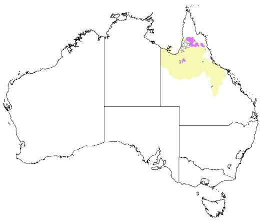
Annual temperature



Annual rainfall



Monsoonal North (East)

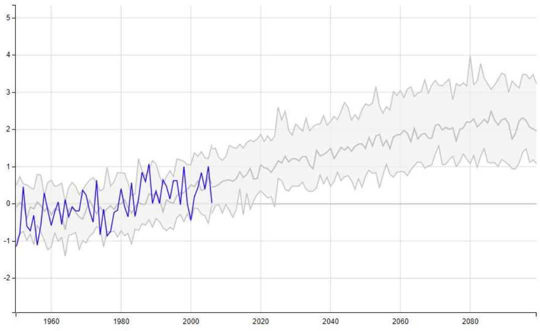


ERF Activity	n projects	Area (ha)
Re-establishment of native forest cover	3	82,207
Savanna fire management	20	2,593,575

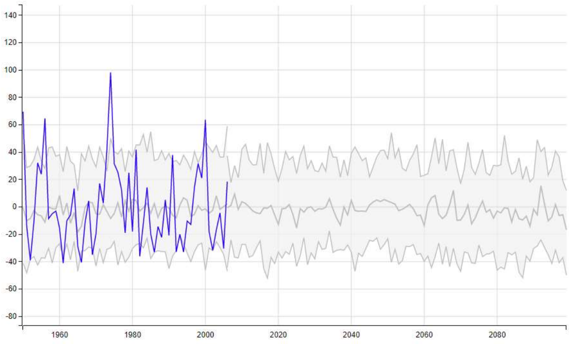
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.4 to 1.3 °C above the climate of 1986 – 2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.5 to 5.0 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.2 to 2.7 °C.
- More hot days and warm spells are projected with *very high confidence*. Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Changes to rainfall are possible but unclear. Providing confident rainfall projections for the Monsoonal North East sub-cluster is difficult because global climate models offer diverse results, and models have shortcomings in resolving some tropical processes. Natural climate variability is projected to remain the major driver of rainfall changes in the next few decades. By late in the century, potential summer rainfall changes are approximately -23 to +15 per cent under an intermediate emission scenario (RCP4.5) and approximately -28 to +28 per cent under a high scenario (RCP8.5). Per cent changes are much larger in winter in some models, but these changes are less reliable because average winter rainfall is very low.
- Increased intensity of extreme rainfall events is projected, with *high confidence*.
- Drought will continue to be a feature of the regional climate variability, but projected changes are uncertain.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase (*medium confidence*).
- Potential evapotranspiration is projected to increase in all seasons as warming progresses (*high confidence*), though the magnitude is known only with *medium confidence.* Projected changes for autumn, winter and spring for 2030 are around 2 to 6 % (about 1 to 5 % for summer) and for 2090 are about 5 to 10 % (about 2 to 10 % for summer) for RCP4.5 and 10 to 20% (about 5 to 15 % for summer) for RCP8.5.
- There is little change projected in relative humidity until later in the century under a high emission scenario (RCP8.5), where a decrease in relative humidity is projected (*medium confidence*), with projected ranges of -6 to +1 % under RCP4.5 and -8 to +3 % under RCP8.5.
- Annual changes in soil moisture for RCP8.5 by 2090 range from around −13 % to +4 % with medium model agreement on substantial decrease. The percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the strong increase in potential evapotranspiration. Given the potential limitations of the underlying methods, there is only *medium confidence* that soil moisture will decline.
- Runoff could increase or decrease under RCP4.5 and RCP8.5 in 2090, though the majority of models suggest decrease. The confidence in these projections is *low* because the method used is not able to consider changes to rainfall intensity, seasonality and changes in vegetation characteristics.
- The primary determinant of bushfire in the Monsoonal North East is fuel availability, which varies mainly with rainfall. Changes to future rainfall will be the determining factor of change to fire frequency. When fire does occur, there is *high confidence* fire behaviour will be more extreme.

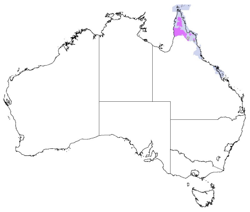
Annual temperature



Annual rainfall



Wet Tropics

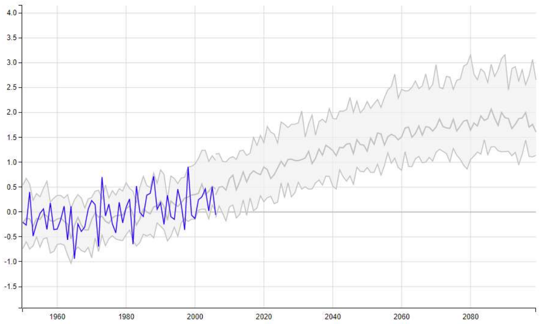


ERF Activity	n projects	Area (ha)
Planting of new forests	6	916
Re-establishment of native forest cover	2	4,596
Savanna fire management	55	4,628,184

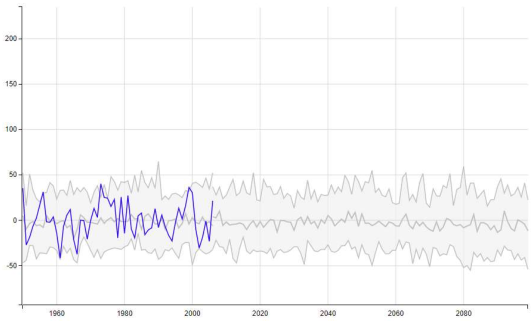
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.3 to 1.1 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.3 to 3.9 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.0 to 2.0 °C.
- More hot days and warm spells and extreme temperatures are projected with *very high confidence*.
- Changes to rainfall are possible but unclear. In the near future (2030) natural variability is projected to predominate over trends due to greenhouse gas emissions. By late in the century, potential summer and autumn rainfall changes are approximately -25 to +20 per cent under a high emission scenario (RCP8.5) and -15 to +10 per cent under an intermediate scenario (RCP4.5).
- Increased intensity of extreme rainfall events is projected, with *high confidence*. However, the magnitude of the increases cannot be confidently projected.
- Drought will continue to be a feature of the regional climate variability, but projected changes are uncertain.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase (*medium confidence*).
- Potential evapotranspiration is projected to increase in all seasons as warming progresses (*high confidence*), with projected seasonal changes generally less than 5 % in 2030 and generally less than 10 % for RCP4.5 and up to 20 % for RCP8.5 in 2090. In absolute terms, changes are largest in summer and autumn, particularly for RCP8.5
- There is *high confidence* on little change in relative humidity for the near future (2030). By 2090 under RCP8.5, there is *low confidence* on increased relative humidity in spring and decreases in summer and autumn.
- Decreases in soil moisture are projected, particularly in winter and spring. The projected annual changes for RCP8.5 late in the century (2090) range from around −20 to +5 % with *medium model agreement* on decreases, except spring where there is *medium agreement* on little change. The percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the strong increase in potential evapotranspiration. Given the potential limitations of this method, there is only *medium confidence* that soil moisture will decline.
- Runoff could increase or decrease following RCP4.5 and RCP8.5 for 2090 relative to 1986–2005, though the majority of models suggest decreases, as indicated by the negative median change. There is *low confidence* in these projections
- In the Wet Tropics where abundant rainfall (wet season) and bushfires (dry season) are common, the projected changes in rainfall are not expected to significantly change the current seasonal cycle. There is high confidence in projections of little change to fire frequency. When and where fire does occur, there is high confidence that fire behaviour will be more extreme.

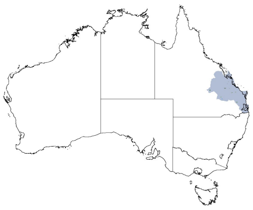
Annual temperature



Annual rainfall



East Coast North

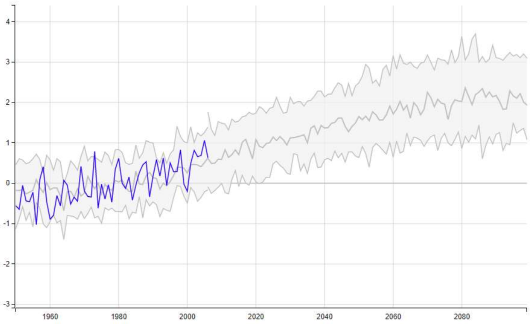


ERF Activity	n projects	Area (ha)
Management of agricultural soils	7	39,238
Planting of new forests	3	8,750
Protection of existing forests	2	11,444
Re-establishment of native forest cover	7	22,085

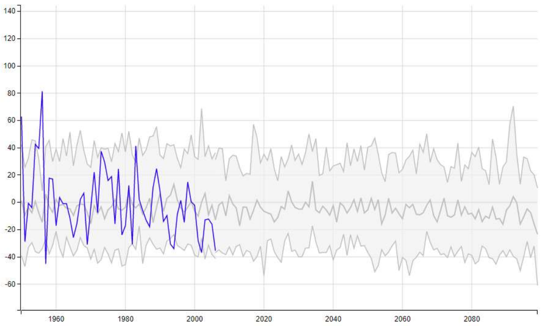
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.4 to 1.3 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.5 to 4.7 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.2 to 2.6 °C.
- More hot days, warm spells and extreme temperatures are projected with *very high confidence*. Some parts of the sub-cluster could experience around two to three times the average number of days above 35 °C under intermediate emission scenarios by late in the century.
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (high confidence).
- Rainfall changes are possible but unclear. Natural climate variability is projected to remain the major driver of rainfall changes in the next few decades. Models show a range of results, with little change or decrease being more common particularly in winter and spring.
- Increased intensity of extreme rainfall events is projected, with high confidence.
- Time spent in drought is projected, with *medium confidence*, to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Potential evapotranspiration is projected to increase in all seasons as warming progresses (*high confidence*).
- Soil moisture. *Currently under revision*.
- Runoff. *Currently under revision*.
- There is little change in relative humidity for the near future, but *medium confidence* in a decrease later in the century.
- There is high confidence that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of that change because of the significant uncertainties in the rainfall projection.

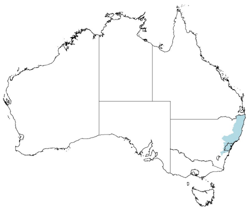
Annual temperature



Annual rainfall



East Coast South

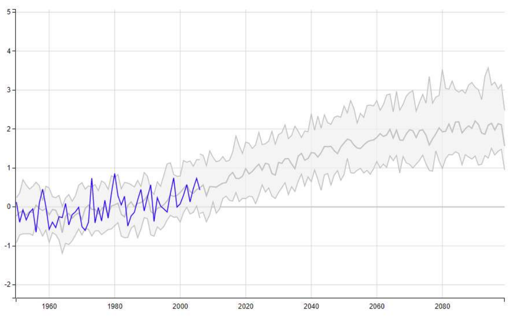


ERF Activity	n projects	Area (ha)
Management of agricultural soils	6	1,665
Planting of new forests	6	1,976
Re-establishment of native forest cover	1	509

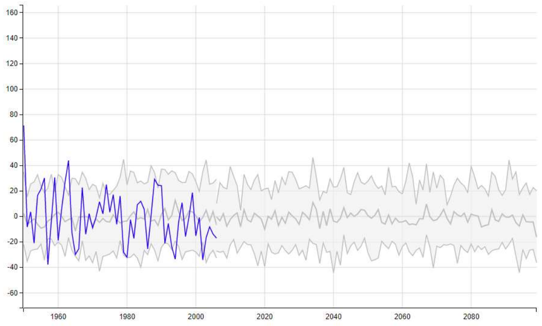
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.5 to 1.3 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.9 to 4.6 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.3 to 2.5 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- Decreases in winter rainfall are projected with *medium confidence*. Other changes are possible but unclear.
- Increased intensity of extreme rainfall events is projected, with high confidence.
- Time spent in drought is projected, with *medium confidence*, to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
- Potential evapotranspiration is projected to increase in all seasons as warming progresses (*high confidence*).
- Soil moisture. *Currently under revision*.
- Runoff. *Currently under revision*.
- There is little change in relative humidity for the near future, but *medium confidence* in a decrease later in the century.
- There is *high confidence* that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of that change because of the significant uncertainties in the rainfall projection.

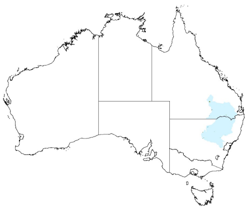
Annual temperature



Annual rainfall



Central Slopes

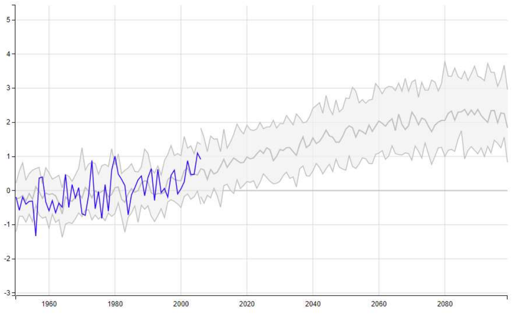


ERF Activity	n projects	Area (ha)
Management of agricultural soils	6	11,450
Planting of new forests	7	1,710
Protection of existing forests	5	29,559
Re-establishment of native forest cover	10	13,926

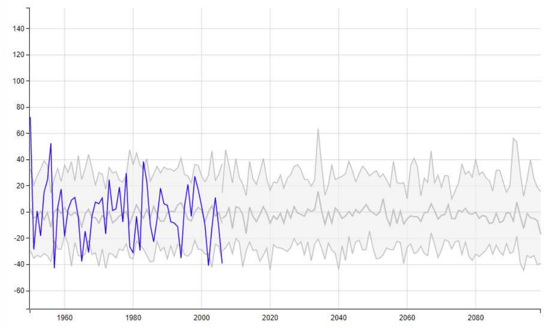
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.6 to 1.5 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 3.0 to 5.4 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.4 to 2.7 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*)
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (high confidence).
- In the near future (2030) natural variability in rainfall is projected to predominate over trends due to greenhouse gas emissions. Late in the century, climate model results indicate decreasing winter rainfall with *high confidence*. There is a good understanding of the physical mechanisms driving this change (southward shift of winter storm systems together with rising mean pressure over the region). Decreases are also projected in spring, with *medium confidence*.
- Potential evapotranspiration is projected to increase in all seasons (*high confidence*). In relative terms, increases are similar amongst the four seasons, with somewhat smaller increases in spring. Projected changes for summer, autumn and winter are around -1 to 8 % (about 1 to 5 % for spring) in 2030 and about 5 to 15 % (about 0 to 10% for spring) and 10 to 25 % (about 5 to 15 % for spring) respectively for RCP4.5 and RCP8.5 in 2090. In absolute terms, changes are largest in summer, particularly for RCP8.5. Despite having high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- For 2030, seasonal reductions in relative humidity for both RCP4.5 and RCP8.5 are generally smaller than -5% and projected increases less than 2 %, for both scenarios and there is medium or high model agreement on little change. For 2090, reductions are more marked, particularly in winter and spring with projected ranges of about -6 to 0 % under RCP4.5 and about -10 to 0 % under RCP8.5. A decrease in relative humidity away from coasts is expected because of an increase in the moisture holding capacity of a warming atmosphere and the greater warming of land compared to sea, leading to increases in relative humidity over ocean and decreases over land. This general tendency for decrease over land can be counteracted by a strong rainfall increase. Taking this and the CMIP5 projections into account, we have *high confidence* in little change for 2030; and *medium confidence* in decrease for summer and autumn by 2090, while for winter and spring there is *high confidence* in decrease.
- Decreases in soil moisture are projected, particularly in winter and spring. The annual changes for RCP8.5 by 2090 range from around -15 % to +2 % with *medium model agreement* on substantial decrease. The percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the strong increase in potential evapotranspiration. Given the potential limitations of this method, there is only *medium confidence* that soil moisture will decline.
- Runoff could increase or decrease following RCP4.5 and RCP8.5 for 2080–2099 relative to 1986–2005, though the majority of models suggest decrease, as indicated by the negative multi-model ensemble median. There is *low confidence* in these projections
- There is high confidence that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change as this is strongly dependent on the rainfall projection.
- Related to the projected decline in winter rainfall, winter solar radiation is projected to increase with *medium confidence*.

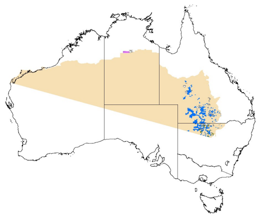
Annual temperature



Annual rainfall



Rangelands North

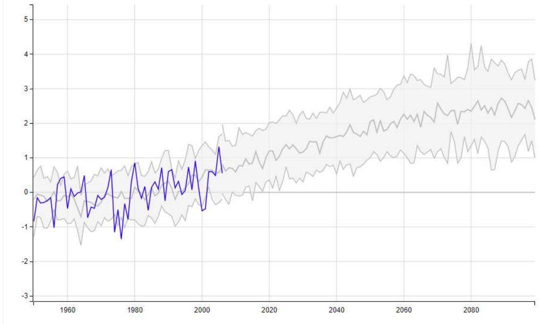


ERF Activity	n projects	Area (ha)
Protection of existing forests	42	600,374
Re-establishment of native forest cover	331	7,803,896

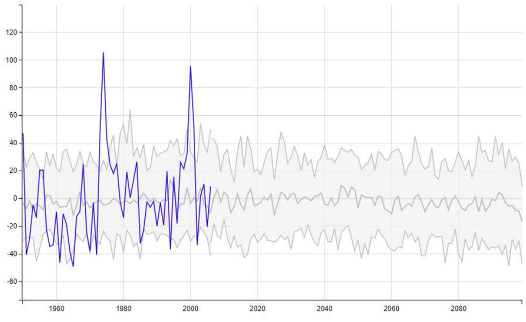
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.6 to 1.5 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 3.1 to 5.6 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.5 to 3.1 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Where frosts (minimum temperatures under 2 °C) occur in the sub-cluster, these are projected to decrease.
- Changes to rainfall are possible, but the direction of change cannot be confidently projected given the spread of model results. In the near future (2030) natural variability is projected to predominate over trends due to greenhouse gas emissions.
- Understanding of the physical processes that cause extreme rainfall, coupled with modelled projections, indicate with *high confidence* a future increase in the intensity of extreme rainfall events, although the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected, with *medium confidence*, to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
- Increases in potential evapotranspiration for all seasons are predicted with *high confidence*. There is not much difference in the increase amongst the four seasons. In absolute terms, changes are largest in summer, particularly for RCP8.5. Despite having high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- A decrease in relative humidity is predicted, with similar changes in both Rangelands North and South. Projected reductions are more marked in winter and spring (about −5 to 0 % under RCP4.5 and −10 to 0 % under RCP8.5 for 2090). There are, however, models that simulate increases in relative humidity, as demonstrated by some positive 90th percentile values, particularly in autumn. In summary, there is *medium confidence* in little change in relative humidity for 2030. By 2090, for summer and autumn, there is *medium confidence* in a decrease, while for winter and spring there is *high confidence* in a decrease.
- Decreases in soil moisture are projected, particularly in winter, when changes for RCP8.5 by 2090 range from −7 to +1 % in North, and −11 to −1 % in the South with medium model agreement on substantial decrease. The percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the strong increase in potential evapotranspiration. However, these estimates are based only on large-scale considerations. Given the potential limitations of this method, there is only *medium confidence* that soil moisture will decline in winter.
- The runoff estimates following RCP4.5 and RCP8.5 for 2080–2099 relative to 1986–2005 suggest decrease in both North and South rangelands. The confidence in these projections is *low*, however, as the method used is not able to consider changes to rainfall intensity, seasonality and changes in vegetation characteristics, factors that each could impact future runoff, particularly at smaller scale.
- There is little change projected for solar radiation in the near future (2030), and for later in the century, decreased radiation is projected in March-May (medium confidence).
- Fire in the Rangelands depends highly on fuel availability, which mainly depends on rainfall. With an unclear direction in rainfall projections it is difficult to determine the direction of fire weather risk expected in future, furthermore, there is low confidence in the magnitude of fire weather projections.

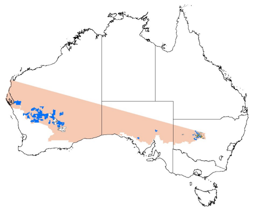
Annual temperature



Annual rainfall



Rangelands South

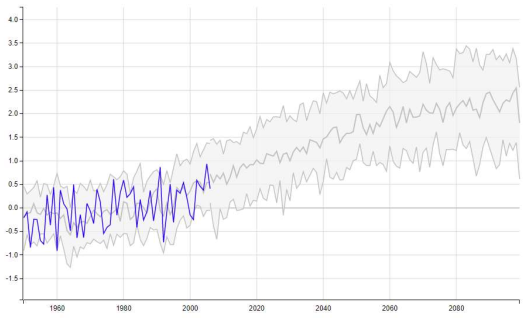


ERF Activity	n projects	Area (ha)
Protection of existing forests	45	343,020
Re-establishment of native forest cover	90	8,914,791

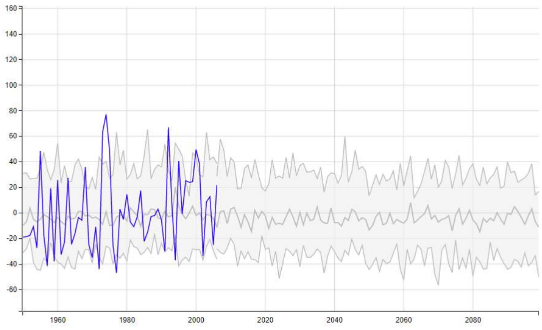
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.6 to 1.4 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.8 to 5.1 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.3 to 2.6 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Where frosts (minimum temperatures under 2 °C) occur in the cluster, these are projected to decrease.
- In the near future (2030) natural variability in rainfall is projected to predominate. Winter rainfall is projected to decline over the century under both intermediate (RCP4.5) and high (RCP8.5) emission scenarios (*high confidence*). There is a good understanding of the physical mechanisms driving this change (southward shift of winter storm systems together with rising mean pressure over the region). Changes to annual and summer rainfall for late in the century are possible, but the direction of change cannot be confidently projected given the spread of model results.
- Understanding of the physical processes that cause extreme rainfall, coupled with modelled projections, indicate with *high confidence* a future increase in the intensity of extreme rainfall events, although the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected, with *medium confidence*, to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Increases in potential evapotranspiration for all seasons are predicted with *high confidence*. There is not much difference in the increase amongst the four seasons. In absolute terms, changes are largest in summer, particularly for RCP8.5. Despite having high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- A decrease in relative humidity is predicted, with similar changes in both Rangelands North and South. Projected reductions are more marked in winter and spring (about −5 to 0 % under RCP4.5 and −10 to 0 % under RCP8.5 for 2090). There are, however, models that simulate increases in RH, as demonstrated by some positive 90th percentile values, particularly in autumn. In summary, there is *medium confidence* in little change in RH for 2030. By 2090, for summer and autumn, there is *medium confidence* in a decrease, while for winter and spring there is *high confidence* in a decrease.
- Decreases in soil moisture are projected, particularly in winter, when changes for RCP8.5 by 2090 range from −7 to +1 % in North, and −11 to −1 % in the South with medium model agreement on substantial decrease. The percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the strong increase in potential evapotranspiration. However, these estimates are based only on large-scale considerations. Given the potential limitations of this method, there is only *medium confidence* that soil moisture will decline in winter.
- The runoff estimates following RCP4.5 and RCP8.5 for 2080–2099 relative to 1986–2005 suggest decrease in both North and South rangelands. The confidence in these projections is *low*, however.
- There is little change projected for solar radiation in the near future (2030), and for later in the century, increased radiation is projected in the south in winter (*medium confidence*).
- Fire in the Rangelands depends highly on fuel availability, which mainly depends on rainfall. A tendency toward increased fire weather risk is expected in future, due to higher temperature and lower rainfall, but there is *low confidence* in the magnitude of fire weather projections.

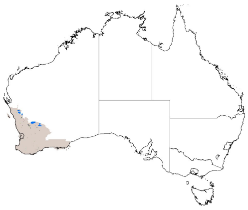
Annual temperature



Annual rainfall



The Southern and South-Western Flatlands West

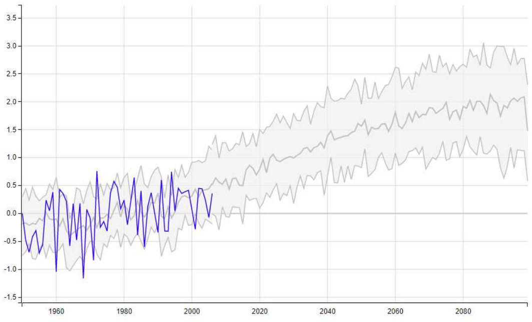


ERF Activity	n projects	Area (ha)
Planting of new forests	31	72,926
Re-establishment of native forest cover	11	568,677

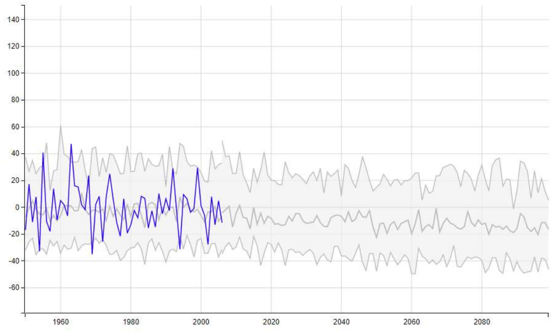
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.5 to 1.2 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.6 to 4.2 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.1 to 2.1 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (very high confidence).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- Early in the century (2030) and under all emission scenarios, winter rainfall is projected to decrease by up to 15 per cent. Late in the century, intermediate emissions (RCP4.5) lead to a projected decrease in winter rainfall of up to around 30%, and under high emissions (RCP8.5) winter rainfall decline is projected to decrease by up to 45% (*high confidence*). Changes in autumn and summer are less clear, although downscaling results suggest a continuation of the observed autumn declines.
- Even though annual mean rainfall is projected to decrease in the region, projections indicate increases in extreme rainfall. Strongly decreasing mean rainfall in this region gives us *medium confidence* in this projection, where for all other Australian regions higher confidence is given. Furthermore, the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected (*with high confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
- For 2030, increases in potential evapotranspiration are less than 10 % in all scenarios. Increases by 2090 are larger. In relative terms, the largest increases are found in winter (10 to 30 % under RCP8.5 and approximately half that for RCP4.5) and autumn (about 10 to 20 % under RCP8.5 and approximately half that for RCP4.5), with lesser increases (about 5 to 15 % following RCP8.5) in summer and spring. In absolute terms, the largest projected increase is found in summer. Despite having high confidence in increased evapotranspiration, there is only *medium confidence* in the projected magnitude of the increase
- Little change in relative humidity is projected for 2030 with *high confidence*. By 2090, for winter and spring across both sub-clusters, there is *high confidence* for substantial decrease of up to 5 % under RCP8.5, with smaller decreases in autumn and summer.
- Decreases in soil moisture are projected, particularly in winter and spring, as are decreases in runoff. The annual changes in soil moisture for RCP8.5 by 2090 are about -10 to 0 % with high model agreement on a substantial decrease. Given that reduced rainfall and increased evapotranspiration both contribute to a decrease in soil moisture and runoff, there is *high confidence* in the projected decrease in soil moisture. However, due to the potential limitations of this method, there is only *low confidence* in the magnitude of change.
- Related to the projected decline in winter rainfall, winter solar radiation is projected to increase (high confidence). Radiation in spring is also projected to increase (medium confidence).
- There is *high confidence* that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change as this is strongly dependent on the rainfall projection.

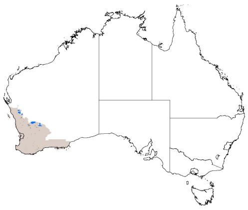
Annual temperature



Annual rainfall



The Southern and South-Western Flatlands East

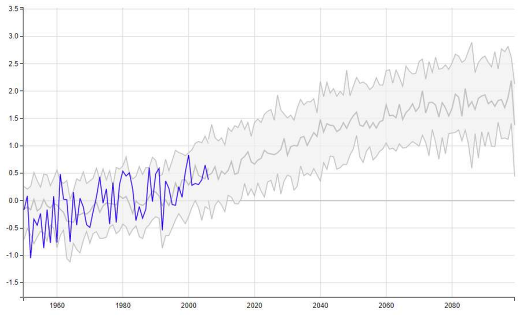


ERF Activity	n projects	Area (ha)
Management of agricultural soils	2	10,155
Planting of new forests	5	2,598
Re-establishment of native forest cover	1	7,864

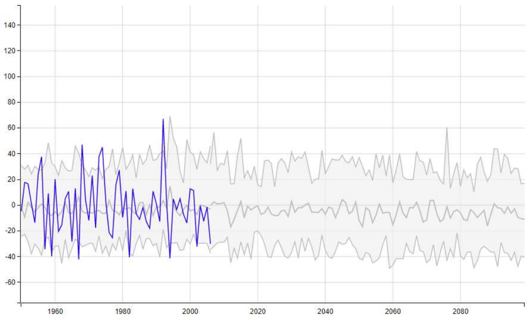
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.4 to 1.1 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.4 to 3.9 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.0 to 1.9 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- Early in the century (2030) and under all emission scenarios, winter rainfall is projected to decrease by up to 15 per cent. Late in the century, intermediate emissions (RCP4.5) lead to a projected decrease in winter rainfall of up to 25%, and under high emissions (RCP8.5) winter rainfall decline is projected to decrease by up to 45%. Changes in autumn and summer are less clear, although downscaling results suggest a continuation of the observed autumn declines (*high confidence*).
- Even though annual mean rainfall is projected to decrease in the region, understanding of the physical processes that cause extreme rainfall, coupled with modelled projections indicate with *high confidence* a future increase in the intensity of extreme rainfall events. However, the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected (*with high confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- For 2030, increases in potential evapotranspiration are less than 10 % in all scenarios. Increases by 2090 are larger. In relative terms, the largest increases are found in winter (10 to 30 % under RCP8.5 and approximately half that for RCP4.5) and autumn (about 10 to 20 % under RCP8.5 and approximately half that for RCP4.5), with lesser increases (about 5 to 15 % following RCP8.5) in summer and spring. In absolute terms, the largest projected increase is found in summer. Despite having high confidence in increased evapotranspiration, there is only *medium confidence* in the projected magnitude of the increase
- Little change in relative humidity is projected for 2030 with *high confidence*. By 2090, for winter and spring across both sub-clusters, there is *high confidence* for substantial decrease of up to 5 % under RCP8.5, with smaller decreases in autumn and summer.
- Decreases in soil moisture are projected, particularly in winter and spring, as are decreases in runoff. The annual changes in soil moisture for RCP8.5 by 2090 are about -10 to 0 % with high model agreement on a substantial decrease. Given that reduced rainfall and increased evapotranspiration both contribute to a decrease in soil moisture and runoff, there is *high confidence* in the projected decrease in soil moisture. However, due to the potential limitations of this method, there is only *low confidence* in the magnitude of change.
- Related to the projected decline in winter rainfall, winter solar radiation is projected to increase (*high confidence*). Radiation in spring is also projected to increase (*medium confidence*).
- There is high confidence that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change as this is strongly dependent on the rainfall projection.

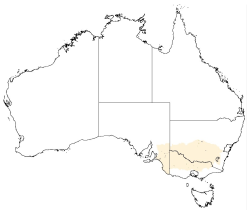
Annual temperature



Annual rainfall



Murray Basin

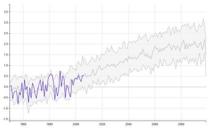


ERF Activity	n projects	Area (ha)
Management of agricultural soils	14	12,157
Planting of new forests	23	9,613
Protection of existing forests	3	12,443
Re-establishment of native forest cover	4	1,625

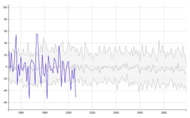
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.6 to 1.3 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.7 to 4.5 °C. Under an intermediate scenario (RCP4.5) the projected warming is 1.3 to 2.4 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- In the near future (2030) natural variability in rainfall is projected to predominate over trends due to greenhouse gas emissions. Late in the century (2090) cool season (April to October) rainfall is projected to decline under both an intermediate (RCP4.5) and high (RCP8.5) emission scenario. In the warm season (November to March), little change, increases and decreases of rainfall are projected by different models. The magnitude of projected changes for late in the century (2090) span approximately -40 to +5 percent in winter and -15 to +25 percent in summer for a high emissions case (RCP8.5).
- Understanding of the physical processes that cause extreme rainfall, coupled with modelled projections, indicate with *high confidence* a future increase in the intensity of extreme rainfall events, although the magnitude of the changes cannot be confidently projected.
- Time spent in drought is projected (*with medium confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Projected seasonal changes for potential evapotranspiration relative to the 1986–2005 baseline period strongly indicate an increase of evaporation in all seasons. Projected increases in 2030 under all RCPS are about 1 to 7 % (3 to 13 % for winter). By 2090, the increases are about 1 to 10 % (about 7 to 20 % for winter) for RCP4.5 and 1 to 20 % (about 15 to 40 % for winter) for RCP8.5. In absolute terms, the largest increases in evaporation are found in summer and autumn, with smaller increases in winter and spring. Although there is *high confidence* in an increase, there is only *medium confidence* in the magnitude of this change
- The magnitudes of the projected decreases in relative humidity depend on the emission scenario and are modulated by the direction of the rainfall projections. By 2030, decreases are up to 4 %, but by 2090 under RCP8.5 can reach double that, particularly in winter and spring. There are, however, models that simulate increases in relative humidity, as evident by large positive 90th percentile values. Climate models have a reasonable ability to simulate the climatology of global humidity, and we conclude that for summer and autumn there is *medium confidence* in decrease, while for winter and spring there is *high confidence* for substantial decrease.
- Decreases in soil moisture predominate, particularly in winter and spring. The annual-mean changes for the high emission scenario range from around −10 to -1 %. Consistent with the directly simulated surface moisture, the percentage changes in soil moisture are strongly influenced by those in rainfall, but tend to be more negative due to the increase in potential evapotranspiration. Given the potential limitations of each method, there is *medium confidence* that soil moisture will decline.
- The median change in runoff for 2090 under RCP8.5 is a decrease of about 20 %, with the majority of models giving a decrease. There is *low confidence* in these projections because the method used is not able to consider changes to rainfall intensity, seasonality and changes in vegetation characteristics.
- By 2030, the CMIP5 models simulate little change in solar radiation (less than 5 %) for both RCP4.5 and RCP8.5. By 2090, there is high model agreement for a substantial increase of 7 and 15 % respectively for RCP4.5 and RCP8.5 in winter and about half that in spring. Projected changes in summer and autumn are smaller with models showing both increases and decreases.
- There is high confidence that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change as this is strongly dependent on the rainfall projection.

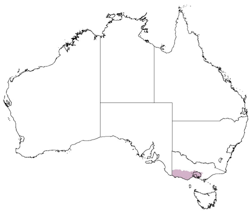
Annual temperature



Annual rainfall



Southern Slopes Victoria West

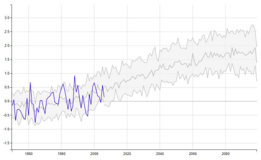


ERF Activity	n projects	Area (ha)
Management of agricultural soils	8	6,736
Planting of new forests	8	11,722

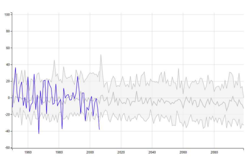
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.4 to 1.1 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.4 to 3.8°C. Under an intermediate scenario (RCP4.5) the projected warming is 1.1 to 1.9 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- In the near future (2030) natural variability in rainfall is projected to predominate over trends due to greenhouse gas emissions. Understanding of physical rainfall processes (southward shift of winter storm systems), supported by climate model results, indicate rainfall decreases for winter and spring (*high confidence*). The projected decreases over Western Victoria are up to 25 per cent in winter and up to 45 per cent in spring by 2090 under high emissions. By the middle of the century, and under high emissions, winter and spring changes are projected to be evident against natural variability. Changes to summer and autumn rainfall are possible but not clear, although there is a tendency for decrease in western Victoria in autumn. Available fine-scale modelling provides further detail on possible spatial variation in rainfall response.
- Even though annual mean rainfall is projected to decrease in the region, understanding of the physical processes that cause extreme rainfall, coupled with modelled projections indicate with *high confidence* a future increase in the intensity of extreme rainfall events. However, the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected (*with high confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
- Potential evapotranspiration is projected to increase substantially in all seasons in the Southern Slopes, with the largest relative increases in winter and spring. Projected changes for 2030 are less than 10 % in all scenarios, but by 2090 under RCP8.5 increases of about 10 to 20 % are projected in summer and spring, and about 10 to 30 % in autumn and winter. In absolute terms, changes are largest in summer, particularly for RCP8.5 is projected to increase in all seasons as warming progresses (*high confidence*). Despite there being high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- A decrease in relative humidity away from coasts is expected because of the increased moisture holding capacity in a warming atmosphere. The greater warming of land compared to sea leads to increases in relative humidity over ocean and to decreases over continents. This general tendency to decrease can be counteracted by a strong rainfall increase. Taking this and the CMIP5 projections into account, there is high confidence in little change for 2030. By 2090, there is *medium confidence* in decrease for summer and autumn, while for winter and spring there is *high confidence* in decrease.
- Decreases in soil moisture are projected in all seasons .There are some differences in the projected changes between sub-clusters, with a greater decline in soil moisture during winter and spring than in the other seasons in the northern regions, but a greater decline during summer and autumn than in the other seasons in Tasmania. For the Southern Slopes as a whole, the annual changes for RCP8.5 by 2090 range from around -14 to -3 % with very high model agreement on substantial decrease. The projected decrease in soil moisture is given *high confidence*. However, due to the potential limitations of this method, there is only *medium confidence* in the magnitude of change indicated here.
- Runoff projected to decrease under RCP4.5 and RCP8.5 by 2090. There is *high confidence* in the direction of change, but due to the limitations in the methods the magnitudes of change cannot be reliably projected.
- An increase in solar radiation and a decrease in relative humidity is projected in the cool season through the century (*high confidence*). This will be influenced by changes in rainfall (and associated changes to cloudiness) and temperature in the sub-cluster. Changes in summer and autumn are less clear.
- There is *high confidence* that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change to fire weather. This depends on the rainfall projection and its seasonal variation. Relative changes are comparable across the other three sub-clusters of Southern Slopes.

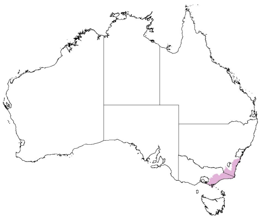
Annual temperature



Annual rainfall



Southern Slopes Victoria East

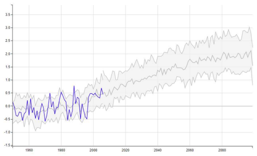


ERF Activity	n projects	Area (ha)
Management of agricultural soils	8	6,736
Planting of new forests	8	11,722

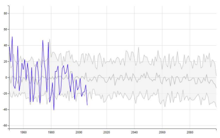
Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.5 to 1.2 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.7 to 4.3°C. Under an intermediate scenario (RCP4.5) the projected warming is 1.3 to 2.2 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- In the near future (2030) natural variability in rainfall is projected to predominate over trends due to greenhouse gas emissions. The winter decreases over Eastern Victoria are up to 30 per cent in 2090 under high emissions. By the middle of the century, and under high emissions, winter changes are projected to be evident against natural variability. Changes to summer and autumn rainfall are possible but not clear.
- Even though annual mean rainfall is projected to decrease in the region, understanding of the physical processes that cause extreme rainfall, coupled with modelled projections indicate with *high confidence* a future increase in the intensity of extreme rainfall events. However, the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected (*with high confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
- Potential evapotranspiration is projected to increase substantially in all seasons in the Southern Slopes, with the largest relative increases in winter and spring. Projected changes for 2030 are less than 10 % in all scenarios, but by 2090 under RCP8.5 increases of about 10 to 20 % are projected in summer and spring, and about 10 to 30 % in autumn and winter. In absolute terms, changes are largest in summer, particularly for RCP8.5 is projected to increase in all seasons as warming progresses (*high confidence*). Despite there being high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- A decrease in relative humidity away from coasts is expected because of the increased moisture holding capacity in a warming atmosphere. The greater warming of land compared to sea leads to increases in relative humidity over ocean and to decreases over continents. This general tendency to decrease can be counteracted by a strong rainfall increase. Taking this and the CMIP5 projections into account, there is high confidence in little change for 2030. By 2090, there is *medium confidence* in decrease for summer and autumn, while for winter and spring there is *high confidence* in decrease.
- Decreases in soil moisture are projected in all seasons .There are some differences in the projected changes between sub-clusters, with a greater decline in soil moisture during winter and spring than in the other seasons in the northern regions, but a greater decline during summer and autumn than in the other seasons in Tasmania. For the Southern Slopes as a whole, the annual changes for RCP8.5 by 2090 range from around -14 to -3 % with very high model agreement on substantial decrease. The projected decrease in soil moisture is given *high confidence*. However, due to the potential limitations of this method, there is only *medium confidence* in the magnitude of change indicated here.
- Runoff projected to decrease under RCP4.5 and RCP8.5 by 2090. There is *high confidence* in the direction of change, but due to the limitations in the methods the magnitudes of change cannot be reliably projected.
- An increase in solar radiation and a decrease in relative humidity is projected in the cool season through the century (*high confidence*). This will be influenced by changes in rainfall (and associated changes to cloudiness) and temperature in the cluster. Changes in summer and autumn are less clear.
- There is high confidence that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change to fire weather. This depends on the rainfall projection and its seasonal variation. Relative changes are comparable across all three sub-clusters.

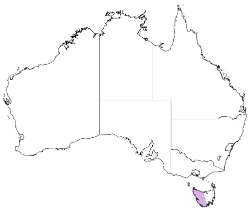
Annual temperature



Annual rainfall



Southern Slopes Tasmania West

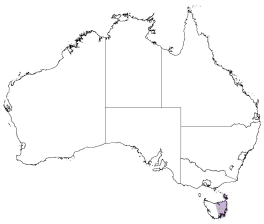


ERF Activity	n projects	Area (ha)
Planting of new forests	6	16,267

Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.2 to 1.1 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.1 to 3.6°C. Under an intermediate scenario (RCP4.5) the projected warming is 0.9 to 1.8 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- In the near future (2030) natural variability in rainfall is projected to predominate over trends due to greenhouse gas emissions. Understanding of physical rainfall processes (southward shift of winter storm systems), supported by climate model results, indicate a rainfall decrease for spring (*high confidence*), and little change or increase for winter (*medium confidence*). The projected winter increase over Western Tasmania is up to 20 per cent and decrease in spring is up to -33 per cent by 2090 under high emissions. By the middle of the century, and under high emissions, spring and perhaps winter changes are projected to be evident against natural variability. Changes to autumn rainfall are possible but not clear, and there is a tendency for projected decrease in western Tasmania in summer.
- Even though annual mean rainfall is projected to experience little change or decrease in the region, understanding of the physical processes that cause extreme rainfall, coupled with modelled projections indicate with *high confidence* a future increase in the intensity of extreme rainfall events. However, the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected (*with medium confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
- Potential evapotranspiration is projected to increase substantially in all seasons in the Southern Slopes, with the largest relative increases in winter and spring. Projected changes for 2030 are less than 10 % in all scenarios, but by 2090 under RCP8.5 increases of about 10 to 20 % are projected in summer and spring, and about 10 to 30 % in autumn and winter. In absolute terms, changes are largest in summer, particularly for RCP8.5 is projected to increase in all seasons as warming progresses (*high confidence*). Despite there being high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- A decrease in relative humidity away from coasts is expected because of the increased moisture holding capacity in a warming atmosphere. The greater warming of land compared to sea leads to increases in relative humidity over ocean and to decreases over continents. This general tendency to decrease can be counteracted by a strong rainfall increase. Taking this and the CMIP5 projections into account, there is high confidence in little change for 2030. By 2090, there is *medium confidence* in decrease for summer and autumn, while for winter and spring there is *high confidence* in decrease.
- Decreases in soil moisture are projected in all seasons .There are some differences in the projected changes between sub-clusters, with a greater decline in soil moisture during winter and spring than in the other seasons in the northern regions, but a greater decline during summer and autumn than in the other seasons in Tasmania. For the Southern Slopes as a whole, the annual changes for RCP8.5 by 2090 range from around -14 to -3 % with very high model agreement on substantial decrease. The projected decrease in soil moisture is given *high confidence*. However, due to the potential limitations of this method, there is only *medium confidence* in the magnitude of change indicated here.
- Runoff projected to decrease under RCP4.5 and RCP8.5 by 2090. There is *high confidence* in the direction of change, but due to the limitations in the methods the magnitudes of change cannot be reliably projected.
- An increase in solar radiation and a decrease in relative humidity is projected in the cool season through the century (*high confidence*). This will be influenced by changes in rainfall (and associated changes to cloudiness) and temperature in the cluster. Changes in summer and autumn are less clear.
- There is high confidence that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change to fire weather. This depends on the rainfall projection and its seasonal variation. Relative changes are comparable across all three sub-clusters.

Southern Slopes Tasmania East



ERF Activity	n projects	Area (ha)
Management of agricultural soils	1	175
Planting of new forests	14	39,987

Climate projection summary

- Average temperatures will continue to increase in all seasons (*very high confidence*). For the near future (2030), the annually averaged warming across all emission scenarios is projected to be around 0.4 to 1.1 °C above the climate of 1986–2005. By late in the century (2090), for a high emission scenario (RCP8.5) the projected range of warming is 2.3 to 4.0°C. Under an intermediate scenario (RCP4.5) the projected warming is 0.9 to 1.9 °C.
- Extreme temperatures are projected to increase at a similar rate to mean temperature, with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (*very high confidence*).
- Frost risk days (minimum temperatures under 2 °C) are expected to decrease across the cluster (*high confidence*).
- In the near future (2030) natural variability in rainfall is projected to predominate over trends due to greenhouse gas emissions. Rainfall increases are projected (*medium confidence*) for SSTE in winter. By the middle of the century, and under high emissions, winter and spring changes are projected to be evident against natural variability. Changes to summer and autumn rainfall are possible but not clear, and regional changes specific to eastern Tasmania are possible.
- Even though annual mean rainfall is projected to experience little change or decrease in the region, understanding of the physical processes that cause extreme rainfall, coupled with modelled projections indicate with *high confidence* a future increase in the intensity of extreme rainfall events. However, the magnitude of the increases cannot be confidently projected.
- Time spent in drought is projected (*with medium confidence*) to increase over the course of the century.
- Mean sea level will continue to rise and height of extreme sea-level events will also increase (*very high confidence*).
- Potential evapotranspiration is projected to increase substantially in all seasons in the Southern Slopes, with the largest relative increases in winter and spring. Projected changes for 2030 are less than 10 % in all scenarios, but by 2090 under RCP8.5 increases of about 10 to 20 % are projected in summer and spring, and about 10 to 30 % in autumn and winter. In absolute terms, changes are largest in summer, particularly for RCP8.5 is projected to increase in all seasons as warming progresses (*high confidence*). Despite there being high confidence in an increase, there is only *medium confidence* in the magnitude of the increase.
- A decrease in relative humidity away from coasts is expected because of the increased moisture holding capacity in a warming atmosphere. The greater warming of land compared to sea leads to increases in relative humidity over ocean and to decreases over continents. This general tendency to decrease can be counteracted by a strong rainfall increase. Taking this and the CMIP5 projections into account, there is high confidence in little change for 2030. By 2090, there is *medium confidence* in decrease for summer and autumn, while for winter and spring there is *high confidence* in decrease.
- Decreases in soil moisture are projected in all seasons .There are some differences in the projected changes between sub-clusters, with a greater decline in soil moisture during winter and spring than in the other seasons in the northern regions, but a greater decline during summer and autumn than in the other seasons in Tasmania. For the Southern Slopes as a whole, the annual changes for RCP8.5 by 2090 range from around -14 to -3 % with very high model agreement on substantial decrease. The projected decrease in soil moisture is given *high confidence*. However, due to the potential limitations of this method, there is only *medium confidence* in the magnitude of change indicated here.
- Runoff projected to decrease under RCP4.5 and RCP8.5 by 2090. There is *high confidence* in the direction of change, but due to the limitations in the methods the magnitudes of change cannot be reliably projected.
- An increase in solar radiation and a decrease in relative humidity is projected in the cool season through the century (*high confidence*). This will be influenced by changes in rainfall (and associated changes to cloudiness) and temperature in the cluster. Changes in summer and autumn are less clear.
- There is *high confidence* that climate change will result in a harsher fire-weather climate in the future. However, there is low confidence in the magnitude of the change to fire weather. This depends on the rainfall projection and its seasonal variation. Relative changes are comparable across all three sub-clusters.

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