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The implications of climate change for biodiversity conservation and the National Reserve System: the tropical savanna woodlands and grasslands

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Adam C Liedloff, Richard J Williams, David W Hilbert, Simon Ferrier, Michael Dunlop, Tom Harwood, Kristen J Williams and Cameron S Fletcher

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Other Authors/Contributors:	Climate Adaptation Flagship, Richard J Williams, David W Hilbert, Simon Ferrier, Michael Dunlop, Tom Harwood, Kristen J Williams and Cameron S Fletcher

Enquiries

Enquiries regarding this document should be addressed to:

Adam C Liedloff

CSIRO Ecosystem Sciences, Darwin, NT

564 Vanderlin Drive

Berrimah NT 0828

adam.liedloff@csiro.au

Enquiries about the Climate Adaptation Flagship or the Working Paper series should be addressed to:

Working Paper Coordinator

CSIRO Climate Adaptation Flagship

CAFworkingpapers@csiro.au

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Executive summary

This report describes the future implications of climate change on the biodiversity, conservation and the National Reserve System (NRS) of the tropical savanna woodlands and grasslands of northern Australia. It is one of nine reports for the Department of Sustainability, Environment, Water, Population and Communities that address this topic across the Australian NRS. It builds on the report *Implications of Climate Change for Australia's National Reserve System. A Preliminary Assessment* by Dunlop and Brown (2008) and is one of four biome reports where the impacts of climate change are considered in greater detail than in the first report. This report incorporates discussions at an expert workshop with modelling results to provide an indication of future environmental stress that is likely to lead to changes in plant and animal communities. The whole project is also synthesised in the NRS report (Dunlop et al. 2012).

The national and international biological significance of the Australian savannas is emphasised by their inclusion of two of Australia's 15 biodiversity hotspots (North Kimberley, WA and Einasleigh and Desert Uplands, Queensland), two world heritage–listed national parks (Kakadu National Park, NT and Purnululu National Park, WA), five Ramsar-listed wetlands (including Cobourg Peninsula, NT and Ord River floodplain, WA), a millennium ecosystem assessment area (the northern Australian floodplains of Kakadu National Park and Blythe-Liverpool rivers in Arnhem Land), and over 30 National Parks and reserves.

The savannas appear remarkably stable with a long evolution associated with generally infertile soils, regular fire and a regular monsoonal wet and dry season. They are also relatively intact, and not influenced by the problems of fragmentation experienced elsewhere. This study challenges the perception that the savannas may be somewhat resilient to future climate-driven change. The expert workshop stressed the importance of thermal tolerances in the savanna biota and how many tropical species may already be close to their thermal limits. The IPCC climate projections and the modelling used in this study highlight the magnitude of change that may arise in the savannas from climate change. This change is dramatic, and possibly worse than other biomes in Australia. This means management of the savannas to conserve the unique biodiversity of the region will face a number of challenges in the future. These challenges are summarised below:

- **Climate:** The projected changes in climate will result in new or novel environments in the savannas. While the same species may remain, they will have to cope with temperatures not currently experienced, and the savannas will not look and feel as they do today for the plants and animals. Any change to rainfall patterns will be critical to the savannas, where most organisms must cope with very limited surface and soil water at the end of the dry season.

- **Gradients:** The savannas are characterised by temperature, rainfall and intensification gradients across large distances. These shallow gradients mean that any change in temperature and rainfall will result in similar environments rapidly shifting across large distances. More research is required on the ability of the biota to shift or cope with this change. The generalist species currently occupying large distributions may not be affected by this change, but specialist species restricted to niche environments may be greatly affected.

- **Refuges:** A range of special habitats exist within the savannas that provide refuge from fire, grazing, lack of water and high temperatures to unique and endemic flora and fauna. These habitats – such as rainforests, monsoon vine forests, wetlands, springs, gorges, rocky escarpments and riparian zones – are critical for the survival of the savanna biota and current conservation. While these refuges will also offer some protection from the harsh conditions of the surrounding savanna, this study questions their ability to continue to protect the current suite of species against the magnitude of future climate change. Further research is required to monitor and understand the ability of these critical habitats to persist under the climate changes predicted.

- **Cyclones, storms and extreme heat:** Extreme events have the ability to rapidly modify the savannas, leading to very different systems if suitable conditions for recovery are not available. Storms and cyclones are predicted to increase in intensity, and extreme heat days, which can result in rapid changes to populations, are expected to increase in frequency with climate change. Climate change may also alter the ability of species and ecosystems to recover from extreme events by influencing fire regimes and weed species.

- **Other disturbances:** The savannas are not currently immune to disturbance. The expert workshop stressed the critical importance of managing many contemporary disturbances, such as fire, weed invasions, grazing and feral predators. Climate change was considered simply another stress on top of the current stresses that the biota must cope with. It is thought that some of the current problems may be worse than the predicted effects of climate change, as they can transform current ecosystems.

- **Management:** The tropical savannas have a history of limited research and data from which to predict future changes and inform management decisions, compared with other biomes. While further research will increase our understanding and ability to predict change in the savannas, it is likely that many ecological impacts of climate change will only be known after they have been observed. For example, we do not know how susceptible many species are to extreme heat as thermal limits have not been documented. The modelling outcomes of this study highlight the dramatic nature of potential ecological change in the savannas in response to expected climate change. These predictions significantly challenge any assumptions that environmental change will not be ecologically significant as the region will remain “hot and seasonally wet”. The moderate 2030 projections indicate there may be some decades to adapt management in this ecoregion. However, the 2070 high-emissions analyses suggested the potential for very significant ecological change; a precautionary approach would be to start planning those levels of ecological change, for example identifying the critical parts of the savannas that currently support some of the unique biodiversity, and also looking for the emergence of novel environments and communities.

The tropical savannas and grasslands are currently exposed to a number of significant impacts that need to be managed both within and outside the NRS. This report shows that climate change will be a significant additional pressure on the unique flora and fauna of this region. Given the biodiversity value of the savannas, much greater attention may need to be given to the tropical north of Australia in future.

1 Introduction

1.1 Aims, background and context

This report describes and illustrates potential impacts of climate change on the tropical savannas and tropical grasslands of northern Australia. It is one of nine reports on the impacts of climate change on the National Reserve System (NRS); the others are three biome reports: hummock grasslands (Smyth et al. 2012), sclerophyll forests of south-eastern Australia (House et al. 2012), temperate grasslands and grassy woodlands (Prober et al. 2012); four modelling reports: climate downscaling (Harwood et al. 2012); generalised dissimilarity modelling (Ferrier et al. 2012); artificial neural network modelling (Hilbert and Fletcher 2012); Bayesian belief network modelling (Martin et al. 2012); and an overall synthesis report (Dunlop et al. 2012). The work in this report has been undertaken by CSIRO in consultation with State and Federal environmental agencies, universities and non-government organisations. It builds on an earlier report on the implications of climate change for the NRS (Dunlop and Brown 2008), which had a national-scale focus. This phase of the project differs by drawing on regional-scale ecological knowledge and analysis.

This project is important because there is mounting scientific evidence for recent biodiversity impacts of climate change in Australia (C_4 grasses, Johnson et al. 1999; CO_2 effects on vegetation, Berry and Roderick 2002; overall impacts, Hughes 2003; birds, Chambers et al. 2005, Gibbs 2007; predator-prey interactions, Madsen et al. 2006; plant physiological changes, Cullen et al. 2008; trends in vegetation cover, Donohue et al. 2009; vulnerability, Steffen et al. 2009). Of particular concern is the forecast that the effects of climate change will continue for the next century even if near-term emission reduction efforts are successful (Fischlin and Midgley 2007). Biodiversity security into the future is important, as human health depends on it (see evidence in Chivian and Berstein 2008), and there is an urgency to develop on-ground climate adaptation policies for biodiversity (Westoby and Burgman 2006). The first phase of the project highlighted that while the strategic regional framework of Australia's NRS was well-suited to addressing the impacts of climate change, it is likely to present considerable challenges to conservation and for the NRS, especially given the history of the development of the NRS over the last 100 years. In particular, the details of regional-scale impacts are likely to be critical.

Climate change impacts on the tropical savannas of northern Australia are a national concern as the biome extends over three jurisdictions (Queensland, Northern Territory and Western Australia); has significant economic, ecological and cultural importance; and is subject to a range of non-climate related threatening processes that compromise its biodiversity and conservation values.

Dunlop and Brown's (2008) hierarchical framework for understanding environmental change envisioned a cascade of impacts as a series of flow-on and feedback effects on the biology and ecology of individuals, species populations, ecosystems and eventually people (Figure 1). Many types of change affect biological and societal phenomena, with considerable uncertainty. It is clear that the responses of individual organisms to climate change will be manifested through changes in the phenology, relative abundances and range of many species (Hughes 2003; Dunlop and Brown 2008; Steffen et al. 2009), community structure (Hilbert and Fletcher 2012) and composition (Ferrier et al. 2012), species interactions (Schweiger et al. 2008) and ecosystem processes (Brown et al. 1997). However, other forceful environmental stressors will interactively affect biological phenomena, the outcomes of which are uncertain. It is certain that changes will occur in all parts of the cascade and conservation management needs to focus on minimising losses of biodiversity values (Dunlop and Brown 2008). There is an urgent need to identify what changes to biodiversity management and the NRS are necessary to manage this process.

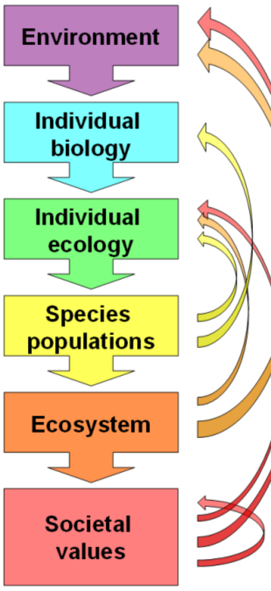

Figure 1 Schematic representation of cascading impacts on biological phenomena and societal values resulting from environmental changes. The direct flow of impacts is represented by large arrows. Important indirect flow is shown as feedback. Changes in the environment trigger many biological and societal changes which feed back to the environment

Source: Dunlop and Brown 2008

In this report, we (i) define the tropical savanna woodlands and grasslands biome, (ii) describe the ecological and land use characteristics of the biome, (iii) identify environmental changes that are likely to occur by 2070 using climate modelling, (iv) postulate on how biodiversity will respond to the environmental changes, and close with (v) a discussion of the implications for climate adaptation in conservation and NRS planning. This report draws on a wide range of biome-specific information, including a literature review, expert workshop, ecological reasoning, and results of several modelling exercises. The modelling aims to quantify projected environmental change in ways that are ecologically more meaningful than direct temperature and rainfall projection. While the modelling itself is robust, it by necessity omits many of the factors and complexities that will determine ecological outcomes, including the direct effects of increases in CO_2 concentrations, changes in disturbances (such as fire), altered species interactions, and other pressures. These issues are addressed as much as possible drawing on the literature and expert knowledge. As such we use the modelling as a guide to help frame biological responses to future environmental change.

The complexity of the climate change-environment-biodiversity system and the extraordinary levels of unknown uncertainty restrict the ecological factors that we can make definitive comments about. In particular, we can make few, if any, statements for most species about threshold changes in species phenological, physiological and population responses to changes in CO_2, temperature, rainfall regimes and extreme events. Similarly, as critical as they are, we know very little about how the dynamics of species-specific interactions will change and what effects that will have on ecological processes.

2 Biome characteristics and ecosystem drivers

The tropical savanna woodlands and grasslands biome (referred to hereafter as the savanna biome) includes the Australian northern coastline and the semi-arid interior from central and northern Queensland to north Western Australia and occupies 25% of the Australian continent. Savannas are characterised by grassland ecosystems with scattered trees. Australia's savanna biome has extensive grassland ecosystems with or without an overstorey ranging from sparse open forests to open woodlands to Acacia shrublands in the more semi-arid parts. While much of this landscape is remote and largely intact with a very low population density, the unique fauna and flora is not immune to a range of disturbances and pressures.

2.1 Geographical distribution and vegetation

For this report, the savanna biome has been defined using the extent of the Tropical and Subtropical Grasslands, Savannas and Shrublands ecoregion in Australia (Ecoregion 90, Figure 2, Olson and Dinerstein 1997) which closely relates to the boundary defined by the Tropical Savanna Management CRC, accepted by researchers in the savannas. This is a large region containing 24 of Australia's 85 Interim Biogeographic Regionalisation for Australia (IBRA V6.1, Thackway and Cresswell 1995) bioregions and includes the tropical savanna, escarpment, coastal floodplains, and black-soil grassland habitats across northern Australia. It does not include the wet tropical rainforest coastal belt of north Queensland, but we do consider rainforest-like environments in this report. As the savannas blend into the arid interior of the continent and the sub-tropical/temperate forests, it is an arbitrary decision as to where the southern boundary of the region is drawn, with Bowman et al. (2010) suggesting that the southern limit to the Australian Monsoon Tropics can be delineated by areas receiving more than 85% of their annual rainfall between November and April. Generally the presence of a continuous grass layer defines the savannas; as such, bioregions such as the Brigalow Belt of southern Queensland were not included in the boundary defined by the Tropical Savannas CRC but are included in this exercise.

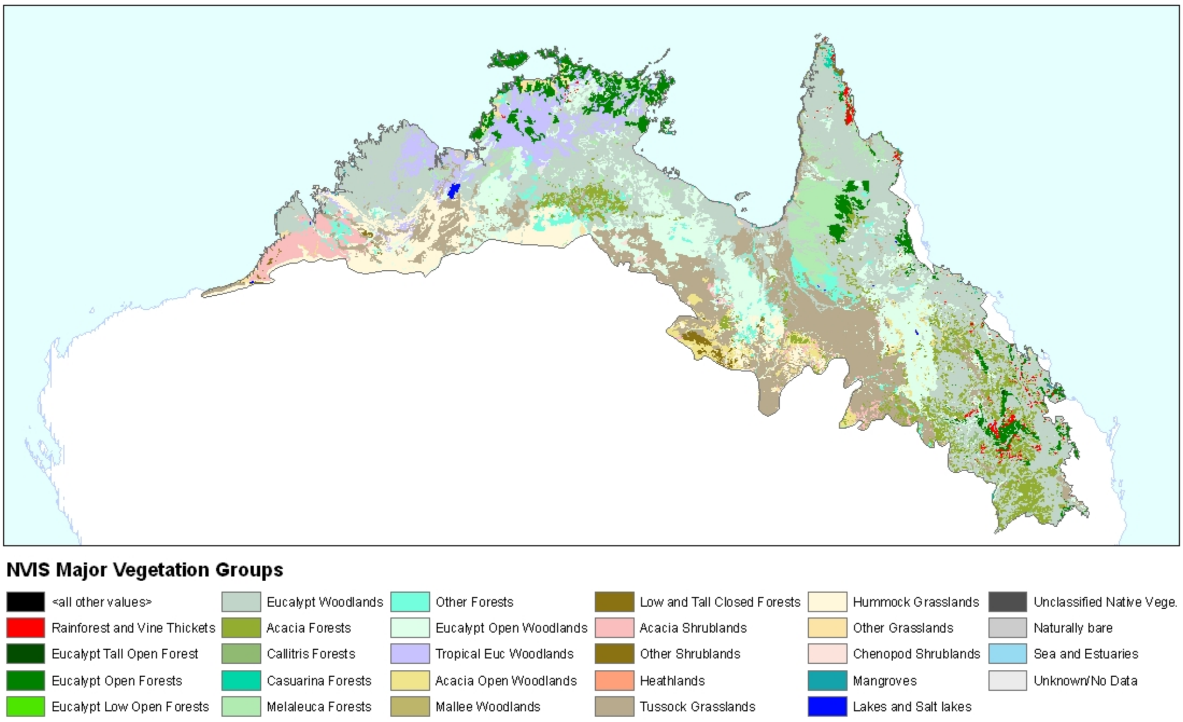

Figure 2 The savanna biome as defined by the Tropical and Subtropical Grasslands, Savannas and Shrublands ecoregion (ecoregion 90) showing the current NVIS major vegetation groups (MVGs)

The savanna biome as delineated in this report contains 22 of the 24 NVIS Major Vegetation Groups (MVGs, ESCAVI 2003; full a full description of each MVG, see DEWR 2007) highlighting its diverse nature as a result of broad continental spread and the aggregated effects of substrate, climate and vegetation structure. Seven of these each account for more than 5% of the region's area, and together they account for 86% of the total area. Some of the smaller MVGs, such as Rainforests, are considered as they support habitats critical for some biota and may shift under climate change at the expense of other biome environments. We will use the pre-1770 NVIS descriptions rather than extant vegetation maps as there is limited clearing in this ecoregion. The extant vegetation map shows some clearing south of Darwin and in the south eastern and central Queensland area of the ecoregion.

The tropical savannas provide a matrix that surrounds and adjoins a number of other important landscapes such as coastal wetlands, riparian zones, monsoonal vine forests, offshore reefs, rainforests and sandstone escarpments. The impact of climate change on these areas – which are often biologically diverse, fire sensitive and isolated with limited dispersal potential – needs to be understood for successful management and conservation of the savannas as a whole.

2.2 Biogeography, biodiversity and conservation significance

The national and international biological significance of Australia's savannas is emphasised by their inclusion as two of Australia's 15 biodiversity hotspots (North Kimberley, WA and Einasleigh and Desert Uplands, Queensland), two world heritage–listed national parks (Kakadu National Park, NT and Purnululu National Park, WA), five Ramsar-listed wetlands (including Cobourg Peninsula, NT and Ord River floodplain, WA), a millennium ecosystem assessment area (the northern Australian floodplains of Kakadu National Park and Blythe-Liverpool rivers in Arnhem Land), and over 30 National Parks and reserves (Figure 3).

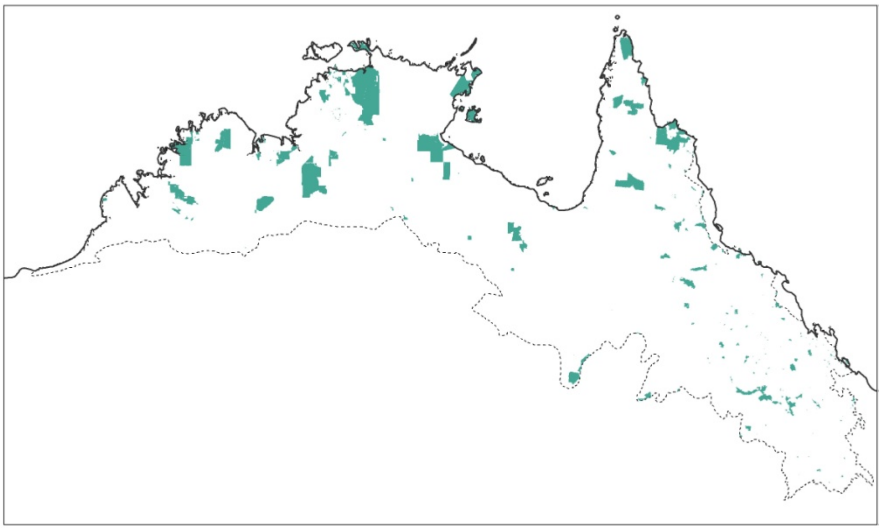

Figure 3 Protected areas (CAPAD 2006) within the savanna biome area

The biodiversity assets of northern Australia are showing signs of stress: recent studies (Woinarski et al. 2007) report alarming declines in small mammal and granivorous bird abundance across the tropical savannas, with predation and current management disturbances such as fire and grazing implicated in the declines.

2.3 People

The population of the savannas is low, with most people present in a few isolated towns (Bowman et al. 2010). Despite a low population base, extensive land use and management in the form of pastoral practices, fire management and road networks have led to an increase in disturbance being seen across the savannas. There is also the pressure of agricultural intensification based on misunderstandings of a plentiful water supply.

2.4 Key ecosystem drivers

The savanna biome has a number of key drivers, some unique to this biome. There are long-term ‘paleo natural’ drivers that have moulded the savannas, such as the monsoonal influence of oscillating wet and dry seasons; contemporary ‘land use’ drivers, relating to development and grazing; and other drivers, such as fire, that cut across these time scales. The biodiversity of this region has adapted to the monsoonal, wet–dry, seasonal rainfall patterns consisting of a reliable wet season with hot, humid days and a subsequent dry season with limited available water and the presence of frequent fire in the landscape. Although the total annual rainfall is high for much of the savannas, water is in fact a limiting resource for a considerable part of the year. Any climate change driven variation in the amount and seasonal distribution of rainfall in this region has the potential to significantly affect the unique flora and fauna.

Two broad classifications of biota inhabit the savannas: the widespread species occupying a broad range of diverse environments and the localised species restricted to specific habitats offering refuge from high temperatures, frequent fire and lack of dry season surface water as seen elsewhere in the savannas. Conserving the biodiversity of the savannas with climate change will require these two groups to be addressed, particularly ensuring that refuges can continue to provide protection for a critical range of species, often endemic to the region.

The savannas exist as a function of the low topographic variability, broad climate gradients and generally infertile soils of the region. Much of the Top End, including Kakadu, is very similar in vegetation. It is not until Tennant Creek, some 900 km south of the coast, that changes occur as a result of the loss of the quasi-monsoonal influence. These slow, landscape-scale changes also result in a remarkably shallow beta diversity change.

The savanna landscapes in Queensland have a somewhat different set of influences to other areas of the savannas. With increasing latitude, inter-annual drought driven by El Niño events drives vegetation structure rather than seasonal drought of the monsoon. Savannas in Queensland also contain major topographic features (mountain ranges), leading to significant climatic gradients. It has been suggested that these gradients lead to the increased heterogeneity seen in Queensland compared with other parts of the savanna biome. It is therefore important to consider processes, impacts and outcomes differently in these two savanna regions.

Many factors shape the savanna biome. We have summarised many of these in Figure 4 but readily admit it is not complete, especially for fauna. Nevertheless, it highlights the complex interactions present in natural systems and the influence that climate change is predicted to have on the various components.

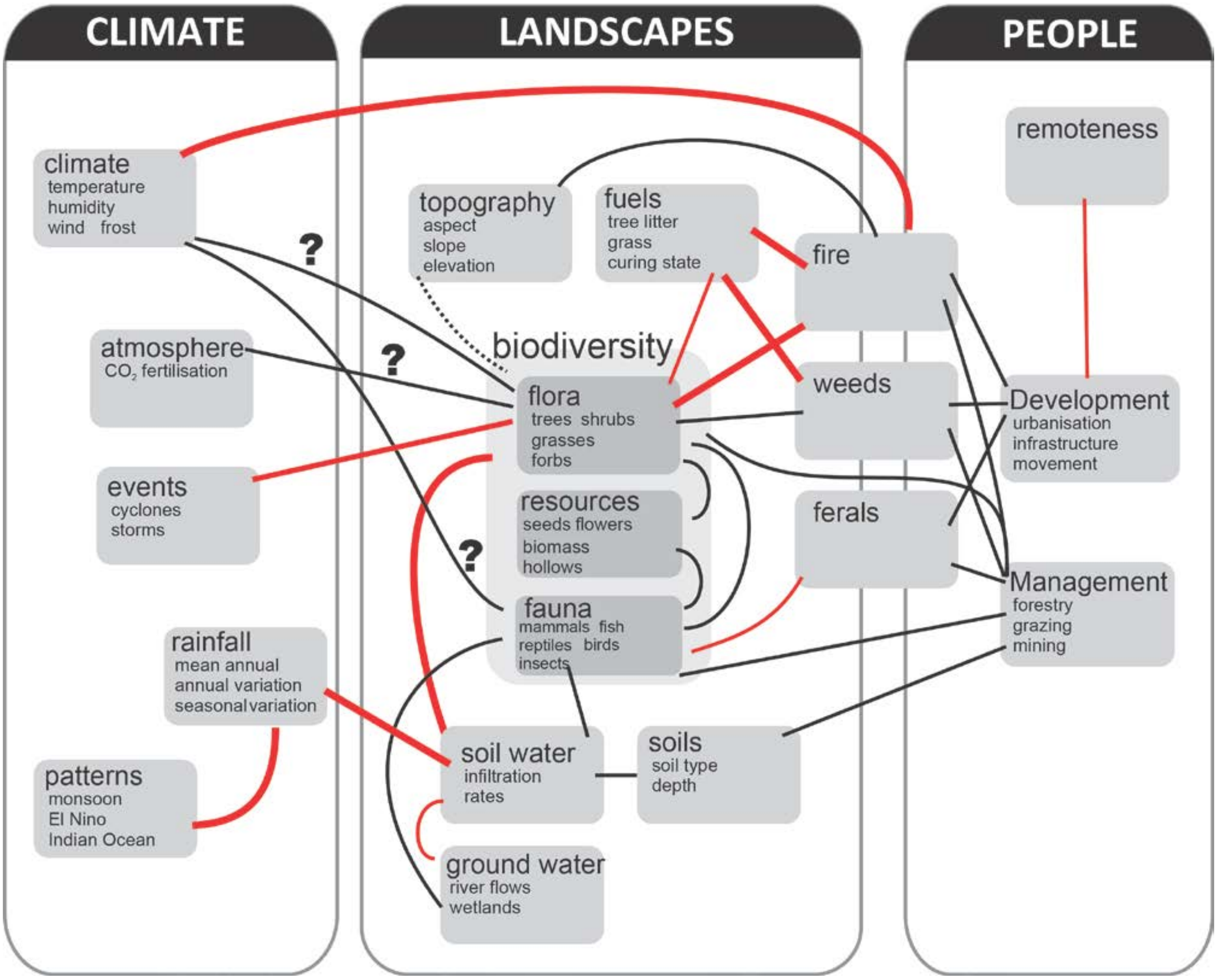

Figure 4 A conceptual flow diagram of savanna processes, with red arrows highlighting the processes predicted to change with climate change. The expected strength of the change is shown by the thickness of the highlight

3 Predicting the effects of climate change in the savannas

Natural systems are complex, with many interacting factors and uncertainties. This makes predicting change difficult. We can tackle the task of predicting how the savanna biome will change with climate by using detailed ecological understanding of habitats and individual species and by classifying the current situation as a whole system and determining how this is likely to change in the future. This was achieved with an expert workshop, which provided the current ecological and management understanding of plant and animal populations and habitats in the savannas and the modelling methodology determining the expected change in the much broader environmental classifications within the savanna ecoregion.

3.1 Expert workshop

To understand how the savannas will respond to climate change, we need to understand what is changing; this workshop was designed to brainstorm what effect the projected changes in temperature and rainfall would have on the current system. It was also important to consider 'sleeper threats', or those changes we may not have currently thought about. Of course this is not a simple matter.

The questions that we needed to think about included:

- What is the influence of 1–2 °C rise in temperature on savanna biota? For example, does the effect whereby increasing temperature changes the sex ratio of developing turtle eggs on northern Queensland beaches apply to the entire tropical coastline?
- What is the influence of increased rainfall variability on savanna biota?
- Can we see evidence that current changes – i.e. woody thickening and exotic grass spread, range changes, altered fire regimes and species declines – are a result of current increases in CO_2 concentrations in the savannas? Can we see examples of these changes in other tropical forested systems where savanna/forest interactions occur, such as the Amazon?

A two-day workshop was held 23–24 April 2009 in Darwin, where a range of experts in ecology and land management from Western Australia, Queensland and the Northern Territory discussed the implications of climate change on the tropical savannas. The workshop discussions are incorporated in this report. The full summary of the workshop is available in Appendix A.

Examples of the ecological questions posed at the expert workshop include:

- Are the projected temperature changes insignificant compared with current temperatures and temperature variability in the tropics, or are plants and animals currently at physiological temperature thresholds?
- Does a small increase in rare but damaging events such as cyclones represent a major shift in savanna composition?
- Is the savannas a homogenous landscape that will facilitate easy movement of organisms and changes in ranges, or are there barriers to movement? Where is movement most likely, north–south or east–west?
- Do alternate climate regions exist within the savannas, or could overall changes in climate result in large changes to the savannas?
- How do climate change projections compare to other disturbances such as agricultural and forestry intensification, feral animals, weeds and changing fire regimes?
- What are the physiological constraints placed on this system with an annual dry season, and can flora and fauna cope with changes in onset and dry season duration?

- Can we use the broad range of habitats across a range of rainfall and temperature gradients in the savannas to predict future change for any location?
- Do the current reserve system and off-reserve areas cover landscape gradients to protect future biodiversity values?

3.2 Modelling environmental stress

The modelling uses relationships between the contemporary patterns of biodiversity (ecosystem classes and species composition) and various environmental parameters to describe future changes in the environment (driven by climate change) in ways that are biologically meaningful. We use the term ‘biotically scaled environmental stress’ (or ‘environmental stress’) to describe these measures of future environmental change. One version of environmental stress relates to how climate and other environmental variables influence vegetation or ecosystem structure (from the ANN models, Hilbert and Fletcher 2012); the other correlates with contemporary changes in species composition in various groups (from the GDM models, Ferrier et al. 2012). Thus they are much more biologically meaningful than direct measures of change in rainfall or temperature. And while not as simple to conceptualise as projected changes in species distributions, we believe these environmental stress measures are actually much more robust as they are based on community- or ecosystem-level patterns (hence they eliminate many idiosyncrasies of species-level patterns and patchy data), and they make no assumptions about future biodiversity responses.

When applied to current environmental data, the GDM models predict *differences in species composition* at the community level between locations. In this report we have used the same GDM models to quantify predicted *change in the environment* at each location *A* that might result from climate change. The GDM quantifies the change in terms of the contemporary difference in composition that would occur, on average, between two locations *A* and *B* whose environments differ (now) by the same amount that the environment is expected to change at location *A*. Thus, it is a measure of future environmental change expressed in terms of *current* patterns of species compositional turnover. Future environmental change is very likely to result in much compositional change, but such changes will be affected by many unquantified factors, including the population dynamics of each species and interactions between species and other environmental factors we have not considered; hence our choice to describe the ANN and GDM outputs as relating to changes in *the environment* rather than presenting them as assumption-laden predictions of changes in *biodiversity*.

Northern Australia and the tropical savannas are relatively data poor compared with other regions of the world and Australia. Additional fundamental animal and plant physiological knowledge is required to understand the actual tolerances of organisms and the upper limits and thresholds with respect to temperature and water requirements. This research will provide an indication as to how close the current system is to climate limits and therefore how important the future changes will be. Also, we need to consider the amount of data available for some of the modelling predictions and be somewhat cautious about extrapolating minimal understanding to the vast savanna biome. For this reason we use the index of biotically scaled environmental stress that does not determine how much the biota are going to change in future, but answers the question: how different will the environment feel from the perspective of the biota under climate change?

Details of the modelling methodology can be found in Appendix B.

4 How will climates and environments change in the savanna biome?

Our use of ‘environmental stress’ means we assume stressful environments will lead to changes in the structure and composition of species present with increases or introductions of species experiencing low or no stress and declines or loss of highly stressed species in the current environment. Therefore, environmental stress is a measure of how likely a location is to be under pressure to change to something different. In some situations we can get an idea of what the system is likely to change to, but of course whether this happens and what the final makeup of a community will be depends on a range of factors, such as dispersal ability, that is very difficult to predict at present. The presentation of stress maps will, however, allow for better management decisions to protect currently vulnerable communities, prepare for new communities and identify communities that may become more abundant with climate change. There is no means of assigning the modelled stress measures to actual changes in biota for the savannas, but we use this measure as an indication of potential trajectory of environmental change.

4.1 Evidence of historic and current climate change

The savannas of northern Australia are located in a geologically ancient and stable landscape. It is sometimes difficult to perceive this system changing from the past or into the future. The structure and composition of the savannas have been stable since the end of the Pleistocene some 12,000 years ago (Nix and Kalma 1971) and there has been very little change in many areas since the European explorers first traversed the savannas (Fensham 2008). While these studies suggest stability, other studies have shown considerable recent change, with introduced woody and grassy weeds (Rossiter et al. 2003) and the thickening of woody vegetation in the savannas (Lewis 2002; Krull et al. 2007).

CO_2 fertilisation has been implicated as some of the cause for woody thickening and encroachment (Bond and Midgley 2000), suggesting that the savannas can change. Broad landscape use such as grazing may also modify the structure and function of the savanna biome (Kutt and Woinarski 2007). We also need to consider that the projected climate under climate change may be different from anything previously experienced by the savannas and the chance that even small changes in the very aspects of the savannas that lead to stability, such as a reliable monsoon, may result in new stresses on the unique biota.

The notion of stability may lead some to suggest that the tropical savannas are resilient to climate change impacts. In fact, the discussions in the expert workshop and modelling results presented in this report suggest the opposite. The savanna ecoregion of Australia could contain some of the most stressed environments with climate change based on both the medium and high emissions scenarios in 2070. The key drivers influencing the affect of stress in the savannas include:

- The savannas currently have consistently high temperatures (30–35 °C) with very high relative humidity levels in summer; as humidity increases, heat stress will become a concern. Flora and fauna must cope with new thermal environments that arise from increases in temperature.

- The shallow topography and temperature and rainfall gradients in the savannas mean any change results in large geographic shifts in the location of similar environmental conditions which may be difficult for the biota to adapt to in relatively short time intervals.

4.2 Climate change predictions

Climate change projections for northern Australia are currently provided by a number of climate model simulations for the IPCC 4th Assessment Report (IPCC 2007).

Temperature is expected to increase over the Australian continent, with inland regions showing greater warming than coastal regions (Suppiah et al. 2007). Most models predict an annual mean change in temperature across the savannas from 0.5 °C to 2 °C by 2030, depending on location and the climate change scenario used. This is expected to increase by 2–4 °C by 2070, based on current worst case scenarios. Generally, the Top End of the Northern Territory and Cape York Peninsula are expected to experience less warming than the inland regions of the savannas (about 1 °C difference).

Projections of the number of extreme temperature days (above 35 °C and 40 °C) are also provided by the models. A general trend of increases in the number of days above 35 °C is expected in the savannas. An increase in days above 40 °C is also predicted, but this is primarily for areas currently experiencing high temperatures such as Longreach and north Western Australia (Halls Creek), with this effect less pronounced by the coast (Darwin and Broome). As the coastal regions currently have a low number of extreme heat days (35 °C Darwin 11, Broome 54; 40 °C Darwin 0, Broome 3) even a slight increase can represent a large change in exposure to high temperatures for the region (35 °C 2030 Darwin 15–46, Broome 61–90; 35 °C 2070 Darwin 31–305, Broome 84–293, depending on the scenario modelled).

Rainfall changes are more complex and harder to project than temperature changes, and to date most models provide changes in rainfall amount and broad seasonality, but do not predict finer-scale changes in distribution, onset and intensity. The models all capture the monsoonal influence of rainfall in the summer months, where there is a strong negative continental rainfall gradient with increasing latitude from the tropical northern coastline. In winter the continental rainfall gradient is reversed, increasing to the south. Based on this general weather pattern and the savanna biome's location, the seasonal pattern of weather is likely to remain, with models projecting changes in amount of rainfall and some regional changes in seasonal rainfall pattern.

Rainfall projections to 2030 show a slight increase (5–10%) in rainfall during the wet season for the Northern Territory and parts of Queensland. For much of the savanna biome there is no predicted change in dry season rainfall (where little or no rain falls) except for parts of north Queensland where a decline of 10% in winter rainfall is predicted.

The current view is that with change in rainfall amount, there will also be changes in when the rain falls, with more rain falling in shorter periods. This somewhat unknown change is likely to have a strong influence on the tropical savannas, particularly the tree component (Liedloff and Cook 2007). Changes in water availability in the dry season could have significant outcomes.

Additional environmental changes such as sea level rise, increases in CO_2 concentrations, changes in cyclonic activity and fire regimes are provided by other sources, most of which infer likely changes as a result of changes in temperature and rainfall. These were not considered in the modelling in this project.

Projected climate change for the biome was based on outputs from the CSIRO Mk3.5 GCM downloaded from OzClim (CSIRO 2012): a *medium* impact scenario, using the A1B emissions scenario, and a *high* impact scenario using the A1FI emissions scenario (IPCC 2000). Future projections were made for 2030 and 2070. These model outputs and scenarios were chosen in consultation with the Australian Government Department of Sustainability, Environment, Water, Population and Communities and the Australian Government Department of Climate Change and Energy Efficiency, and because they provided the best range of parameters for inputs to subsequent environmental modelling.

4.3 Important climate factors

The three variables (out of 47) used by the ANN model with the greatest influence on classifying the savanna ecoregion were the BIOCLIM (Busby 1986) variables relating to Mean Moisture Index of Coldest Quarter (soil water in the dry season or winter), Highest Period Moisture Index (soil moisture in the wet season or summer) and Moisture Index Seasonality (wet–dry seasonality). This is not surprising as these three variables identify the tropical wet–dry seasonality that differentiates the savannas from the arid biomes and southern forests. The variables were discussed in the expert workshop.

The ability of the ANN model to classify the environmental envelope of the MVGs in the savanna biome was also related to the seasonality, moisture, precipitation and radiation variables from the BIOCLIM spatial layers. The fact that the modelling was able to classify these MVGs shows that there are distinct units or bioregions within the savannas. The limited discrimination of some of these MVGs suggests that more research is required to determine the biogeographical zonation within the savannas (Bowman et al. 2010).

Much of the stress predicted in the modelling results was influenced by the dramatic change in climate variables predicted for the Kimberley region of the tropical savanna.

4.4 How much will change?

The ANN modelling predicts that the savanna biome will have a similar distribution in 2070 under the two emission scenarios as is present today (Table 1). Differences in the area modelled occur along the southern boundary of the ecoregion and particularly the southern area (Brigalow Belt) in Queensland, which is not classified as savanna in 2070 (Figure 5; see also Appendix C, where the medium emissions scenario for 2070 is also shown). This seems sensible since these boundaries are where the environment's suitability is likely to be intermediate between the classes.

Table 1 The area (km^2) covered by the savanna ecoregion from current NVIS mapping and under the medium and high emission climate change scenarios in 2070 using ANN modelling

CURRENT		CLIMATE CHANGE	
MAPPED	MODELLED	2070 MEDIUM	2070 HIGH
1 829 212	1 863 552	1 946 568	1 833 316

While the predicted extent of savanna remains similar with climate change, the area classified for each MVG environment within the region does change. Figure 6 shows the difference in area (km^2) between the current NVIS MVG map and the predicted area of the top 11 MVGs (95% of savanna area). This determines whether the area modelled for each MVG is increasing or decreasing under climate change, but does not indicate whether it has shifted to a different location.

It is somewhat difficult to distinguish the difference between some of the MVGs occurring in the savanna biome as much of the Eucalypt-dominated savanna appears remarkably similar. These modelling results do suggest that these MVGs can be explained by different environmental factors that will change with climate change. This suggests that it is not appropriate to consider the savannas as one eucalypt woodland region, but the biome should be considered as a range of habitats distributed along broad rainfall and temperature gradients. Subtle changes in the composition of the savanna biome may mean that this biome is actually very sensitive to future changes in climate as suggested by the ANN modelling.

The vegetation class showing the greatest decline in suitable area with climate change is the Eucalypt Woodlands (MVG 5). These woodlands are defined as a transitional zone between the higher rainfall forested margins of the continent and the hummock grasslands and shrublands of the interior. The vegetation classes showing an increase in the amount of similar environment in the savannas are the Eucalypt Open Woodlands (MVG 11), Tropical Eucalypt Woodlands/Grasslands (MVG 12) and Other Grasslands (MVG 21). The Eucalypt Open Woodlands are characterised by wide spacing between trees; they currently occupy the semi-arid interior of the continent and contain many of the species in the Eucalypt Woodlands. The Tropical Eucalypt Woodlands/Grasslands is typical of the Eucalypt communities of the northern parts of the Northern Territory and Cape York, with a suite of tall annual grasses. The Eucalypt Woodlands therefore provide a transitional community between Eucalypt Open Woodlands and the Tropical Eucalypt Woodlands/Grasslands. The increase in Other Grasslands (MVG 21) in the savannas is due to changes in communities typical of south-western Queensland that adjoin the savannas and indicate a change in environment towards that of the channel country in southern parts of the savanna biome.

Climate change driven spatial shifts in the MVGs occur where the environmental conditions for current vegetation classes move to a new location. When this occurs the current biota can move, adapt to the new environment, or disappear. The maps presented in Figure 5 provide an indication of the environmental stress expected across the savannas presently and under the climate change scenario of high emissions in 2070. As much of the biome changes with climate change, this imposes an additional stress, with similar spatial patterns, to that already experienced by the biota. The greatest stress and likely subsequent changes are in the semi-arid savannas through the Kimberley (WA), Victoria River District (NT), western Cape York Peninsula and the woodlands of central Queensland. The least stress is predicted in the Tropical Eucalypt Woodlands of the Top End (NT) and the grasslands around the Mt Isa district, suggesting that this is a distinct habitat and the conditions are not likely to change dramatically in the future.

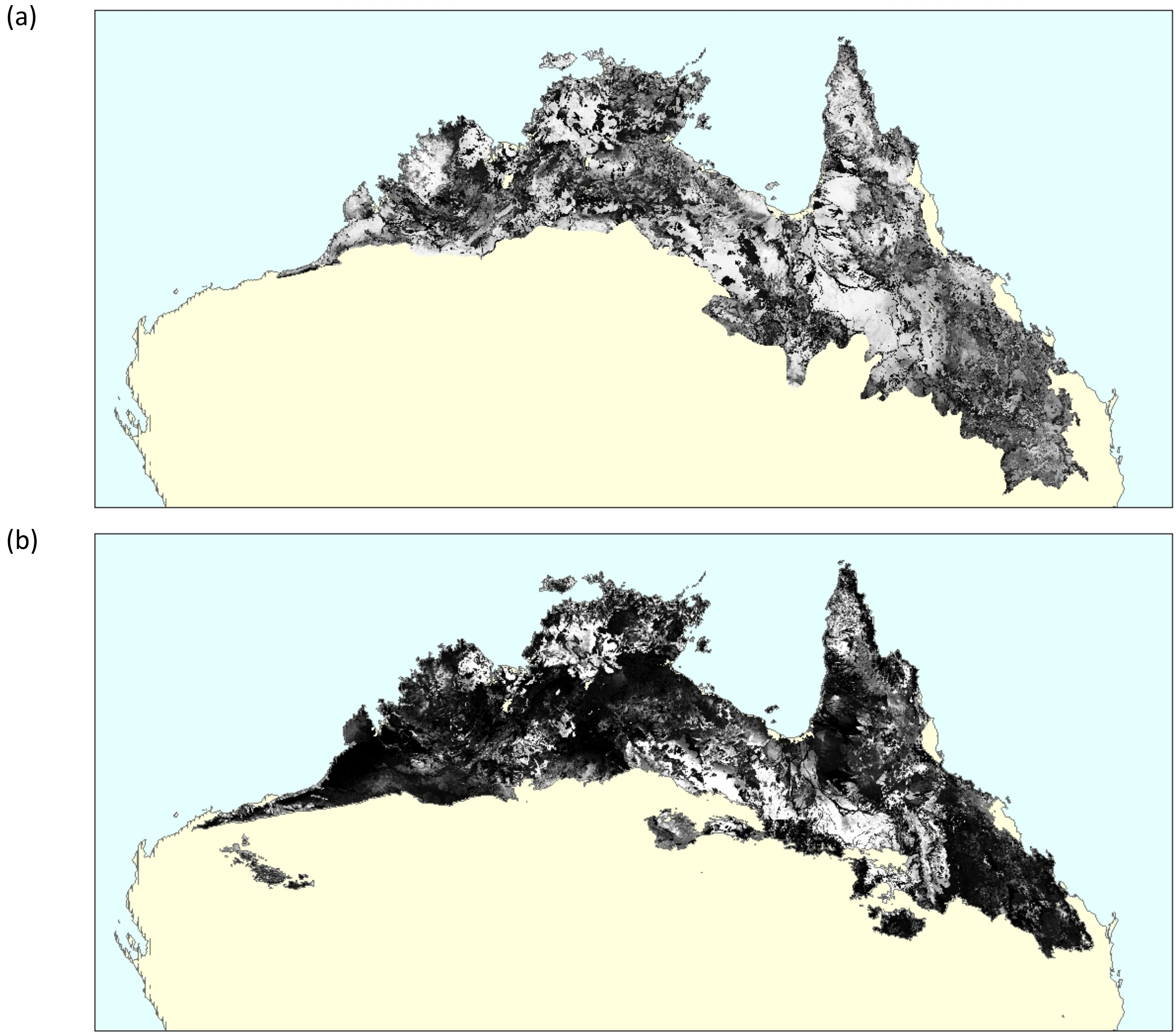

Figure 5 Modelled environmental stress (ANN dissimilarity) (a) present and (b) 2070 high emissions scenario in the savanna biome. Dark shading represents the greatest environmental stress. Cream areas are outside the savanna biome

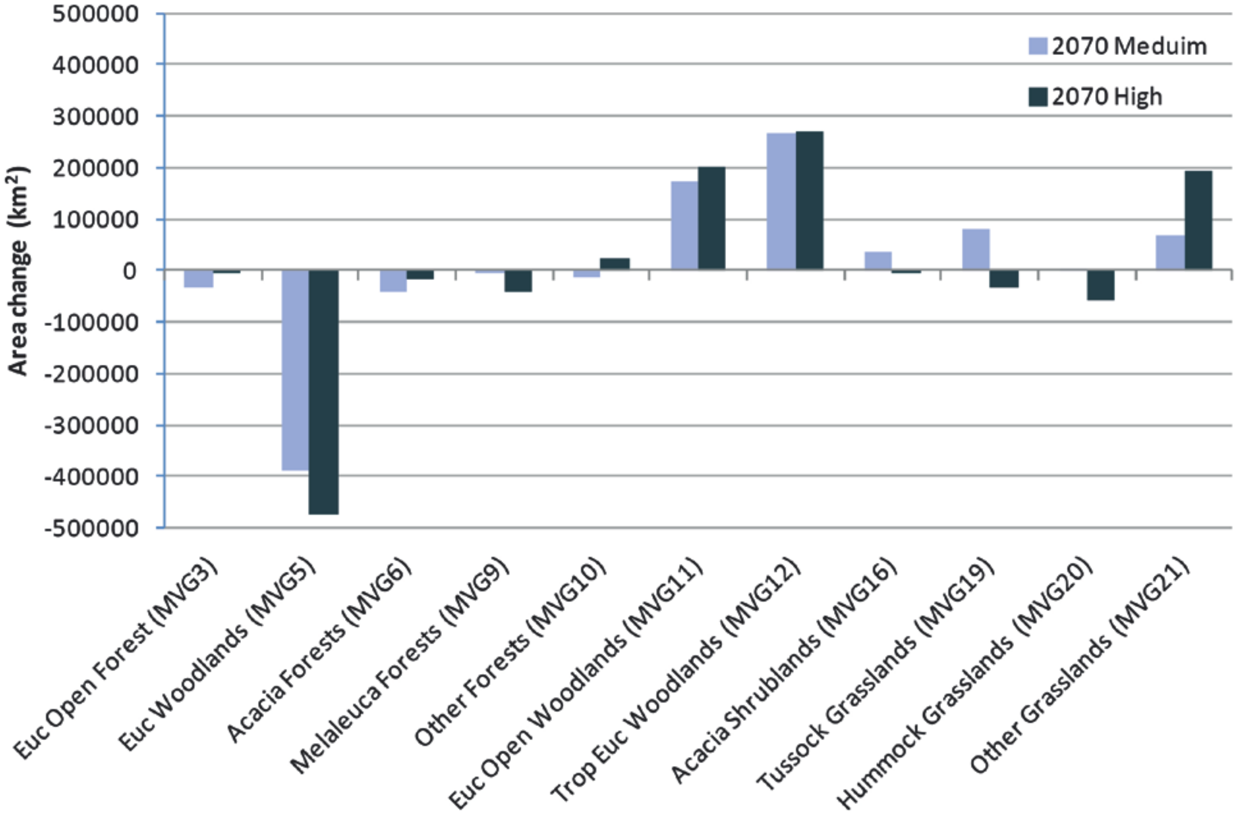

Figure 6 The change in area (km^2) modelled for the main major vegetation groups (MVGs) within the savanna biome between the current NVIS map and future climate change based on 2070 medium and 2070 high emissions scenarios

When we consider the biome's vegetation groups with climate change (Figure 7), the lowest mean environmental stress under the two climate change scenarios is around 0.5 while the highest is around 0.85 suggesting the environments for currently mapped MVGs will change dramatically by 2070. The implication of this for biota is hard to predict, but it is likely that some ecological communities as we know them today will change.

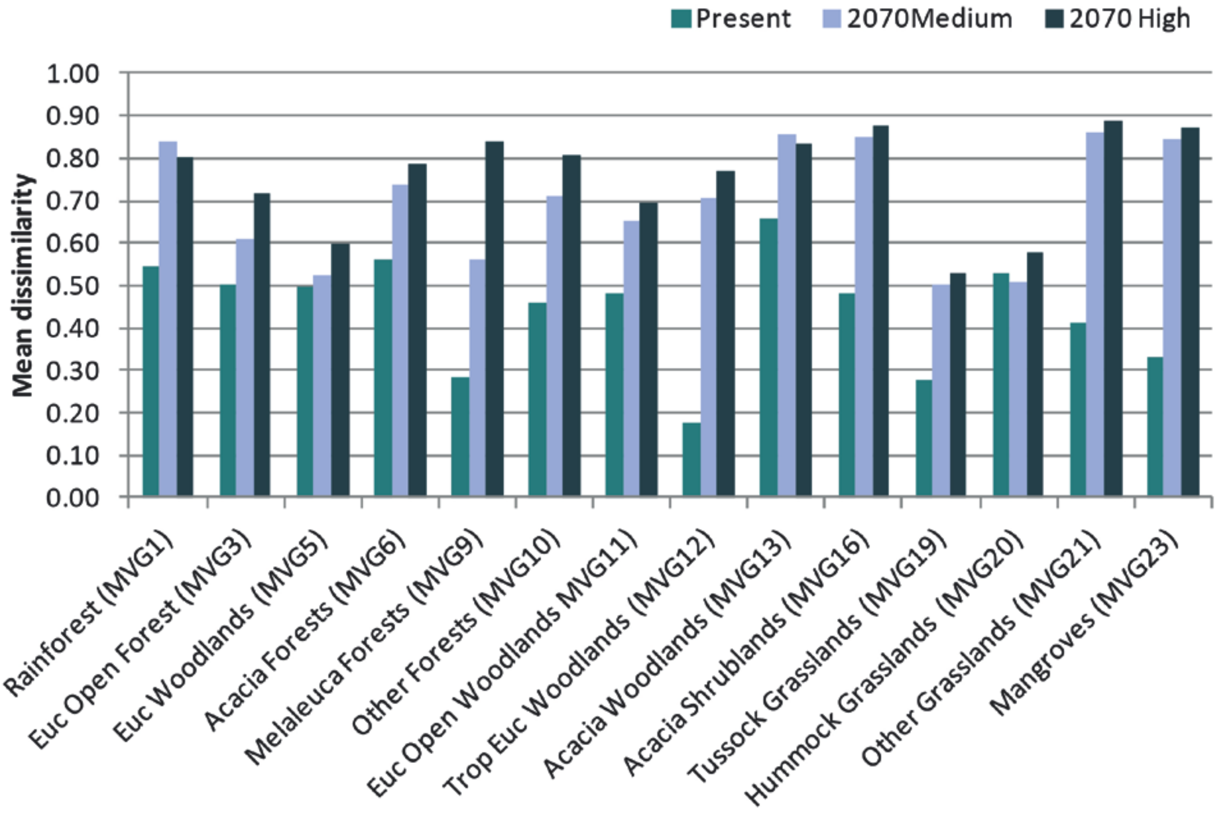

Figure 7 The mean environmental stress (ANN dissimilarity) for each important MVG in the savanna biome for the present and the 2070 medium and high emissions scenarios

4.5 Species compositional turnover by selected taxon groups

There is good evidence that in general compositional turnover increases with temperature, so warming may be a more significant driver in the tropics than in temperate zones. Also, species will be closer to fundamental physiological limits in the tropics. Hence, it was agreed during the workshop that increasing temperature is a cause for concern in the savannas, possibly even more so than elsewhere. We do not know, and cannot know because of the geographic constraints, whether and to what extent the savanna biota can tolerate temperatures higher than present. Mostly, the ANN modelling 'assumes' that they can, but other studies are starting to show that climate change may be as, or more, important in hot climates as in cold areas. It was also agreed during the workshop that extreme events – such as cyclones, extreme temperature days, droughts and floods – are likely more important in producing change than average increases in temperature and rainfall, as they can cause very rapid mortality in populations.

Locations with higher inter-annual climate variability often have decreased diversity. For example, the Karoo (Africa), which has low variability, and the Nullarbor, which has high variability, appear similar in bio-climate, but have very different biome diversity. The long-term stability of inter-annual climate variability is a predictor of species diversity in the Wet Tropics, while intra-annual (within the year) variability is a predictor of species abundance. These relationships may be even more important in the savannas. In contrast, however, small changes in average parameters can also be important; for example, depth of seasonal drought (versus extreme drought) and frequency of fire are expected to lead to long-term changes in vegetation.

There are reports of dramatic changes in the savanna biome. These include small mammal population declines, increases and decreases in vine/rainforest extent and pressure on obligate-seeder species through changing fire regimes. The declines in small mammals in the savanna biome have been shown though faunal surveys over 15 years with declines to half original populations five years ago to populations barely present currently (Woinarski et al. 2010). Workshop attendees reported declines in possums on Cape York Peninsula (Qld) and complete loss of Phascogales around Jabiru (NT). The reasons are still unclear and could be due to predation by feral animals, diseases or disturbances such as fire regimes and grazing (Woinarski et al. 2007). For example, recent research shows that once cattle were removed from areas of the Kimberley (WA) there were increases in abundance of many small mammals (Legge et al. 2011). Critical weight range mammals are also surviving in a specific band in the Kimberley. It seems that recovery of cover after fire may be important and this recovery relies on rainfall. Changes in rainfall with climate change may therefore interact with post-fire vegetation recovery, leading to changes in mammal populations.

The savanna biome exists across a number of temperature, rainfall, disturbance and intensification gradients. The strengths of these gradients in the north, with shallow temperature gradients and steeper rainfall gradients, impact on changes in richness and structure. If species distributions are sensitive to temperature, then even small changes in temperature, in combination with shallow gradients across broad landscapes, could lead to large geographic changes in climatic niches. Species with limited ability to move, either by mobility or by being restricted to a particular geographic location, will not cope with the resulting change. This also means that connectivity in the landscape is particularly important. This is not only in habitat, but may also include subtle differences arising from plant communities responding to time since last fire. Thus it is important to understand a temporal and spatial heterogeneity of disturbance in the savannas and not simply consider them as a vast homogeneous landscape. This connectivity needs to be considered across a range of spatial scales representing the movement of different organisms from termites to magpie geese. It is likely that climate change will alter this mosaic of time-since-disturbance by increasing the frequency and/or intensity of cyclones, storms and fire.

Given the gradients present in the savannas, the flora and fauna have evolved to cope with this system either by utilising refugia, moving across the landscape to follow resources (flowers, seeds, rainfall), or becoming flexible and able to use the broad landscape available. Climate change is likely to affect these groups differently. It is likely that the generalists will be advantaged more than the specialists, as generalists are favoured in periods of rapid change. Specialists require a particular resource and often have narrow niches. Some examples to consider are thermal specialists that exist in their current location because of the favourable thermal environment; specialist species of mammals and birds in the savannas located within somewhat uniform environmental gradients; and particular geographic specialists, such as the burrowing skinks in Queensland where there is no scope for expanding or moving. Changing climatic conditions also mean that a species may change from being restricted to specific microhabitats to being more widespread and even moving from specialist to generalist in strategy with new favourable conditions. This may be extremely important for exotic plant species, leading to ‘sleeper weeds’ scattered throughout the biome rapidly becoming widespread or locally abundant. It is not known how many species are likely to become weeds or pests in the new environment. There are also a number of generalist species in the savannas, probably as a result of the somewhat homogeneous nature of the vast, flat savanna woodlands.

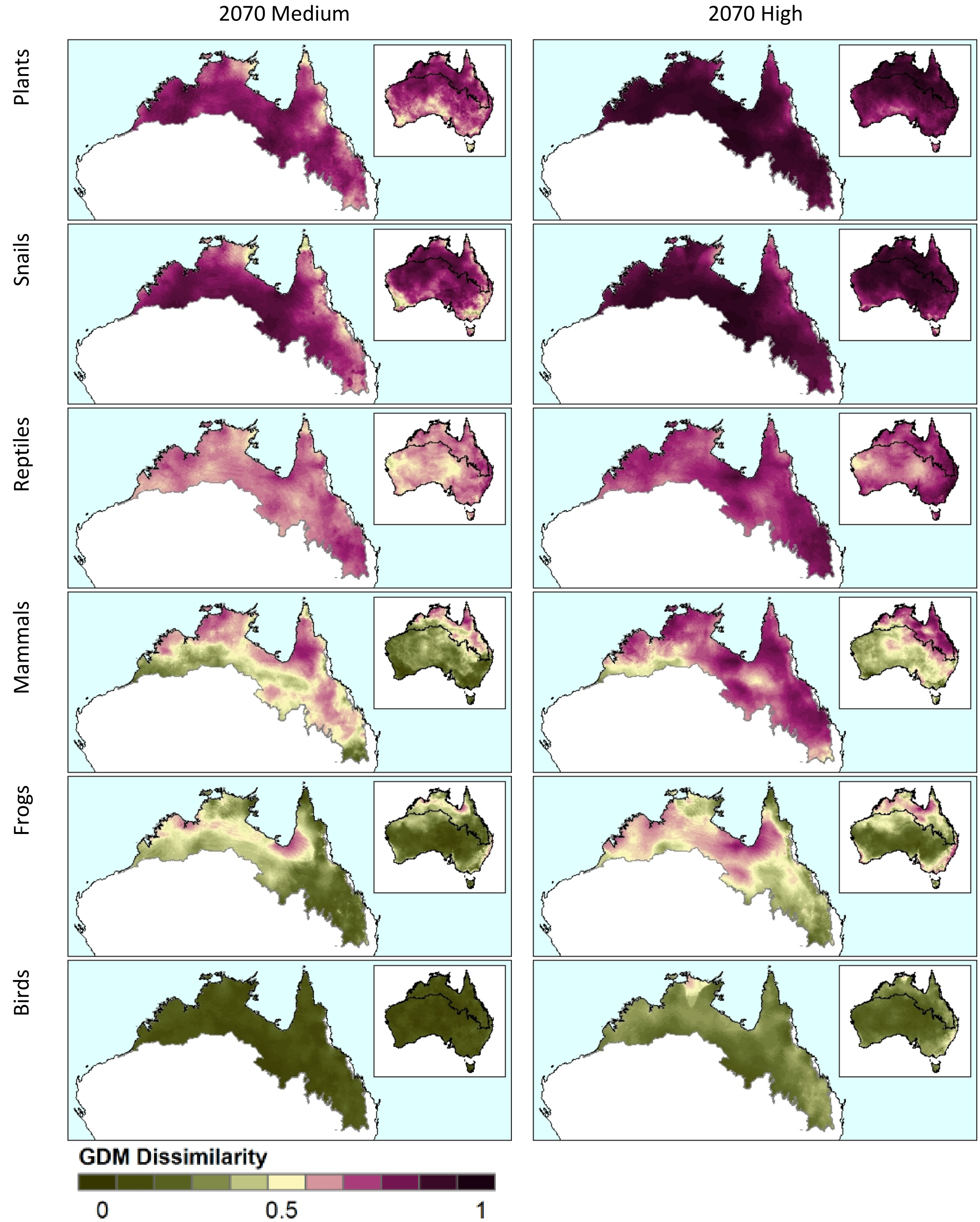

Figure 8 The expected compositional change calculated from the GDM modelling for each 1 km^2 cell for the present climate against each future emission scenario in 2070 where high dissimilarity (dark pink) indicates a high level of stress, and low dissimilarity (dark green) indicates low stress for six biota

The GDM modelling results (Figure 8 and Appendices D–I) show that present species–environment relationships in the savanna biome are predicted to change for a range of biota. The results show the biota in decreasing order of stress are plants (Appendix D), snails (Appendix E), reptiles (Appendix F), mammals (Appendix G), frogs (Appendix H) and birds (Appendix I). Modelling for frogs (Appendix H), mammals (Appendix G) and plants (Appendix D) shows that the greatest stress is located in the savanna biome for these biota, and it is often the savannas where the first signs of stress are found (2030 medium and high climate change scenarios were added to show an intermediate effect of climate change before 2070; see Appendices D–I). The stress of the plant biota matches that observed from the ANN modelling for the tropical savannas where the semi-arid savanna band appears highly stressed. This is also true of snails, reptiles and frogs, whereas the birds and mammals show highest stress at the coast, declining towards the semi-arid zone. The modelling undertaken for this project does not fully account for the interactions between biota. Therefore, a change in vegetation structure may result in additional stress for biota relying on specific vegetation communities.

The mean compositional change for each biota within the dominant MVGs are also provided both for the entire biome and only considering areas within the current NRS (Appendix J). These results show that in general the compositional change or environmental stress is relatively uniform across the savannas regardless of MVG. There is a slight additional predicted stress for birds in the Tropical Eucalypt Woodlands and Other Grasslands. Plants show a constant stress across MVGs with an increase under the 2070 high emissions scenario. Some vegetation groups such as Other Forests appear to have lower stress under climate change in the NRS than outside. Mammals and frogs show the greatest difference in stress both between MVGs and the NRS and rest of savanna biome, suggesting that a regional, fine-scale pattern of compositional change may be occurring with this biota. Except for birds (and frogs to a lesser degree), all biota are predicted to be under considerable stress regardless of MVG under both climate change scenarios.

Table 2 shows the environmental stress (mean dissimilarity) within each MVG for the six biota modelled. The highlighted cells have a stress greater than the mean over the entire biome for the given biota and given climate change scenario. This is designed to show the disproportional stress across MVGs. While almost every MVG shows a dissimilarity of greater than 0.5 for every biota, suggesting environmental change, this analysis shows the areas of greatest expected compositional change through stress. These areas should be considered as high priority for conservation, particularly if they currently contain important species that are regarded as ‘climate-sensitive’ and critical to conserve for the future. Appendix K shows the same results, but only includes values for MVGs contained within the current NRS in the savanna biome. While the NRS is a subsample of the entire biome, there are some slight scale differences in the most stressed biota and MVGs in the current NRS boundaries under climate change.

Table 2 The mean environmental stress (GDM disimilarity) for each biota in each of the main major vegetation groups (MVG) in the savanna biome, with MVGs highlighted with stress greater than the entire biome for the given biota and climate change scenario

		BIRDS		FROGS		MAMMALS	
		M2070	H2070	M2070	H2070	M2070	H2070
1	Rainforest	0.237	0.334	0.250	0.369	0.546	0.734
3	Euc Open Forest	0.215	0.352	0.351	0.461	0.601	0.741
5	Euc Woodlands	0.210	0.314	0.368	0.486	0.538	0.701
6	Acacia Forests	0.205	0.300	0.274	0.409	0.484	0.698
9	Melaleuca Forests	0.202	0.312	0.512	0.600	0.637	0.724
10	Other Forests	0.179	0.287	0.389	0.525	0.472	0.631
11	Euc Open Woodlands	0.183	0.298	0.379	0.531	0.530	0.699
12	Trop Euc Woodlands	0.212	0.339	0.453	0.537	0.592	0.699
13	Acacia Woodlands	0.131	0.208	0.315	0.483	0.524	0.699
16	Acacia Shrublands	0.178	0.293	0.353	0.489	0.344	0.497
19	Tussock Grasslands	0.156	0.248	0.337	0.489	0.477	0.645
20	Hummock Grasslands	0.157	0.269	0.397	0.524	0.384	0.538
21	Other Grasslands	0.188	0.306	0.384	0.501	0.545	0.676
23	Mangroves	0.237	0.367	0.375	0.472	0.572	0.714
Whole biome area		0.191	0.298	0.370	0.497	0.518	0.677

		PLANTS		REPTILES		SNAILS		MEAN	
		M2070	H2070	M2070	H2070	M2070	H2070	M2070	H2070
1	Rainforest	0.707	0.856	0.695	0.790	0.674	0.819	0.580	0.716
3	Euc Open Forest	0.681	0.856	0.642	0.742	0.655	0.819	0.580	0.724
5	Euc Woodlands	0.726	0.884	0.655	0.754	0.713	0.843	0.603	0.736
6	Acacia Forests	0.726	0.895	0.670	0.777	0.727	0.870	0.587	0.735
9	Melaleuca Forests	0.763	0.905	0.656	0.742	0.766	0.864	0.659	0.765
10	Other Forests	0.774	0.909	0.625	0.721	0.791	0.894	0.623	0.745
11	Euc Open Woodlands	0.773	0.916	0.651	0.754	0.788	0.895	0.631	0.762
12	Trop Euc Woodlands	0.745	0.900	0.635	0.723	0.738	0.860	0.630	0.748
13	Acacia Woodlands	0.816	0.933	0.640	0.728	0.832	0.927	0.638	0.757
16	Acacia Shrublands	0.779	0.898	0.597	0.687	0.793	0.886	0.600	0.714
19	Tussock Grasslands	0.791	0.918	0.633	0.725	0.819	0.914	0.627	0.747
20	Hummock Grasslands	0.811	0.922	0.625	0.707	0.843	0.921	0.635	0.741
21	Other Grasslands	0.751	0.894	0.635	0.728	0.748	0.870	0.617	0.740
23	Mangroves	0.690	0.853	0.638	0.742	0.645	0.806	0.581	0.720
Whole biome area		0.753	0.899	0.646	0.742	0.756	0.873	0.615	0.743

The GDM modelling suggests that the environments required for each biota will vary and the associated stress will vary spatially across the savannas and Australian continent. Discussions during the expert workshop included the differences between plants and animals in the extent to which realised and potential niches differ. It was suggested that often animals are close to the limits of their fundamental niche while plants are a lot further from theirs. This may be due to the mobility of animals and the ability to move and adjust to the edges of spatially and temporally dynamic niche boundaries. Some people suggested that plants less frequently fill their fundamental niches. Plant ecologists often tend to be less accepting of the idea that plant communities may change greatly with climate change; this is possibly due to the strong empirical associations between community types and geographic environment (although such patterns might actually suggest sensitivity to changing environment) or long lags in response to change. In contrast, animal ecologists are more pessimistic and accept change is occurring or will occur, possibly due to dramatic changes in faunal populations, including extinctions, in the last 200 years. The dramatic change in plant species composition shown in the GDM modelling is therefore alarming. If plant environments are predicted to be under such stress in the savannas, the faunal component may be under even greater pressure. This was not suggested in the GDM models for various fauna (Figure 8), but perhaps even small expected stress in biota such as mammals needs to be critically considered.

It is also important to consider the degree of population patchiness, the spatial structure of intra-specific genetics and population connectivity across the savanna gradients. These areas of research have not been undertaken to date. An example of a geographic divide occurs with the north–south divide in sub-species of the black-throated finch, with the northern population stable but the southern population endangered. Therefore, it is important to ensure that the northern sub-species that occurs in the savannas is maintained is important. Other smaller environments that contain specialist species – such as the Howard Springs (NT) sand sheets and Mitchell grass areas around Victoria River (NT), Barkly (NT) and Mt Isa (Qld) – need to be considered with respect to climate change.

4.6 Plant species compositional turnover – a case study on the buffering effects of environmental heterogeneity at continental, regional and local scales

We consider the GDM modelling of the plant biota to investigate how environmental heterogeneity may buffer the effects of climate change in the savannas. The vascular plant biota was selected as it contains the greatest data, and it is assumed that plant community composition and associated structure is important to savanna dynamics and function and the associated fauna. The vascular plant data consisted of 2,995,841 records from 12,881 species at 374,640 sites across Australia.

4.6.1 DO THE ENVIRONMENTS CURRENTLY IN THE BIOME OCCUR ELSEWHERE IN THE FUTURE?

While the modelling shows stress in the savannas and the area available for some of the MVGs declines, similar environments will be present elsewhere in Australia. Table 3 shows the area of each of the 23 NVIS MVGs modelled with the ANN model in the savanna biome and elsewhere in Australia. While areas classified as suitable for Tropical Eucalypt Woodlands are only found in the savanna biome, this environment is still present under climate change. The savanna biome does contain the majority of environments suitable for Other Grasslands and Melaleuca Woodlands under future climate. This suggests that there are no major environments specific to the savannas that are likely to disappear from the continent. We are not, however, able to comment on some of the smaller specialised habitats that exist within or adjacent to savanna MVGs. These include riparian zones, monsoonal vine thickets and gorges that are at a spatial scale finer than the ANN analysis.

Table 3 ANN modelling predicted area of environmental class (km^2) for the 23 NVIS MVGs within the savanna biome and elsewhere in Australia for the 2070 medium and high emissions scenarios

	CURRENT		MEDIUM 2070		HIGH 2070	
	SAVANNA	ELSEWHERE	SAVANNA	ELSEWHERE	SAVANNA	ELSEWHERE
Rainforest (1)	11 500	33 412	20 868	27 752	10 412	19 548
Euc Tall Open Forest (2)	312	39 556	4	37 104	0	42 744
Euc Open Forest (3)	86 392	303 364	54 732	286 720	81 608	240 272
Euc Low Open Forest (4)	148	4 748	180	12 372	1 272	9 432
Euc Woodlands (5)	622 856	643 420	234 876	335 120	14 7704	216 488
Acacia Forests (6)	111 540	341 028	70 096	278 184	92 972	296 512
Callitris Forests (7)	5080	31 196	8 260	153 792	96	92 488
Casuarina Forests (8)	3148	148 372	1 872	164 848	912	210 368
Melaleuca Forests (9)	68 836	11 116	64 612	9 844	28 208	860
Other Forests (10)	43 736	23 960	30 408	52 684	67 140	74 796
Euc Open Woodlands (11)	254 496	176 484	428 668	193 040	456 284	445 912
Trop Euc Woodlands (12)	96 412	0	361 376	0	365 880	0
Acacia Woodlands (13)	29 360	267 648	1 548	241 584	916	222 884
Mallee (14)	164	376 232	3 516	314 968	1 568	170 296
Low Closed Forest (15)	0	22 352	1 296	41 192	520	22 660
Acacia Shrublands (16)	44 692	740 812	80 376	651 304	41 412	377 572
Other Shrublands (17)	9 596	127 996	4 060	91 156	688	150 100
Heathlands (18)	0	6 372	112	6 124	664	2 372
Tussock Grasslands (19)	289 536	213 580	370 668	373 660	25 7544	499 264
Hummock Grasslands (20)	108 100	1 091 500	113 380	851 784	50 744	878 180
Other Grasslands (21)	16 524	32 780	84 936	38 936	208 648	79 356
Chenopod Shrublands (22)	4 100	410 172	2 956	732 220	6 560	1 050 848
Mangroves (23)	4 184	1 464	7 768	3 868	11 564	5 848

We can use the results from the GDM modelling to determine if any plant communities are likely to disappear from the savannas under climate change. This is achieved by comparing the minimum dissimilarity in a 50 km search area around any point in the landscape with a sample across the entire continent under climate change. Figure 9 presents this minimum dissimilarity for the medium and high emissions scenarios in 2070. These figures show that for plants, the environments over much of the western tropical savanna biome will not be found elsewhere under the 2070 medium emissions scenario. The effect is more severe for the 2070 high emissions scenario. The average environmental stress of greater than 0.5 in Figure 9 (pink to purple) indicates that there has been a class change and this environment has disappeared.

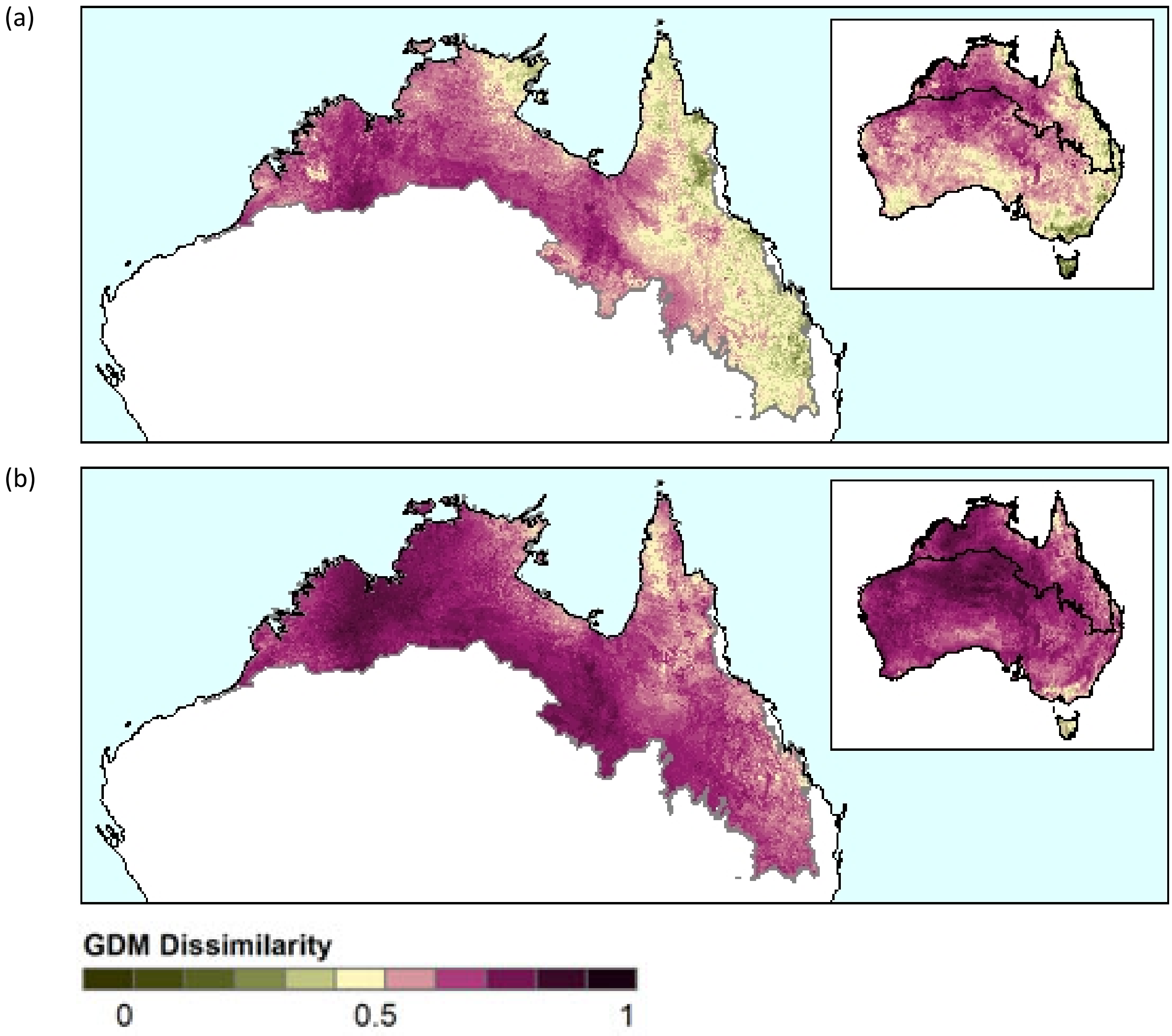

Figure 9 The lowest value of compositional dissimilarity for plants, for each present cell compared with all cells within a 50 km radius *and* a sample (1 in 1000) of the rest of the continent for the 2070 (a) medium and (b) high emissions scenarios where high dissimilarity (dark purple) indicates that the current environment is likely to disappear.

4.6.2 ARE THERE ANY NOVEL ENVIRONMENT TYPES? WHERE?

The previous results showed how the present compared with the future. Figure 10 shows how the future compares with the present to indicate where novel environments will occur. The results show that many of the savanna environments may be lost under climate change and that what replaces these areas is something different compositionally to those described today. This is because these areas are already some of the hottest and most seasonal in the continent and so any further increase in temperatures and changes to seasonality represented in the climate projections produces an environment not currently seen in Australia. This explains why many of the biota show stress in this environment. It must be remembered that as this is a novel environment, many of the relationships between biodiversity and this habitat are currently unknown and it could be that the present complement of species may persist and cope with this change. As Figure 10 shows there are few areas in Australia, other than the mountainous eastern coastline, that are not new and novel in 2070 under the high emissions scenario, suggesting a major change in how current flora and fauna cope with the novel environments.

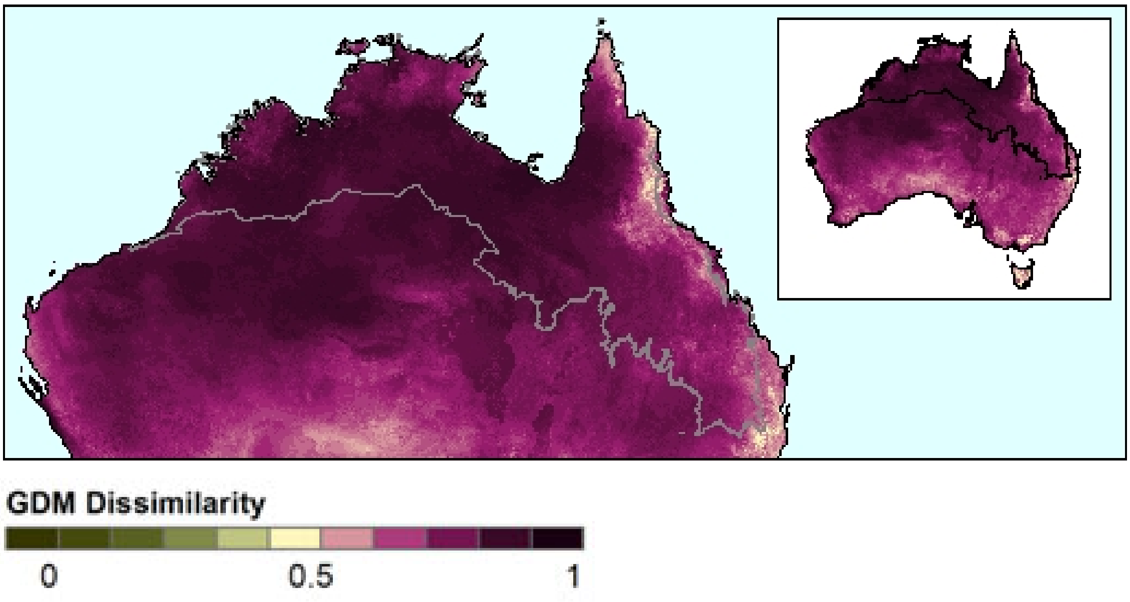

Figure 10 The lowest value of plant compositional dissimilarity for each cell in the 2070 high emissions scenario compared with all present cells within a 50 km radius and a sample (1 in 1000) of the rest of the continent. High dissimilarity (dark purple) indicates that the future environment is not currently represented on the continent (i.e. novel environments)

4.6.3 HOW MUCH BUFFERING IS PROVIDED BY LOCAL-SCALE LANDSCAPE HETEROGENEITY?

We use the GDM model to investigate change in effective habitat area (EHA), which is the sum of the similarities of all cells within a given radius relative to the present state of the central cell. Since each cell is 1 km^2 and the similarity goes from 0 to 1, this is essentially an area in km^2. The measure of change in EHA is the future EHA divided by the present EHA, effectively normalising the effects of different radii. Figure 11 answers the question ‘To what extent will different buffer areas of the landscape around a given point change in their environmental capacity to support similar species compositions in the future?’ Low values of <0.5 (dark brown) indicate increased stress within the area, neutral values of approximately 1 (pale) show little change within the radius, while high values of >1 (dark greens) predict an increase in total suitable environmental conditions within the area.

Of course dispersal is a limitation; if the full radius cannot be reached, the statistic has reduced relevance. For this analysis, we consider the two extremes of radii modelled, 1.5 km and 100 km, to represent the biota with very limited dispersal ability and those plant species utilising much larger areas of the tropical savannas.

Regardless of the scale used or the climate change scenario simulated, the proportional environmental change is high for the whole biome (Figure 11). The coarser scale did show less stress (Figure 11), but this means the community must be widespread or able to move large distances (up to 100 km). Even if these distances can be achieved, the modeling still shows there will be stress in the 2070 medium emissions scenario. When we model the 2070 high emissions scenario we find further increases in stress (Figure 11) and less effective buffering to climate change by increasing the area considered. This analysis suggests that there is limited localised buffering offered in the savannas, with buffering provided at broader (100 km) scales. This may be describing the relative abundance of refuges in the savannas surrounding them.

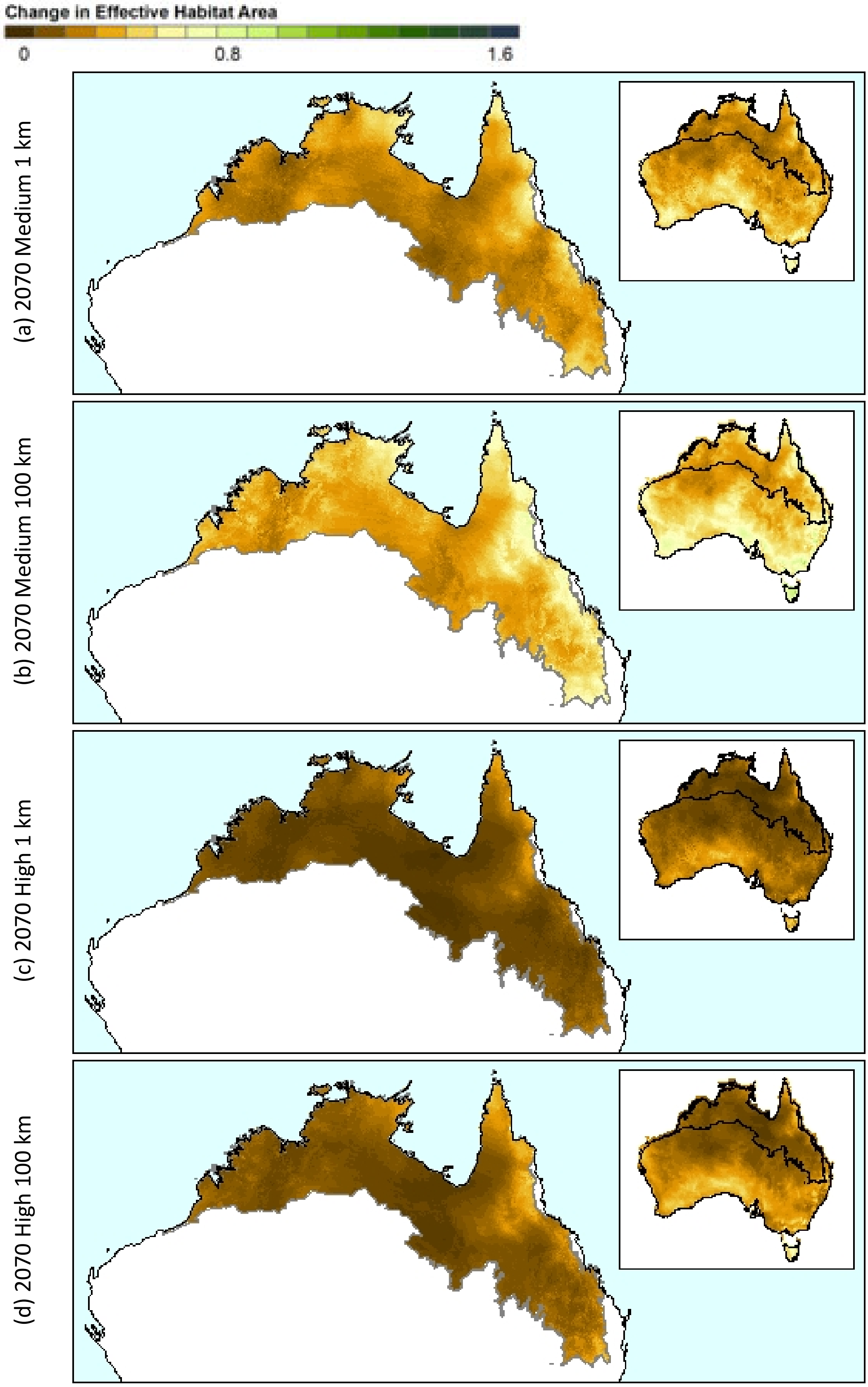

Figure 11 The proportional change in effective habitat area within a surrounding radius of 1.5 km and 100 km, where effective habitat area is the summed area of all cells within this radius, with each cell weighted according to the predicted similarity ($1-d_{ij}$) between the composition of this cell (current versus future) and the current composition of the focal cell. Dark browns indicate increased stress within habitat; dark greens (>1) indicate increase in total suitable environment in the area

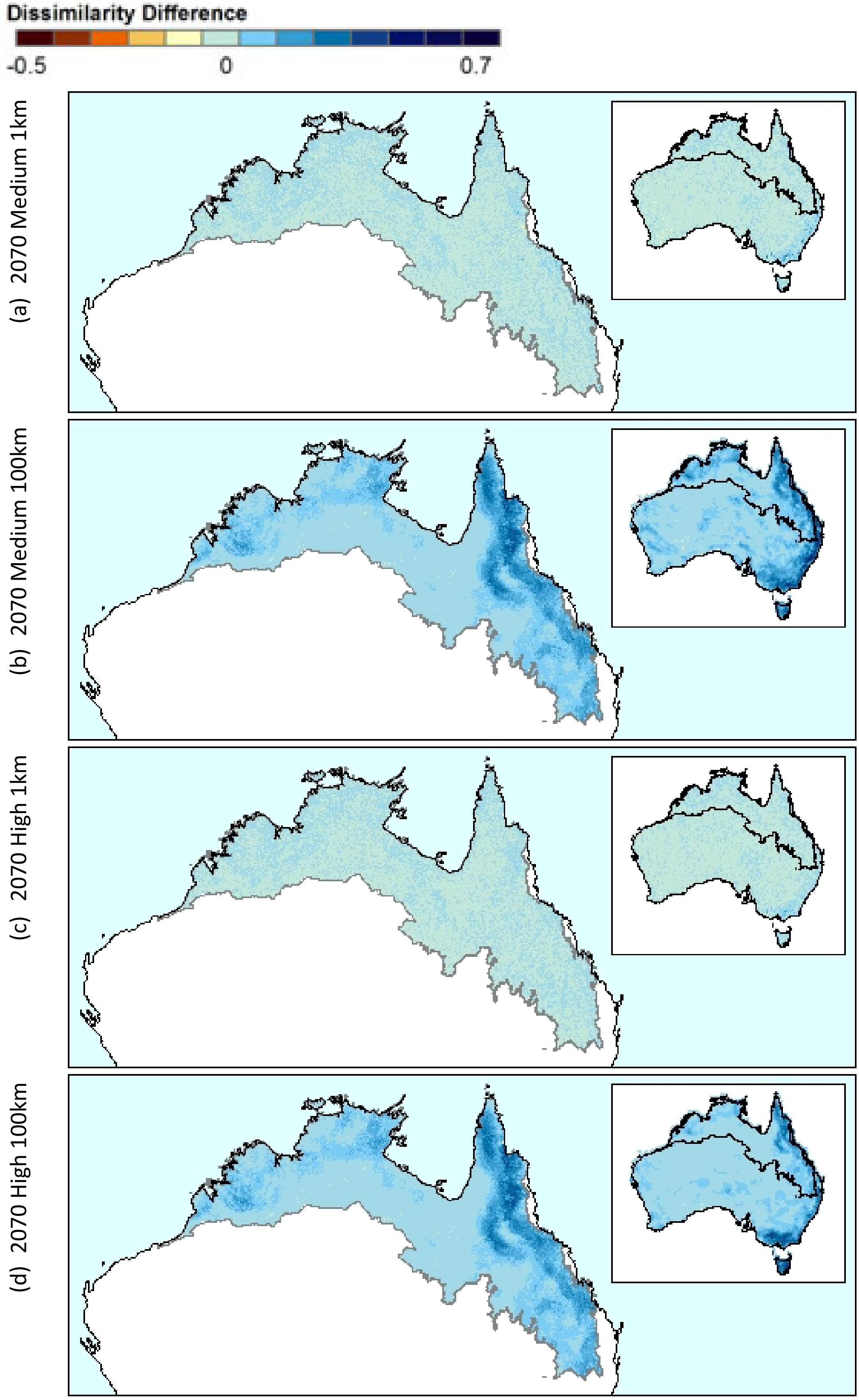

Figure 12 Difference in dissimilarity between that of the central cell and the minimum dissimilarity within (a,c) 1.5 km and (b,d) 100 km radius for the 2070 (a,b) medium and (c,d) high emissions scenarios. Dark blues indicate good buffering (more similar environments within the radius than in the central cell)

We next consider the question 'To what extent will there be less stressful habitat at other points within the radius in the future than in the central cell?' We use the difference in dissimilarity between that of the central cell and the minimum dissimilarity which can be found within the radius (1.5 km and 100 km). This is a measure of whether suitable environments can be found nearby in future.

In Figure 12 low values around 0 (pale blue) mean the buffer zone offers no advantage, while high values (dark blues) equate to good buffering and suggest that there is more similar landscape to be found within the radius than at the source. There is also another rare state where very low values (browns) are where the future value inside the cell is more similar than that found anywhere else in the radius.

Both the 1.5 km radius results for 2070 medium (Figure 12a) and high (Figure 12c) emissions scenarios show low values, suggesting poor effective buffering from climate change at the local scale. However, at broader scales (100 km radius), buffering via landscape heterogeneity is effective for pockets of the biome, particularly for areas of Cape York, and to a lesser degree areas around Gove, NT; Broome, WA; and southern Queensland.

4.7 Savanna biodiversity hot spot case studies

To understand the implications of projected climate change at finer resolutions within the biome, we will consider two nationally recognised biodiversity hot spots: North Kimberley (Western Australia), and Einasleigh and Desert Uplands (Queensland). Once again, we will concentrate on the vascular plant GDM modelling. We can assume that most other biota will respond in a similar way to the plants as they often have vegetation alliances. Similar conclusions for the other biota can be made from investigating other figures provided in this report (Appendices D–I).

These two areas are representative of parts of the savannas offering topography and ruggedness, which in turn provides refuges considered critical for many of the habitat-specific and often endemic biota. This is the primary reason these areas have maintained high biodiversity value. We will consider the predicted change on these two locations and the ability of critical savanna refuge habitats to cope with climate change. We recognise that many refuges used by habitat-specific species in the savannas are small and will not be accounted for by the GDM modelling, which was undertaken using a 1 km^2 grid cell and does not consider fire refuges or the ability of biota to avoid cattle. Nevertheless, we are seeking to understand broad patterns of environmental change.

4.7.1 NORTH KIMBERLEY (WESTERN AUSTRALIA)

This region provides a number of rare features, including springs, swamps and associated rainforests, providing refuge for invertebrates from the surrounding fire and grazing disturbances. The area also supports the endangered Gouldian Finch and threatened mammals such as the Golden bandicoot, scaly-tailed possum and rock wallaby (SEWPaC 2009).

Environmental stress is predicted to be moderate in 2030 under the high emission scenario (Figure 13), which is in the mid range compared with all levels expected for the savannas (Appendix D). The North Kimberley region does have a lower expected stress than other surrounding areas, but we are still expecting a 50% change in composition in 20 years. By 2070 under the high emission scenario, the North Kimberley is under very high stress at local and great scales, implying that the plant biota will experience different environments to today.

The heterogeneity of this region becomes apparent when we consider the ability of the landscape to buffer climate change. Figure 14 shows that there are a number of areas throughout the region offering good buffering ability (dark blue) for the 2030 high emissions scenario based on a 25 km radius. The buffering offered under the 2070 high emissions scenario is somewhat less effective, but still present along rivers such as the Prince Regent River.

The dramatic difference between 2030 and 2070 high emissions scenario predictions (Figure 13) suggests this region may experience dramatic change by 2070. The 2030 high scenario shows that there is some scope to prepare for the big changes. The 2030 scenario may also reflect the current status of this region and show that it is under less stress than surrounding areas; however, the 2070 predictions suggest that we cannot rely on the North Kimberley remaining a region of lower stress.

The ability of part of the North Kimberley to provide refuge to the biota is important. The 2070 moderate GDM model results show that even within 20 years this area does offer the buffering or refuges necessary for the biota; however, the decreasing trend to the high emissions scenario would suggest that this buffering ability may not be ensured into the future. We would expect that regardless of the dramatic changes predicted in Figure 13, the refuge areas will continue to provide some protection and different environments to the surrounding savanna, but the requirements of today's biota may not be maintained even in these critical environments.

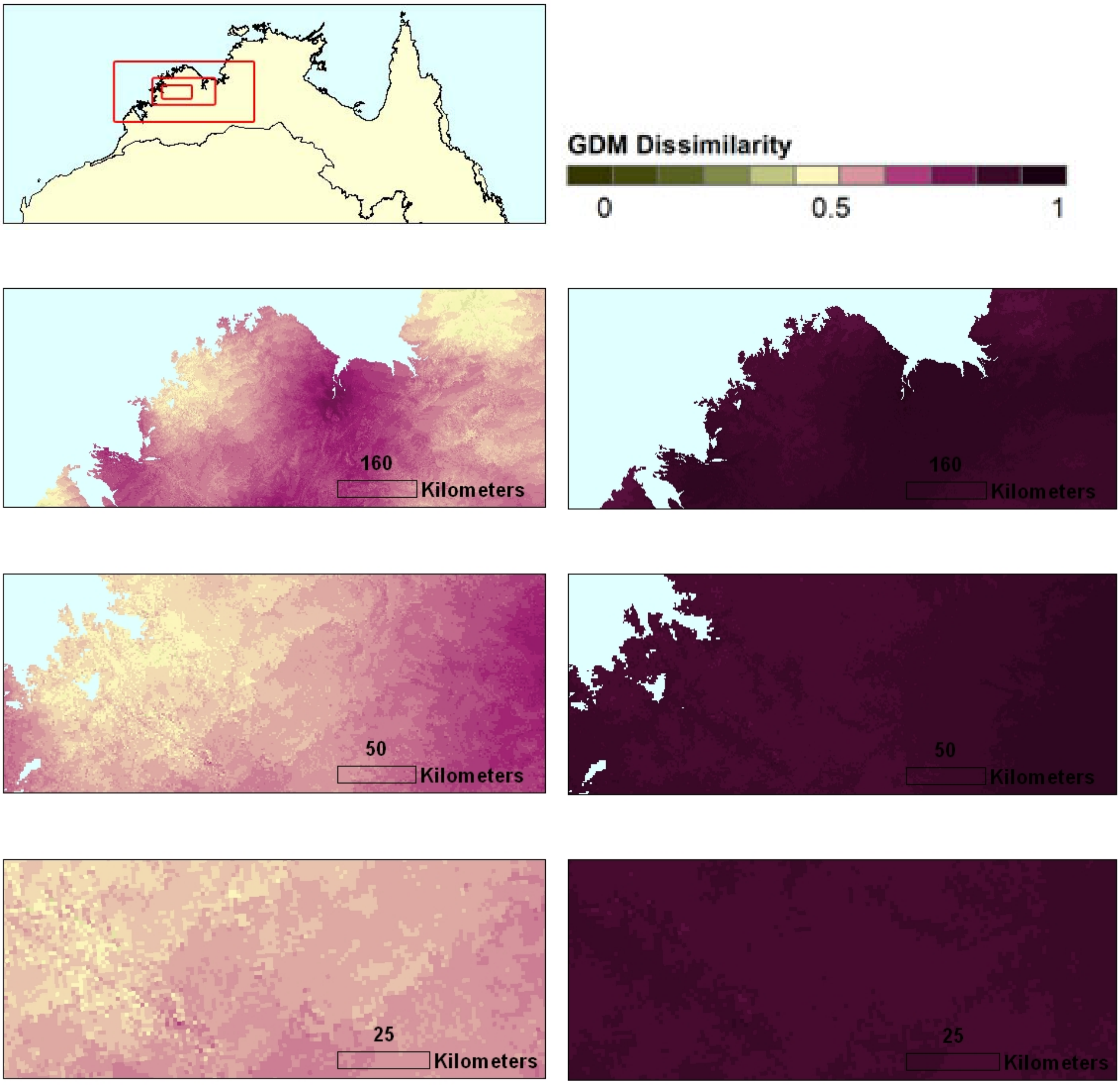

Figure 13 The environmental stress predicted for vascular plants from the GDM dissimilarity for the North Kimberley (WA) biodiversity hotspot, showing a range of spatial scales using the 2030 (left column) and 2070 (right column) high emission scenarios

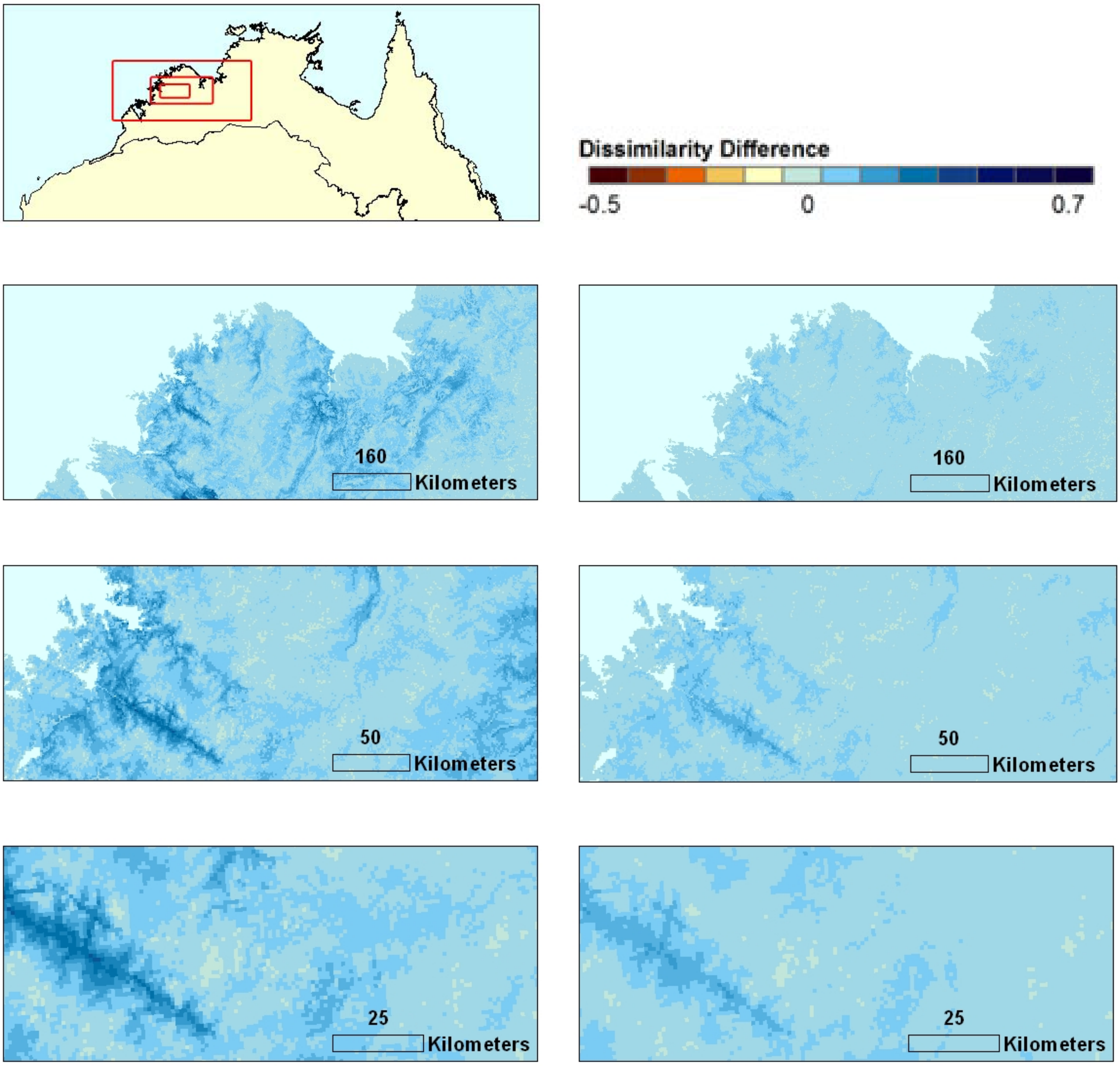

Figure 14 The ability of the landscape to buffer environmental change predicted for vascular plants from the GDM for the North Kimberley (WA) biodiversity hotspot, showing a range of spatial scales using the 2070 medium (left column) and high (right column) emission scenarios

4.7.2 EINASLEIGH AND DESERT UPLANDS (QUEENSLAND)

This region is a combination of the high plateaus of the Einasleigh and plains and low ranges of the Desert Uplands. There are 22 rare or threatened species in the Desert Uplands alone, with the biota utilising the lava flows and tubes of the Einasleigh and aquifers, spring complexes, lakes and wetlands (SEWPaC 2009).

This region offers lower stress for plants than the Northern Kimberley region 2030, with parts of the region predicted to have only 30% change in environments as measured by turnover of species composition (Figure 15). However, by 2070 under the high emissions scenario, this region is highly stressed, like the savanna biome in general.

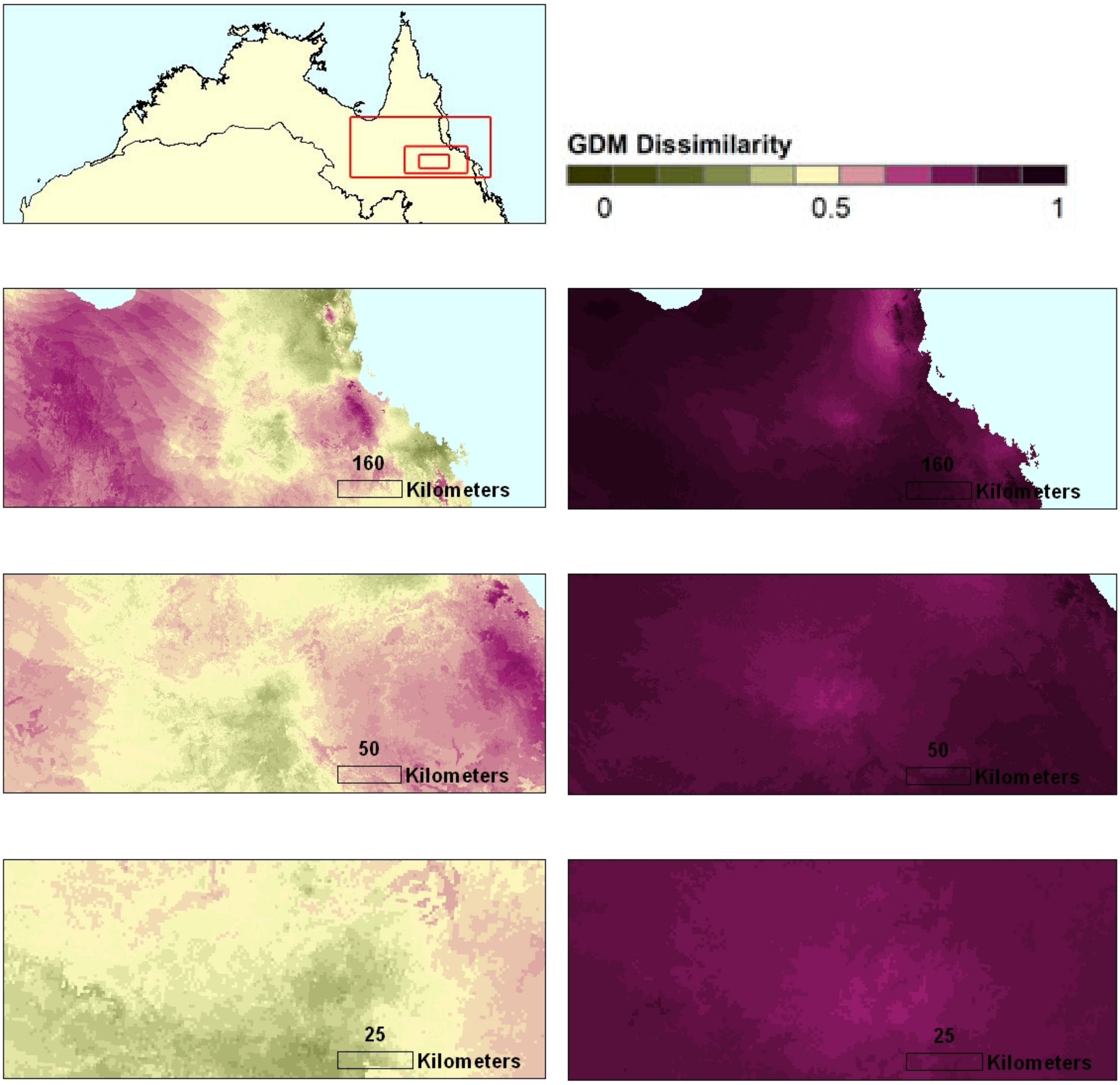

Figure 15 The environmental stress predicted for vascular plants from the GDM dissimilarity for the Einasleigh and Desert Uplands (Queensland) biodiversity hotspot, showing a range of spatial scales using the 2030 (left column) and 2070 (right column) high emission scenarios

Figure 16 shows that there is a buffering ability offered by this landscape, much like the North Kimberley, that is decreasing by 2070, suggesting that the ability of refuges in this region to protect the current flora may not continue into the future. The fine-scale analysis of this region shows a more broadscale buffering rather than the dendritic buffering which is seen along rivers of the North Kimberley.

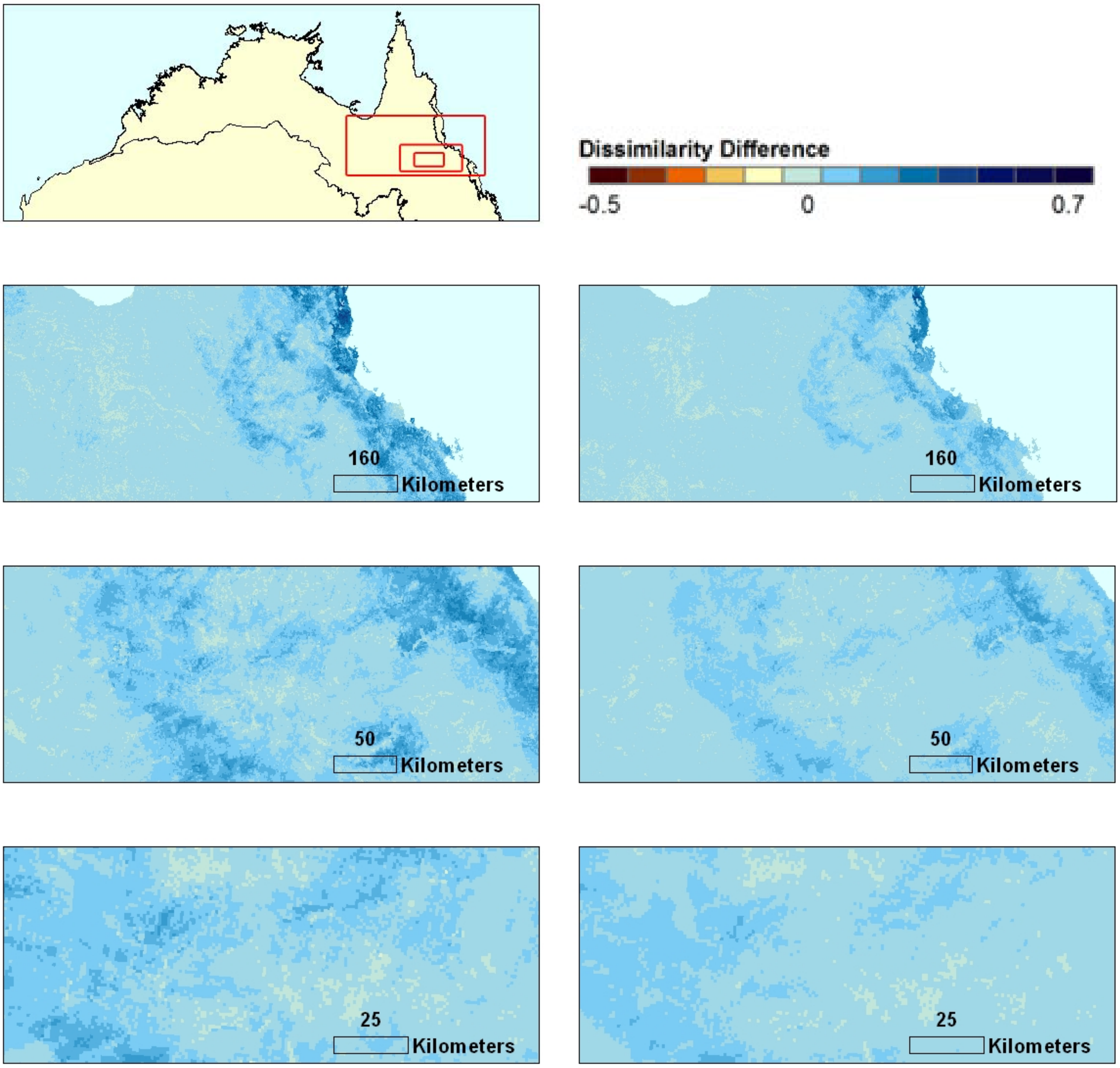

Figure 16 The ability of the landscape to buffer environmental change predicted for vascular plants from the GDM for the Einasleigh and Desert Uplands (Queensland) biodiversity hotspot, showing a range of spatial scales using the 2070 medium (left column) and high (right column) emission scenarios

5 Other factors influencing environmental change

While the models presented in this report provide a broad understanding of the influence of a wide range of environmental factors on the savanna biome, there are a number of other factors that the expert workshop considered critical to the future of the savannas that are not included in the modelling.

5.1 Fire

To understand the response of savanna systems to climate change we also need to determine the natural system to measure against. This relates particularly to fire management. For example, there has been an invasion of sorghum into Kakadu National Park as a result of changing fire regimes from traditional patchwork burning to big landscape fires. There are also interactions between grazing and fire. This leads us to the question: what do we want to preserve and manage for? The answer to this question will also influence adaptation to climate change.

The savanna biome is presented as a case study of the effect of climate change on fire and Australia's NRS (Williams et al. 2009). The savanna biome is one of the most flammable biomes in the world. For this reason it is unlikely that fire frequency will increase in many areas from the current annual/biennial frequency. However, changes in temperature, rainfall and CO_2 levels may influence fire management in the savannas. A reduction in the number of days where prescribed burning is possible as a result of increased temperatures (and extreme fire weather days) may limit prescribed burning and result in late dry-season, uncontrolled fires. In the southern areas of the savannas, changes in rainfall may reduce fuel loads and fuel accumulation, resulting in an increase in the interval between fires. Changes to rainfall, fuel loads and an increase in fire weather may result in fire suppression being difficult in Queensland and an increase in large fires.

5.2 Weeds and feral animals

Feral animals and weeds are a current threat to savanna biodiversity and will continue to place the same or more pressure on ecosystems under climate change. There is a pressing need to show the environmental impact of feral animals and weeds to decision makers even before new environmental changes occur. It is very important that some of these threats are managed as they may exceed the impacts of future climate change.

The buffel grass modelling example presented in an accompanying report, Martin et al. (2012), did not show suitable habitat in the savanna biome, but its suitability is predicted to increase, except in the south-east (Queensland) areas of the biome. However, this is only one species out of a suite of currently known and sleeper weed species (e.g. gamba grass) that may increase under the novel environments in the savannas resulting from climate change.

5.3 Intensification

Development and intensification in northern Australia are other current pressures placed on savanna environments. Land clearing and extraction of water resources will potentially magnify the effects of climate change on hydrological cycles and alter the ability of the biota to cope with this change.

5.4 Extreme weather (heat days, cyclones)

While ecosystems may cope with gradual change, the biggest risks to biodiversity are extreme weather situations that can cause rapid, dramatic change. To understand this threat we need to consider the extreme events proposed for the savannas under climate change and explore the resilience and adaptive capacity of the system.

Cyclone, drought and fire are three disturbances capable of causing rapid changes to the savannas. While these are natural events, climate change may change the frequency and severity of these disturbances, causing changes to the ecosystem. Cyclones are expected to get more intense under climate change, which may result in greater mortality and general forest change when they do occur. As previously discussed, Queensland savannas already experience droughts from El Niño events, but the strength of these events could increase, and changes to dry-season length in the monsoonal savannas could also result in tree death and resulting tree population declines. Fire is currently frequent and of relatively low intensity in the savannas. Increasing fire weather, reduced ability to undertake safe control burns and the spread of exotic weeds with large fuel loads could result in fire intensities and extents larger than currently experienced. These extensive fires reduce the patchiness of habitats in the landscape. These three disturbances introduce the idea of changes we should be concerned about but may not be able to manage for.

5.5 Increased CO_2 concentration

Increasing atmospheric CO_2 concentrations are known to affect a range of plant production processes, including photosynthesis, water use efficiency, the mix of C_3 and C_4 species, nutritional value, toxicity, water relations, seed viability and the spread of woody species. The expression of these impacts is complex and varies with water availability, nutrient availability, between ecological communities and between species and still needs more study. However, it is clear that the physiological impacts of elevated CO_2 concentrations could significantly add to the range of species and ecosystem process level changes in the savanna ecoregion driven by changes in climate. For example, altered CO_2 concentrations could possibly affect grass species mix and grass-tree competition leading to impacts on fire regimes, which would further affect species compositions.

5.6 Other factors not currently predicted

The wet–dry nature of northern Australia and the predicted changes in rainfall amount and distribution suggest that access to water may be a critical factor defining ecosystems under climate change. This was reflected in the importance of the moisture variables in the modelling in this report. Smaller areas within MVGs such as riparian strips often have diverse fauna, though not necessarily diverse flora, and need to be considered in management plans. Three areas of importance with respect to water are coastal inundation, seasonal water supplies and water temperatures. Low-lying coastal freshwater areas are susceptible to sea level rise and salt water inundation. Salt water intrusion will kill trees such as Melaleuca, resulting in a complete ecosystem change. These areas then are either converted to mangroves if the natural barriers/barrages are broken by people, boats, storms or pigs and buffalo, or remain as freshwater systems with dead trees, resulting in a loss of species, but not complete change. Availability of free-standing water at the end of the dry season and springs to provide river flows are critical. These areas are important to protect and also heavily used by feral species such as pigs and cattle. We need to understand how changes in rainfall will affect these important water sources, particularly at the end of the dry season when water supplies are very important. Finally, water temperature may be important, particularly if oxygen thresholds are exceeded more regularly, resulting in freshwater fish kills in billabongs and rivers.

6 Management implications

This section provides a summary of the management implications of the findings of this study specific to the savanna biome and is based on discussions from the expert workshop. For a full report of NRS management under climate change, refer to the accompanying report *The Implications of Climate Change for Biodiversity Conservation and the National Reserve System: Final Synthesis* (Dunlop et al. 2012).

Things are going to change in the savannas, and so managing for a healthy ecosystem while protecting biodiversity means maintaining a system that can cope with this change. People currently have the ability to manage and interact with the savannas through grazing and fire management and by preventing the spread of weeds and feral animals. The level of fire management has been previously discussed but there is still information required to inform appropriate levels of grazing.

Management in the savannas is also based on much smaller human populations to support than in southern systems, and the savanna biome also contains significant areas of Indigenous lands managed by traditional owners. It is important to discuss both the requirements of the natural system with the aspirations of the Indigenous land holders. While you can manage the parks for purely ecological outcomes, when the broader landscape and off-park areas need to be managed there is a great deal of management difference (co-management). Even park management for ecological outcomes will be overlaid with a social and economic layer. We need to ensure that the environmental values are realised and not merely economic costs considered.

The discussions at the expert workshop covered a broader context than simply current NRS, as participants soon realised the current systems and species will have to move with climate change. The climatic gradients covering the tropical savannas mean movements may involve large distances in a relatively short amount of time. Any future management will have to include off-park management in the plan. We therefore need to consider the role of the NRS in the whole landscape; for example, should it focus on key locations in the landscape (e.g. refuges, isolates), enabling key processes (hydrological flows, species migration), or providing nodes of different environment / habitat type scattered through the biome? We need to ask whether we will be able to protect rare habitats, such as vine forests, given the predicted shifts in suitable habitats shown by the modelling in this project.

There are also a number of other threatening processes, such as changes to groundwater through water use, pest animals and spread of weeds. In discussing the potential impacts of climate change we need to ensure that the current threatening processes are not forgotten in management decisions. Indeed, it is critical to focus on threats and ask how climate change may alter their impacts and management at landscape scales.

From a fire perspective, it seems important to introduce more heterogeneity of time since fire in the landscape and to reduce big fires (intense fires, late in the dry season, burning large areas). We currently know something about fire interval, but now need to know about the fine-scale responses of flora and fauna to fire. There are now fire monitoring options and the ability to measure from remote sensing, but we need to understand some of the population processes. Fire modelling in the savannas (Liedloff and Cook 2007) shows that there can be a lag of up to 50 years before changes in the age structure are seen for a given fire regime (e.g. regular, early dry season fires). This is driven by processes such as recruitment and mortality of young trees in the flame zone, resulting in a decline in trees even at a fire interval of one in three years. This raised an interesting discussion on the importance of demographic processes, especially with trees, in understanding ecosystem change.

Considering scale in management actions is very important. There is now a need to manage for whole system and landscape change. This is particularly important when we consider the gradients in the savannas and how changes may result in large movements of species and ecosystems. Biodiversity in individual reserves will likely change with climate change, and so off-reserve protection, including

Indigenous lands and the NRS as a whole, needs to be considered. We also need to consider what land is available, how big reserves need to be in the savannas to protect the habitat diversity of an area, and the orientation of parks to include ecological and climatic gradients for the movement of organisms and coverage of the spread of current habitats. The Northern Territory Government currently plans to provide reserves to link the NT coast to Alice Springs and the NT southern border. This series of reserves effectively covers the range of habitats along the north–south rainfall gradient. Likewise, protection of east–west flowing rivers may need to be considered differently to north–south flowing rivers.

7 Conclusions

This study used a combination of an expert knowledge workshop and modelling to explore the likely impacts of future climate change on the savanna biome of northern Australia. The expert workshop was used to gather expert advice on the likely impact of climate change on individual species and habitats, while two modelling approaches determined a measure of environmental stress using species–environment relationships as a basis of climate change scenario modelling.

It may be argued that the savanna biome is likely to be resilient to climate change, given how long it has maintained a stable state and its long evolution associated with generally infertile soils, regular fire and a regular monsoonal wet and dry season. The savannas are also relatively intact, and not influenced by the problems of fragmentation experienced by southern biomes. Unlike the mountainous eastern seaboard already experiencing change along elevation gradients, the savannas are relatively flat, covered by large areas of intact savanna woodland and adapted to high temperatures, and so could be expected to cope with a changing climate. This study challenges this perception. The expert workshop stressed the importance of thermal tolerances in the savanna biota and how increases in extreme heat days may witness a critical tipping point for some species. Shallow climate gradients mean that any change in climate will require movements over large distances to find similar environments. The IPCC (2007) climate projections and the modelling also highlight the magnitude of change that may arise from climate change in the savannas. This change is dramatic, and possibly worse than many other biomes in Australia.

The major findings of this report are now summarised below:

- **Climate:** The projected changes in climate will result in new or novel environments in the savannas. While the same species may remain, they will have to cope with temperatures not currently experienced and the savannas will not look and feel as they do today for the plants and animals. More research is required into the thermal tolerances of the savanna biota. Current projections are not able to comment on changes in rainfall distribution and the onset of wet and dry seasons. Any change to rainfall patterns will be critical to the savannas, where most organisms must cope with very limited surface and soil water at the end of the dry season.

- **Gradients:** The savannas experience temperature, rainfall and intensification gradients across large distances. These shallow gradients mean that any change in temperature and rainfall will result in similar environments rapidly shifting across large distances. More research is required on the ability of the biota to shift or cope with this change. The generalist species currently occupying large distributions may not be affected by this change, but specialist species restricted to niche environments may be greatly affected.

- **Refuges:** A range of special habitats exist within the savannas that provide refuge from fire, grazing, lack of water and high temperatures to unique and endemic flora and fauna. These habitats – such as rainforests, monsoon vine forests, wetlands, springs, gorges, rocky escarpments and riparian zones – are critical for the survival of the savanna biota and current conservation. Many of the savannas' unique biodiversity and areas with the highest conservation status are associated with these refuges. While these refuges will also offer some protection from the harsh conditions of the surrounding savanna, this study questions their ability to continue to protect the current suite of species against the magnitude of future climate change. Further research is required to monitor and understand the ability of these critical habitats to persist under the climate changes predicted.

- **Cyclones, storms and extreme heat:** Extreme events have the ability to rapidly modify the savannas, leading to very different systems if suitable conditions for recovery are not available. Storms and cyclones are predicted to increase in intensity, and extreme heat days, which can result in rapid changes to populations, are expected to increase in frequency with climate change. Climate change may also alter the ability of species and ecosystems to recover from extreme events by influencing fire regimes and weed species.

- **Other disturbances:** The savannas are not currently immune to disturbance. The expert workshop stressed the critical importance of managing many contemporary disturbances, such as fire management, weed invasions, grazing and feral predators. Climate change was considered simply another stress on top of the current stresses that the biota must cope with. It is thought that some of the current problems may be worse than the predicted effects of climate change as they can transform current ecosystems.

- **Management:** The tropical savannas have a history of limited research and data from which to predict future changes and inform management decisions, compared with other biomes. While further research will increase our understanding and ability to predict change in the savannas, it is likely that many ecological impacts of climate change will only be known after they have been observed. For example, we do not know how susceptible many species are to extreme heat as thermal limits have not been documented. The modelling outcomes of this study highlight the dramatic nature of potential ecological change in the savannas in response to expected climate change. These predictions significantly challenge any assumptions that environmental change will not be ecologically significant as the region will remain “hot and seasonally wet”. The moderate 2030 projections indicate there may be some decades to adapt management in this ecoregion. However, the 2070 high-emissions analyses suggested the potential for very significant ecological change; a precautionary approach would be to start planning those levels of ecological change, for example identifying the critical parts of the savannas that currently support some of the unique biodiversity, and also looking for the emergence of novel environments and communities.

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Appendix A Expert workshop discussion summary

A summary of discussion at the expert workshop for the savanna biome held at CSIRO Tropical Ecosystems Research Centre, Darwin, Thursday 23 April 2010 – Friday 24 April 2010.

Savanna biome workshop notes

These workshop notes provide a record of the general discussion and presentations given at the savanna biome workshop for the NRS2 project. They have been compiled into general themes and so do not reflect the actual flow of the agenda. Comments made by specific participants are highlighted with their initials.

Attendees

NAME	ORGANISATION (NAME AT TIME OF WORKSHOP)
Dr Adam Liedloff (Organiser)	CSIRO Sustainable Ecosystems, Darwin
Dr Michael Dunlop (Facilitator)	CSIRO Sustainable Ecosystems, Canberra
Dr Dick Williams	CSIRO Sustainable Ecosystems, Darwin
Dr David Hilbert (Project leader)	CSIRO Sustainable Ecosystems, Atherton
Dr Stuart Blanch	NT Environment Centre, Darwin
Dr Melanie Bradley	NT Environment Centre, Darwin
Mr Tim Bond	Department of the Environment, Water, Heritage and the Arts, Canberra
Dr Tracy Dawes	CSIRO Sustainable Ecosystems, Darwin
Dr Simon Ferrier	CSIRO Entomology, Canberra
Ms Liz Dovey	Department of Climate Change, Canberra
Dr Alex Kutt	CSIRO Sustainable Ecosystems, Townsville
Dr Ian Radford	Western Australia Government, Kununurra
Dr Stephen Williams	James Cook University, Townsville
Mr Steve Winderlich	Parks Australia, Kakadu, NT

Further input may be obtained from the following people unable to attend the workshop:

- Dr John Woinarski (NT Govt Biodiversity Unit, Darwin)
- Dr Alaric Fisher (NT Govt Biodiversity Unit, Darwin)
- Dr Mike Lawes (CDU, Darwin)
- Dr Stephen Garnett (CDU, Darwin)
- Dr Gay Crowley (NT NRETAS, Darwin)
- Dr Chris Chilcott (WA Government, Perth)
- Dr Michael Douglas (CDU, TRaCK, Darwin)
- Colin Yates (WA)
- Gordon Guymer (Qld)

NRS2 and this workshop

The first NRS (National Reserve System) report on the effects of climate change (Dunlop & Brown 2008) concluded that targeting habitat diversity at multiple scales was a very robust way of setting priorities for protecting habitat under climate change; and they suggested to enable that, the bioregional framework could be extended for guiding habitat protection both inside and outside the NRS. This second report aims to look at the implications and impacts of climate change at various resolutions in greater detail.

What was the rationale behind the selection of the four biomes? The four biomes selected for this report were selected on a number of bases. Each biome needed to be relevant to a number of states, not a single jurisdiction. Grass and forest systems were identified in the first stage of the project as possibly being exposed to a relatively high number of ecological impacts under climate change. The arid lands and savannas were also considered particularly important nationally. The Australian savannas were included as they are globally important, being the largest of this biome, relatively pristine and contain large IPAs (Indigenous Protected Areas). Both stages (NRS1 and NRS2) place the NRS in a landscape context, with the biome workshop findings feeding into the modelling stages of this project.

For each biome there will be:

- A review
- A workshop
- Other input from relevant people
- A draft report internally distributed for checking
- Modelling work will feed in
- Comparison of four biomes in final report on management implication and information requirements.

Climate change research

Liz Dovey gave a presentation to the group on the Department of Climate Change and the range of research being undertaken in Australia.

The environment and biological change

The outcomes of environmental change (i.e. changes in rainfall and temperature, fire, storms, etc) affect individual organisms. For example, changes in temperature influence leaves and individual plants. These effects feed into the ecology of the organism through changes in reproduction, growth and survival. From this, impacts on whole populations are realised. As a large number of species are affected, whole ecosystems change, which in turn influences societal values. There are also a number of critical feedbacks where a change in one population may affect individuals of another species; ecosystem change can affect the environment and influence habitats, resulting in further changes of species present. These changes are all occurring as a result of climate change. What can society do? Three types of response: mitigate to reduce the rate of climate change, manage biodiversity to help it adapt, and alter our expectations of biodiversity and the values it provides. The first two will be difficult, so the third is critical; it also informs the second response.

We currently know a lot of information about one aspect of how distributions may change: species shifts with elevation or towards poles. We also know about how the timing of various events, such as flowering, may change. Other impacts, including changes in interactions, are certain to occur and may dominate biodiversity outcomes; however, they are typically much harder to detect, attribute to climate change once detected, and predict. Similarly we don’t understand how the drivers and feedbacks will change. We should not ignore these other changes in planning simply because they are difficult to observe.

There may be differences between plants and animals in the extent to which realised and potential niches differ. It was suggested that often animals are close to their fundamental niche while plants are a lot further from theirs. This may be due to the mobility of animals and the ability to move and adjust to the edges of spatially and temporally fluid niche boundaries. Some people suggest that plants less frequently fill their realised niches. Plant ecologists often tend to be less accepting of the idea that plant communities may change fundamentally with climate change; this is possibly due to the strong empirical associations between community types and geographic environment (although such patterns might actually suggest sensitivity to changing environment). In contrast the animal ecologists are more pessimistic – possibly due to dramatic changes in faunal populations including extinctions in the last 200 years – and accept change is occurring or will occur.

It is agreed that species will respond to climate change individually, distributions will change and abundance will change, but the full range of such changes is very hard to predict. Three mental models were provided to answer the question: If I came back in 50 years, what would I see in my favourite ecosystem?

- Change in relative abundance in situ (1)
- A few rapid or long-distance range expansions, with a few species having big impact on others (2)
- Gradual distribution changes of most species / whole community changes (3)

The models were proposed in NRS1, focusing at the national level. NRS2 will ask if other models are more appropriate in specific biomes.

We can start to explore these three mental models by looking at how systems have changed in the past in Australia and elsewhere in the world. An example of Model 1 is the spread of cane toads across northern Australia and the resulting changes in relative abundance of species as a result of direct mortality from consumption of toads to removal of food or predators. The spread of invasive, exotic grass is an example of Model 2 where the species range changes, often with human assistance, and the species present at the invasion are outcompeted or affected by new fire regimes as a result of the invasive grass presence. Examples of Model 3 include tropical–semi-arid environment boundaries and the rainforest–savanna boundaries around the world. Most of these processes are currently naturally occurring in the savannas with or without climate change.

An additional mental model to consider would be the complete loss of species, or complete change in an ecosystem. The models describe different change processes; if the magnitude of change is sufficient, any of them could lead to complete species loss or change in ecosystems.

How the savannas work

The savanna biome has a number of key drivers, some unique to this biome, that we needed to consider during this workshop. These drivers can be divided into the paleo and contemporary drivers: those long-term natural drivers that have moulded the savannas, such as the monsoonal season of wet and dry seasons; those modern drivers, relating to development and grazing; and those that cross these time scales, such as fire management. The savanna biome is, like much of regional Australia, remote and as with much of northern and central Australia, under Traditional ownership and management. This remoteness and lack of development may provide benefits to biodiversity adapting to a changing climate. There are also a number of other threatening processes such as changes to groundwater through water use, pest animals and spread of weeds. In discussing the potential impacts of climate change we need to ensure that the current threatening processes are not forgotten. Indeed, it is critical to focus on threats and ask how climate change may alter their impacts and management at landscape scales.

To understand how the savannas will respond to climate change, we need to understand what is changing. This workshop was designed to brainstorm what effect the projected changes in temperature and rainfall would have on the current system. It was also important to consider ‘sleeper threats’ or those changes we may not have currently thought about. Of course this is not a simple matter.

The questions that we needed to think about included:

- What is the influence of 1–2 °C rise in temperature on savanna biota? For example, does the effect whereby increasing temperature changes the sex ratio of developing turtle eggs on northern Queensland beaches apply to the entire tropical coastline?
- What is the influence of increased rainfall variability on savanna biota?
- Can we see evidence of current changes as a result of current increases in CO_2 concentrations in the savannas? i.e. woody thickening and exotic grass spread, range changes, altered fire regimes and species declines. Can we see examples in other tropical forested systems where savanna/forest interactions occur, such as the Amazon?

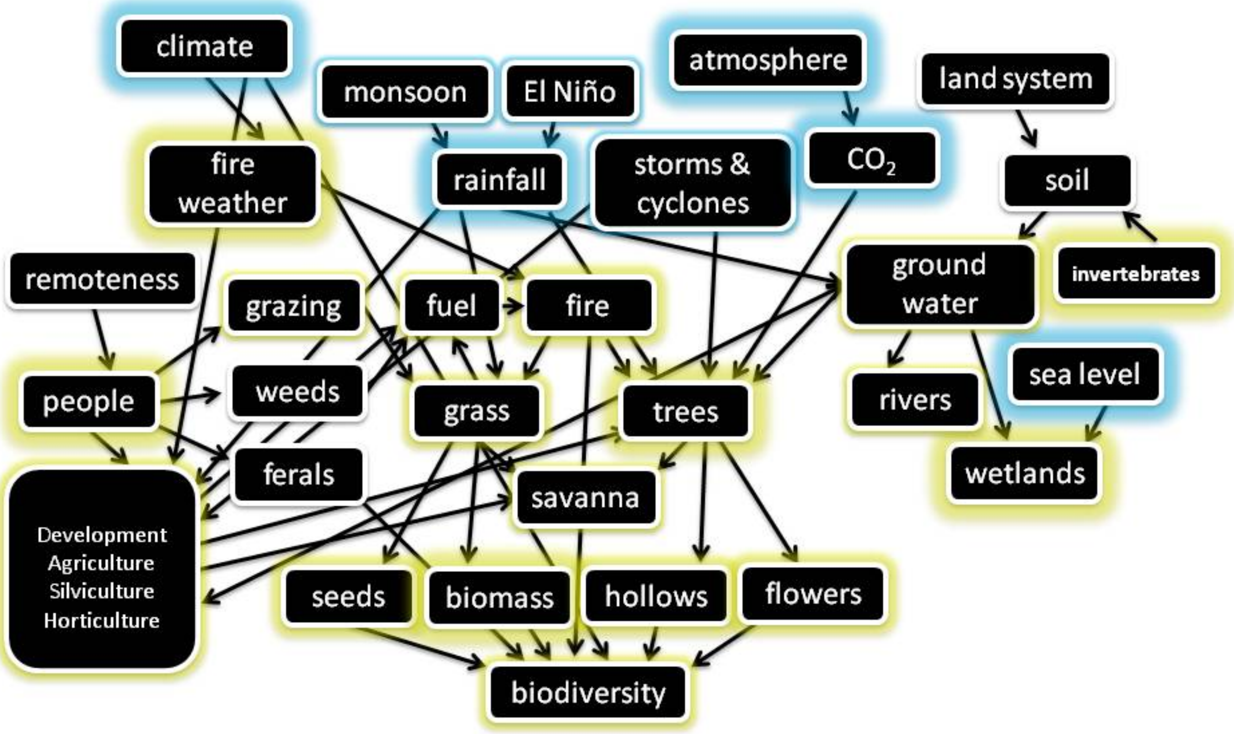

Figure A.1 A flow diagram of savanna processes, with blue highlighting the processes likely to change with climate change and green showing the processes affected by climate change. The expected strength of the change is shown by the thickness of the highlight

A conceptual diagram of savanna processes was provided for discussion (Figure A.1). It was noted that while this was a comprehensive savanna system model, it did have greater focus on trees and plants and needed a better faunal component.

Location and map

For this workshop, the savanna biome was defined using the extent previously defined by the Tropical Savanna Management CRC (see Figure 2 of review). This region covers the tropical savanna, escarpment, coastal floodplains, and black-soil grassland habitats across northern Australia. It does not include the wet tropical rainforest coastal belt of north Queensland. There was full agreement with this biome boundary, as most workshop participants had the mental map of the savannas being the northern environments, excluding the rainforest (but including monsoonal vine forests) and blending into the arid interior of the continent. However, we will also map the key vegetation groups in the biome (from NVIS), identifying IBRA regions dominated by and including these key vegetation groups.

The workshop then discussed the spatial variability of habitats in the savannas. As a function of the low topographic variability, broad climate gradients, similar soils, etc., there appears to be very little coarse heterogeneity across the savannas. For example, much of the Top End – including Kakadu – is very similar in vegetation. It isn't until Tennant Creek, some 900 km south of the coast that changes occur as a result of the loss of the quasi-monsoonal influence. These slow landscape changes also result in a remarkably shallow beta diversity change.

The savanna landscapes in Queensland have a different set of influences. Here inter-annual drought driven by El Niño events, rather than seasonal drought, drives vegetation structure, and there are major topographic features (mountain ranges) leading to significant climatic gradients. It was suggested that the shallow gradients of parts of the NT savanna are bland compared with the heterogeneity seen in Queensland. It is therefore important to consider processes, impacts and outcomes differently in these two savanna regions.

Fire in the Savannas

Dick Williams gave a presentation on the upcoming Department of Climate change report: Williams RJ, Bradstock RA, Cary GJ, Enright NJ, Gill AM, Liedloff AC, Lucas C, Whelan RJ, Andersen AN, Bowman DJMS, Clarke P, Cook GD, Hennessy K and York A (2009) *Interactions between climate change, fire regimes and biodiversity in Australia: A preliminary assessment*. Report to the Department of Climate Change and Department of the Environment, Water, Heritage and the Arts, Canberra.

There was discussion about the reasons for control burning in Kakadu National Park, which reflects the fire management of much of the savannas of NT and WA. Most fire management in the Top End of the NT is to reduce the risk of fires late in the dry season that are larger in both extent and severity. This fire management is therefore to reduce the risk to life and property.

To understand the response of savanna systems to climate change we also need to determine the natural system to measure against. This relates particularly to fire management. For example, there has been an invasion of sorghum into Kakadu National Park as a result of changing fire regimes from traditional patchwork burning to big landscape fires through history. There are also interactions between grazing and fire. This leads us to the question: what do we want to preserve and manage for? The answer to this question will also influence adaptation to climate change.

From a fire perspective, it seems important to introduce more heterogeneity of time since fire in the landscape and to reduce big fires. We currently know something about fire interval, but now need to know about the fine-scale responses of flora and fauna to fire. There are now monitoring options and the ability to measure from remote sensing, but we need to understand some of the population processes. The Flames model shows that there can be a lag of up to 50 years of a given fire regime (e.g. regular, early dry season fires) before changes in the age structure though lack of recruitment and mortality of young trees in the flame zone results in a decline in trees even at a fire interval of 1 in 3 years. We are currently at 20+ years mark in the Flames model, which suggests that change is about to happen. This raised an interesting discussion on the importance of demographic processes, especially with trees, in understanding ecosystem change.

What is changing/will change in the savannas?

A presentation was given by Adam Liedloff to introduce some of the changes expected in the savannas resulting from current disturbances and climate change. This presentation used the Flames model of savanna dynamics to explore some of the potential changes to tree populations which carry on to fauna through modified habitats and fire regimes. Following the presentation there were discussions on the overall big changes that may occur in the savannas and how resistant to climate change the savanna biome is. The controversial statement ‘The savannas are already hot and wet, what more can change?’ was the catalyst to further discussion. There is good evidence that in general, compositional turnover increases with temperature so warming may be a more significant driver in the tropics than temperate zones; also, species will be closer to fundamental physiological limits. Hence, it was agreed that increasing temperature is a cause for concern in the savannas, possibly even more than elsewhere.

One area of current uncertainty is the effects of increasing CO_2 concentrations on tree and grasses through a CO_2 fertilisation effect. These effects are currently difficult to predict as field and lab trials to date show different effects. One question to answer is will the trees (C_3) or grasses (C_4) ‘win’ in the savanna tree–grass balance under elevated CO_2? It is frequently predicted that C_3 plants would dominate C_4 plants through more efficient photosynthesis. However, there is some evidence that other impacts of elevated CO_2 may counter this, for example, reduced reproductive output and success in a C_3 grass leading to increased abundance of a C_4 grass has been observed in a FACE experiment (Hovenden et al. 2006). Similarly, another plant community FACE experiment has revealed that it is not straightforward to predict which species might show the greatest growth responses: for example, increased water use efficiency in dominant plants may lead to increased water availability and growth in other plants (Stokes et al. 2004). These are examples of different ecosystem process and population feedbacks that are hard to predict yet might determine outcomes, and need to be considered for a full system understanding of the effects of climate change.

Another area of discussion arising from Adam's presentation was what are the dominant drivers of change from climate change projections? It is clear that extreme events such as cyclones, extreme temperature days, droughts and floods are more important in producing change than average increases in temperature and rainfall. Locations with higher inter-annual variability often have decreased diversity. For example, the Karoo (Africa) and Nullarbor appear similar in bio-climate, etc., but have very different biome diversity. The long-term stability of inter-annual climate variability is a predictor of species diversity in the Wet Tropics, while intra-annual (within the year) variability is a predictor of species abundance. These relationships may be even more important in the savannas. In contrast, however, small changes in average parameters can also be important, for example, depth of seasonal drought (vs. extreme drought) and frequency of fire are expected to lead to long-term changes in vegetation.

There are reports of dramatic changes in the savanna biome. These include small mammal population declines, increases and decreases in vine/rainforest extent and pressure on obligate-seeder species through changing fire regimes. The declines in small mammals in the savanna biome have been shown though faunal surveys over 15 years, with declines to half original populations five years ago to populations barely present currently. There have been declines in possums on Cape York Peninsula (Qld) and complete loss of Phascogales around Jabiru (NT). The reasons are still unclear and could be climate change, feral animals, diseases or fire regimes. This pattern isn't necessarily universal across the savannas. For example, data show that once cattle were removed from areas of the Kimberley (WA), there were good increases, and areas under grazing in Queensland show good captures. Critical weight range mammals are surviving in a specific band in the Kimberly. It seems that recovery of cover after fire may be important, and this recovery relies on rainfall. Changes in rainfall with climate change may therefore interact with post-fire vegetation recovery, leading to changes in mammal populations.

It is also important to consider other key taxa with important landscape engineering and ecosystem services (pollinators) roles that, if affected by climate change, could lead to a cascade of other changes. For example, there is a very important link between the soil, soil biota and vegetation. Soil macroinvertebrates are important at creating and maintaining soil structure and function, with termite species critical to capture and maintain water in the soil. These species operate in defined temperature and rainfall bounds. Changes in temperature and rainfall may therefore influence diversity with implications for the functioning of the soil. The link between below- and above-ground processes is very important in the savannas. The intensity of rainfall is important as soils have to be able to capture first rains that are a critical trigger for a number of biological processes such as germination. Soil macropores are important for capturing this rainfall. The four or five key invertebrate species for creating macropores in any one location are active all year round and provide a stable food supply for other animals. Fire, grazing and climate change all influence termites; it is critical that these processes and species are understood in order to predict whole-of-ecosystem changes. It could also be that current management such as grazing affects these macroinvertebrates more than climate change will.

Some of the smaller habitats located in the savanna matrix may be more susceptible to climate change than the broad savanna. This is especially true if these habitats can't move through associations with topography, water or the inability to survive in the fire-prone savanna woodland. The coastal floodplains and wetlands are sensitive to changing rainfall patterns, saltwater intrusion from rising sea levels, storm surge and pressure from land use. This system occupies some 6 million hectares and any change in the savanna-wetland boundary can cause large changes in the ecosystem and local livelihoods. Research is now applying risk assessment methodology to these wetland systems.

While we have identified key drivers to which the savannas is potentially very sensitive, at this point we have not come up with a clear uniform understanding about what will change.

The savanna biome exists across a number of temperature, rainfall, disturbance and intensification gradients as outlined in the review. The strengths of these gradients in the north, shallow temperature gradients and steep rainfall gradients impact on changes in richness and structure. If species distributions are sensitive to temperature, then even small changes in temperature, in combination with shallow gradients across broad landscapes, could lead to large geographic changes in climatic niches. Species with limited ability to move either by mobility or being restricted to a particular geographic location will not cope with the resulting change. This also means that connectivity in the landscape is particularly important. This is not only in habitat, but may also include subtle differences arising from plant communities responding to time since last fire. Thus it is important to understand a temporal and spatial heterogeneity of disturbance in the savannas and not simply consider them as a vast homogeneous landscape. This connectivity needs to be considered across a range of spatial scales representing the movement of different organisms from termites to magpie geese. It is likely that climate change will alter this mosaic of time since disturbance by increasing the frequency and/or intensity of cyclones, storms and fire.

Given the gradients present in the savannas, the flora and fauna have evolved to cope with this system either by tolerating the conditions, moving across the landscape to follow resources (flowers, seeds, rainfall), or becoming generalists able to use the broad landscape available. Climate change is likely to affect these three groups differently. It is more likely that the generalists will be advantaged than the specialists, as generalists are favoured in periods of rapid change. Specialists require a particular resource and often have narrow niches. Some examples to consider are thermal specialists that exist in their current location because of the favourable thermal environment; specialist species of mammals and birds in the savannas located within somewhat uniform environmental gradients; and particular geographic specialists, such as the burrowing skinks in Queensland where there is no scope for expanding or moving. Changing climatic conditions also mean that a species may change from being restricted to specific microhabitats to being more widespread and even moving from specialist to generalist in strategy with new favourable conditions. This may be extremely important for exotic species, leading to ‘sleeper weeds’ scattered throughout the biome rapidly becoming widespread or locally abundant. It is not known how many species are likely to become weeds in the new environment. There are also a number of generalist species in the savannas, probably as a result of the somewhat homogeneous nature of the vast, flat savanna woodlands.

It is also important to consider the degree of population patchiness, the spatial structure of intra-specific genetics across the savanna gradients and population connectivity. These areas of research have not been undertaken to date. An example of a geographic divide occurs with the north–south divide in sub-species of the black-throated finch, with the northern population ok but the southern population endangered. Therefore ensuring the northern sub-species that occurs in the savannas is maintained is important. Other smaller environments that contain specialist species – such as the Howard Springs (NT) sand sheets and Mitchell grass areas around Victoria River (NT), Barkly (NT) and Mt Isa (Qld) – need to be considered with respect to climate change.

Savanna change scenarios

A number of savanna change scenarios were suggested by the workshop organisers and these are presented in the previous section. Further scenarios were defined by the workshop participants, including:

- Vegetation changes drive changes in soil macroinvertebrates, while termites may affect vegetation. Difficult feedbacks to predict.
- Around Mt Isa (Qld), buffel grass is taking over tussock grasses. Pastoralists are able to remove the unproductive porcupine grass through seeding buffel grass and using fire to improve pasture.
- Studies are looking at the importance of fire patchiness for fairy wrens (Steve Murphy).
- Increases in fire frequency, especially around camp grounds and the track to Mitchell Falls, will affect biodiversity.

Managing the savannas

Things are going to change in the savannas, and so managing for a healthy ecosystem while protecting biodiversity means maintaining a system that can cope with this change. People currently have the ability to manage and interact with the savannas through grazing and fire management and by preventing the spread of weeds. The level of fire management has been previously discussed but there is still information required to inform appropriate levels of grazing. Some people suggested that any grazing has a negative impact on biodiversity.

Management in the savannas is based on much smaller human populations to support than in southern systems and the savanna biome also contains significant areas of Indigenous lands managed by traditional owners. It is important to discuss both the requirements of the natural system with the aspirations of the land holders (Indigenous). While you can manage the parks for purely ecological outcomes when the broader landscape and off-park areas need to be managed there is a great deal of management difference (co-management). Even park management for ecological outcomes will be overlaid with a social and economic layer. We need to ensure that the environmental values are realised and not merely economic costs considered.

The savannas of northern Australia are located in a geologically ancient and somewhat stable landscape, and it is sometimes difficult to perceive this system changing from the past or into the future. While ecosystems may cope with gradual change, the biggest risks to biodiversity are extreme weather situations that can cause rapid, dramatic change. To understand this threat we need to consider the extreme events proposed for the savannas under climate change and explore the resilience and adaptive capacity of the system.

Cyclone, drought and fire are three disturbances capable of causing rapid changes to the savanna. While these are natural events, climate change may change the frequency and severity of these disturbances, causing changes to the ecosystem. Cyclones are expected to get more intense under climate change. This may result in greater mortality and general forest change when they do occur. As mentioned in the review, Queensland savannas already experience droughts from El Niño events, but the strength of these events could increase. Changes to dry-season length in the monsoonal savannas could also result in tree death and resulting tree population declines. Fire is currently frequent and of relatively low intensity in the savannas. Increasing fire weather, reduced ability to undertake safe control burns and the spread of exotic weeds with large fuel loads could result in fire intensities and extents larger than currently experienced. These extensive fires reduce the patchiness of habitats in the landscape. These three disturbances introduce the idea of changes we should be concerned about but may not be able to manage for.

Considering scale in management actions is very important. There is now a need to manage for whole system / landscape change. This is particularly important when we consider the gradients in the savannas and how changes may result in large movements of species and ecosystems. Biodiversity in individual reserves changes with climate change, so off-reserve protection (including Indigenous lands) and the reserve network as a whole needs to be considered. We also need to consider what land is available and how big reserves need to be in the savannas to protect the habitat diversity of an area. We also need to consider the orientation of parks to include ecological and climatic gradients for the movement of organisms and coverage of the spread of current habitats. The Northern Territory Government currently plans to provide reserves to link the NT coast to Alice Springs and the NT southern border. This series of reserves effectively covers the range of habitats along the north–south rainfall gradient. Likewise, protection of east–west flowing rivers may need to be considered differently to north–south flowing rivers.

Fire management is currently important for conservation and will be important under climate change. Current prescribed burning aims to increase interval between fires and assist species that need periods without fire. This is particularly important for escarpment fire management where the aim is to preserve biodiversity where hotspots of endemism are present. If burning frequency increases, there is a decline in obligate seeders. Fire management will be performed in these areas regardless of climate change, but it is important we understand how climate change will affect our ability to manage fire in these environments. There is also concern about the impacts of changing fire regimes elsewhere in the savannas. Alteration of fire regimes in the biome may additionally be driven by management responses to mitigation policy.

The wet–dry nature of northern Australia and the predicted changes in rainfall amount and distribution suggest that access to water may be a critical factor defining ecosystems under climate change. Riparian strips often have diverse fauna, though not necessarily diverse flora. Three areas of importance with respect to water are coastal inundation, water temperatures and seasonal water supplies. Low-lying coastal, freshwater areas are susceptible to sea level rise and salt water inundation. Salt water intrusion will kill trees such as Melaleuca, resulting in a complete ecosystem change. These areas then either are converted to mangroves if the natural barriers/barrages are broken by people, boats, storms or pigs and buffalo, or remain as freshwater systems with dead trees, resulting in a loss of species, but not complete change. Availability of free-standing water at the end of the dry season and springs to provide river flows are critical. These areas are important to protect and also heavily used by feral species such as pigs and cattle. We need to understand how changes in rainfall will affect these important water sources, particularly at the end of the dry season when water supplies are very important. Finally, water temperature may be important, particularly if oxygen thresholds are exceeded more regularly, resulting in freshwater fish kills in billabongs and rivers.

As we have mentioned in a number of areas, feral animals and weeds are a current threat to savanna biodiversity and will continue to place the same or more pressure on ecosystems under climate change. There is a pressing need to show environmental impact of feral animals and weeds to decision makers even before new environmental changes occur. It is very important that some of these threats are managed as they may exceed the impacts of future climate change.

A better understanding of the ecological consequences of climate change, as provided by this workshop, will assist management decisions. For example, the allocation of considerable current on-ground resources may be aimed at reducing para grass, which is a serious biodiversity threat. However, with salt water inundation this grass may be killed in future, and resources would be better spent now on other issues. Current research also highlights the data required to answer the ‘what if’ questions. Detailed digital elevation maps (DEM) are required for large areas to predict the impact of sea level rise over areas with very shallow topography.

The current focus for management and the NRS in the savannas to prepare for climate change and preserve the current biodiversity should be targeted towards areas of high endemicity (Arnhem escarpment), north–south versus east–west river systems, coastal regions with shallow gradients (storm surge and sea level rise) and protecting specialist environments in the savanna matrix.

Workshop summary – PRELIMINARY

The mix of participants attending this workshop resulted in most discussions relating to the ecological consequences of current disturbances threatening biodiversity and the likely impacts of future climate change. The workshop aimed to extend the current views and try and predict large-scale impacts of climate change in the savannas. This then informs how the current and future NRS can be managed and designed to protect ecosystems under these changes.

Unfortunately, a number of people were unable to attend the workshop. We aim to invite comment from these people and will include the additional information in the final report.

The discussions covered a broader context than simply current NRS, as participants soon realised that the current systems and species will have to move with climate change. The climatic gradients covering the tropical savannas mean movements may involve large distances in a relatively short amount of time. Any future management will have to include off-park management in the plan. We therefore need to consider the role of the NRS in the whole landscape; for example, should it focus on key locations in the landscape (e.g. refuges, isolates), enabling key processes (hydrological flows, species migration), or providing nodes of different environment / habitat type scattered through the biome?

Northern Australia and the tropical savannas are relatively data poor compared with other regions of the world and Australia. Simple animal and plant physiological understanding is required to understand the actual tolerances of organisms and the upper limits and thresholds with respect to temperature and water requirements. This research will provide an indication as to how close the current system is to climate limits and therefore how important the future changes will be.

Appendix B Description of modelling performed

Rather than consider the likely outcomes of each climate change process (e.g. temperature, humidity, rainfall, extreme heat day, etc), we use two modelling techniques (artificial neural networks [ANN] and generalised dissimilarity modelling [GDM]) to look at the environmental stress throughout the savanna biome as a function of all factors changing with climate change (28 BIOCLIM and environmental factors). While this approach makes it difficult to pinpoint exactly what processes are influencing the biota, it does allow for the emergent outcome of many factors to be considered and highlights the general outcomes suggested for the medium and high emission scenarios in 2070.

B.1 Artificial neural network modelling

This study uses maps of vegetation classes at various scales along with detailed, spatial estimates of climate, topographic and edaphic variables to objectively classify environments that are characteristic of these vegetation classes. The goal is to transform a high dimensional, physical environment space (many climate variables and, in the case of the Major Vegetation Groups [MVGs], a number of terrain and soil variables as well) into a lower dimensional, ecologically meaningful space. This is accomplished through supervised classification. Then, given any spatial scenario of change in the climate we can map these ecological environments in geographic space. Most importantly, we can compare this new spatial map of environments with what we estimate it is today and also with the spatial distribution and extent of the actual ecological classes. In this way, we can quantify how the extent and distribution of the environmental classes may change in the future and infer how climate change may affect vegetation classes and, consequently, biodiversity and function.

We used ANNs for the supervised classification of environments based on mapped vegetation classes. This methodology builds on the successes of a similar approach that was used in the Wet Tropics Bioregion of north-east Queensland where an ANN was used to classify 15 structural/physiognomic forest environments based on a range of climatic, edaphic and topographic variables (Hilbert and Van Den Muyzenburg 1999, Hilbert et al. 2001). For all of Australia, we classified environments at two vegetation scales, seven terrestrial ecoregions (global biomes) and 23 MVGs. The ecoregions are derived from Thackway and Cresswell's (1995) biogeographic regionalisation for Australia. The MVG data consist of a digital map of their pre-clearing distributions at a one hectare resolution for the entire continent (Thackway et al. 2007).

We used FANN (Fast Artificial Neural Network Library) to classify environments of both the ecoregions and the MVGs. This software is an open source neural network library available from http://leenissen.dk/fann/, which implements multilayer artificial neural networks in C. For the ecoregions, the network structure consisted of 23 bioclimatic inputs, 150 hidden nodes and seven output nodes, corresponding to the ecoregions. We used the largest output node value to map ecoregions in the current and climate change scenarios. For the MVGs we used a single, multiple-output neural network to classify the available environmental variables by MVG class with 35 input nodes (23 bioclimatic variables, three soil variables and nine topographic variables), 150 hidden nodes and 23 output nodes representing the MVGs. We used the largest output node value to map MVGs in the current and climate change scenarios.

We also trained individual classifications for each of the ecoregions and each of the MVGs using the Tiberius software (Brierley unpublished) to rank variable importance using the Gini Coefficient (Breiman et al. 1984). Here, we used 35 bioclimatic variables for the ecoregions and 35 bioclimatic variables plus the additional 12 soil and topographic variables for the MVGs.

The ANNs provide much more information than is apparent in a classification, where the output node with the largest value is chosen as a pattern's (location's) classification. By using the values of all the output nodes we calculated the dissimilarity of this vector to the vector with the value of 1.0 for the class that is mapped at that location and all other values of 0.0. The dissimilarity is the vector angle between the two, normalised to the range [0,1] (Hilbert and Van Den Muyzenburg 1999). For example, a location that is mapped as Rainforest and vine thickets with a dissimilarity of 0.1 has an environment that is more typical of this class than another location, also mapped as this class, with a dissimilarity of 0.4. Hilbert and colleagues (Hilbert et al. 2001, Hilbert & Ostendorf 2001) interpret dissimilarity as an index of relative environmental stress. It could also be thought of as a propensity to change. Dissimilarities greater than 0.5 indicate environments that are more like that of some other class than the one that is mapped.

A detailed description of the methods used in this project is provided in the accompanying report, Hilbert and Fletcher (2012).

B.2 Analysis of biotically scaled environmental stress using generalised dissimilarity modelling

Generalised dissimilarity modelling (GDM) is a statistical technique for modelling the compositional dissimilarity between pairs of geographical locations, for a given biological group (e.g. reptiles), as a function of environmental differences between these locations (Ferrier 2002; Ferrier et al. 2002, 2007). The measure of compositional dissimilarity (*d*) employed in this project is the Sorenson, or Bray–Curtis, index:

$$d_{ij} = 1 - \frac{2A}{2A + B + C}$$

where *A* is the number of species common to both locations *i* and *j*
B is the number of species present only at location *i*
C is the number of species present only at location *j*

In other words, based on this measure, the compositional dissimilarity between a given pair of locations is the proportion of species occurring at one location that do not occur at the other location (averaged across the two locations) – ranging from 0 if the two locations have exactly the same species through to 1 if they have no species in common.

GDM uses data on species recorded at a sample of locations across the region of interest to fit a model predicting the compositional dissimilarity between pairs of locations as a non-linear multivariate function of the environmental attributes of these locations. Another way of viewing this is that GDM effectively weights and transforms the environmental variables of interest such that distances between locations in this transformed multidimensional environmental space now correlate, as closely as possible, with observed compositional dissimilarities between these same locations (see Ferrier et al. 2007 for full explanation).

This project employed a set of GDM models already derived for the Australian continent by a separate (then) DEWHA-funded Caring for Our Country Open Grants project performed by CSIRO in collaboration with DEWHA and the ANU Fenner School of Environment and Society (Williams et al. 2009). These models were derived using continent-wide biological data collated within DEWHA’s Australian Natural Heritage Assessment Tool (ANHAT) database – a compilation of species-location records from a large number of herbaria, museums, State and Commonwealth departments, and private individuals. The models were fitted at 1 km^2 grid resolution[1] across the entire continent using best-available environmental layers for 76 climate, terrain and substrate variables (Williams et al. 2009). Models were derived for 12 different biological groups, six of which were employed in the work described in this current report:

- vascular plants (model based on data for 12,881 species at 374,640 locations – i.e. 1 km^2 grid cells)

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[1] The models were fitted to data based on 0.01° by 0.01° grids, which are approximately 1 km by 1 km, but their exact dimensions vary with latitude.

- land snails (model based on 2,774 species at 19,118 locations)
- frogs (model based on 218 species at 100,143 locations)
- reptiles (model based on 819 species at 83,661 locations)
- birds (model based on 690 species at 242,814 locations)
- mammals (model based on 298 species at 100,369 locations).

The current project used the above models to infer potential changes in biological composition as a function of projected changes in climate across the continent. This is based on the assumption that the amount of change in species composition expected for location *A* as a result of climate change will be equivalent to the compositional dissimilarity currently observed between location *A* and another location *B* with a current climate matching that projected for location *A* (Ferrier and Guisan 2006; Ferrier et al. 2007). It is likely that the actual change in biological composition resulting from climate change will be shaped by many factors, and associated sources of uncertainty, beyond those considered in this modelling, such as biotic interactions, indirect effects of changed fire regimes, dispersal ability, lag effects, adaptation capacity and plasticity. The level of compositional change predicted by the GDM approach is therefore best interpreted as no more than a relative indicator of potential 'environmental stress' expected to be experienced by species in a given biological group under a given climate scenario.

The GDM-based analyses performed in this project resulted in maps depicting the following:

- The predicted dissimilarity between the current composition of each grid cell and its composition under a given climate scenario, as a general indicator of potential environmental stress on a cell-by-cell basis. This was estimated and mapped separately for each of the six biological groups (listed above). A weighted average of these six maps was also derived, in which each biological group was weighted according to the total amount of spatial turnover exhibited by the group under current climate conditions (see Williams et al. 2009 for further explanation of this weighting). All of the remaining analyses below were performed for vascular plants only
- The minimum predicted dissimilarity between the current composition of each cell and the future composition of all cells on the continent under a given climate scenario, as an indicator of 'disappearing [biotically scaled] environments' (as per Williams et al. 2007)
- The minimum predicted dissimilarity between the future composition of each cell under a given scenario and the current composition of all cells on the continent, as an indicator of 'novel or no-analogue [biotically scaled] environments' (as per Williams et al. 2007)
- Two measures of the potential contribution that environmental heterogeneity around each cell may make to ameliorating, or buffering, the effects of a given climate scenario:
  a. the proportional change in effective habitat area within a surrounding radius varying from 750 m up to 100 km, where 'effective habitat area' is the summed area of all cells within this radius, with each cell weighted according to the predicted similarity ($1-d_{ij}$) between the composition of this cell (current versus future) and the current composition of the focal cell (see Ferrier et al. 2004, and Allnutt et al. 2008 for a more detailed explanation of this concept)
  b. the predicted dissimilarity between the current and future composition of each cell (from the first dot point above), minus the minimum predicted dissimilarity between the current composition of this cell and the future composition of any other cell within a radius varying from 750 m to 100 km.
- An extension of the analysis of 'proportional change in effective habitat area' described above to consider the added effect of habitat loss and fragmentation. In this case only cells mapped as extant vegetation (based on the National Vegetation Information System) are allowed to contribute to the calculation of effective habitat area.

A detailed description of the above methods is provided in the accompanying report by Ferrier et al. (2012).

The methodology to generate the 1 km^2 resolution climate change scenarios was as follows. Two scenarios were considered, both using outputs from the CSIRO Mk3.5 GCM downloaded from OzClim (www.csiro.au/ozclim): a medium impact scenario, using the A1B emissions scenario, and a high impact scenario using the A1FI emissions scenario (IPCC 2000). The main future date considered was 2070, although an intermediate 2030 scenario was also developed.

The first step was to download monthly climate change grids at 0.25° resolution for maximum temperature, minimum temperature, rainfall and evaporation, by specifying the above scenarios in OzClim. Spatial downscaling was carried out using the ANUCLIM software (Houlder et al. 2000; fennerschool.anu.edu.au/publications/software/anuclim.php), which incorporates three submodels: ESOCLIM, which outputs raw climate variable grids; BIOCLIM (Busby 1986), which outputs grids of average bioclimatic parameters; and GROCLIM, which can output gridded indices from simple growth models. The beta release of ANUCLIM version 6.0 was used, which allows climate change grids to be applied over the historical 1990-centred climate surfaces. Software (Harwood and Williams 2009) was written to interpolate the raw 0.25° CSIRO grids to cover the whole Australian land mass, and relate evaporation change to the date range used in ANUCLIM 6. Following this interpolation, monthly maximum temperature, minimum temperature, rainfall, and evaporation change grids were input into ANUCLIM 6 with a 0.01° digital elevation model. The result was a suite of monthly 0.01° (≈1 km^2) resolution future climate surfaces for maximum temperature, minimum temperature, rainfall, evaporation and radiation, with 35 BIOCLIM variables and four plant growth indices for each scenario.

B.3 Bayesian modelling

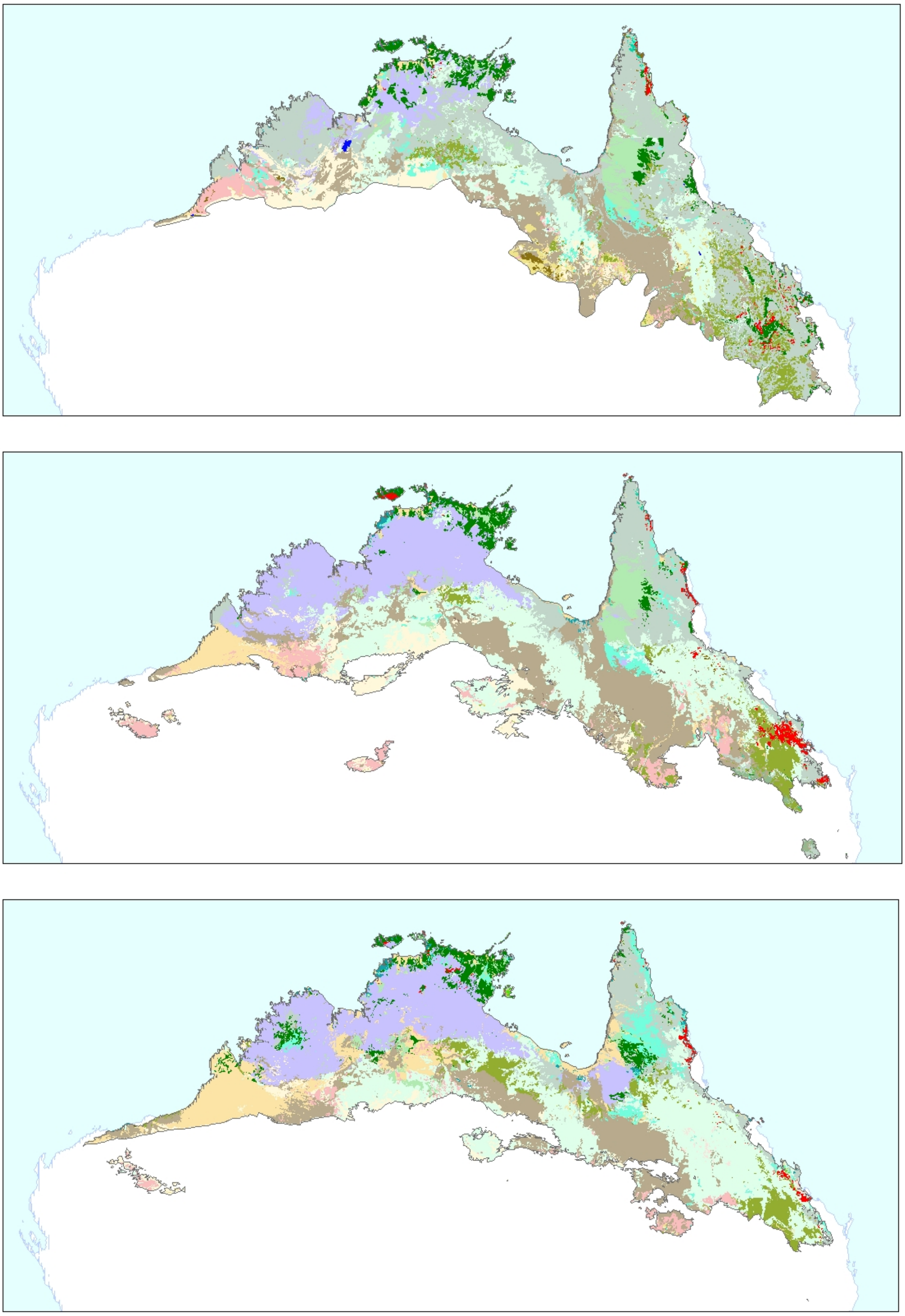
Bayesian belief networks (BBNs) are useful tools for modelling ecological predictions and assisting natural resource management decision-making (Marcot et al. 2001; Marcot et al. 2006; Smith et al. 2007). BBNs represent a tool for examining probabilistic scenarios where the structure of the network is formally decided by an expert panel. Data feeding into these types of models are typically the result of expert judgement through an expert elicitation process but can also be based on empirical or modelled data about the process of interest. In ecological research, the use of BBNs to represent ecological processes is a growing area of research. How to elicit and use expert knowledge in particular is becoming a focus point in ecology (Kuhnert et al. 2010). Expert elicitation represents a way of capturing knowledge and informing management and policy when empirical data are limited, but it presents a number of interesting challenges: namely, the collection of robust and accurate, unbiased information from one or more experts and quantifying the uncertainty around the elicited response. If collected carefully, taking into account the inherent biases induced from eliciting judgements, this information can be used in a BBN to examine a range of probabilistic scenarios.

BBNs are used in this project to assess the relative threat of weed species invasion across Australia. For this project we have chosen buffel grass (*Pennisetum ciliare* [syn.] *Cenchrus ciliaris*) as a case study, as it has a broad distribution and currently poses a threat to the NRS. Specifically we ask: what is the current suitability of the Australian continent to buffel grass colonisation, and how will climate change influence the suitability of the continent for buffel grass colonisation in the future?

A full description of the results of the Bayesian modelling component of this project is available in the accompanying report by Martin et al. (2012).

Appendix C The savanna biome

Figure B.1 The savanna biome as defined by the tropical woodland and grassland ecoregion showing the NVIS major vegetation groups (MVGs) for (a) current mapping and (b) medium 2070 and (c) high 2070 emissions climate change scenarios predicted by the artificial neural network (ANN) modelling



Appendix D Environmental stress for major vegetation groups

Table D.1 The mean (and standard deviation) environmental stress for each NVIS MVG modelled and located within the savanna biome for the 2070 medium and high emissions scenarios determined from the artificial neural network (ANN) modelling

	2070 MEDIUM		2070 HIGH	
NVIS MVG	MEAN	SD	MEAN	SD
Rainforest	0.84	0.17	0.80	0.22
Euc Tall Open Forest	0.98	0.00	0.00	0.00
Euc Open Forest	0.61	0.27	0.72	0.27
Euc Low Open Forest	0.82	0.15	0.89	0.13
Euc Woodlands	0.52	0.30	0.60	0.29
Acacia Forests	0.74	0.21	0.78	0.18
Callitris Forests	0.84	0.13	0.88	0.11
Casuarina Forests	0.78	0.15	0.85	0.14
Melaleuca Forests	0.56	0.32	0.84	0.18
Other Forests	0.71	0.28	0.81	0.19
Euc Open Woodlands	0.65	0.31	0.69	0.29
Trop Euc Woodlands	0.71	0.31	0.77	0.29
Acacia Woodlands	0.86	0.15	0.83	0.10
Mallee	0.84	0.10	0.92	0.09
Low Closed Forest	0.84	0.16	0.77	0.13
Acacia Shrublands	0.85	0.17	0.88	0.16
Other Shrublands	0.87	0.13	0.72	0.23
Heathlands	0.65	0.21	0.87	0.12
Tussock Grasslands	0.50	0.38	0.53	0.35
Hummock Grasslands	0.51	0.27	0.58	0.24
Other Grasslands	0.86	0.19	0.89	0.16
Chenopod Shrublands	0.82	0.17	0.82	0.19
Mangroves	0.85	0.21	0.87	0.17

Appendix E Compositional change for plants

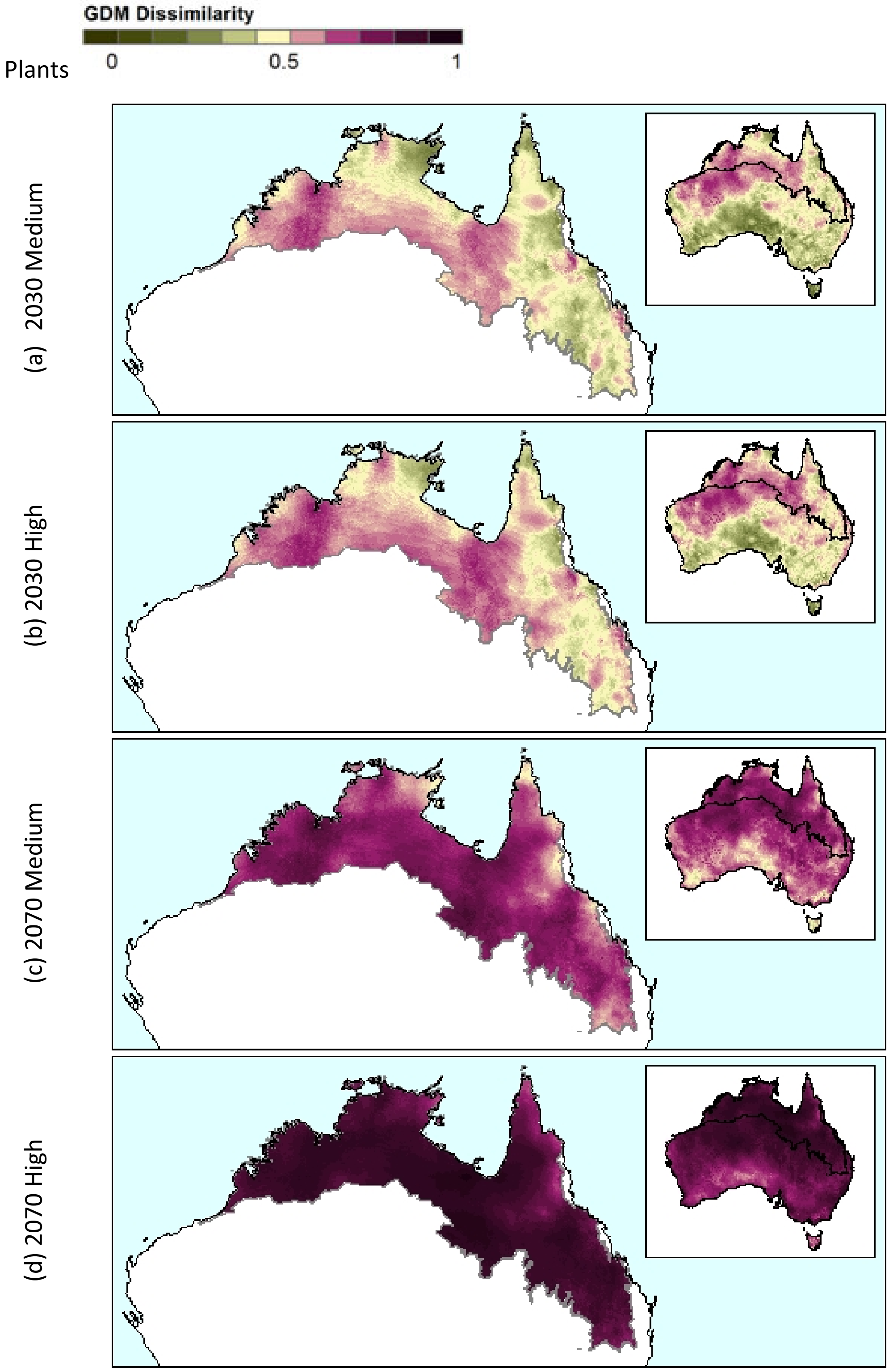


Figure D.1 The expected compositional change for plants calculated from the GDM modelling for each 1 km^2 cell for the present climate against each (a) medium, (b) high emission scenarios in 2030 and (c) medium and (d) high emissions in 2070 where high dissimilarity (dark pink) indicates a high level of stress and low dissimilarity (dark green) indicates low stress

Appendix F Compositional change for snails

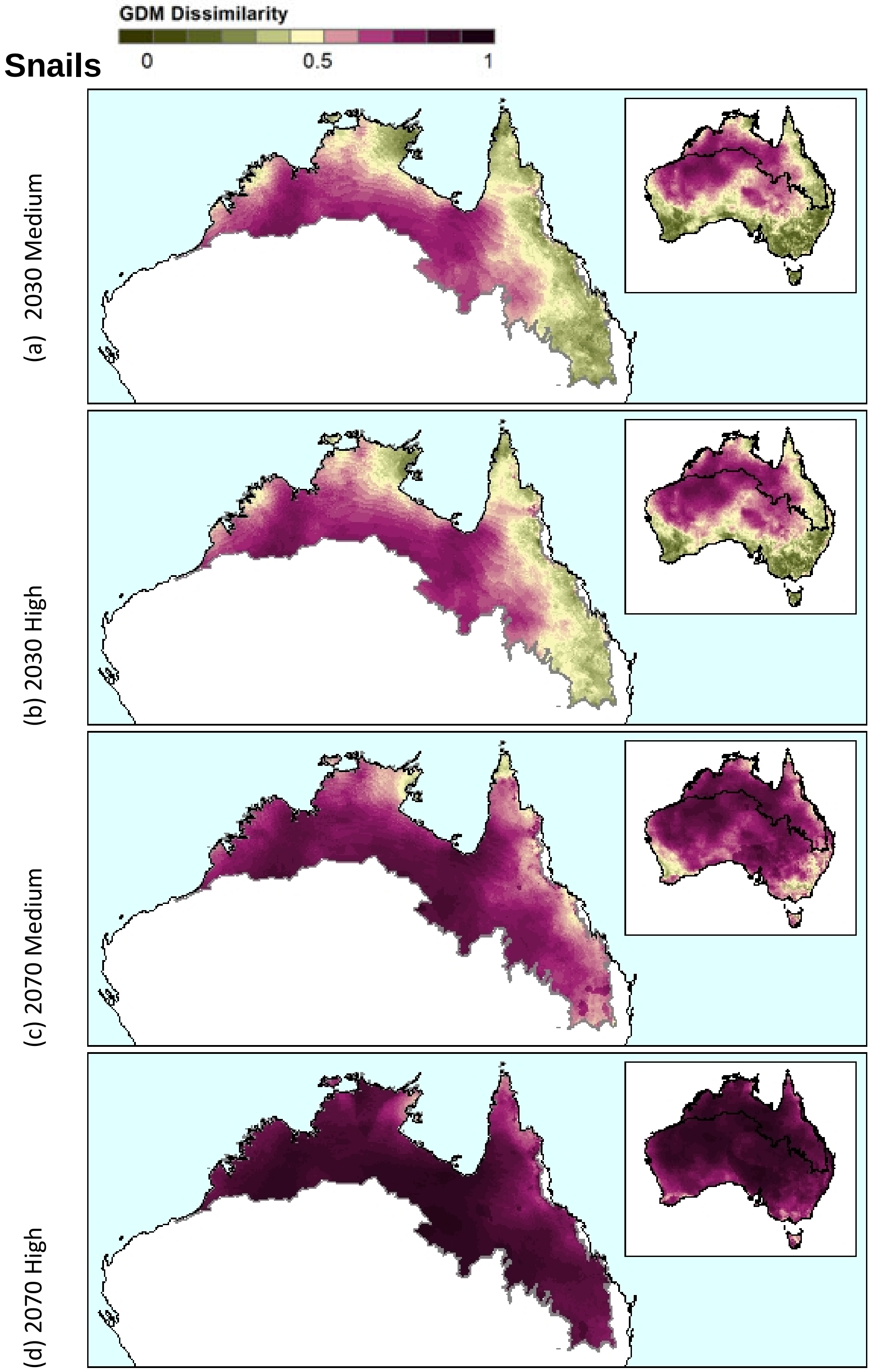


Figure E.1 The expected compositional change for snails calculated from the GDM modelling for each 1 km^2 cell for the present climate against each (a) medium, (b) high emission scenarios in 2030 and (c) medium and (d) high emissions in 2070 where high dissimilarity (dark pink) indicates a high level of stress and low dissimilarity (dark green) indicates low stress

Appendix G Compositional change for reptiles

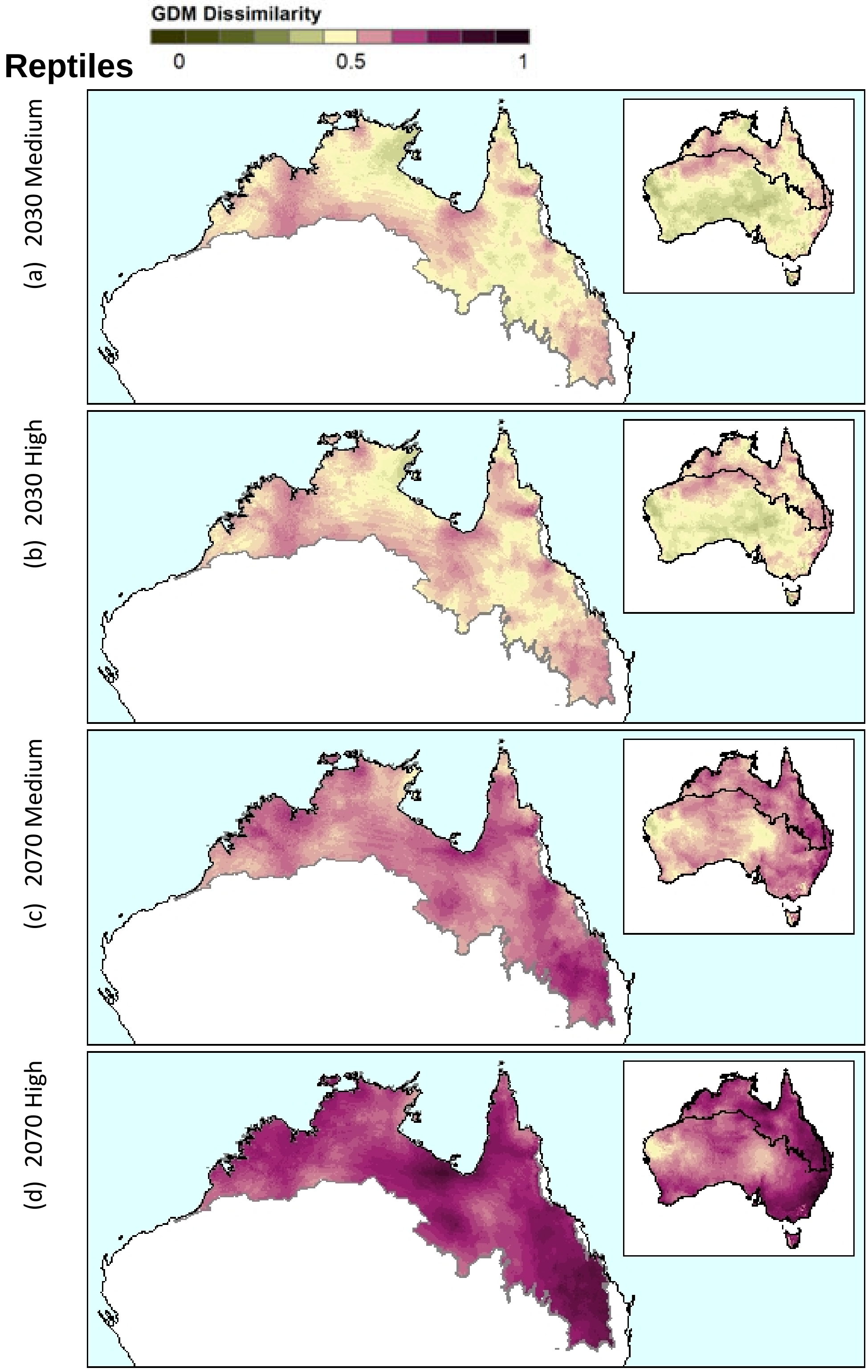


Figure F.1 The expected compositional change for reptiles calculated from the GDM modelling for each 1 km^2 cell for the present climate against each (a) medium, (b) high emission scenarios in 2030 and (c) medium and (d) high emissions in 2070 where high dissimilarity (dark pink) indicates a high level of stress and low dissimilarity (dark green) indicates low stress

Appendix H Compositional change for mammals

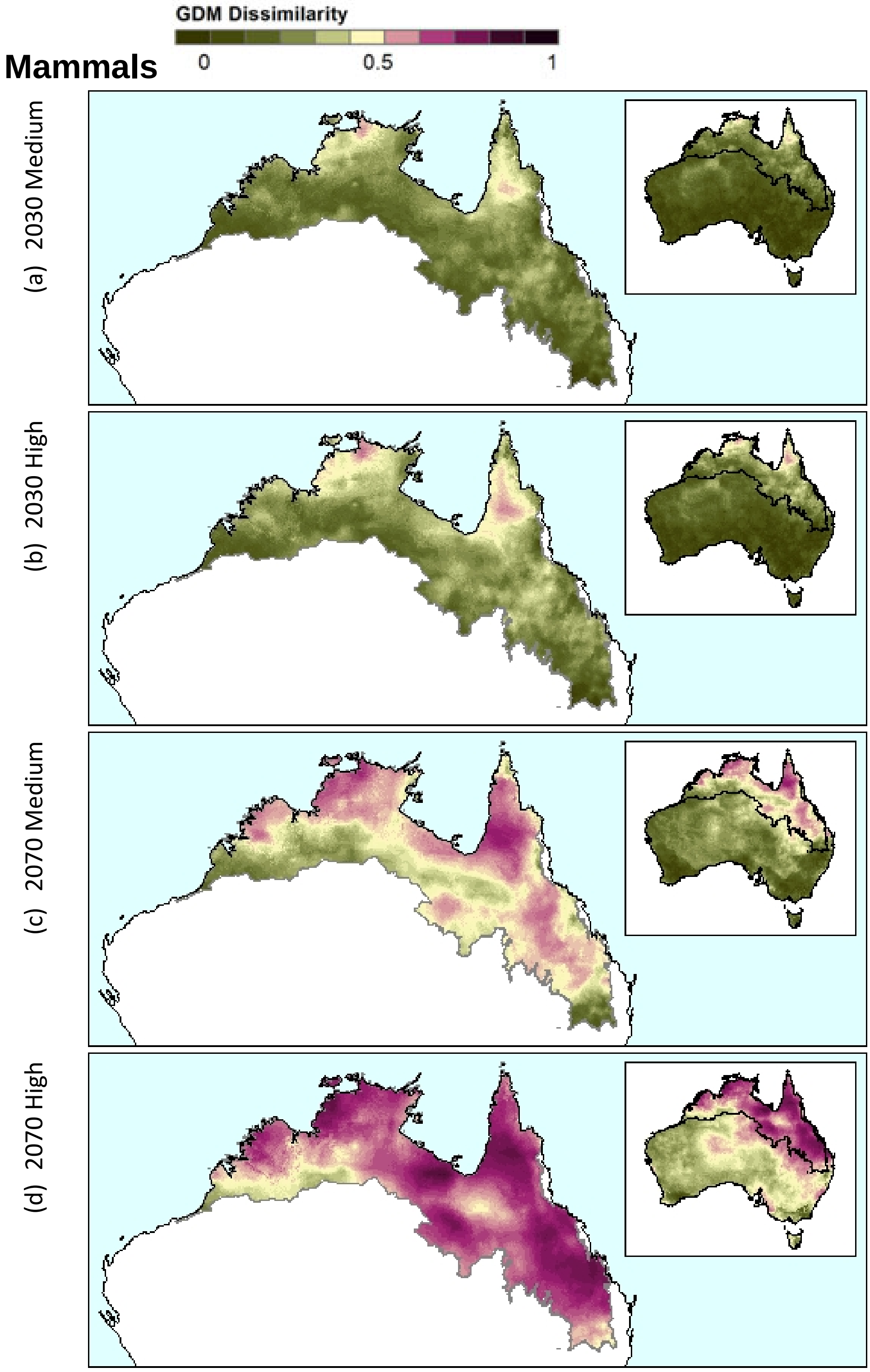


Figure G.1 The expected compositional change for mammals calculated from the GDM modelling for each 1 km^2 cell for the present climate against each (a) medium, (b) high emission scenarios in 2030 and (c) medium and (d) high emissions in 2070 where high dissimilarity (dark pink) indicates a high level of stress and low dissimilarity (dark green) indicates low stress

Appendix I Compositional change for frogs

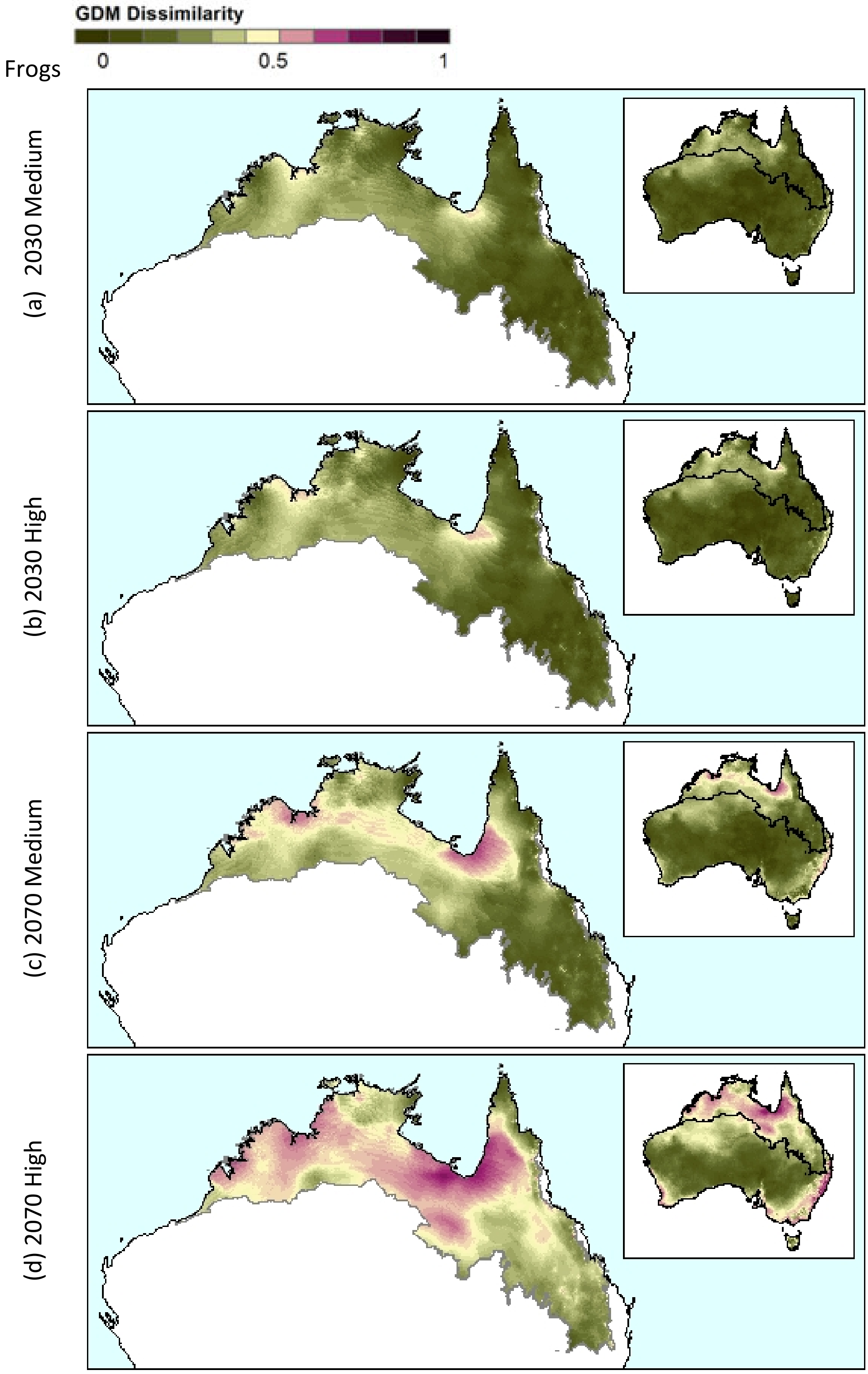


Figure H.1 The expected compositional change for frogs calculated from the GDM modelling for each 1 km^2 cell for the present climate against each (a) medium, (b) high emission scenarios in 2030 and (c) medium and (d) high emissions in 2070 where high dissimilarity (dark pink) indicates a high level of stress and low dissimilarity (dark green) indicates low stress

Appendix J Compositional change for birds

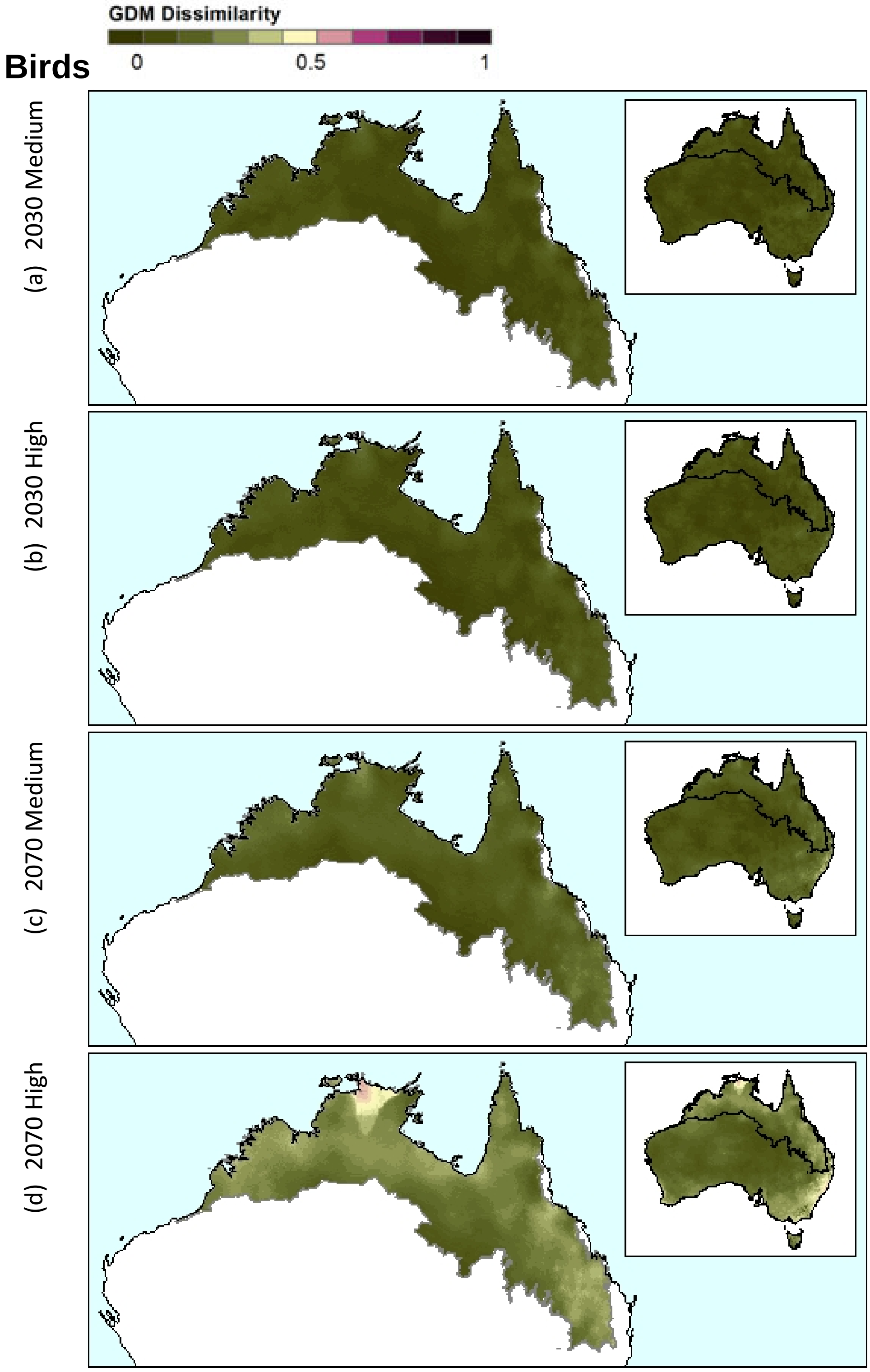
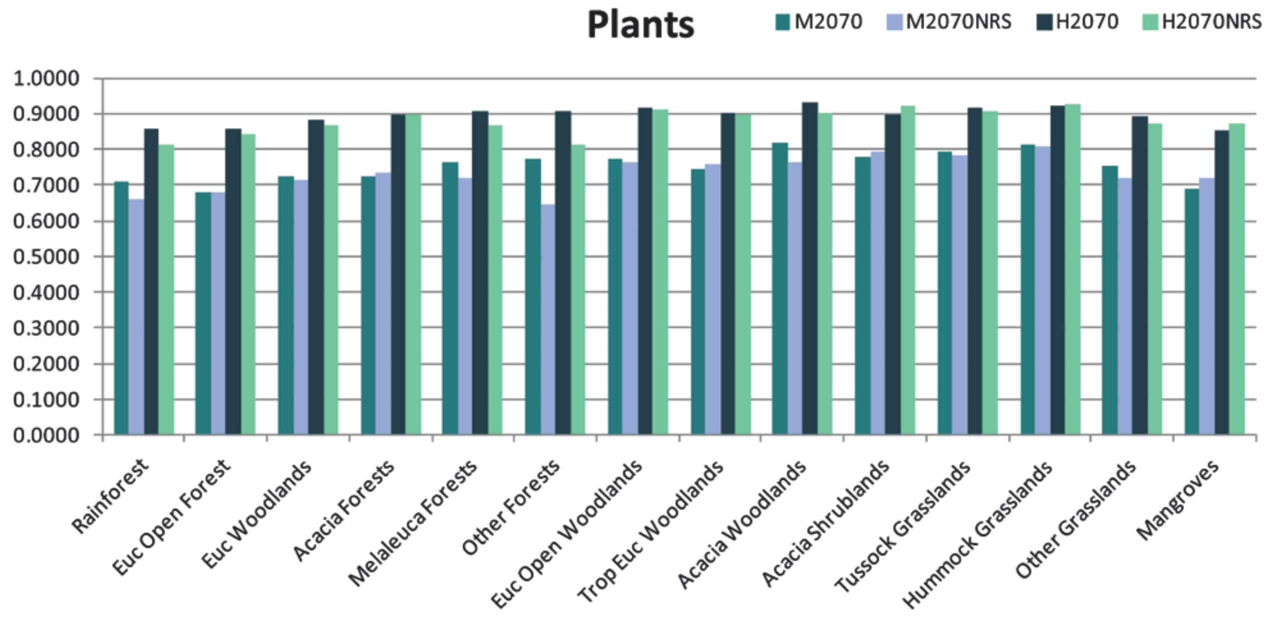


Figure I.1 The expected compositional change for birds calculated from the GDM modelling for each 1 km^2 cell for the present climate against each (a) medium, (b) high emission scenarios in 2030 and (c) medium and (d) high emissions in 2070 where high dissimilarity (dark pink) indicates a high level of stress and low dissimilarity (dark green) indicates low stress

Appendix K Mean expected compositional change



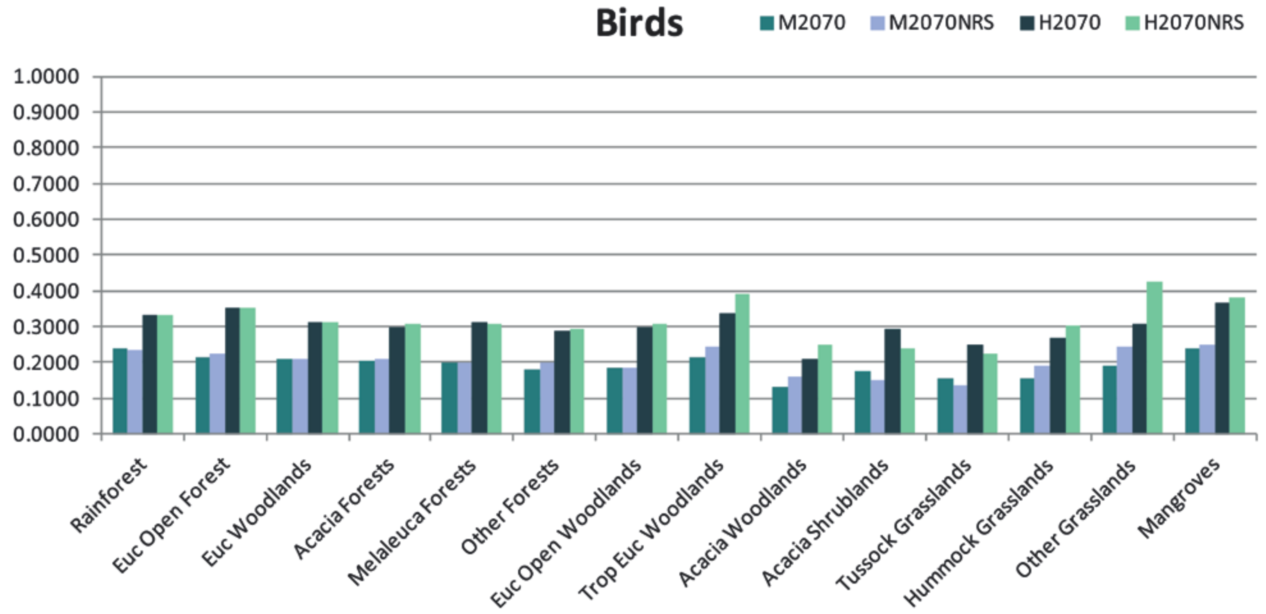
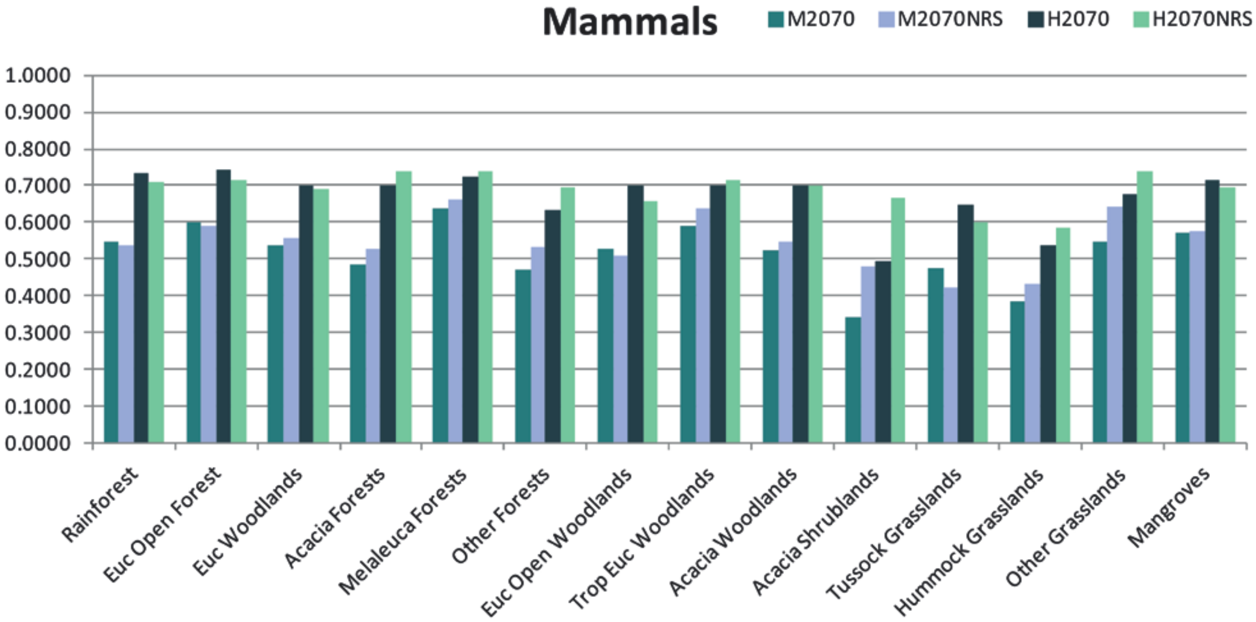
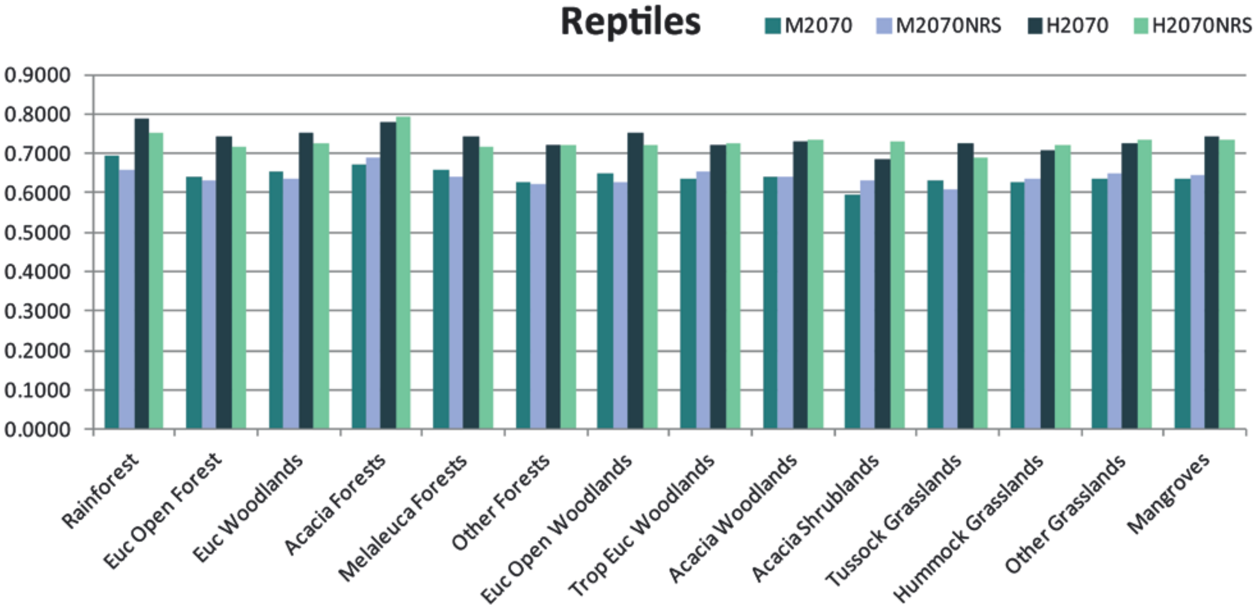
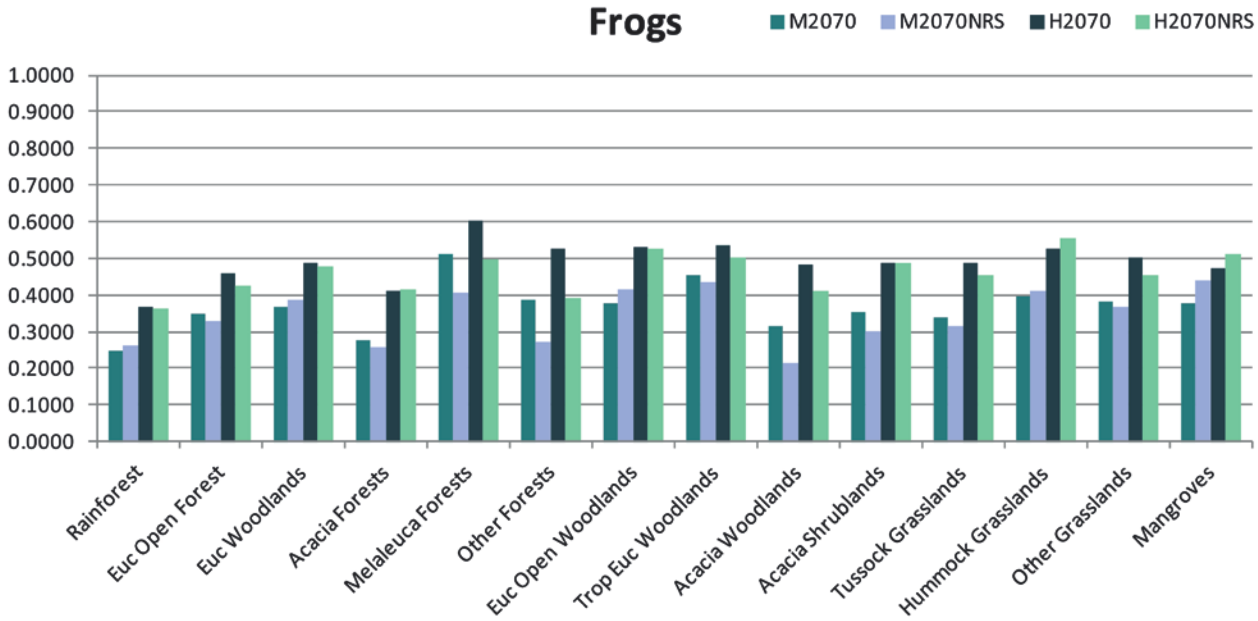
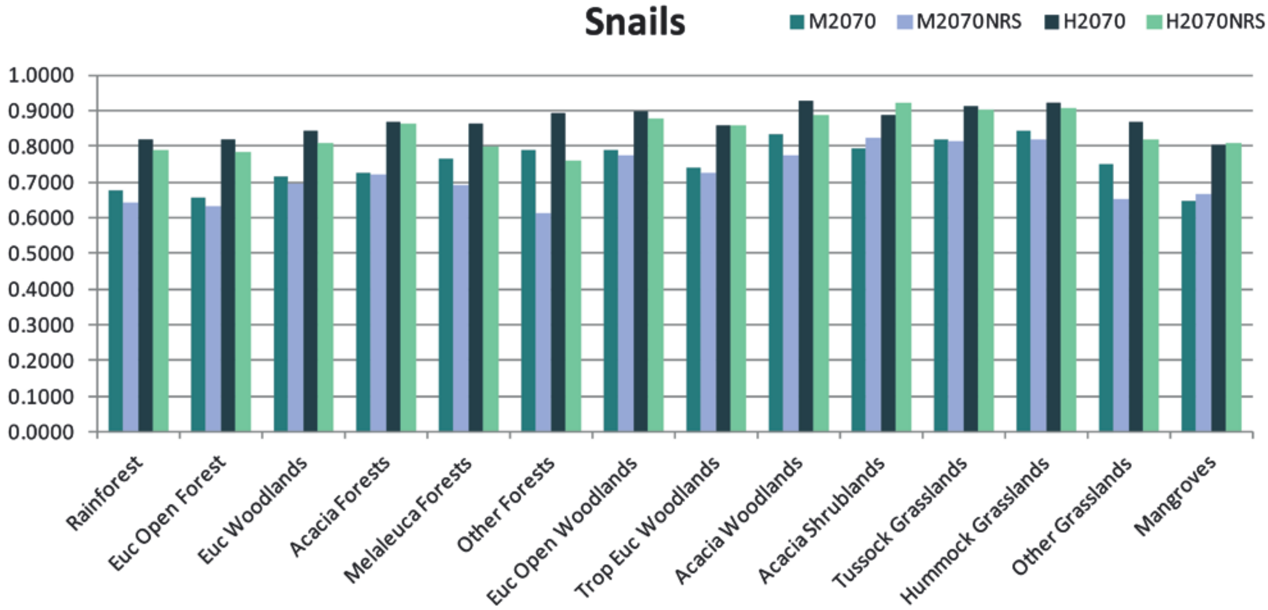


Figure J.1 The mean expected compositional change for plants, birds, mammals, reptiles, frogs and snails predicted by GDM modelling for the dominant major vegetation groups (MVGs) present in the savanna biome showing the effect of the medium (light shades) and high (dark shades) emission scenarios both inside the NRS (orange) and for the entire savanna biome (green). Standard errors are not displayed as they are on average 0.0002


Mammals
M2070
M2070NRS
H2070
H2070NRS
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
Rainforest
Euc Open Forest
Euc Woodlands
Acacia Forests
Melaleuca Forests
Other Forests
Euc Open Woodlands
Trop Euc Woodlands
Acacia Woodlands
Acacia Shrublands
Tussock Grasslands
Hummock Grasslands
Other Grasslands
Mangroves


Reptiles
M2070
M2070NRS
H2070
H2070NRS
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
Rainforest
Euc Open Forest
Euc Woodlands
Acacia Forests
Melaleuca Forests
Other Forests
Euc Open Woodlands
Trop Euc Woodlands
Acacia Woodlands
Acacia Shrublands
Tussock Grasslands
Hummock Grasslands
Other Grasslands
Mangroves


Frogs
M2070
M2070NRS
H2070
H2070NRS
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
Rainforest
Euc Open Forest
Euc Woodlands
Acacia Forests
Melaleuca Forests
Other Forests
Euc Open Woodlands
Trop Euc Woodlands
Acacia Woodlands
Acacia Shrublands
Tussock Grasslands
Hummock Grasslands
Other Grasslands
Mangroves


Snails
M2070
M2070NRS
H2070
H2070NRS
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
Rainforest
Euc Open Forest
Euc Woodlands
Acacia Forests
Melaleuca Forests
Other Forests
Euc Open Woodlands
Trop Euc Woodlands
Acacia Woodlands
Acacia Shrublands
Tussock Grasslands
Hummock Grasslands
Other Grasslands
Mangroves

Appendix L Environmental stress for each biota in the NRS

		BIRDS		FROGS		MAMMALS	
MVG		M2070	H2070	M2070	H2070	M2070	H2070
1	Rainforest	0.232	0.330	0.262	0.364	0.536	0.710
3	Euc Open Forest	0.224	0.353	0.330	0.426	0.592	0.715
5	Euc Woodlands	0.212	0.315	0.385	0.478	0.556	0.689
6	Acacia Forests	0.210	0.306	0.259	0.416	0.528	0.737
9	Melaleuca Forests	0.202	0.307	0.407	0.496	0.661	0.740
10	Other Forests	0.199	0.292	0.273	0.392	0.535	0.694
11	Euc Open Woodlands	0.183	0.309	0.416	0.526	0.508	0.657
12	Trop Euc Woodlands	0.246	0.390	0.436	0.500	0.638	0.716
13	Acacia Woodlands	0.161	0.247	0.214	0.409	0.546	0.702
16	Acacia Shrublands	0.151	0.242	0.301	0.489	0.482	0.669
19	Tussock Grasslands	0.134	0.224	0.316	0.456	0.424	0.598
20	Hummock Grasslands	0.190	0.304	0.413	0.554	0.434	0.585
21	Other Grasslands	0.246	0.427	0.366	0.452	0.645	0.736
23	Mangroves	0.251	0.384	0.438	0.510	0.575	0.697
All NRS Areas		0.208	0.324	0.381	0.478	0.557	0.687

		PLANTS		REPTILES		SNAILS		MEAN	
MVG		M2070	H2070	M2070	H2070	M2070	H2070	M2070	H2070
1	Rainforest	0.659	0.815	0.658	0.753	0.642	0.789	0.554	0.688
3	Euc Open Forest	0.677	0.841	0.630	0.718	0.630	0.783	0.567	0.699
5	Euc Woodlands	0.716	0.868	0.636	0.724	0.696	0.811	0.597	0.716
6	Acacia Forests	0.736	0.898	0.691	0.794	0.719	0.862	0.594	0.743
9	Melaleuca Forests	0.718	0.869	0.642	0.716	0.693	0.798	0.613	0.720
10	Other Forests	0.647	0.811	0.621	0.723	0.612	0.761	0.536	0.675
11	Euc Open Woodlands	0.762	0.910	0.627	0.723	0.775	0.880	0.625	0.747
12	Trop Euc Woodlands	0.757	0.899	0.651	0.726	0.726	0.858	0.638	0.747
13	Acacia Woodlands	0.763	0.904	0.642	0.736	0.775	0.887	0.599	0.733
16	Acacia Shrublands	0.792	0.922	0.630	0.728	0.826	0.920	0.623	0.752
19	Tussock Grasslands	0.783	0.907	0.609	0.690	0.813	0.902	0.609	0.724
20	Hummock Grasslands	0.808	0.924	0.634	0.719	0.818	0.909	0.640	0.753
21	Other Grasslands	0.718	0.873	0.651	0.736	0.653	0.821	0.600	0.730
23	Mangroves	0.720	0.871	0.644	0.735	0.667	0.809	0.606	0.729
All NRS Areas		0.727	0.877	0.635	0.722	0.710	0.831	0.603	0.723

Table L.1 The mean GDM disimilarity (environmental stress) within the NRS for each biota in each of the main major vegetation groups (MVGs) in the savanna biome with MVGs highlighted with stress greater than the entire biome for the given biota and climate change scenario.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

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FOR FURTHER INFORMATION

Ecosystem Sciences
Adam Liedloff
t +61 8 8944 8446
e adam.liedloff@csiro.au
w www.csiro.au/people/adam.liedloff