

The implications of climate change for biodiversity conservation and the National Reserve System: hummock grasslands biome

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Contents

Acknowledgements	v
Executive summary.....	vii
1 Introduction	1
1.1 Aims, background and context	1
2 Biome characteristics and ecosystem drivers	3
2.1 Geographical distribution	3
2.2 Biogeography, biodiversity and conservation significance.....	5
2.3 People	7
2.4 Key ecosystem drivers structuring the biome	8
3 Methods	15
3.1 Review.....	15
3.2 Expert workshop.....	15
3.3 Predicting change in today’s environments.....	15
4 How will future climate and environments change in the HGB?.....	16
4.1 Future climate	16
4.2 Environmental change	17
5 Other factors affecting environmental change.....	24
5.1 CO ₂ fertilisation	24
5.2 Fire	24
5.3 Increasing aridity – water and heat stress	25
5.4 Invasive plants.....	25
5.5 Does habitat loss magnify changes in environments or reduce the buffering?	28
6 Implications of potential responses of biodiversity to changing environments.....	29
6.1 Biogeographical responses – potential places of diversification, refugia and endemism.....	29
6.2 Broad ecological responses.....	30
7 Management implications	33
7.1 Capability issues.....	33
7.2 Issues affecting where to manage	34
7.3 Unknown uncertainty issues.....	35
8 Conclusions	39
References	40
Appendix A Workshop summary	49
Appendix B Climate modelling in detail.....	54
Appendix C Changes in the environments of spinifex and non-spinifex major vegetation groups of hummock grasslands biome	58

Appendix D	Relationship between CO ₂ and daytime growing season temperature of C ₃ and C ₄ grasses...	59
Appendix E	Projected mapping of major vegetation groups for dry hummock grasslands based on environmental change in 2070 for high emission scenario.....	60
Appendix F	Compositional change in current taxon groups responding to environmental change under 2070 medium and high climate scenarios by major vegetation groups	61

Figures

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.....	2
Figure 2	Map of Australia’s hummock grasslands biome, showing the major and minor functional components and the focal area for this report (i.e. report boundary). The major component forms a moderate to high proportion of <i>Triodia</i> hummock grasslands (spinifex) in the biome, while the minor component is a small proportion of <i>Triodia</i> hummock grasslands of biodiversity significance. Assessment was based on data from the National Vegetation Information System 3.1, State and Territory herbarium records and expert advice provided by State and Territory government environmental agencies	4
Figure 3	Ecosystem drivers of the hummock grasslands biome, showing the ecological relationships, environmental stressors due to human activity and the potential impacts of climate change in red. The ecological processes and the environmental stressors interactively influence the community structure and ecosystem function of the hummock grassland biome. Its resilience and capacity to recalibrate in response to climate change (interactively with other stressors) will have implications for ‘climate adaptation’ conservation and NRS planning. (*high ability to photosynthesise carbohydrate, so plants have energy-rich arils, extra-floral nectaries and fleshy fruits, structural defences against herbivores (e.g. tannins))	9
Figure 4	Annual rainfall and cumulative rainfall residuals above and below the century mean annual rainfall for Karratha (WA), Alice Springs (NT) and Renmark (SA) rainfall stations in the hummock grassland biome. Polynomial curves are fitted for each rainfall variable. Rain year is August to July, cum sum = cumulative sum, Poly. (cum sum) = polynomial curve for cum sum	11
Figure 5	Relative environmental stress maps (measured by ANN dissimilarity) in the HGB, showing modelled current situation and future changes under 2070 medium and high scenarios. (Dark shading represents the greatest environmental stress. Patchiness ranges from 1 km ² grid cell to broader scales).....	17
Figure 6	Example of regional relative environmental stress maps (measured by ANN dissimilarity) for pre-1770 (a) and present (b) Murray Mallee region, South Australia showing future change under 2070 high scenario. (Dark shading represents the greatest environmental stress).....	18
Figure 7	Projected compositional change for each 1 km ² cell calculated from GDM modelling for reptiles, plants and snails. (Stress level: green – low, yellow – moderate, dark pink - high, dark purple – extremely high)	19
Figure 8	(a) – (b) The lowest value of environmental change (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 in the 2070 medium and high scenario. Environmental change: green = environments similar to today’s will still be found somewhere in 2070, pinks = present environments likely to disappear by 2070. (c) – (d). Environmental change: green = future environments have a contemporary analogue somewhere, pinks = future environments not currently represented in the continent	21

Figure 9 The proportional change in buffering (effective habit area) for radii of 3 km and 100 km surrounding a 'central location' (1 km² grid cell) with the HGB. (Dark browns = increased environmental stress per buffering scale, so poor projected landscape buffering via landscape heterogeneity; light green = little change in buffering compared to the present; dark greens (> 1) = improved buffering similar to today's environments) 22

Figure 10 Local (3 km radius) and broadscale (100 km radius) buffering via landscape heterogeneity projected for 2070 medium and 2070 high emissions scenarios for present plant species composition. Dark blues = good buffering relative to 'focal location' (more similar environments within the buffer zone than any other location (1 km² grid cell) in the biome); pale blues (~ 0) = little buffering as present environments for present plant species composition are highly stressed; brown = rare cases where the 2070 environments are more similar than that found anywhere else at the scale of buffering..... 23

Figure 11 Biome boundaries (a) and probability of high suitability for buffel grass colonisation under current climate scenario (b), 2070 medium emissions scenario (c), 2070 high emissions scenario (d), change in predicted high suitability between current climate and 2070 medium emissions scenario (e), and current climate and 2070 high emission scenario (f). (b–d: pale purples – low probability (< 20%, medium purples – moderate probability (20–39%), dark purples – high probability (40–59%), royal blue – very high probability (>60%) of high suitability; e–f: brown shades – increasing suitability; blue shades – decreasing suitability) . 27

Figure 12 Proportional change in buffering (effective habitat area) for a radius of 50 km from a central location (1 km² grid cell) based on extant vegetation within the Flinders Ranges (FR) and Murray Mallee (MM) Regions, South Australia. (Dark browns = less buffering; pales to greens (> 0.5) = buffering increasing) 28

Figure 13 (a) Settlements and population centres in the rangelands (representative of the biome) and (b) travel patterns of Aboriginal people from settlements 34

Figure 14 Distribution of water sources for Australia (representative of the biome) in 2002..... 35

Figure D.1 Commonly reported prediction of atmospheric CO₂ and growing-season temperature conditions that favour the growth of C₃ and C₄ grasses, based on the quantum yield of photosynthesis, a measure of the inefficiency caused by photorespiration 59

Figure E.1 (a) NVIS pre-clearing vegetation map, and ANN modelled distribution of environments for (b) current climate, (c) medium 2070, and (d) high 2070 emissions climate change scenarios. Hatched area indicates approximate biome boundary. (Note: Casuarina Forests and Woodlands in central Australia represents Desert Oak *Allocasuarina decaisneana* woodlands and *Casuarina pauper* (Black Oak) in the south) 60

Tables

Table 1 Approximate area statistics of the hummock grassland by State and land use 5

Table 2 Adaptations of desert wildlife representative of the hummock grasslands biome 6

Table 3 Mid-summer and mid-winter temperature statistics (based on 30-year climatology) for four climate stations in the arid/semi-arid hummock grassland bioregion..... 10

Table 4 Proposed climate changes based on CSIRO OzClim and Bureau of Meteorology for 2070 high scenario for the whole dry hummock grasslands biome (up arrow – increase, down arrow – decrease, two arrows – severe implications for biodiversity) 16

Table 5 Postulated responses of biota to key projected environmental changes in the dry hummock grassland biome based on literature, expert advice and modelling. (Bold – 'peer reviewed' field-based evidence, No bold

– expert opinion; up arrow – increase, down arrow – decrease, 2 arrows – greater change, Win-Spr – winter-spring, Veg – vegetation, Spp. – many species, * see Appendix E, projected mapping of major vegetation groups based on environmental change).....31

Table 6 IBRAs and sub-IBRAs where today’s environments undergo substantial change (compositional dissimilarity >0.7) and taxon are projected to undergo high environmental stress36

Table 7 Combined information to postulate places of vulnerability (environmental stress > 0.7 for modelling, very high suitability 0 to -0.4 and key landform features) at the IBRA level.....37

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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 hummock (spinifex) grasslands biome (HGB). It is one of nine reports for the Department of Sustainability, Environment, Water, Population and Communities that address this topic. The work builds on an earlier report on the implications of climate change for the National Reserve System (Dunlop and Brown 2008). That report had a national-scale focus, whereas this phase of the project has drawn on ecological knowledge and analysis at the regional scale.

The HGB is extensive, covering about 60% of Australia. It is relatively intact, with stunning landscapes such as Uluru–Kata Tjuta, Purnululu, Watarrka, Hamersley Ranges, King Leopold Ranges, MacDonnell Ranges National Parks. It also contains internationally recognised Ramsar sites and is socio-economically important for Indigenous and outback culture, mining and ecotourism.

The arid ecosystems of the biome (the focus of this report) make it special on a world scale. They are characterised by endemic, hummock-forming perennial grasses (*Triodia* species) with an overstorey of sparse woodlands and shrublands. A large number of the plants and animals living in these ecosystems are not found elsewhere in the world, even in other deserts. The wildlife survives in extreme aridity not matched anywhere else in the world. The lizard fauna is the richest of any desert in the world and has a unique lineage different from other Australian vertebrates.

Unpredictable rainfall and fire have been shaping the biome over 20 million years; not surprisingly, the wildlife has many quirky adaptations to the resulting aridity, such as C₄ photosynthetic pathways in plants, nocturnal activity, burrowing and aestivation by frogs. Today, the wildlife is pressured by changing fire regimes, invasives (camels, donkeys, goats, rabbits, cats and foxes, as well as buffel grass and other weeds), cattle grazing and climate change. In recognition of its natural heritage value, 15% of the biome is part of the NRS although there is little on-ground management in these reserves. Their remoteness from a potential workforce and from infrastructure make on-ground regular management extremely difficult – perhaps impossible.

What are the key ecosystem drivers of the biome?

Aridity via water and heat stress is a key process structuring vegetation and animal dynamics of the biome. In the dry (semi-arid/arid) parts, aridity is presently the norm in most parts, with unpredictable rainfall in amount from place to place and over the years to decades. The exception is the southern portion, which has a Mediterranean climate with mostly predictable dry summers replenished by annual rainfalls in late autumn, winter and early spring. The dominance of C₄ grasses and the extinction of many mid-sized mammals have been attributed by some researchers to increasing aridity as well as other ‘human related’ factors. Rainfall, which is mostly very low (150–300 mm per year), has a dramatic impact on water and resource availability in semi-arid and arid ecosystems, thereby affecting water stress responses of species and ecological communities in general. High-frequency rainfall variability, especially significant rainfall events, drive plant growth and plant productivity, both of which stimulate herbivores, animal numbers and their predators. Other than rain, groundwater is the only other source of water. The biome contains unique ecosystems with endemic organisms. The high plant productivity after big rain events provides ample fuel for widespread, patchy fires, which structure the biome in other ways. Different landforms such as rocky ranges and outcrops, sand plains, sand dunes, lakes and uncoordinated drainage systems have provided places for diversification and refugia during historical climate fluctuations. They are still important today.

How will future climate and environments change in the dry (arid/semi-arid) parts of the biome?

Despite the many assumptions, imprecision of modelling and uncertainty about species–climate interactions, using the precautionary principle and the ethos of adaptive management that is already prevalent in biodiversity

conservation, we are confident that most biota will encounter extraordinary changes in living conditions over the next 60 years.

By 2070, temperatures are expected to increase by 3–7 °C, especially in summer. Rainfall is expected to increase in the Pilbara region but decrease everywhere else, especially in the south. Its variability and intensity is expected to increase, especially in the western half of Queensland. Sea inundation and increased storm activity are predicted for coastal Western Australia. Overall, moister environments are expected in the north-west, but increasing aridity is expected elsewhere in the biome, especially in the Mediterranean south.

Climate change will continue to lead to very significant environmental change in the biome by 2070; it is projected to experience the second highest level of biotically scaled environmental stress of the four case studies. The environmental stress is projected to be extreme for plant, reptile and snail species (> 0.7 on a scale of 0 to 1.0). For bird, mammal and frog species, environmental stress is projected to be less, opening up a window for strategic management in the immediate term. In the immediate future by 2030, environmental stress patterns project an environmental change front which appears to extend from the north of the biome with the leading edge gradually creeping in a southerly direction. The temporal nature of this change suggests that opportunities exist for strategic NRS and biodiversity conservation planning.

What are the implications for the biome's biodiversity?

Environments supporting the familiar ecological communities of today are projected to shift and this will affect the biome's biodiversity. In response, ecological communities and species populations of the biome will restructure and change in distribution in ways that are impossible to predict. For example, some present environments supporting present-day plant communities will completely disappear, while novel environments not previously witnessed in the biome in the past or today are projected to emerge. If today's plant species can be buffered from such dramatic changes by exploiting landscape heterogeneity at multiple scales (microhabitat to broader scales) as the front of environmental change expands, they may be able to survive. However, our modelling predicted poor environmental buffering at local scales (within a 3 km radius). Reasons for this are unclear as it is possible that the modelling was too coarse to detect fine-scale buffering, or perhaps the environmental change will exceed the buffering at this scale. At broader scales (100 km radius), some good buffering of environmental change for biodiversity was mapped for a few pockets if the biota had the capacity to track these areas over 100 km during the next six decades. These pockets exist in rocky ranges and outcrops as well as on the flatter sand plains / dune fields. Ecological and quantitative analysis of buffering and refuges is a rapidly developing research area, so the extent to which environmental heterogeneity provides buffering in different parts of this biome remains open and important research.

What are the implications for management?

We minimise the number of qualitative statements about the implications of climate change on the species management mainly because of our extremely poor field knowledge about how climate change phenomena such as CO₂, temperature, rainfall regimes and extreme events explicitly affect key ecological processes known to drive 'climate change related' threshold responses of species (e.g. phenology, physiology population dynamics). Similarly, as critical as they are, we know very little about how the dynamics of species-specific interactions will change and what effects they will have on ecological processes in the biome. The hummock grasslands span most of Australia, making it highly diverse biologically and environmentally at multiple spatial and temporal scales. While modelled projections about environmental stress provide more management information, they nevertheless are correlative and remain untested by field experiments for most of the biome's species and communities, and thus should be interpreted critically to avoid counterproductive management.

Nevertheless, some guiding principles for the biome's management have emerged:

- The biome is predicted to become hotter and more arid and have environmental shifts by 2070 that differ from what we know today and are likely to lead to considerable compositional and structural changes in its ecological communities.
- Increasing aridity in the southern Mediterranean parts and its loss in the northern parts of the biome may push some species beyond their ecophysiological thresholds and lead to extinctions. When habitat loss is

considered alongside of climate change in the Murray Mallee region in the south, the pressures of environmental change are accentuated.

- Very significant levels of environmental change are predicted for the biome by 2070; therefore high levels of ecological change via diversification, contraction and re-sorting are hypothesised to occur unevenly throughout the biome.
- Places of refuge and sources of species radiation especially in the south-eastern parts of the biome, which also are predicted to be highly suitable for buffel grass, will need special management.
- Massive fires occur at a scale much bigger than the NRS properties, creating random disconnectedness among environments. Under climate change, future fire management will therefore need to extend beyond NRS boundaries and be flexible to cope with random events.
- The biome is too big and difficult to manage as a single unit due to contrasting climates and different threatening processes in the north and south. Smaller management units will need to be created and managed as a network.
- Strategic management that adopts the precautionary principle and an 'adaptive management' ethos will be essential to reduce uncertainty in management.
- Threats must be eradicated or minimised to secure environmental diversity within and outside the NRS and biodiversity monitoring and evaluation (M&E) implemented to track changes and management responses in the long term. Local Indigenous people populate the biome in small settlements, and are a potential workforce that could manage the local landscapes jointly with the government.
- Biodiversity M&E should have robust actionable outcomes, places prioritised, viability assessment undertaken on the priority places and a multiple criteria decision analysis done to prioritise timely and effective management.
- Large, isolated and remote areas of the biome where there are no nearby settlements or infrastructure to support a regular workforce to manage for climate change related impacts on biodiversity will need to be left to self-regulate.

1 Introduction

1.1 Aims, background and context

This report describes the future implications of climate change on the biodiversity, conservation and the National Reserve System (NRS) of the hummock (spinifex) grasslands biome (HGB). It is one of nine reports on Australia's biodiversity and the NRS that the Department of Sustainability, Environment, Water, Population and Communities is addressing on this topic, using four biomes as case studies (savanna woodlands and grasslands biome, Liedloff et al. 2012; sclerophyll forests of south-eastern Australia, House et al. 2012; temperate grasslands and grassy woodlands, Prober et al. 2012) and four approaches to climate modelling applied on each biome where scientifically meaningful (climate downscaling, Harwood et al. 2012; generalised dissimilarity modelling for biomes, Ferrier et al. 2012; artificial neural networks modelling for biomes, Hilbert and Fletcher 2012; Bayesian belief network modelling of buffel grass, 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, private consultants and the Climate Change in Agriculture and Natural Resources Working Group (CLAN). It builds on an earlier report on the implications of climate change for the NRS (Dunlop and Brown 2008). That report had a national-scale focus, whereas this phase of the project has drawn 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, making climate adaptation a challenge (Fischlin and Midgley 2007). Biodiversity security into the future is important as the health of humans depend on it (see evidence in Chivian and Berstein 2008). There is an urgency to develop on-ground climate adaptation interventions 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 impact on the HGB is a national concern as it extends over five jurisdictions (WA, NT, Qld and SA, with small areas in NSW) and is the largest relatively intact biome in Australia. Despite HGB biotic richness being relatively lower than other regions of Australia, the biome supports a large number of desert plants and animals not found elsewhere in the world and, even on a world scale for deserts, no other biota survives in such 'extreme bioclimatic habitats' (Pavey and Nano 2006). The desert lizard fauna, which is the richest of any desert in the world (Pianka 1969; Griffin 1984; Morton and James 1988) has developed differently from other Australian vertebrates (Powney et al. 2010). The biome has internationally valuable social and economic assets such as ecotourism and mining worth billions of GDP dollars.

Dunlop and Brown (2008) developed a hierarchical framework for understanding the 'cascade of impacts' by climate change based on changes in the environment. Impacts at this basic level trigger a cascade of changes as flow-on and feedback effects are felt on the biology and ecology of individuals, species populations, ecosystems and eventually people (Figure 1). Many types of changes will affect biological and societal phenomena with a little known but a lot of unknown uncertainty. It is clear that the responses of individual organisms to climate change will translate into changes in the phenology, relative abundances and range of many species (Hughes 2003; Dunlop and Brown 2008; Steffen et al. 2009), community structure and composition (Ferrier et al. 2012; Hilbert

and Fletcher 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 at all stages and the role of conservation is to manage this change in a way that minimises losses of biodiversity values (Dunlop and Brown 2008). There is an urgent need to identify what changes to biodiversity management and the NRS are needed to manage this process.

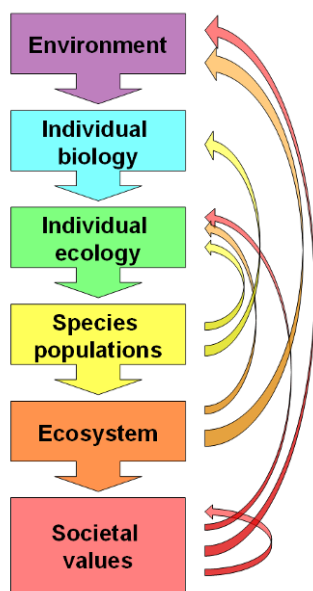


Figure 1 Schematic representation of cascading impacts on biological phenomena and societal values resulting from environmental changes. The direct flow of impacts is represented by large arrows. Important indirect flow is shown as feedback. Changes in the environment trigger many biological and societal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

Source: Dunlop and Brown 2008

In this report, our aim is fourfold: (i) describe the geographical distribution, biodiversity and ecosystem drivers structuring the biome and its people, (ii) identify future environmental changes caused by climate change, (iii) postulate how biodiversity will respond to environmental changes, and (iv) discuss the implications of future environmental change and biodiversity responses in terms of climate adaptation in conservation and NRS planning. This report draws on a wide range of biome-specific information, including a literature review, an expert workshop, ecological thinking about Australia’s arid ecology (Stafford Smith and Morton 1990; Morton and Landsberg 2003; Morton et al. 2011), and the 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 statistically robust, it by necessity omits many of the factors and complexities that will determine ecological outcomes, including the direct effects of increases in CO₂ 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 as we lack the evidence base. We minimise the number of qualitative statements for most species about threshold changes in species phenological, physiological and population responses to changes in CO₂, 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 in the biome, mainly because the biome is so diverse at multiple spatial and temporal scales.

2 Biome characteristics and ecosystem drivers

2.1 Geographical distribution

The HGB is most recognised for its hummock-forming grasses, a growth form rarely found outside of Australia (Rice and Westoby 1999). It is commonly known as spinifex of the genus *Triodia*; it forms great expanses of perennial ground cover in arid/semi-arid Australia and is compositionally diverse. It commonly occurs in association with other vegetation types that form an overstorey of diverse, fire-tolerant woodland and shrubland dominated by mallee eucalypt, desert oak, acacia, hakea and grevillea species. Where woodlands and shrublands are sparse, spinifex is floristically and structurally dominant and is mapped nationally in the National Vegetation Information System (NVIS) as the Hummock grasslands Major Vegetation Group (MVG 20, DEWR 2007). The hummock grasslands can also include three other hummock-forming grasses of the genera *Symplectroidia*, *Monodia* (Allan and Southgate 2002) and *Zygochloa*, which are not spinifex (*Triodia*). For the purposes of this report, we focus on spinifex-associated environments.

Spinifex occurs on soils that are well-drained and low in nutrients, usually with acid surfaces (Griffin 1984; Rice & Westoby 1999). With stiff and pointed leaves, plants often grow as expanding domes with active leaves on the outer surface. Over time, the dome may develop into a ring or semi-circle as the centre subsides. It is highly flammable and burns regularly, as discussed later. It tolerates very high moisture stress but generally is absent from extreme environments such as mobile dune crests (Griffin 1984). Perennial shrubs can be found interspersed between spinifex clumps all year round unless recently burnt. After rains, a carpet of annual grasses, daisies and other herbs cover the ground, interspersed among spinifex clumps.

Because spinifex is not fully represented by the MVG 20 of the NVIS, we used three criteria to derive the HGB:

- Spinifex forms the major functional component of the vegetation, including the vegetation associations/ecosystems that have sparse trees, which form over the spinifex stratum (e.g. mallee woodlands).
- Minor functional components of spinifex in other major vegetation groups that have biodiversity significance and which are possibly susceptible to climate change impacts are included.
- The boundary of the HGB aligns with [Interim Biogeographic Regionalisation for Australia](#) (IBRA) subregions, so that we deal with landscapes as functional units rather than patches of a specific vegetation type within a landscape.

This was achieved by first mapping a combination of the lower level data of the Hummock grasslands (MVG 20) from the NVIS 3.1 with vegetation mapping of *Triodia* species from State and Territory herbarium records. We then overlaid this information with the IBRA subregions to produce a draft boundary for review by the workshop and other State government agency experts. During this process, it was apparent from the review that both types of spatial data did not accurately map the distribution of spinifex for some IBRA subregions. The map shown in Figure 2 is a national consensus of distribution of the HGB in Australia using the criteria above.

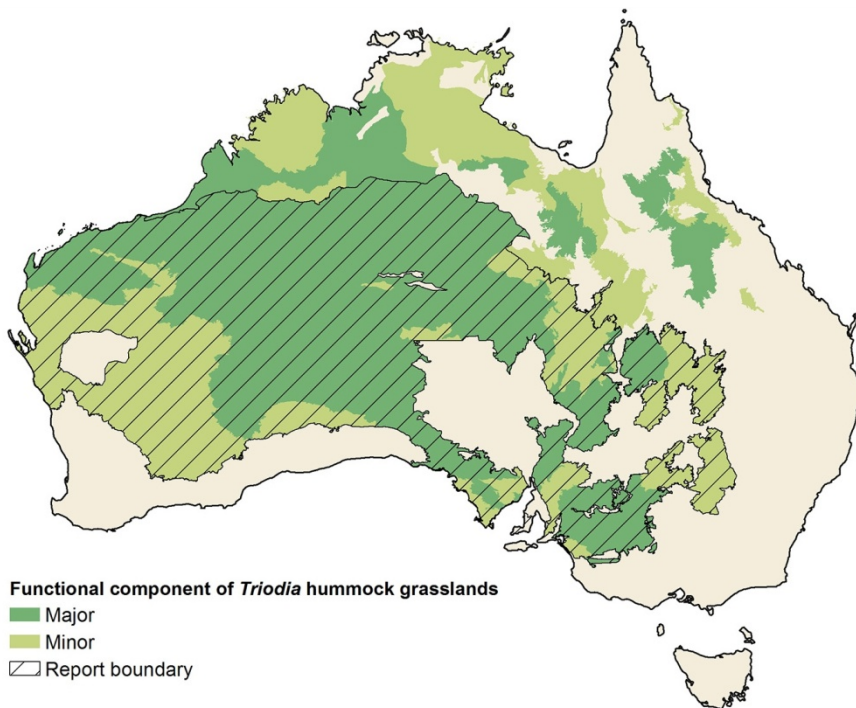


Figure 2 Map of Australia's hummock grasslands biome, showing the major and minor functional components and the focal area for this report (i.e. report boundary). The major component forms a moderate to high proportion of *Triodia* hummock grasslands (spinifex) in the biome, while the minor component is a small proportion of *Triodia* hummock grasslands of biodiversity significance. Assessment was based on data from the National Vegetation Information System 3.1, State and Territory herbarium records and expert advice provided by State and Territory government environmental agencies

The HGB covers 4,697,609 km² (~ 60% of the continent) when mapped at the IBRA subregional level. The major functional component covers just over a third of the continent (2,823,578 km²) but is extended by almost a third again by the 'biodiversity significant' minor component belonging to other MVGs (Table 1). This component shows a larger functional distribution than occurs on the ground because it was extrapolated to IBRA subregions. The biome has about 40 IBRA regions, with the Pilbara, Great Sandy Desert, Gibson Desert, Little Sandy Desert, Great Victoria Desert, Tanami and Simpson-Strzelecki Dunefields IBRAs having the most extensive distributions. Topographically, it is diverse with many arid mountain ranges such as King Leopold, Hamersley, Petermann and MacDonnell Ranges, which give way to sand plains and dune fields. It is relatively intact, with about 3% lost to vegetation clearing and increased salinity, particularly in Western Australia and the southern Murray Mallee region in the south-eastern part of the biome (Table 1). Relative to its extent in Australia, the biome is well-represented in the NRS, although at the time of writing South Australia has less protected than other jurisdictions. When considering the NRS (all IUCN categories), the area represented in the HGB is 12% (540,199 km²). Tenure is mainly Crown or Aboriginal land in almost all jurisdictions. In the Northern Territory and Western Australia, large areas of pastoral land are covered by soft or gummy spinifex *T. pungens* or the prostrate curly spinifex *T. bitextura*.

To avoid a large overlap with the report on Savanna woodlands and grasslands (Liedloff et al. 2012), we concentrated on the Dry and the drier parts of Mediterranean agro-climate zones of the biome (Hobbs and McIntyre 2005), hereafter termed the 'dry' HGB (hatched area in Figure 2).

Table 1 Approximate area statistics of the hummock grassland by State and land use

HUMMOCK GRASSLAND COVER	WESTERN AUSTRALIA	NORTHERN TERRITORY	SOUTH AUSTRALIA	QUEENS-LAND	NEW SOUTH WALES	VICTORIA
Area (km ²) ^a	2,061,426	1,172,280	527,333	719,293	173,060	44,216
Major component	1,224,425	818,368	389,946	292,157	54,467	44,216
Minor component	837,002	353,912	137,388	427,136	118,592	0
% of State covered ^a	82	87	54	42	22	19
Dominance in jurisdiction ^b	1	1	2	5	low	low
% change since settlement ^b	0.05	0.03	<0.01	0.02	<0.01	<0.01
% National Reserve System per State ^c	~81	~88	~28	~23	21	44

^a Statistics extrapolated using the map in Figure 2; ^b NVIS 2005 data – total equals 1,760,100 km² but after subsequent jurisdictional revisions of vegetation mapping, it is reduced to 1,367,973 km² (DEWR 2007); ^c CAPAD 2010 'DETAIL' figures for 'gazetted area' of all IUCN categories at the IBRA level of the biome.

2.2 Biogeography, biodiversity and conservation significance

2.2.1 BIOTIC RESPONSES TO HISTORICAL CLIMATE CHANGE

Since 20 million years ago (Ma), the biota of inland Australia have evolved from warm, humid environments to persist in cold, arid ones (Byrne et al. 2008). During the late Miocene, the once prevalent *Nothofagus* and mixed Gondwanan broad-leafed forests were progressively succeeded by sclerophyll communities, open grassland and chenopod plains which were better suited to the increasingly arid conditions and magnified seasonality. During increasingly severe glacial periods of the Pliocene (~5 Ma), temperatures decreased beyond those previously experienced by biota. Frosts became more common, and arid environments expanded significantly. The spatial and temporal climatic extremes of the Pleistocene caused intense aridity and low temperatures that exceeded thresholds of vegetation in many regions and, through loss of vegetation, greatly increased erosion and land surface wind speed. At the Last Glacial Maximum 20,000 years ago (20 Ka), temperatures were as low as -10 °C. In these harsh times, vegetation loss led to reactivation of dunes and greatly expanded the arid environments. In other parts of world, evidence of these rapidly changing glacial (xeric) and interglacial (mesic) times indicates that there were cyclical shifts in the dominance of C₃ to C₄ vegetation, with C₄ tending to dominate with increasing aridity, in part because of CO₂ concentrations being low (e.g. Mampuku et al. 2008). Presently, we are in an interglacial period that is drier than historic interglacials (Martin 2006).

Desert biota (representative of the HGB) evolved during the Pliocene before the dramatic Pleistocene aridity that stabilised at about 400 Ka (Byrne et al. 2008). It is thought that intra-specific diversification from the mesic northern and southern parts rather than speciation during the Pleistocene influences present adaptations to aridity and species distributions (Byrne et al. 2008). Some of today's taxa have diversified from a single ancestral form from the tropics or temperate zone (*Calotis*, *Lepidium*, *Ctenophorus* lizards, diving beetles, amphipods, woodswallows, *Gossypium* (tropical origin), *Flindersia* (tropical origin)). Examples of those that have diversified from multiple ancestral forms in more mesic environments are acacias, dasyurid marsupials and sphenomorphine skinks. Halophytic chenopods are highly correlated with the emergence of saline water. Overall, sclerophyllous vegetation and heat and desiccation tolerance of reptiles today are adaptations to aridity and colonisation during increasing aridity.

Although some Pliocene sedentary species survived through adaptations, the rapidity of the changing climates in the Pleistocene is likely to have selected against many species too (Byrne et al. 2008). Those that survived probably used multiple, localised refugia on a microgeographical scale throughout their distributions. Local populations probably diverged via repeated contractions and expansions of distributions using 'refugia within refugia', strongly indicating an idiosyncratic (species-specific) basis for places of refugia. Mobile species (birds, snakes, lizards, freshwater prawns, fish) responded via rapid expansions across large areas; but without a leading

edge supported by hybridisation, polyploidisation and parthenogenesis, some would have become reproductively isolated.

Changes from tropical warm conditions to extreme heat, aridity and salinity during the Pleistocene glacials have forced plants and animals of the arid interior to evolve morphological, behavioural and physiological adaptations to water, heat and salinity stresses (Table 2) that enable them to sustain viable populations under the contemporary, extreme climatic conditions (Morton and Landsberg 2003; Pavey and Nano 2006). However, extreme frost may have a severe impact as contemporary vegetation has never been exposed to frosts beyond ~-10 °C during the glacial fluctuations (Byrne et al. 2008). There are no major centres of endemism in the biome (most are coastal, Crisp et al. 2001), reflecting that biota are well adapted to aridity of the Last Glacial Maximum.

Table 2 Adaptations of desert wildlife representative of the hummock grasslands biome

TAXON	STRATUM	ADAPTATION MORPHOLOGY	BEHAVIOURAL	PHYSIOLOGICAL
Plants	Above ground	Sclerophyllous (hard) waxy/hairy leaves (spinifex), greatly reduced leaves (cladodes, desert oak), vertically flattened phyllodes (acacias), succulent leaves and stems (parakeelyas)	Vertically oriented leaves to minimise solar radiation	C ₄ photosynthesis to maximise CO ₂ uptake, decreases organic material and nutrient loss; rapid growth and seed production after significant rain (short-lived plants); long-term/ staggered seed banks, seed resistance to available moisture until significant rains
	Below ground	Perennial rhizomes/tubers (nardoo); deep tap roots into groundwater (mulga), extensive lateral root systems for surface water uptake	Topographical microhabitat use to maximise water and nutrients (e.g. mulga groves)	
Animals			Nocturnal activity, burrowing, total subterranean life (e.g. marsupial mole, termites, ants), selection of microhabitats to reduce heat stress (change body position; climb to higher position; use shade from vegetation, cavities, rock overhangs, other fauna), daily drinking at permanent water sources (seed-eating birds, medium- to large-sized mammals)	Water from food and its digestion (foliage, nectar, seeds, other animals); highly concentrated urine and very dry faeces; aestivation (frogs), torpor, hibernation and rapid reproduction after significant rains (frogs, shield shrimps), parrots' water economy index is among the lowest that have been reported for desert-adapted birds (Williams et al. 1991).

Source: summarised after Morton and Landsberg (2003), Pavey and Nano (2006)

2.2.2 BIODIVERSITY

Nineteen of the 23 MVGs occur in the biome. Seven biogeographically distinct spinifex alliances have been identified (Allan and Southgate 2002), covering a total of 93% of the biome. Plant richness is comparatively lower compared to other more mesic biomes. For example, up to 154 and 180 species have been recorded for the sand plains in central Australia (Griffin 1984). *Triodia* itself is very diverse at 64 species. A few species are widespread (e.g. *T. pungens*, *T. basedowii*), or have very large populations (e.g. *T. schinzii*). Most, however, have localised distributions or occur in localised specialised habitats (Allan and Southgate 2002). Most places tend to be dominated by a single species with some intermixing by a second species, depending on the topography. For example, *T. basedowii*, the most widespread, commonly occurs on sand plains and dune systems south-west of Alice Springs in the Simpson Desert and channel country in Qld, the Western Deserts of WA and north-western SA. Other alliances are found on rocky hills, mountain range slopes, ephemeral dry watercourses, salt lake systems, coastal limestone islands (e.g. Barrow Island) and gibber plains of WA.

Animal richness for most groups is relatively low except for the desert lizard fauna, which is the richest of any desert in the world (Pianka 1969; Morton and James 1988; Griffin 1984), making the biome a 'hotspot' for reptiles. Frogs, reptiles, birds and mammals represent approximately 20%, 26%, 30% and 26% of Australia's species respectively (Pavey and Nano 2006). Frogs are poorly surveyed as they are not commonly encountered, although they can be found around the few permanent water sources, mostly after significant rain. Reptile fauna is rich, supporting most groups, some unique fauna (such as the thorny devil *Moloch horridus*) and large numbers (up to 400 individuals per hectare for 40 species in central Australia). Birds are the most well-known taxa of the biome (Smyth and James 2004). About 40 species of birds are biome-dependent and common, whereas the rest (just under 200) occur outside the biome across Australia. Around 95 species of mammals were reported for Australian deserts at the time of settlement; 22 species are now extinct. In central Australia (and possibly elsewhere in the biome, although it is not known), freshwater fish occur in permanent and semi-permanent waterholes of which most (possibly all) are sustained by groundwater (Box et al. 2008). These waterholes, which occur at local scales of less than 1 km², are special relicts of mesic paleoclimates of 14–16 Ma and are contemporary models of climate refugia. Three species of fish are endemic to this region and possibly other regions of the biome. As for invertebrates, little is known about terrestrial and aquatic taxa mainly because of a lack of taxonomic knowledge as new species continue to be discovered (Pavey and Nano 2006; Box et al. 2008). However, it is recognised that insects are the largest taxonomic class in number and biomass, and groups such as the termites and ants play an important role in ecosystem functioning (Stafford Smith and Morton 1990). Groundwater appears to be a biodiversity hotspot for stygofauna.

2.2.3 CONSERVATION SIGNIFICANCE

Conservation significance of biota is notable for an intact biome. Although there are no ecological communities listed as threatened or of conservation concern for the whole biome, a number of plant taxa are, including *T. fitzgeraldi*, under the Northern Territory legislation. This species, which occurs in the rocky hills, is threatened by 'stochastic events'. Thirty-one animal species (butterflies, land snail, fish, reptiles, birds and mammals) are listed as threatened or conservation significant for the whole biome. However, when the dry HGB is assessed from a regional perspective, all of the IBRAs (24 in total) have some plant and terrestrial vertebrate species reported as extinct by 2001. More significant is that 20 IBRAs continue to have biota declining. Birds, which tend to have a higher reporting rate than other taxa, are reported to be declining in 13 of them (summarised from Table 1 in Smyth and James 2004). If the same level of reporting occurred for other taxa, the conservation significance could be more alarming.

2.3 People

The spinifex deserts have great social and cultural significance for Aboriginal people (Davies et al. 2008). Stafford Smith (2008) described the socio-economic characteristics of Australian deserts (also representative of the dry HGB). The sparseness and patchiness of the human population and the remoteness of the arid deserts largely influence the predictability in and the lack of control over markets, labour and government policy. The human population is sparse at 0.05 persons per km² (177,000 people), living mostly in regional centres, but there are many Aboriginal settlements of 30–1,000 people (see Davies et al. 2007 for a subset of statistics for the spinifex deserts). More importantly, the population is highly mobile in the short and longer term, with Aboriginal people being mostly mobile among the Western Desert remote communities and Alice Springs.

Major land uses are tourism, mining, nature conservation, customary harvest and pastoralism, particularly in the Pilbara and Kimberley regions (sheep and cattle) and parts of the Tanami Desert (cattle) (Fisher et al. 2005). Many opportunities for Aboriginal livelihoods have been identified, the most notable being custodial management of country (landscapes) using local rangers (Davies et al. 2008).

2.4 Key ecosystem drivers structuring the biome

2.4.1 ECOLOGICAL RELATIONSHIPS

The HGB's ecosystems are shaped by complex ecological process and environmental stressors, including climate change. They are composed of many individuals of multiple species that interact with each other, the climate, water, nutrient and soil resources, and fire to form complex community structures and dynamics (Figure 3). These are modified by environmental stressors resulting from human activities.

With unpredictably low rainfall and rare significant rains in most of the arid/semi-arid parts of the biome, extreme high temperatures and high evaporation rates, water (surface and groundwater), nutrients, ancient soils and fire are natural processes fundamental to structuring the biome. Water resulting from rain events or groundwater creates a cascade of ecological processes, namely vegetation growth and seed production (Griffin & Friedel 1985), irruptions of herbivores and increased total herbivore pressure in response to increased plant productivity (e.g. folivorous insects, kangaroos, livestock and camels), dispersal of seeds by granivores (e.g. mammals, birds), and increased predation of herbivores by carnivores. Once dried, the plentiful vegetation produced after significant rains provides ample activity for detritivores (e.g. termites, microbes) and fuel for fires, some of which historically were massive wildfires. Fires stimulate different vegetation responses, depending on the season and amount of follow-up rains. However, environmental stressors (as shown in Figure 3) can cause threshold shifts and send biodiversity on new trajectories that may have positive, adverse or no effects.

Although generalisations can be made about the drivers of the biome's ecosystems, there remains a lack of mechanistic understanding about how all the linkages translate into landscape patterns and patchiness at smaller scales. This has implications for understanding the responses of biota to climate change and means the interpretation of climate modelling should be done with caution.

2.4.2 ECOSYSTEM DRIVERS

Temperature and water stress

Heat stress due to extremely high temperatures is a major issue for species and ecological communities of arid/semi-arid Australia and the HGB. In summer, daily temperatures soar above 40 °C followed by hot nights (Table 3). The daily range and mean monthly maximum temperatures are the highest in Australia. In winter, temperatures range greatly (increasing with latitude) but vary extremely in the mountain ranges (e.g. variability index for Central Australia and Northern Flinders Ranges). Frost stress is another issue for mountain ranges where 'black frost' events (usually below -5 °C) damage or kill vegetation.

Rainfall in arid Australia, and apropos the HGB, has a dramatic impact on water and resource availability, thereby affecting water stress responses of species and ecological communities. It varies from a distinctly tropical warm-season wet pattern in the Kimberley region to a predominantly dry climate (Hobbs and McIntyre 2005). Most descriptions of rainfall are based on annual means, which are strongly skewed towards a long tail of infrequent large events for arid/semi-arid Australia.

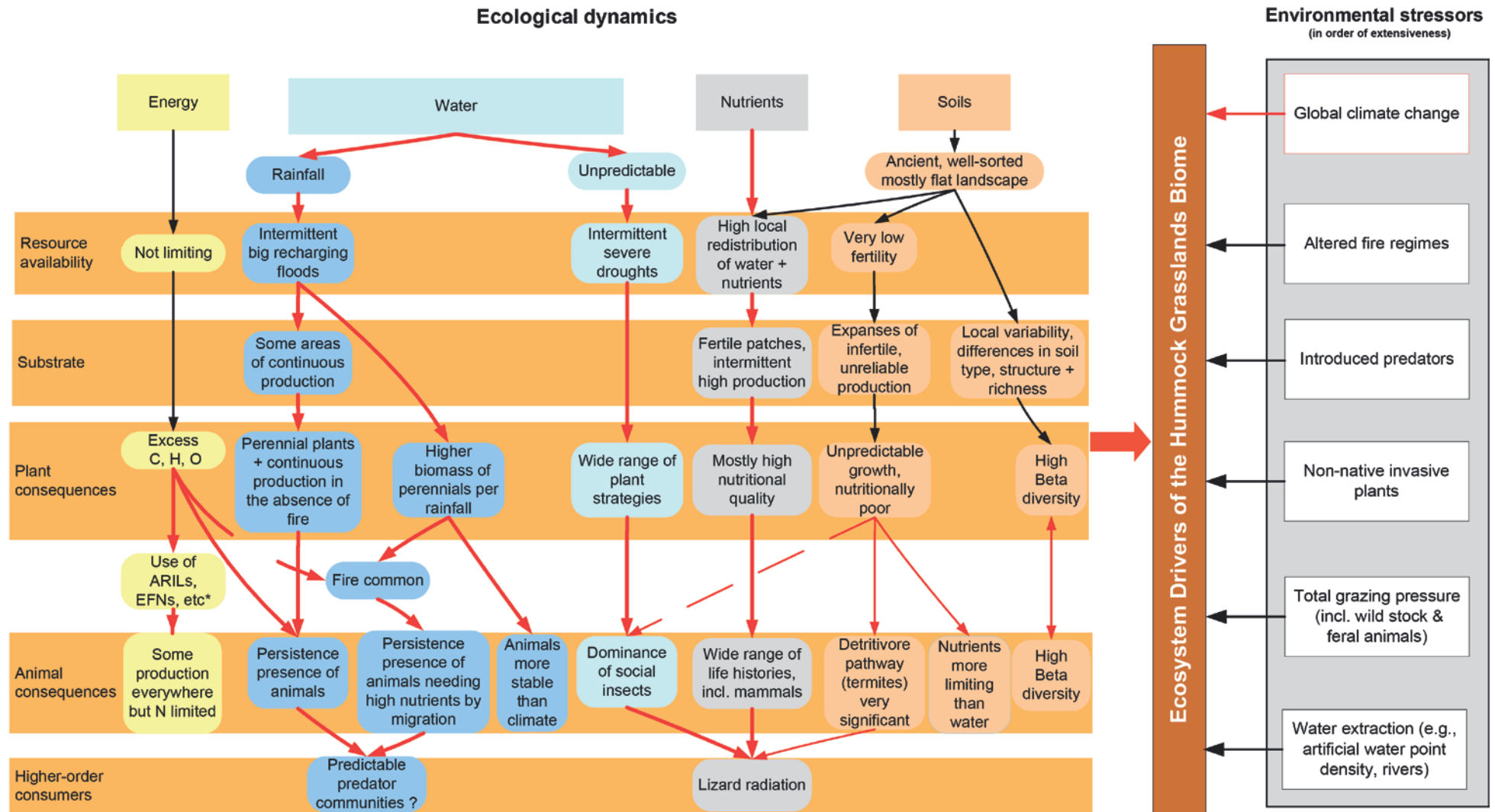


Figure 3 Ecosystem drivers of the hummock grasslands biome, showing the ecological relationships, environmental stressors due to human activity and the potential impacts of climate change in red. The ecological processes and the environmental stressors interactively influence the community structure and ecosystem function of the hummock grassland biome. Its resilience and capacity to recalibrate in response to climate change (interactively with other stressors) will have implications for ‘climate adaptation’ conservation and NRS planning. (*high ability to photosynthesise carbohydrate, so plants have energy-rich arils, extra-floral nectaries and fleshy fruits, structural defences against herbivores (e.g. tannins))

Source: modified after Stafford Smith and Morton (1990)

Table 3 Mid-summer and mid-winter temperature statistics (based on 30-year climatology) for four climate stations in the arid/semi-arid hummock grassland bioregion

(DATA: 1961–1990)	PILBARA REGION (WA)	CENTRAL AUSTRALIA (NT)	SIMPSON DESERT (QLD)	NORTHERN FLINDERS RANGES (SA)
January (mid-summer)				
Mean Min – Max	26.1–40.4	21.3–36.2	23.9–38.6	19.5–33.6
Daily range	30.1	34.7	35.8	34.9
Highest maximum	48.8	44.7	48.0	45.3
Mean no. days ≥ 40 °C	21.3	6.5	13.3	4.2
Lowest minimum	18.7	10.0	12.2	10.4
Variability Index ¹	0.2	0.3	0.3	0.4
July (mid-winter)				
Mean Min – Max	11.8–26.8	3.7–19.5	6.4–20.6	3.2–15.9
Daily range	32.8	37.4	34.1	18.2
Highest maximum	37.1	29.9	32.4	26.0
Lowest minimum	2.2	-7.5	-1.7	-5.0
Mean no. days ≤ 0 °C	0.0	7.0	0.1	7.8
Variability Index ¹	0.2	3.1	1.3	3.3

¹ Variability Index = (90 percentile – 10 percentile)/50 percentile

Data source: Bureau of Meteorology nd

A recent study suggests that terrestrial ecosystems are highly sensitive to high-frequency climate variability (Medvigy et al. 2010). Consequently, a rain year in the dry HGB is best assessed on a seasonal basis using Cumulative Summation of Deviations from the Mean (CUSUM) analysis. Worldwide CUMSUM analysis of rainfall trends revealed that a drying sequence of events occurred in 1894 in Australia, which broadened the arid zone (Kraus 1958). Kerle et al. (2007) found that the drying sequence continued until 1973, especially from the late 1920s for Alice Springs (Figure 4). This long-term drying event coincided with increasing total grazing pressure (McKeon et al. 2004). Since 1974, the time when most biological research has occurred in these regions (Kerle et al. 2007), central Australia and Broken Hill have experienced a wetter cycle. The patterns in Figure 4 tend to be associated with El Niño and La Niña ENSO events (McKeon et al. 2004; Holmgren et al. 2006) and the Indian Ocean Dipole warming and cooling events (Ummenhofer et al. 2009).

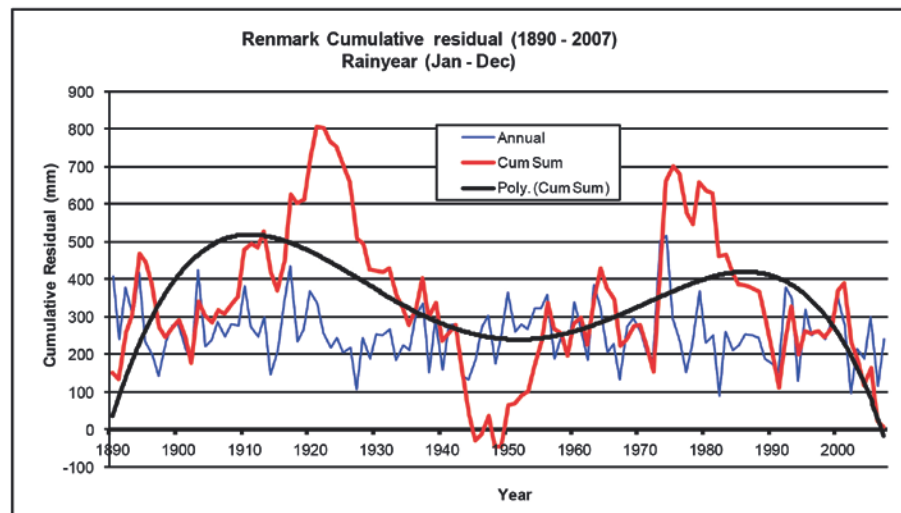
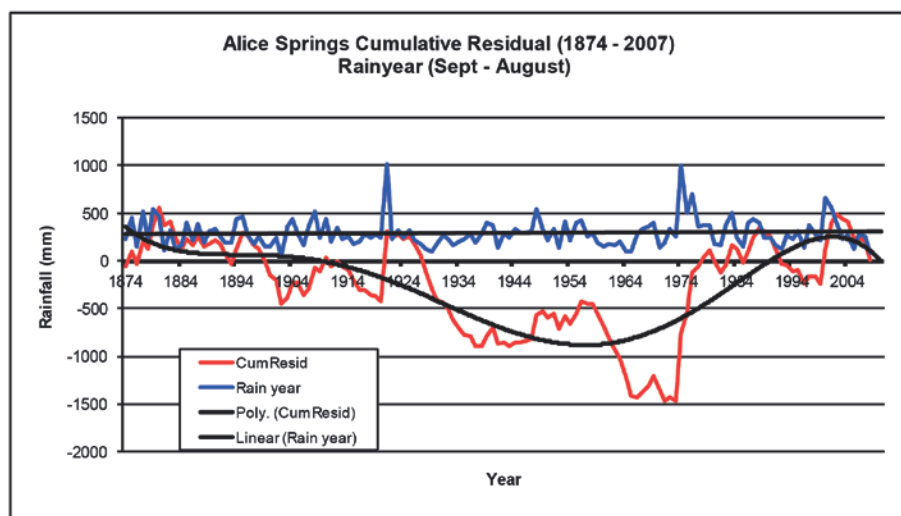
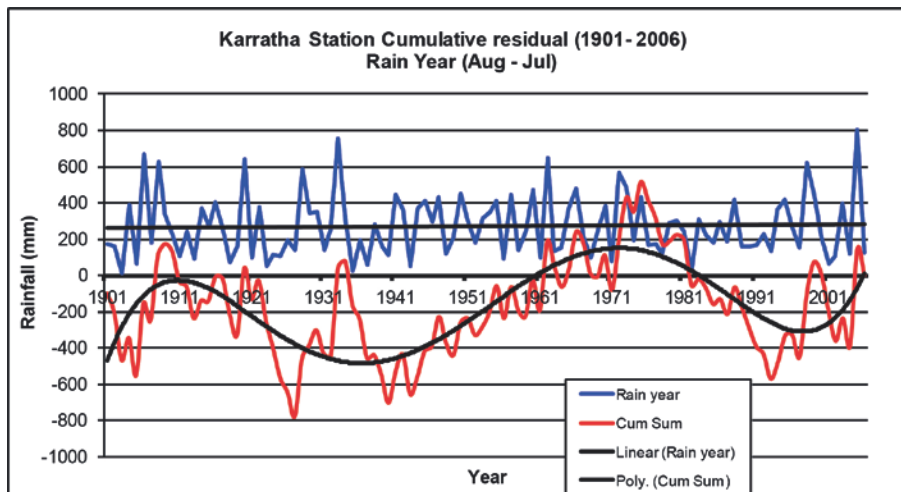


Figure 4 Annual rainfall and cumulative rainfall residuals above and below the century mean annual rainfall for Karratha (WA), Alice Springs (NT) and Renmark (SA) rainfall stations in the hummock grassland biome. Polynomial curves are fitted for each rainfall variable. Rain year is August to July, cum sum = cumulative sum, Poly. (cum sum) = polynomial curve for cum sum

Source: Jeff Foulkes, Department for Environment and Heritage, South Australia, in lit. 2009.

Historical and contemporary fire regimes

The hummock grasslands have been fire-maintained for over 20 My (Hodgkinson et al. 1984). For thousands of years, lightning and burning by Aboriginal people have shaped the diversity of species and ecological communities, the structure and ecosystem function of the hummock grasslands. Historically, we know traditional burning in the Western Deserts (Great Victoria Desert, Great Sandy Desert, Little Sandy Desert and Gibson Desert) produced a landscape mosaic of small burnt patches of vegetation (mean = 63.9 ha, range 5–6,005 ha) at different post-fire succession (Burrows et al. 2006). This suited a diversity of species and ecological communities and subsequently secured people's access to plant and animal bush food (Griffin et al. 1993; Whitehead 2001; Allan and Southgate 2002; Burrows et al. 2006). Fire was also regularly used purposely for many other reasons (Kimber 1983; Griffin 1992; Gill 2000; Allan and Southgate 2002; Burrows et al. 2006). Burning was preferably undertaken in the cooler months of winter and early spring (Kimber 1983). Often, Aboriginal people used knowledge of wind condition, relative humidity, season and natural fire barriers (e.g. claypans, sand dunes) to control the size and intensity of fires (Kimber 1983; Burrows et al. 2006).

Fire continues to have deep ceremonial importance, but traditional burning has ceased as lifestyles have changed (Griffin 1984; Allan and Southgate 2002; Burrows et al. 2006; Davies et al. 2007; Edwards et al. 2008). With the spread of pastoralism, fires have also been suppressed to protect people, stock and infrastructure. In the NRS, fire is managed to conserve biodiversity, and to protect human life, property and cultural values, with a limited degree of success (Edwards et al. 2008). The role of fires in contributing to greenhouse gases emissions and biochar has stimulated new management challenges.

Contemporary fires in the hummock grasslands are affected by fuel load (e.g. 13 t per ha) and the rate of spread. Hummock grasses are fire-tolerant, responding to fire via seeding or resprouting, depending on the environmental conditions and fire patterns (Rice & Westoby 1999). Fuel accumulation rates vary within and between hummock grass alliances but increase with significant rainfall and the time since last fire (Gill 2000; Allan and Southgate 2002; Myers et al. 2005; Wright & Clarke 2007a; Edwards et al. 2008). Flammability of fuels influences the rate of spread. In the hummock grasslands, the size and distance among clumps affects the spread, especially if following good rains. The areas between clumps of hummock grasses support a high cover of short-lived grasses and forbs (especially in the southern Mallee) because when dry, it provides additional fuel for fire or continuance of spread (Griffin 1984; Noble 1989; Bradstock and Gill 1993). Similarly, hummock grasses under mulga communities provide continuance of fire spread (Gill 2000). Other factors influencing fuel accumulation and flammability are seasonal patterns in rainfall, temperature (Turner et al. 2008) and wind (Kimber 1983; Bradstock and Gill 1993; Burrows et al. 2006). In the hummock grasslands, widespread fire events occur following two or more consecutive years of above-average rainfall. They have increased in size and number, occur mostly in the warmer months but some activity is occurring in cooler months, and there is an increase in the number of ignitions associated with settlements, pastoral leases and roads (Allan and Southgate 2002; Burrows et al. 2006; Edwards et al. 2008; Turner et al. 2008).

CO₂ fertilisation

Today's biota have been responding to increasing CO₂ for some time, but it is projected to reach 710 ppm in 2070 which is about twice the present level (Solomon et al. 2007). Considerable effort has been devoted to understanding the responses of plants with C₃ or C₄ photosynthetic pathways. Sixty percent of C₄ species are grasses (Edwards et al. 2010). C₄ grasslands dominate 90–100% of the biome in its north-west and central parts, but in the far south-eastern parts (Flinders Ranges, SA and NSW) C₃ grasses displace the C₄ species, reflecting transition between 'warm wet summers' and 'cold, wet winters' (Hattersley 1983). C₄ grasslands, with their high rate of foliage production, sustain the world's high levels of herbivore consumption (Edwards et al. 2010).

Introduced predators

Feral cats and foxes have spread across most of the HGB (and most of Australia). There is a large body of research on their impacts on native species in Australia's rangelands, and this is relevant to the HGB. They impact on biodiversity through predation and possibly the spread of exotic diseases such as toxoplasmosis, which has been reported as local occurrences (Johnson et al. 1988). Predation by feral cats and foxes has led to local extinctions, which have escalated into regional and national extinctions (e.g. the night parrot around Alice Springs and southern Australia by feral cat, and the numbat in central Australia with the arrival of the fox). They are a particular threat around wetlands and gnammas (water) holes such as in the Gibson Desert region (McKenzie et al. 2007).

Under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), predation by feral cats and foxes is listed as a 'key threatening process' for Australia.

Non-native invasive plants

Non-native invasive plants are threats to all regions of the biome. Some growth forms are very likely to dominate vegetation, or at least the stratum they invade. These 'transformer species' have serious consequences for biodiversity. They include buffel grass (*Pennisetum ciliare* [syn.] *Cenchrus ciliaris*), prickly acacia (*Acacia nilotica*), athel pine (*Tamarix aphylla*) and mesquite (*Prosopis* spp.). They impact by direct competition as they out-compete native plants for requirements, and they can alter fire regimes.

Buffel grass is of particular concern for the HGB. It has socio-economic value as an improved pasture and rehabilitation species of degraded land and is widespread in the biome; its bioclimatic habitat suggests it could spread over most of the continent under present climatic conditions. In central Australia, it caused the decline of all native plant growth forms (nine classes of ground-layer species) and species richness in the Simpson Gap National Park of central Australia over a 27-year period (Clarke et al. 2005). Even in the early stages of invasion, buffel grass can influence plant and bird compositional shifts (Smyth et al. 2009a). Historically, buffel grass never occurred along the Stuart Highway between Alice Springs and Adelaide but now it occurs along the whole route, utilising roadside run-on moist areas.

Total grazing pressure (including feral herbivores and kangaroos)

Pastoral production covers the northern and central Kimberley (cattle), Dampierland (sheep and cattle), Pilbara (sheep and cattle), western part of the Great Victoria Desert (cattle), central Australia (cattle), outer perimeter of the Simpson Desert (cattle), the Flinders Ranges and southern Mallee regions (sheep) (Whitehead 2001; McKenzie et al. 2007; Fisher et al. 2005; Bastin and ACRIS management Committee 2008). Stocking densities are comparatively low at < 2 DSE/km² (versus up to > 100 DSE/km² in central Qld) for most regions except for the Dampierland and Kimberley regions, where it is between about 25 to 40 DSE/km². Since 1983–1991, stocking densities have declined in the Kimberley, Dampierland and south Mallee; increased in central Australia and the Flinders Ranges; and are much the same elsewhere. High densities of artificial waterpoints mean widespread environmental degradation through soil erosion, trampling of soil crusts and vegetation (especially cane grass in the southern Simpson Desert, pers. obs. Anita Smyth), fouling of water supplies (natural water sources) and increased weed invasions. The dry Mediterranean portion of the biome (Flinders Ranges and the southern Mallee regions) is more intensively watered than the interior. Feral herbivores also stress ecosystems of the biome. Camels are the highest methane producing species in Australia, followed by cattle, sheep and goats. Kangaroo densities have also increased in response to the installation of waterpoints and in response to large rain events.

Groundwater extraction

Groundwater extraction is becoming the greatest challenge to sustainable water use (Beeton et al. 2006). Groundwater is being used unsustainably in many groundwater management units. Over-extraction can result in lowering of water tables, decreased access to groundwater (threats to plants, stygofauna and humans), decreasing environmental flows to groundwater-dependent ecosystems, movement of saline

water into aquifers, land subsidence, and a decline in the amount of recharge to the base flow of river systems. Apart from physical structure and land use, rainfall is critical to recharge of groundwater. Changes in climate over a long time scale can have very significant impact on groundwater availability. A shift has the potential to change the frequency and timing of recharge events, altering groundwater recharge regimes.

2.4.3 MANAGING NATURAL BIODIVERSITY

Conservation effort is centred on current environmental stressors, and the approaches used depend on the extensiveness of the impact of the stressors. There are three policy instruments used to support management of natural biodiversity: (i) facilitation/extension, (ii) incentives, and (iii) regulation via compliance policies. Facilitation of conservation values to counter unsustainable use for human activities (e.g. unsustainable harvesting of native animals for recreation or traditional purposes) is done via different forms of community awareness programs. In the Mallee Woodlands and Shrublands, short-term incentives policies have been implemented to restore native vegetation, rehabilitate natural water courses, encourage uptake of conservation covenants, and improve invasive pest and disease management. However, the most extensive conservation effort is via expansion of the NRS which presently covers 12% of the biome, most of which is in the Northern Territory and the least in New South Wales (Table 1).

3 Methods

We assessed the changes in future climates and environments of the HGB using information from a literature review, an expert workshop, ecological reasoning and the results of modelling exercises.

3.1 Review

All relevant scientific literature, government reports and web materials were consulted and incorporated in a literature review. It was circulated to an expert panel as background information for the technical workshop. Content from the review and feedback have been incorporated throughout the report.

3.2 Expert workshop

The purpose of the workshop was to canvas a range of experts across the science–policy spectrum about the impacts of climate change on the biome’s biodiversity and its implications for conservation and NRS planning. Twenty-two terrestrial and groundwater biologists from State and Territory government environmental agencies, universities, CSIRO and private consultants who had extensive on-ground expertise in the biome contributed to the workshop. The workshop was held over two days in late May 2009 in Adelaide. Representatives from all jurisdictions of the biome were either at the workshop or were able to provide input via teleconference later.

A summary of the workshop is attached in Appendix A.

3.3 Predicting change in today’s environments

The modelling is novel as it 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. The environmental change is based on the occurrence patterns of biota. 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 2010); 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. This approach was applied to both pre-1770 and extant biotically scaled environments.

Further detail on the modelling is attached in Appendix B.

4 How will future climate and environments change in the HGB?

4.1 Future climate

Projected climate change for the biome was based on two 1 km² resolution scenarios using output 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. Together with these results and feedback from the expert workshop, we summarise future changes for the biome (Table 4). 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.

Table 4 Proposed climate changes based on CSIRO OzClim and Bureau of Meteorology for 2070 high scenario for the whole dry hummock grasslands biome (up arrow – increase, down arrow – decrease, two arrows – severe implications for biodiversity)

PROJECTED CLIMATE CHANGE	DRY (ARID PILBARA – INLAND)	DRY-MEDITERRANEAN (SEMI-ARID-SOUTH)
Temperature	Summer 3 to >7°C ↑ Winter 3 to 6°C ↑	Summer 3 to 5°C ↑ Winter 3°C ↑
Total rainfall	Summer -40 to -80 mm Winter -10 to > 40 mm (Pilbara)	Summer -10 to -60 mm Winter -30 to -80 mm
Rainfall variability	Summer ↑Eastern biome Winter/Spring ↓South-west biome	Autumn ↑ Winter ↓
CO ₂	540–710 ppm	540–710 ppm
Storms/cyclones	Variability ↑, intensity ↑	Unknown uncertainty
Sea level	West coast inundation	-
Relative humidity	Winter-Spring ↓	Winter-Spring ↓
Wind speed	Winter-Spring ↑	Summer ↑winter ↓
Evapotranspiration	Autumn-winter ↑ Spring-Summer ↓	Autumn-Winter ↑↑

In the dry arid portion of the biome, temperatures are expected to increase, which will limit summer growth. Rainfall variability is projected to increase in the eastern part of the dry arid portion in summer and the southern and western portions in autumn. However, winter and spring rains are expected to decrease during the peak growing seasons. A decrease in relative humidity and an increase in wind speed in the arid dry portion are projected to increase aridity during winter and spring with countering effects in evapotranspiration. Storms are predicted to increase in seasonality and intensity, which could bring significant rains to parts of the biome. Overall, the arid dry portion is projected to experience increasing aridity.

The projections for the dry Mediterranean portion indicate favourable temperatures and wind speeds during the growth season from late autumn to spring. However, less rain, declining relative humidity and increasing evapotranspiration indicate considerable climate stress during the peak growing season. Overall, increasing aridity during the growing season is expected in the southern part of the biome. Decreased projected rainfall in winter also matches the actual declining 100-year seasonality trend for rainfall at Renmark in the southern region (Figure 4).

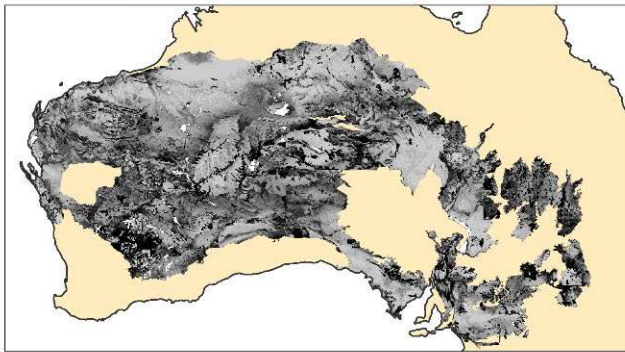
4.2 Environmental change

4.2.1 ECOSYSTEM CLASSES

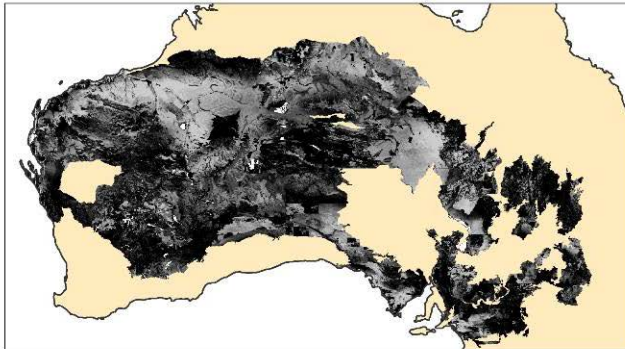
Major vegetation groups (MVGs) have been mapped for all of Australia (DEWR 2007) and were used as a surrogate for ecosystem variability. When mapped spatially, the levels of environmental stress throughout the dry HGB are expansive but patchy on multiple scales from 1 km² (grid cell) to much broader scales (Figure 5). Such environmental heterogeneity offers opportunities for diversification by biota either locally via refugia or following a leading front of change in response to climate change in 2070. This is more apparent when magnified (Figure 6).

Ten of 20 of the most highly ranked explanatory variables used in ANN consistently explained contemporary variation (as projected by MVGs) in the biome as shown in Appendix C. They fell into five groups of which four are climate-related and one is a soil variable (soil permeability) (see Hilbert and Fletcher 2012 for more descriptions of all variables used in modelling).

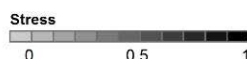
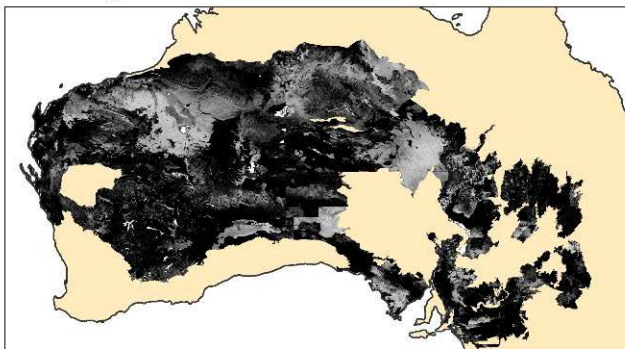
Modelled



2070 Medium



2070 High



The climate variables were: (i) precipitation seasonality, (ii) temperature seasonality, (iii) lowest period radiation, (iv) annual mean moisture index, (v) highest period moisture index, (vi) mean moisture index (an indicator of soil moisture based on rainfall and evaporation) of highest quarter, (vii) summer moisture index, (viii) winter moisture index, (ix) moisture index seasonality, and (x) soil permeability. Precipitation seasonality, moisture index seasonality, moisture in the highest quarter, mean moisture index in the coldest quarter and soil permeability consistently were the top five explanatory variables of environmental change for the biome's ecosystem classes. Soil permeability is likely signalling a gradient from sandy/gravel soils (MVG 20: Hummock Grasslands) to heavy clays (MVG 19: Tussock Grasslands).

Four of the top 20 ranked climate variables (annual precipitation, precipitation of wettest and driest period, and of wettest quarter) that explained patterns outside the biome did not explain any contemporary variation among MVGs in the HGB. Most of the topographical explanatory variables in the list were also not important in the HGB. This is not surprising on a continental scale, as variability-frequency in rainfall plays a greater role (Stafford Smith and Morton 1990).

Figure 5 Relative environmental stress maps (measured by ANN dissimilarity) in the HGB, showing modelled current situation and future changes under 2070 medium and high scenarios. (Dark shading represents the greatest environmental stress. Patchiness ranges from 1 km² grid cell to broader scales)

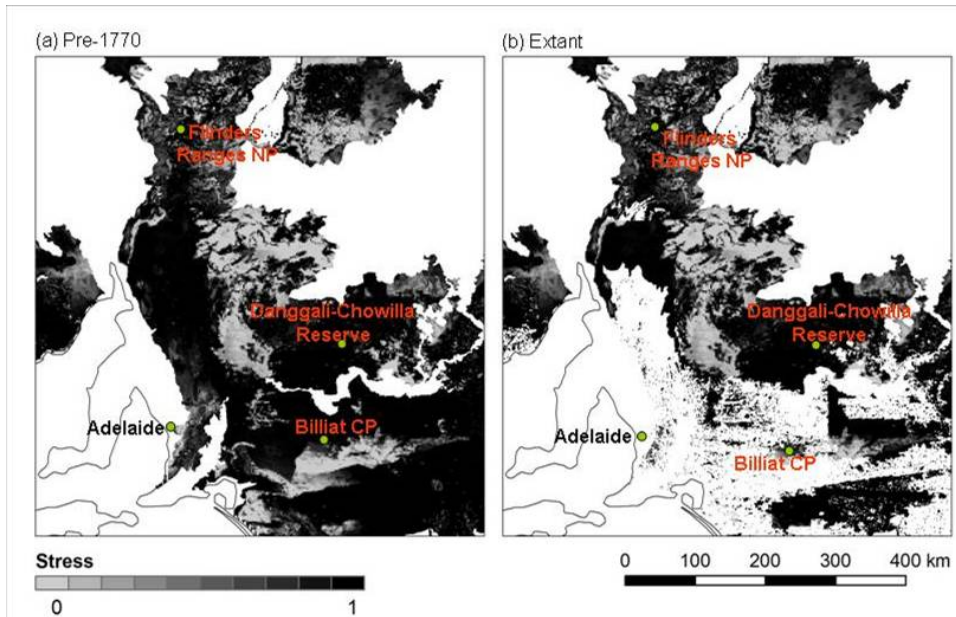


Figure 6 Example of regional relative environmental stress maps (measured by ANN dissimilarity) for pre-1770 (a) and present (b) Murray Mallee region, South Australia showing future change under 2070 high scenario. (Dark shading represents the greatest environmental stress)

4.2.2 SPECIES COMPOSITIONAL TURNOVER BY SELECTED TAXON GROUPS

Patterns of future environmental change (calibrated to variation in species composition) vary notably between 2030 and 2070 under medium and high emission scenarios (Figure 7). Most recognisable is the gradual southward creep of biotically scaled environmental stress (increasing compositional dissimilarity) projected in 2030 and accentuated in 2070 for all groups. By 2030, environments are predicted to have changed substantially for reptiles, plants and snails (Figure 7). By 2070, environmental stress is predicted to be significant; suggesting that most species in these groups at scales of greater than 1 km² will need to respond to widespread change in their current environments. For frogs and mammals, projected environmental change in 2030 is relatively low, until 2070 when substantial environmental change occurs in the north, central, eastern and most southerly parts in the Flinders Ranges and the Murray Mallee region of SA (Figure 7 cont.). Birds are predicted to encounter relatively little physical environment change, although if vegetation composition were included as predictors the results may project a different pattern (following work by Pavey and Nano [2009] of arid/semi-arid vegetation and bird occurrences).

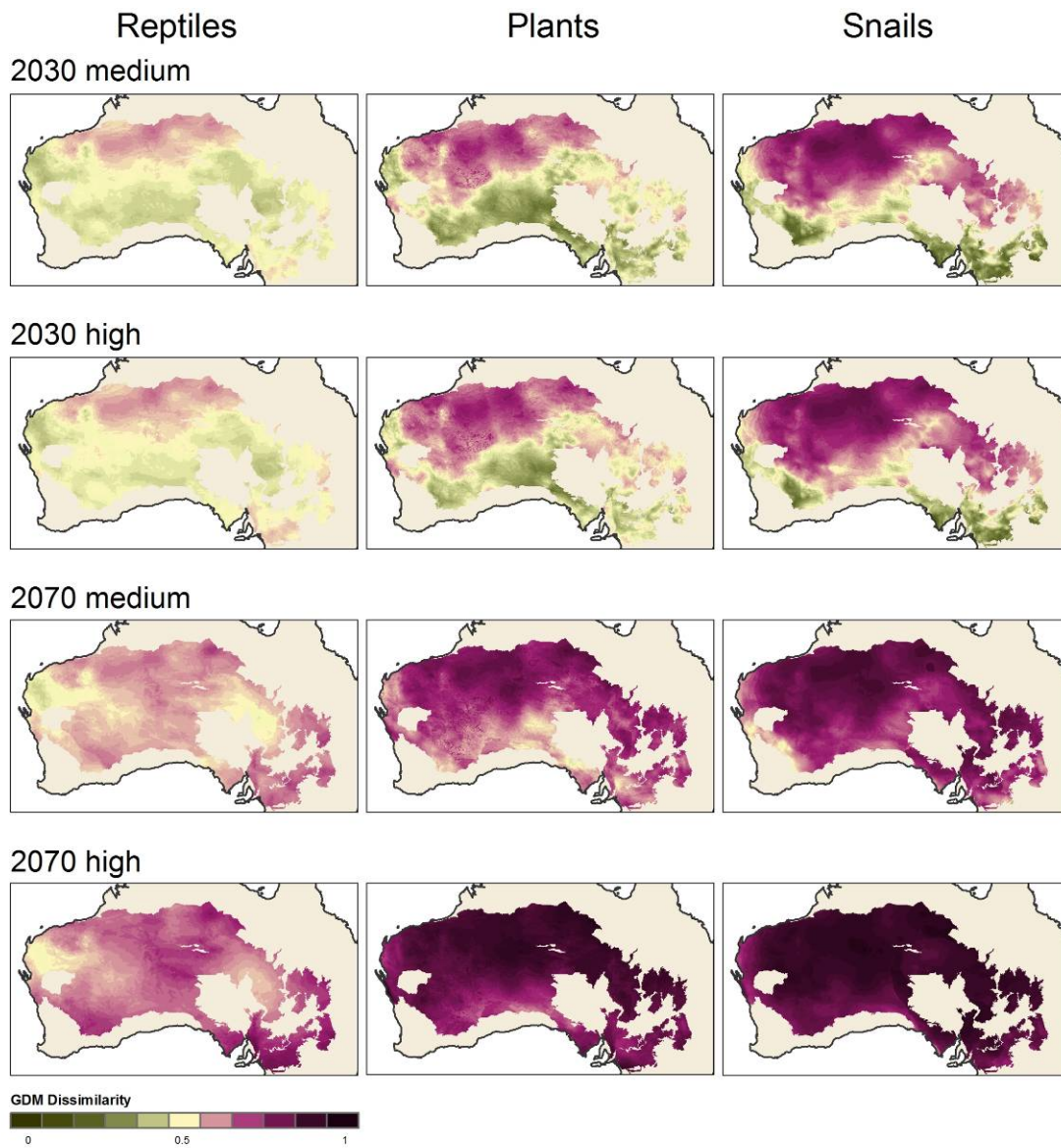


Figure 7 Projected compositional change for each 1 km² cell calculated from GDM modelling for reptiles, plants and snails. (Stress level: green – low, yellow – moderate, dark pink - high, dark purple – extremely high)

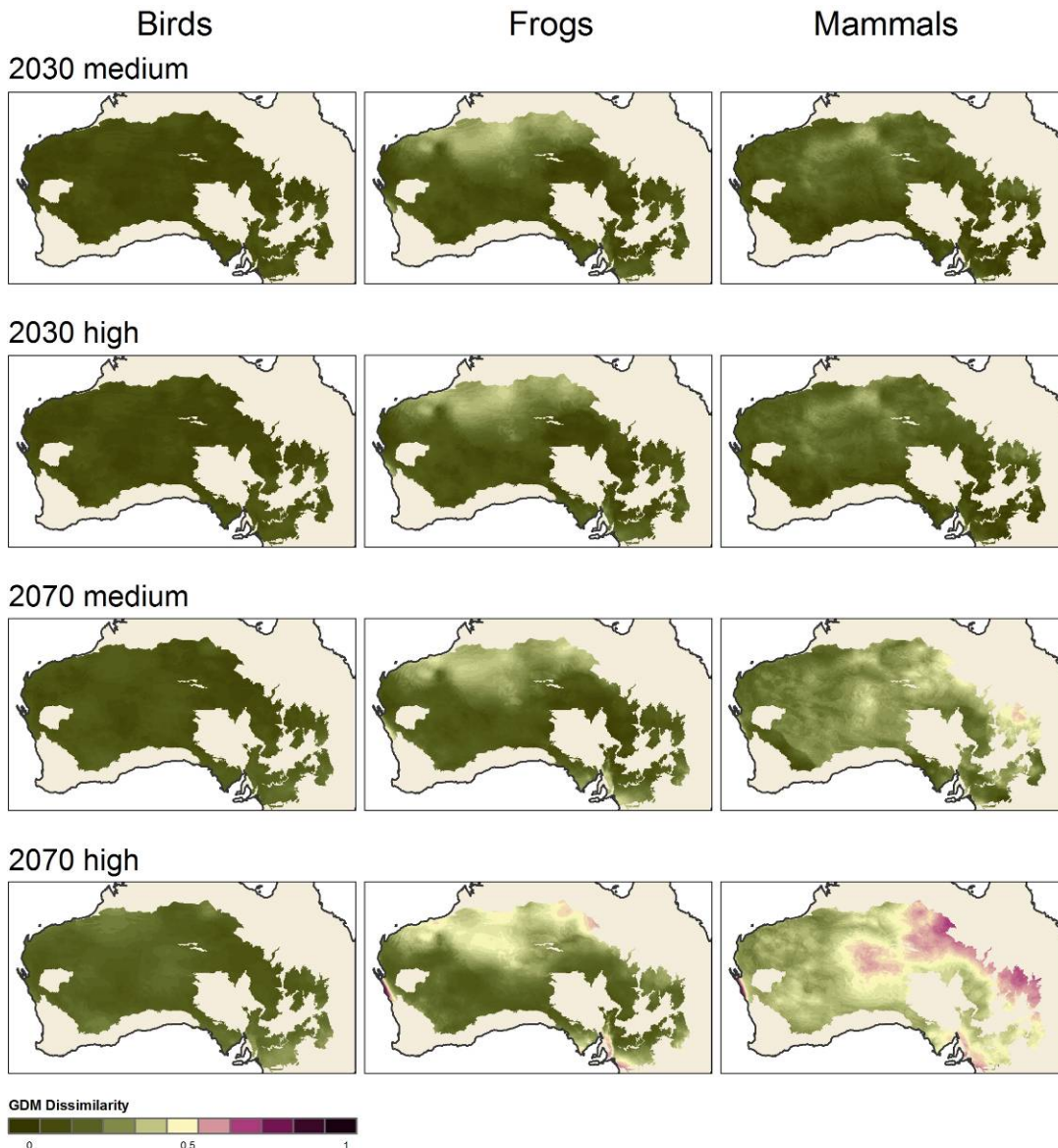


Figure 7 cont. Projected compositional change for each 1 km² cell calculated from GDM modelling for birds, frogs and mammals (Stress level: green – low, yellow – moderate, dark pink - high, dark purple – extremely high)

It is important to note that environmental change in these analyses is based on a resolution of 1 km², which in terms of spatial modelling at a continental scale is sufficient to capture the geographic distribution of most species. However, within the distributions, individuals of species populations such as endemic plants, endemic snails, frogs and subterranean biota (legless lizards, marsupial moles) will be functional at ‘micro scales’, which are smaller than a grid cell. We are also aware that survey sampling for rare, endemic or burrowing biota with small distributions (e.g. snails, burrowing animals) are under-represented by compositional turnover; it will be biased towards the common, widespread species. Information on adverse changes in biotically scaled environments for common species is notable for NRS management. We also need to remember that plant–animal interactions are likely to be modified substantially by plant responses to future climate change. Given that substantial change is projected for plants, it is likely that the favourable habitats of animals will change in unpredictable ways not projected by these analyses. While these are issues of assumptions, complexity and modelling imprecision, the signalling of potential environmental change as done here is nevertheless an advance in understanding the broad patterns of climate change impact.

Ultimately, species of the selected taxon groups will need to respond to future environmental change at multiple scales in different places in different parts of the biome. Most importantly, the modelling indicates that species with short generation times have options to diversify in response to climate change as there appear to be broad leading fronts of no change to moderate change in 2030, especially for frogs, mammals and, to a lesser extent, reptiles. For plants, this is more sustained in the southern parts of the biome.

4.2.3 USING PLANT SPECIES COMPOSITIONAL TURNOVER TO STUDY THE BUFFERING EFFECTS OF ENVIRONMENTAL HETEROGENEITY AT MULTIPLE SPATIAL SCALES

Do plant environments occur elsewhere in the biome in the future?

Apart from the environments in the Gawler Ranges (SA), most of the biome's present environments are projected to have changed significantly or disappeared by 2070 under the medium scenario (Figure 8a). This pattern is accentuated under the high scenario (Figure 8b) such that all environments as we know them will disappear. Similarly, future environments in the biome will be relatively novel, that is, unlike any current environments in the biome (Figs 8c and 8d).

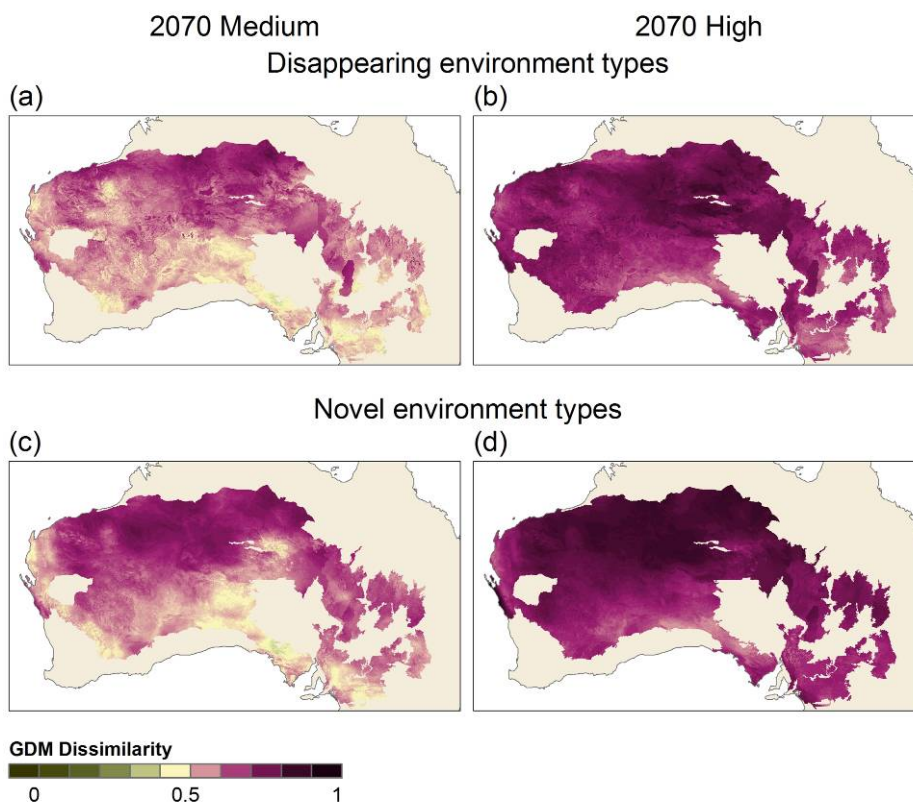


Figure 8 (a) – (b) The lowest value of environmental change (compositional dissimilarity) for plants, for each present cell compared with all cells within a 50 km radius and a sample (1 in 1000) of the rest of the continent in the 2070 medium and high scenario. Environmental change: green = environments similar to today's will still be found somewhere in 2070, pinks = present environments likely to disappear by 2070. (c) – (d). Environmental change: green = future environments have a contemporary analogue somewhere, pinks = future environments not currently represented in the continent

How much buffering is provided by local-scale landscape heterogeneity?

We use the GDM model to assess the extent of multi-scale buffering (radius = 1, 3, 12.5, 25, 50 and 100 km) against climate change in 2070 for plant 'species compositional turnover' as we know it today. Buffering is measured in terms of effective habitat area with a radius about a 'central location' (1 km² grid cell) in the landscape (see Ferrier et al. 2012 for technical details on measuring effective habitat area). Low

values of < 0.5 (dark brown) indicate high proportional change, suggesting poor buffering within the landscape in the future. Neutral values at approximately 1 (light green) indicate similar buffering for plant compositions as today, while high values > 1 (dark greens) project little change in effective habitat area due to buffering within the specified radius.

The effectiveness of buffering for plant species, however, will primarily depend on species seed dispersal capacity. If there is a mismatch between the scales of landscape buffering and dispersal capacity, then buffering against environmental change at a local landscape (effective habitat area) is less relevant. For this analysis, we consider the two buffering scales (3 km and 100 km radii) to represent the extremes mainly because there was a trend of increasing scale of buffering with decreasing environmental change. By choosing extremes scales, we represented the plant species with limited and widespread seed dispersal capacity over 60 years (by 2070) within the biome (e.g. wind dispersal).

Regardless of the scenario simulated, there was mostly poor buffering for present plant species composition at both scales under 2070 high emission scenarios (Figure 9). Buffering (as measured by proportional change) was improved at the 100 km radius for 2070 medium emissions scenario (slight green tinge on the map) in South Australia in the Great Victoria Desert Biome (GVD6 and GVD3 sub-IBRAs) and the Gawler Ranges (GAW2 sub-IBRA) and the Murray Mallee south of the Murray River (MDD1 and MMD2 sub-IBRAs). These places represent a mix of elevated, flat and drainage line topography. It should be noted, however, that the resolution of the environmental modelling was coarser than much of the environmental heterogeneity that is ecologically critical in the biome.

Greater buffering under the medium emission scenario implies adaptation to future environmental change would be greatly enhanced by effectively reducing greenhouse gas emissions.

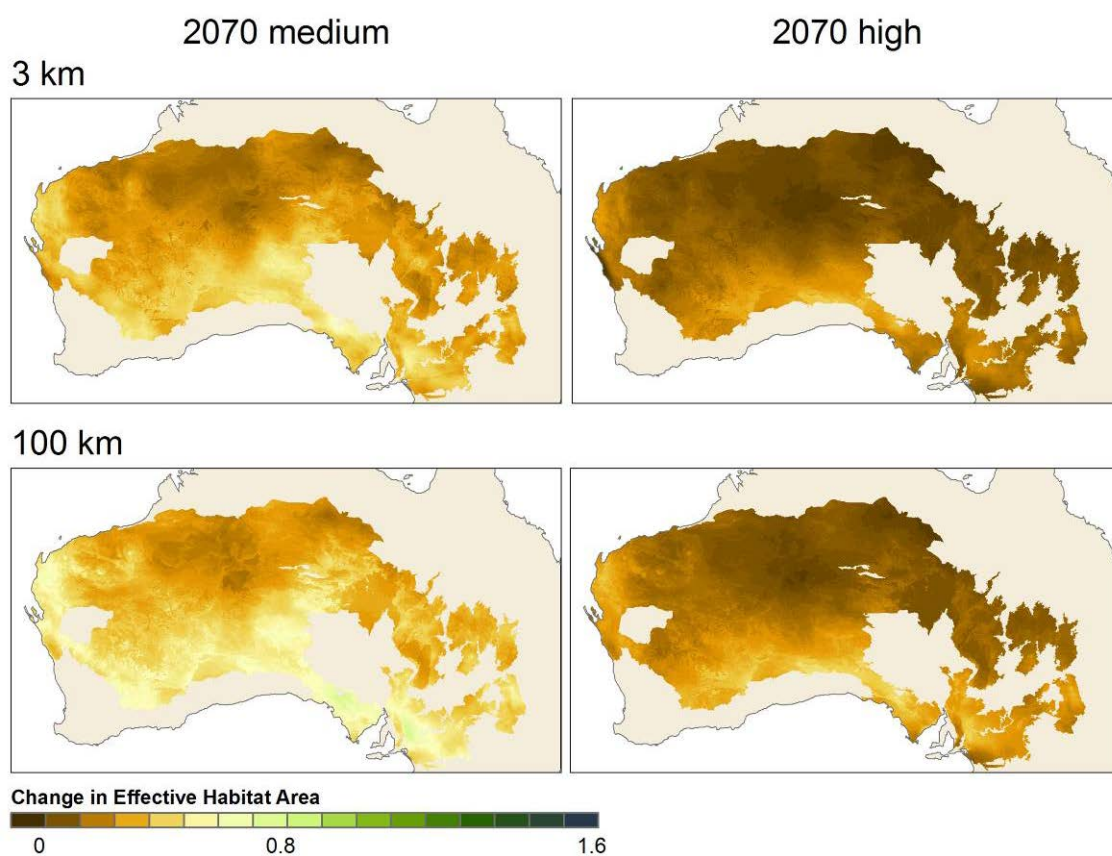


Figure 9 The proportional change in buffering (effective habitat area) for radii of 3 km and 100 km surrounding a 'central location' (1 km² grid cell) with the HGB. (Dark browns = increased environmental stress per buffering scale, so poor projected landscape buffering via landscape heterogeneity; light green = little change in buffering compared to the present; dark greens (> 1) = improved buffering similar to today's environments)

Where is the greatest/least buffering?

We addressed this question by assessing the extent to which the current environment of a focal cell may be more similar to the future environments of nearby cells (within 3 km or 100 km) than its future environment (see Ferrier et al. 2012 for technical details about measurement of neighbouring environmental heterogeneity relative to a 'focal location').

The analyses revealed poor overall local buffering against the environmental changes expected by 2070 (Figure 10). At the regional scale (100 km radius), there are some isolated pockets of moderate buffering (darker blue) across elevated and flat topography in some parts of the Pilbara (Hamersley Ranges), south-west of the biome, Great Victoria Desert, Little Sandy Desert and Cobar Plain. Again, buffering is much greater for the medium compared to the high emissions scenario.

Overall, there is little effective local buffering but there appears some moderate buffering at a broader scale, implying that isolation may be an issue for those plant species with limited dispersal capacities that cannot track broadscale buffering. Landscape functional (dispersal) connectivity and maintenance of outlying (cryptic) populations will be important for maintaining populations of widespread dispersing species in the future based on our projections. Given the critical importance of fine-scale variability for current ecological processes, and the general low level of local and regional buffering revealed by the modelling, the importance of maintaining environmental heterogeneity remains a compelling and open question.

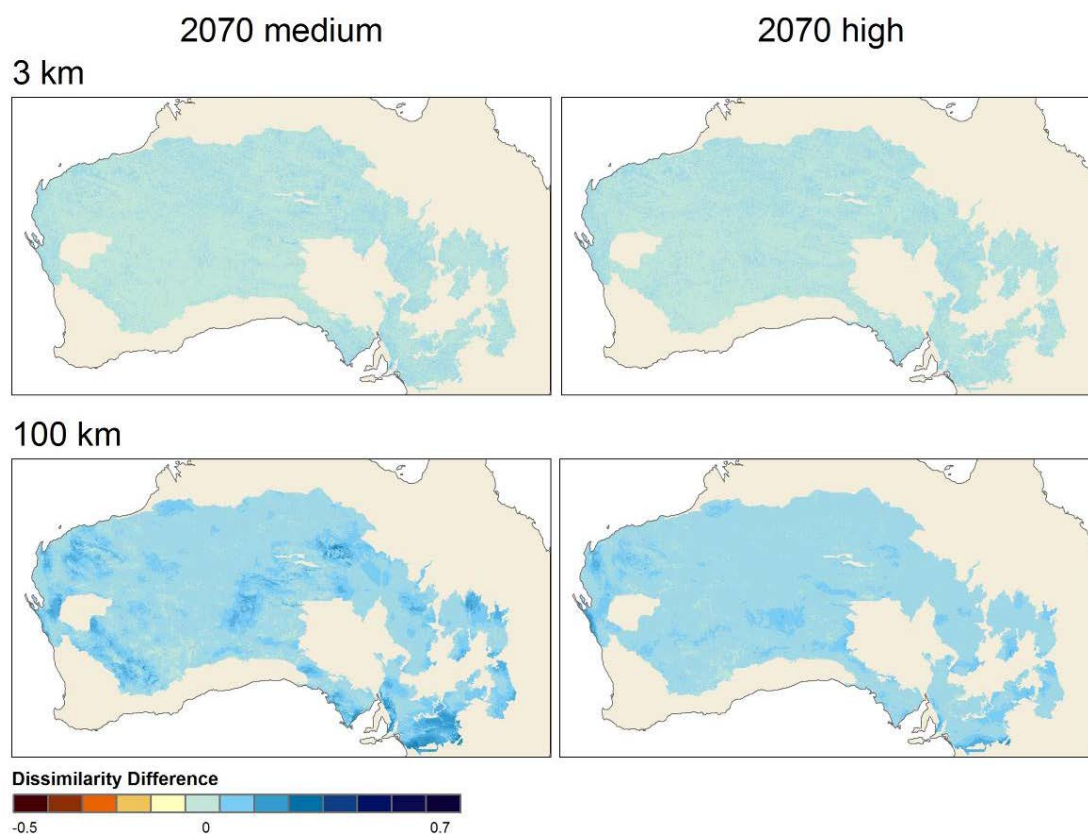


Figure 10 Local (3 km radius) and broadscale (100 km radius) buffering via landscape heterogeneity projected for 2070 medium and 2070 high emissions scenarios for present plant species composition. Dark blues = good buffering relative to 'focal location' (more similar environments within the buffer zone than any other location (1 km² grid cell) in the biome); pale blues (~ 0) = little buffering as present environments for present plant species composition are highly stressed; brown = rare cases where the 2070 environments are more similar than that found anywhere else at the scale of buffering

5 Other factors affecting environmental change

5.1 CO₂ fertilisation

C₃ grasses have been predicted to outperform C₄ species above a critical threshold of CO₂, the level of which depends on the 'growing season' temperature (Appendix D). This model partly underpins future impacts of global change in the C₃–C₄ balance. Similarly, C₃ woody plants (woody thickening) may be favoured over C₄ grasses (Williams et al. 2010). However, results from numerous studies suggest that there are no simple generalities and workshop experts believe that spinifex species, C₄ grasses, will continue to dominate the biome. Berry and Roderick (2002) also argue that factors other than CO₂, such as land clearing, may determine C₃ plant distribution in Australia. For grasslands as a whole, aridity, topography, soil properties and fire are dominant drivers of the C₃–C₄ balance in addition to CO₂ fertilisation (Edwards et al. 2010). The Tasmanian Free-Air CO₂ Enrichment (TasFACE) experimental results of a net increase in the C₄ grass *Themeda triandra* at the expense of C₃ *Austrodanthonia* is further evidence that factors other than CO₂ fertilisation can equally determine landscape pattern and structure (Williams et al. 2007).

Another aspect of elevated CO₂ levels not addressed in the workshop that could indirectly affect the biome is the decline in vegetation quality for all herbivores. Laboratory studies indicate that enhanced levels of CO₂ can impact on the morphology and growth of C₃ and C₄ plants (Lincoln et al. 1993) and the chemistry, especially for C₃ plants. Nutritional value for C₃ plants under elevated CO₂ generally decreases for herbivores because of declines in total N (-16.4%) and protein, and a corresponding increase in secondary 'toxic' compounds (+29.9%) (Stirling and Cornelissen 2007; Gleadow et al. 2009). In insect herbivores, this can have a number of secondary effects. They are decreasing herbivore abundance (-21.6%), increased relative consumption rates (+16.5%), increased developmental rates (+3.87%), decreased relative growth rates (-8.3%), decreased pupal weight (-5.03%), decreased conversion efficiency (-19.9%), increasing susceptibility to disease and higher predation due to poor fitness. While these relationships are less of an issue for C₄ vegetation, it has enormous implications for biota dependent on insect herbivore populations in the southern part of the biome.

5.2 Fire

It is already apparent that climate change is affecting fire weather. Williams et al. (2010) state that:

Fire regimes across Australia currently differ because of variation in four key drivers: (i) the rate of vegetation (and hence fuel) growth; (ii) the rate at which fuels dry; (iii) the occurrence of suitable fire weather for the spread of fire across the landscape; and (iv) ignition. Consequently, fire regimes in some regions are constrained primarily by availability of fuel, and in others by occurrence of periods of suitable weather.

Climate change is expected to change fire regimes by its effects on these four key drivers.

Animal responses to fire are affected by floristic composition and structure. Mallee fowl *Leipoa ocellata* in the southern Mallee require long-unburnt mallee (Bradstock and Cohn 2002). The diversity of lizards is influenced by fire patchiness (Masters 1996; Letnic et al. 2004). 'Time since fire' (along with rainfall and the season of burn) affects the production of yakirra seed, the diet of the bilby (Southgate and Carthew 2007), the composition of birds in different-aged Mallee, and mammals and reptiles (Masters 1996; Southgate and Masters 1996). Small ground mammals in the Simpson Desert were more influenced by rainfall variability (apropos food availability) than experimental patch burning. However, patch burning is likely to maintain species richness and the 'resilience' of fire-sensitive species (e.g. *Pseudomys desertor*) by reducing the extent of wildfire (Letnic 2003; Letnic and Dickman 2005; Letnic et al. 2005). Mulgara (Körtner et al. 2008) and small ground mammals (Letnic et al. 2005) are exposed to increased predation risk, especially by introduced predators after large wildfires.

Experts reported that increased summer rainfall in the north may favour faster spinifex biomass accumulation and also more frequent pulses of non-spinifex fuels, both of which affect fire characteristics, especially frequency and intensity. In the dry Mediterranean south, fire seasons were postulated to be longer, fires more extensive and severe with unpredictable frequency. However, biome experts felt that our understanding of the season, types, extent, intensity and interval between fires was poorly characterised in a quantitative sense for the biome. Fire regimes need to be described in terms of relationships with climate dynamics that drive productive cycles, which are also poorly quantified. Consequently, the management of biodiversity is a difficult task.

In summary, traditional patch burning maintains habitat spatial and temporal heterogeneity, which may maintain and sustain the richness of species and ecological communities more so than homogenisation of habitat. However, this will be a challenge to manage in such remote areas. The toolbox designed by Hill (2003) to empower Aboriginal land managers may be a way forward.

5.3 Increasing aridity – water and heat stress

Present biodiversity of the biome is well-adapted to aridity, but increasing aridity together with fire may impact biodiversity on many levels via physiological and phenological stress. While the community-climate-environment models take into account aridity variables to determine environmental change, they do not consider mechanistic responses of biodiversity to aridity. Emerging phenological studies on animals are describing changes in timing of breeding by arid birds (Barrientos et al. 2007); reproductive failure in extreme drought conditions (Bolger et al. 2005) and altered migration patterns (e.g. butterflies, Dingle et al. 2000).

In general, some workshop experts reported greater variability increases with greater aridity in the biome. A loss of productivity and greater environmental change are due to variable rainfall patterns. If rainfall means remain the same and greater environmental change occurs, or the rainfall mean decreases with a correspondingly great environmental change, or both occur, then the stress on biodiversity will be extreme and it will knock out those species in functional groups that cannot match such linked patterns. Increasing aridity (low mean rainfall, a surrogate for low productivity) with other environmental stressors such as predation by cats and foxes (McKenzie et al. 2007); bats (Bullen and McKenzie 2005) and 'critical weight range' (Johnson and Isaac 2009) together explain declines in arid mammals. Workshop experts also observed that with increasing aridity, feral herbivores and native animals (especially bats) may contract to artificial waterpoints in greater numbers. While they may have a role to play in supporting native wildlife, such water sources may become highly degraded by ferals (goats in the south, Smyth and Rioux 2009; camels, Brim-Box et al. 2010). This has many implications for aquatic biodiversity of the biome's water bodies (Box et al. 2008).

5.4 Invasive plants

Non-native invasive plants are threats to all regions of the HGB. Around Alice Springs and in the dry Mediterranean of the south, woody thickening of native vegetation and shrubs, presumably in response to CO₂ fertilisation and changed fire patterns, are already reported. Some growth forms are very likely to dominate vegetation, or at least the stratum they invade. These 'transformer species' have serious consequences for biodiversity. They impact by direct competition as they out-compete native plants for requirements, through their effects on availability of resources for animals, and by modifying ecological processes (Clarke et al. 2005; Friedel et al. 2006; Smyth et al. 2009a; Kriticos et al. 2010 for SA invasive plants under climate change). An example of a 'transformer species' that we better understand is buffel grass.

Buffel grass invasion is a serious threat for the biome. Although it has societal value as an improved pasture and as a rehabilitation species of degraded land, it is widespread and can burn more frequently and at higher intensity than most uninvaded vegetation, although some *Triodia* species are observed exceptions in some parts of the biome. Around Alice Springs in central Australia, buffel grass has caused the decline of

all native plant growth forms and species richness over a 27-year period (Clarke et al. 2005). Even in the early stages of invasion, buffel grass can influence plant and bird compositional shifts (Smyth et al. 2009a). Most alarming is that between-cultivar hybridisation has been observed in buffel grass, suggesting locally adapted plants are better suited to survive environmental stresses. Historically, buffel grass never occurred along the Stuart Highway between Alice Springs and Adelaide but now is present along the whole route, utilising roadside run-on moist areas.

Results of Bayesian belief network (BBN) modelling by Martin et al. (2010) indicate the majority of the HGB (70%) is highly suitable for buffel grass invasion (mean suitability = $39\% \pm 21$ s.d, range: 1–77%) (Figs 11a and 11b). Highly suitable areas are the southern parts of the East Kimberley (WA), Gawler Ranges (SA), northern portion of Mallee Woodlands and Shrubland (MVG 14) in SA and NSW. The proportion of the biome falling within the high suitability class (40–59% probability) decreases mostly in the Pilbara and western deserts of WA under both future climate scenarios (50% in 2070 medium, Figure 11c; 45% in 2070 high, Figure 11d). Despite this, the mean buffel suitability across the biome increases to 46% for 2070 medium emissions scenario due to a higher proportion of very highly suitable habitat (> 60% suitability) occurring across the biome (increasing from 9% to 16%). Under high emissions scenario, there is a marginal increase to 40%. Notable is that maximum suitability actually decreases (to 62%) under the 2070 high scenario, while it remains unchanged (at 77%) in the medium scenario.

The largest changes in suitability across the biome are seen in the Pilbara, Gascoyne and Little Sandy and Gibson Desert areas, which all markedly decrease in suitability (blues) under both scenarios (Figs 11e–11f). Significant increases in suitability (browns) occur in the minor component of the HGB in the Yalgoo IBRA (WA) and Gawler Ranges, Flinders Ranges and Murray–Darling Depression IBRAs of the Mallee Woodlands and Shrublands.

The patterns of ‘high suitability’ and ‘change in predicted high suitability for buffel colonisation’ also hold for the NRS.

However, despite this valuable information on potential patterns under climate change, we do need to keep an open mind about the reliability of information produced in the maps. Due to the lack of geocoded field data on soil quality, the spatial modelling in the maps does not capture distributional patterns of soil quality used in the BBN. This is problematic as Martin et al. (2010) found soil quality to be a major driver of buffel grass establishment and persistence. We suspect soil quality was used in the BBN by experts as a surrogate for the amounts and distribution of phosphorous, another key driver of buffel grass distribution. For the projected maps, soil type was used as a surrogate for soil quality which is also problematic as soil chemistry changes at scales of centimetres in the field within the same soil type, especially in dryland soils.

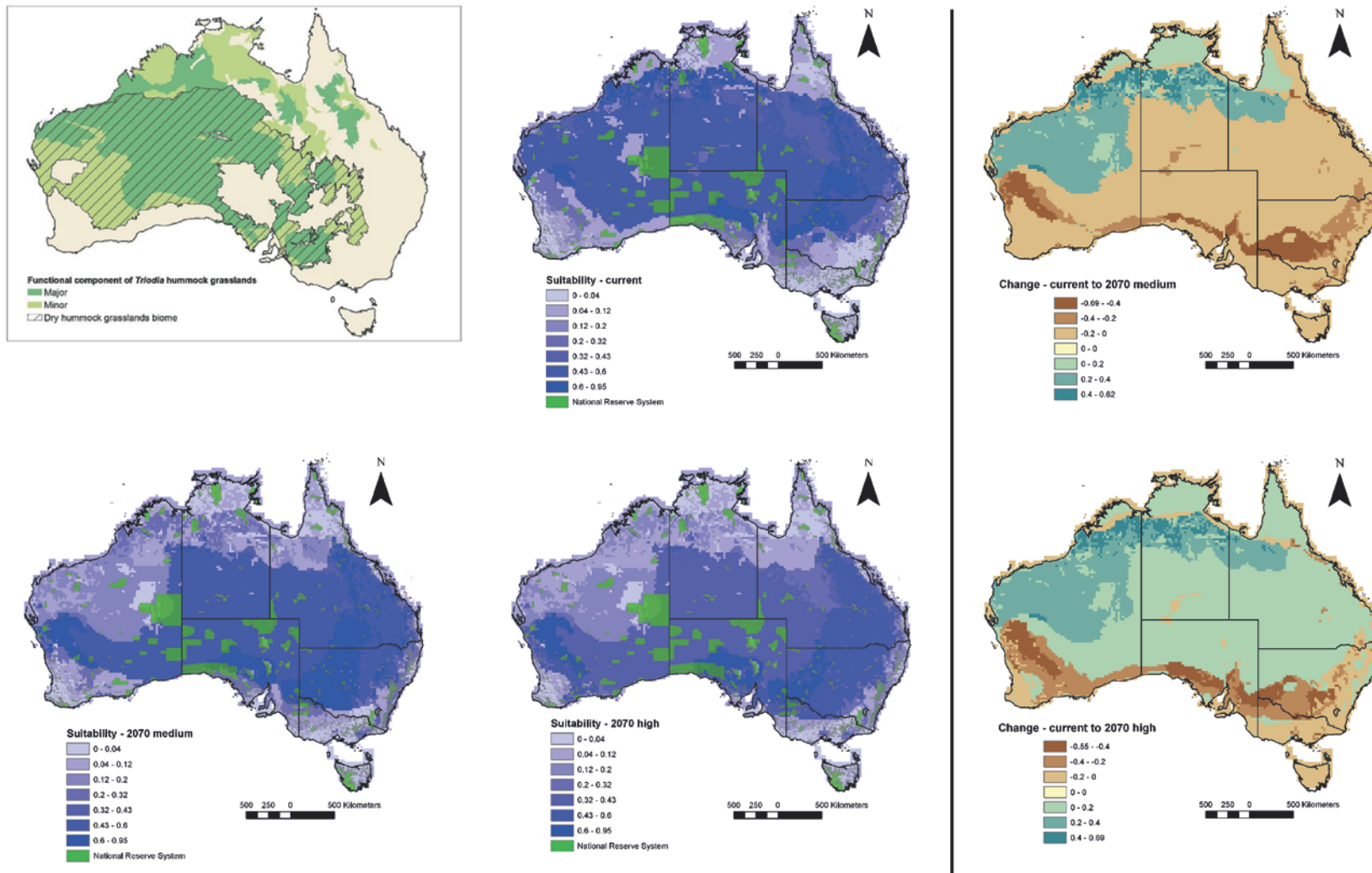


Figure 11 Biome boundaries (a) and probability of high suitability for buffel grass colonisation under current climate scenario (b), 2070 medium emissions scenario (c), 2070 high emissions scenario (d), change in predicted high suitability between current climate and 2070 medium emissions scenario (e), and current climate and 2070 high emission scenario (f). (b–d: pale purples – low probability (< 20%, medium purples – moderate probability (20–39%), dark purples – high probability (40–59%), royal blue – very high probability (>60%) of high suitability; e–f: brown shades – increasing suitability; blue shades – decreasing suitability)

Source: Martin et al. (2012).

5.5 Does habitat loss magnify changes in environments or reduce the buffering?

Habitat loss and degradation in the biome can occur indirectly through overgrazing and degradation at natural water sources. In South Australia, the Native Vegetation Act directly links overgrazing to vegetation clearing. Other habitat loss in the biome can be via groundwater extraction for primary industries (pastoralism and mining) or drinking by ferals from desert water bodies dependent on ground water. Our baseline knowledge of these ancient sources of drinking water is poorly understood but what is known for some is that they are places of great endemism (Box et al. 2008). We were able to model the interactive impacts of environmental change and vegetation clearing on plant compositional turnover for the Murray Mallee region to see whether together both stressors magnified changes in environments or reduced the buffering offered by environmental heterogeneity.

Despite there being little overall vegetation clearing in the biome since settlement, the Mallee Woodlands and Shrublands is one spinifex major vegetation group that has undergone notable vegetation clearance (~ 20% since pre-1770). When the interactive effects of vegetation clearing and climate change are projected, environmental change is much greater and buffering of the present day complement of plant species is substantially reduced (Figure 12).

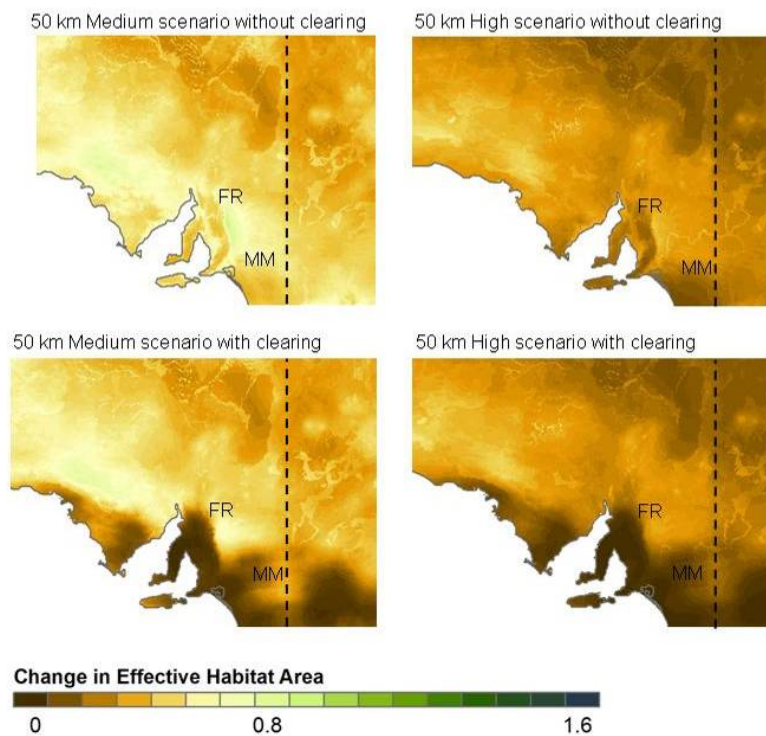


Figure 12 Proportional change in buffering (effective habitat area) for a radius of 50 km from a central location (1 km² grid cell) based on extant vegetation within the Flinders Ranges (FR) and Murray Mallee (MM) Regions, South Australia. (Dark browns = less buffering; pales to greens (> 0.5) = buffering increasing)

6 Implications of potential responses of biodiversity to changing environments

Biodiversity continually responds to physical environmental change in a number of complex ways. We postulate that ultimately changes in physical environments will impact on individual organisms in the form of new morphological, behavioural, physiological and phenological changes (Dunlop and Brown 2008). These changes will in turn alter reproductive capacity, mortality and migration, so species populations will change in number and distribution, paving the way for changes in community patterns (composition, structure, species interactions). In terms of risk, the potential outcomes of species' responses to future environmental change may be: (i) safe today and in the future, (ii) at risk today and in the future, (iii) at risk today and newly safe in the future, (iv) departing today, going extinct locally, so no future, (v) not here today, returned due to improving environmental conditions, and (vi) new species due to novel environments. If today's species are unable to diversify or use places of local refugia as the expansion front of environmental change progresses, then it is hypothesised that species will depart from the biome. The complexity of the climate change-environment-biodiversity system and the extraordinary levels of unknown uncertainty restrict definitive comments about biodiversity responses. We draw on the literature and feedback from workshop experts to make some general comments.

6.1 Biogeographical responses – potential places of diversification, refugia and endemism

Some biome experts postulated that the biome's arid biota is well adapted to respond to future environmental change. Over the past 100 years, some species have undergone major changes. Not all made it but those that have survived to today are probably sufficiently robust to tolerate future climate change. Even so, it is possible to postulate generalisations about places of diversification, endemism and refugia using modelling of projected environmental change in 2030 and 2070 under high emission scenario (excluding snails) and biotic responses to historical environmental change as starting points. Snail responses are excluded because many arid snails are endemic to localised water holes at microscales within 1 km² grid cell and we suspect that baseline data is unevenly sampled in the biome (Box et al. 2008). The postulates are most relevant to a subset of species that have dispersal/movement capabilities to track expansion fronts of environmental change.

In parts of the biome the 'ecosystem class' modelling predicted multiple gradients of environment change at multiple scales (Figure 6a and 6b), implying opportunities for diversification. Places considered by some workshop experts that have been a source of radiation in the past have been the Kimberley Plateau (see Liedloff et al. 2010), Hamersley Ranges, and central Australian ranges (Petermann, James, MacDonnell, Davenport Ranges) and the sandhills in the drier north (Little Sandy Desert). These places may not be sources in the future; nevertheless a closer look at the variability in environmental change gradients for 'ecosystem classes' around the Kimberley Plateau, Hamersley Ranges and the Little Sandy Desert may continue to favour diversification, but not the central Australian ranges which are predicted to be under high environmental stress by 2070 (high emissions scenario). In the southern biome, the Gawler and Flinders Ranges would be under extreme environmental change by 2070.

Modelled environmental change based on compositional turnover in 2030 (high) projects an expansion front of change from the north-western half of the biome for most taxon groups (not birds and mammals). For mammals, it comes from the north-eastern portion, whereas for birds in 2070 (high) it comes from the north and south-eastern (Murray Mallee region) portions. If biota follow historical diversification patterns (and this is uncertain), radiation could continue to occur from the southern parts in the Hamersley Ranges for reptiles; Hamersley, Gawler and Flinders Ranges for plants; Hamersley Ranges for frogs; and all ranges for mammals. Birds may continue to radiate in any direction from the central ranges (Figure 7). By 2070, most of today's environments are projected to have disappeared to be replaced by novel environments for

most taxa except birds and frogs (Figure 7). If sand plains and dune fields become sources of radiation, the Great Victoria Desert would favour continued radiation for most taxa.

In terms of less mobile biota using places of refugia to cope with environmental change, experts suggest that fixed topographical features such as islands, ranges, rocky outcrops, paleodrainage systems, lakes, groundwater-dependent ecosystems and outlying pockets of spinifex are likely large-scale places of refugia (Moreton et al. 1995). By 2070, a few isolated 'regional scale' pockets within places listed as refugia today are projected to exist with less environmental stress. There may well be refugia within them as indicated by Morton et al. (1995).

Major places of endemism for Australia's flora today are located in coastal (relicts of wetter environments) pockets in response to aridity during the Last Glacial Maximum (Crisp et al. 2001). By 2070 (high), pockets of endemism representing today's taxa may not exist in the biome for plants as most of the biome is projected to be highly dissimilar to today's environments. The Hamersley Ranges may be a major centre of endemism for a range of animal taxa. Climate modelling for the 100 km radius buffer for 2070 medium emissions scenario shows that places of endemism for today's plant species are north of the Nullabor (GVD6 sub-IBRA), in the Great Victorian Desert (GVD3 sub-IBRA), the Gawler Ranges (GAW2 sub-IBRA) in South Australia and the Murray Mallee south of the Murray River (MDD1 and MMD2 sub-IBRAs an agro-ecological system). However, species will need to be widespread seed dispersers (over 100 km for seed establishment) under medium climate change conditions, if such levels exist in the future.

Most of the places postulated for diversification, refugia and endemism above are largely part of the NRS, implying that buffer zones and ecological connectivity in relation to these and other key fixed topographical features are important for climate adaptation planning for biodiversity in the dry HGB.

6.2 Broad ecological responses

Results of the 'ecological classes' modelling indicated that soil moisture and permeability, interactively with other climate variables, are the foremost factors steering changes in environments of the biome. This is not surprising for arid/semi-arid systems, as water availability affects plant productivity which stimulates animal responses (Stafford Smith and Morton 1990). The ecological responses of biota to the interactive effects of changing climates and environments for the dry HGB in the future are presented in Table 5. These have been broadly postulated based on the literature, workshop advice and results of the modelling, where appropriate.

Table 5 Postulated responses of biota to key projected environmental changes in the dry hummock grassland biome based on literature, expert advice and modelling. (Bold – ‘peer reviewed’ field-based evidence, No bold – expert opinion; up arrow – increase, down arrow – decrease, 2 arrows – greater change, Win-Spr – winter-spring, Veg – vegetation, Spp. – many species, * see Appendix E, projected mapping of major vegetation groups based on environmental change)

PROJECTED CHANGE	DRY (ARID PILBARA - INLAND)	DRY-MEDITERRANEAN (SEMI-ARID-SOUTH)
Growing season		
- Summer rains	Grass productivity ↑	Infrequent productivity ↓
- Win-Spr rains	Short-lived plant growth ↓	Major productivity ↓↓
Composition	C₄ grasses (Spinifex) ↑↑ C ₃ plants ↓ Buffel grass ↑↓ (Murchison) ‘Heat sensitive’ species ↓ (Pilbara) ‘Fire-sensitive’ species ↓ Sub-tropical plant, reptile, frog species ↑	C ₄ grasses (Spinifex) ↑ C ₃ plants ↓↓ Buffel grass ↑↑ ‘Heat sensitive’ species ↓ ‘Fire-sensitive’ species ↓↓ Arid mammal, reptile, frog species ↑ Semi-arid species ↓
Veg structure	Eucalypt open woodland (north) ↑* Desert Oak woodland ↓* Acacia vegetation ↓* Non-spinifex grasslands ↑* Chenopod shrubland ↑* Ground organic matter ↓	Mallee woodland & shrubs ↓ Chenopod shrubland ↑ Ground organic matter ↓
Aridity	‘Xeric tolerant’ biota (Pilbara) ↓↓ ‘Mesic tolerant’ biota (Pilbara) ↑↑	‘Mesic tolerant’ biota ↓↓ ‘Xeric tolerant’ biota ↑↑
Species interactions	Feral herbivores ↑ - habitat degradation ↑ Fire-predation ↑ - prey numbers ↓ Insect-plant herbivory - unchanged Pollination/Nectivory ↓ Granivory ↓(Pilbara)	Feral herbivores ↑ - habitat degradation ↑ Fire-Fox predation ↑↑ - prey numbers ↓↓ Insect-plant herbivory ↑ Pollination/Nectivory ↓ Granivory ↑

Projected climate and environmental changes discussed in the previous chapter imply opposing shifts in growing seasons, community composition and structure, and species interactions at the latitudinal extremes of the dry HGB. The precision of these postulates is highly uncertain as our knowledge of mechanistic processes not only assumes that biota will respond as we understand it today, but it is also confounded by the interplay of many other sustaining pressures. We summarised potential broad responses in Table 5.

In the north-west, increases in summer rains and declines in winter rains will result in compositional shifts in plants species that primarily germinate during summer (e.g. perennial grasses) and winter/spring (e.g. short-lived annuals) rains. Plant composition will also respond differently to changed fire patterns (due to increased fuel loads), the spread of invasive C₄ weeds such as buffel grass, habitat degradation by increased feral herbivore densities at waterpoints at the expense of native animals, and the overall expansion front of environmental change from the tropical north. At the same time, familiar structural components will possibly expand, contract or both, in opposing parts of the biome. Most notable are: (i) the projected loss of aridity and its subsequent impact on ‘xeric tolerant’ biota, and (ii) postulated changes in species interactions, especially the shifts in the rates of ecological processes such as adverse changes in plant–animal herbivory (CO₂ fertilisation), predator–prey, pollination and granivory relationships. The complete loss of biota due to sea level rises, variability in cyclone/storms, more extreme events and high wind speeds is a concern because it threatens people’s lives and their livelihoods.

At the other extreme in the south, the projected decrease in winter rains in the stressed southern landscapes (abutting the intensive agricultural areas) is postulated to decrease plant productive substantially. With the possible change in vegetation composition and structure, increasing aridity and altered species interactions (buffel grass competition), especially for the isolated NRS (Billiat, Karte and Danngali Conservation Parks), present biota sensitive to water, heat and fire stress and reliant on shrinking woodland and shrubland environments will be pressured substantially, as shown by modelling of environmental change of present vegetation types in Appendix E.

In the inland parts of the biome, future changes are postulated to be transitional between the north and south, probably with increasing sub-tropical influences, and more extreme events due to the variability of significant rains events and length of dry periods.

Up to this point, we have proposed responses mainly in relation to water and heat stress. Fire will also have a dramatic impact on biotic responses. Altered fire regimes (interactively with other threatening process) are affecting biodiversity through regime shifts in floristic composition and structure, changes in the habitat requirements of some animals and increased exposure to predation (e.g. Gouldian Finch). Although plants have evolved traits enabling species to survive periodic fires (Hodgkinson et al. 1984; Noble 1989; Allan and Southgate 2002), they require distinctive fire regimes (e.g. dominant obligate seeder *Callitris* spp. and resprouting *Eucalyptus* spp. compared with ephemeral herbs and grasses, Bradstock and Cohn 2002). Different regimes in central Australian hummock grasslands will affect soil temperatures, which then affect floristic composition and structure (Wright and Clarke 2007a, 2007b). Similar patterns have been recorded elsewhere in the biome (e.g. southern Mallee, Noble 1989; Bradstock and Cohn 2002). Large wildfires that burn into nearby 'fire sensitive' mulga communities in central Australia (together with many other factors: Nano and Clarke 2008) can shift floristic composition in favour of fire-tolerant, 'woody' communities at the expense of the original mulga communities (e.g. van Etten 1988; Allan and Southgate 2002; Van Leeuwen et al. 1994; Bowman et al. 2007; Nano and Clarke 2008). Of particular concern is the interaction between fire and weed invasion, especially where a spiral of non-native grass invasion and increased fire frequency occurs (e.g. buffel grass, Friedel et al. 2006; Smyth et al. 2009a).

In summary, the expansion front of environmental change in the biome is likely to favour diversification from the rocky ranges, spinifex outcrops, sand plains and other fixed topographical features at a biome scale. Within these places of radiation, 'refugia within refugia' are already providing and may continue to provide microhabitats for biota with limited dispersal capacity, although this is largely unknown. Despite only having three reference points (now, 2030 and 2070) it appears the expansion front will, in a qualitative sense, progress rapidly for some biota and not others. In ecological terms, responses will be diverse across the biome, depending on the variability in the levels of water, heat and fire stress biota experience, together with other environmental stressors.

7 Management implications

The guiding principle for management agreed in the workshop was whatever on-ground management occurs, the aim must be to ‘retain population structure’ for ‘susceptible’ species and manage by removing the threatening processes (facilitating local adaptations) to maximise reproductive (ecological/ecosystem) processes and local adaptations while minimising genetic loss. An example of this type of management intervention is the plant–herbivore interactions between rabbits and *Casuarina* species. Once rabbits are removed from the system (via exclosures, rabbit control), *Casuarina* seedlings have a chance to establish under background stress. At the ecosystem level this translates into maximising environmental diversity, but how can this be achieved in the biome?

7.1 Capability issues

Government instruments for managing threats to biodiversity basically fall into three categories: facilitation (via information provision); incentives to change land management behaviour (e.g. levies, taxes auctions); and regulation (invasive pest management, NRS). To date, management has been a mix of these approaches depending on the scale of management required. There are several issues to do with the ‘desert syndrome’ that make management a challenge in the biome (following Stafford Smith 2008).

The human population is sparse with most people living in urban centres (e.g. Alice Springs, Kalgoorlie, Renmark). There are many small Aboriginal settlements with highly mobile populations in the short and longer term (Figs. 13a and 13b). Tourists and fly-in/fly-out miners also contribute to the mobility. The remoteness of the HGB makes it distant from markets, education and centres of power (e.g. parliament, corporations, universities, high schools). Many opportunities for Aboriginal livelihoods have been identified, the most notable being custodial management of country using local rangers (Davies et al. 2008).

Other than the NRS and custodial management of country, there are limited opportunities for on-ground management in the biome. To this end the workshop strongly advocated for a joint management approach between government and Aboriginal custodians. It was strongly recommended that governments continue to invest in socially driven conservation enterprises on Aboriginal lands and engage traditional ecological knowledge and practices, especially about fire management. Where there are no settlements, experts postulated that these places were best left unmanaged.

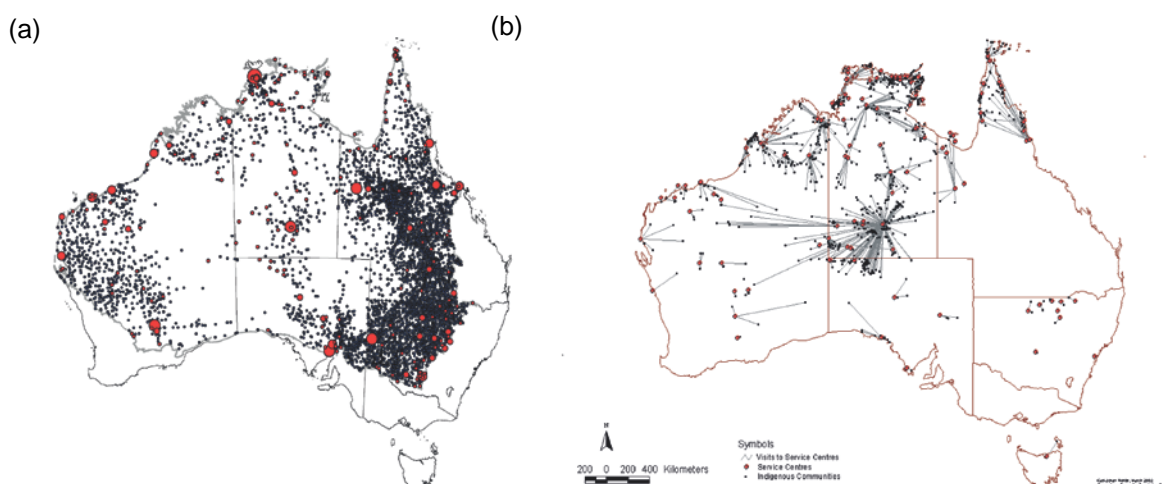


Figure 13 (a) Settlements and population centres in the rangelands (representative of the biome) and (b) travel patterns of Aboriginal people from settlements

Source: (a) CSIRO 2006 (b) Taylor 2002

7.2 Issues affecting where to manage

Several challenging issues affect decisions about which priority places to manage for climate change impacts on biodiversity in the biome. They concern the biome's climate diversity latitudinally, present and future environmental diversity 'hotspots', biota-environmental stress-threats relationships, multitude of potential biotic responses to changing physical environments and the role of artificial waterpoints in times of increasing aridity.

The whole biome covers five agro-climate zones (Hobbs and McIntyre 2005). Within these zones, there are a number of opposing climate systems that drive ecosystem dynamics such as a warm wet season in the north-west in summer and a cold wet winter in the south. As a first step towards reducing uncertainty in management, it may be best to divide the biome into management zones with a revision of Hobbs and McIntyre based on projected climate change. Initially, zones could be based on our best knowledge today (low confidence) but revised as new knowledge (moderate uncertainty) reduces uncertainty and refines management zones.

Today's environmental diversity is largely represented in the NRS, but extensive areas also occur outside. In view of the projected poor buffering for today's plant environments in the biome under future climate change, the present NRS will need extensive 'buffer zone' management to minimise threats to environmental diversity (a surrogate for biodiversity) and the natural rainfall–fire relationships that operate beyond protected areas. Fires can create disconnectedness between places of diversification and refugia within and among the NRS. Consequently, biodiversity needs to be managed for ecological (structural, resource and functional) connectivity at multiple spatial scales and in random fashion to reflect natural fire frequencies.

The compounding effects of threatening processes and that of the projected environmental stress of climate change should be managed integratively to maximise scarce resources. Ideally, it would be ecologically sensible to manage for the myriad of species responses to environmental stress but an extensive meta-analysis of species–climate interactions (based on 1000 biotic interactions from 688

publications) concluded that species responses were so idiosyncratic that they were difficult to predict (Tylianakis et al. 2008). This reality makes management a challenge, but not insurmountable.

With increasing aridity predicted, water and heat stress for biodiversity will increase. An opportunity to manage water stress of birds, kangaroos and dingos (the only meso-predator in Australia) are artificial water sources. Instead of decommissioning them, they may be vital for the management of these taxa as they are densely distributed throughout the most of the biome (Figure 14).

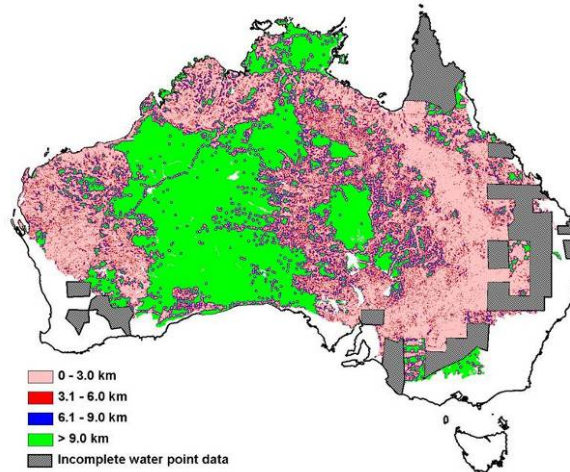


Figure 14 Distribution of water sources for Australia (representative of the biome) in 2002

Source: CSIRO Biograzing project, James et al. unpublished data.

Places of special interest to manage include places of proposed diversification, endemism and refugia specifically associated with rocky ranges, some sandy deserts, lakes and drainage systems such as the Amadeus paleodrainage system and other groundwater-dependent ecosystems (Box et al. 2008).

7.3 Unknown uncertainty issues

A reoccurring theme of this report is the challenging levels of unknown uncertainty: they impact on management decisions, and, while they are confronting, they do not have to halt management (Mearns 2010). Knowing how to make decisions in a way that reduces the uncertainty of climate change management over time is important for local, regional and national managers of biodiversity. In the face of uncertainty, it may be best to employ strategic approaches to conserve biodiversity across the spectrum of projected environmental change. One approach which has been advocated by researchers and State and Territory environmental agencies for the past ten years that has urgent relevance now is biodiversity monitoring and evaluation (M&E) to inform effective and timely intervention. It offers the ability to shift from the costly 'repair after degradation' to 'intervention for prevention' approach based on risk management.

The steps in M&E are straightforward: (i) strategic planning, (ii) research and development (R&D), (iii) monitoring and adaptation, (iv) evaluation, and (v) reporting (following Watson and Novelly 2004). Although the strategic planning is the first step for setting up the high level scope and governance, it is the R&D that will reduce the uncertainty in a number of ways (following Sarkar 2002; Wallace et al. 2003; Smyth and Rioux 2009; Smyth et al. 2009b and references therein; Kriticos et al. 2010). This is because we identify:

- objectives and desired outcomes of management

- priority places (target areas) for conservation action based on present biodiversity content. Prioritisation is necessary since socio-economic constraints will preclude conserving all places with any native biodiversity
- biodiversity values of priority places relative to the projected environmental changes for the biome. Viability analysis could be undertaken using methods that may involve further work on community modelling (GDM, ANN) at finer resolutions, population trends of species of conservation concern (e.g. aridity-tolerant species in the north and mesic-tolerant species in the south of the biome) and threat analysis to assess management risk
- priority biodiversity inventions based on a multiple criteria decision analysis of the options that meet management outcomes but minimise socio-economic costs.

An example of a coarse ‘place prioritisation’ assessment might involve assessing which sub-IBRAs in the biome are likely to face extreme levels of environmental change (environmental stress > 0.7 under high emission scenario in 2070 as more representative of present emission trajectory, Barnett 2009). Only plants and reptiles were projected to encounter completely different environments (see Appendix F for other taxa) and this would happen in about half of the biome’s sub-IBRAs (Table 6). Most of these sub-IBRAs could be grouped at the IBRA level or even coarser resolution where abutting IBRAs show extreme environmental change for both taxa. The Great Sandy Desert is an exception, showing a difference between taxa. This assessment provides a starting point from which to undertake a viability analyses about biodiversity values.

Table 6 IBRAs and sub-IBRAs where today’s environments undergo substantial change (compositional dissimilarity >0.7) and taxon are projected to undergo high environmental stress

IBRA	SUB-IBRA	PLANTS	REPTILES	IBRA	SUB-IBRA	PLANTS	REPTILES
Burt Plain	BRT1	✓	✓	Gibson Desert	GD2		✓
Coolgardie	COO2	✓	✓	Great Sandy Desert	GSD3	✓	
	COO3	✓	✓		GSD4		✓
Cobar Penepplain	CP3	✓	✓	MacDonnell Ranges	MAC1	✓	✓
	CP4	✓	✓		MAC2	✓	✓
	CP5	✓	✓		MAC3	✓	✓
Central Ranges	CR1	✓	✓	Murray Darling Depression	MDD1	✓	✓
Davenport Murchison Ranges	DMR1	✓	✓		MDD2	✓	✓
	DMR3	✓	✓		MDD4	✓	✓
Eyre York Block	EYB3	✓	✓		MDD6	✓	✓
	EYB4	✓	✓	Mulga Lands	MUL3	✓	✓
	EYB5	✓	✓		MUL5	✓	✓
			MUL8		✓	✓	
Flinders and Olary Ranges	FLB1	✓	✓	Naracoorte Coastal	NCP4	✓	✓
	FLB2	✓	✓		Riverina	RIV3	✓
	FLB3	✓	✓	RIV5		✓	✓
	FLB4	✓	✓				
Gawler	GAW1	✓	✓	Tanami	TAN2	✓	✓
	GAW2	✓	✓		TAN3	✓	✓

A crude example of a viability analysis is shown in Table 7. In this analysis, we use the results of the future environmental stress modelling, expert modelling about a threat (high suitability of buffel grass) and expert advice for the workshop to flag future ‘climate driven’ vulnerability of biodiversity in the sub-IBRAs. This time we identified which IBRAs met three criteria:

- a value of high environmental stress (> 0.7 under high emission scenario in 2070)
- high predicted suitability for buffel grass establishment and spread (probability 0 to -0.4)

- (iii) high diversity of landforms (1 to 4) covering rocky ranges and outcrops, sand plains, water bodies (lakes, rocky waterholes, paleodrainage systems) and dune fields. Landforms are important for supporting places of diversification, refugia and endemism and therefore were considered a surrogate for places of conservation significance for biodiversity.

In some respects, these criteria describe the relationship between future environmental change (upper extreme of the spectrum) and biodiversity responses where landform diversity is used as a surrogate for spatial environmental heterogeneity, an important factor facilitating ecological processes and eventually adaptations. It is clear in this example that IBRAs in the biome have different biodiversity values when the 'climate change' lens is applied, but these patterns can be interpreted a number of ways for management intervention depending on the desired management outcomes.

Table 7 Combined information to postulate places of vulnerability (environmental stress > 0.7 for modelling, very high suitability 0 to -0.4 and key landform features) at the IBRA level

IBRA	VEG CLASSES (ANN)	SPECIES COMP (GDM)	BUFFEL GRASS (BBN)	ROCKY RANGES, OUTCROPS	SAND PLAINS	WATER BODIES	DUNE FIELDS
Burt Plain	✓	✓			✓		
Carnarvon	✓						✓
Cobar Plain		✓	✓		✓		
Central Ranges	✓	✓		✓		✓	
Channel Country	✓					✓	✓
Dav-Murchison		✓		✓			
Eyre York Block	✓	✓	✓	✓			
Flinders/Olary	✓	✓		✓		✓	
Gawler		✓	✓	✓		✓	
Gibson Desert	✓	✓			✓	✓	✓
Great Sandy Des	✓	✓		✓	✓	✓	✓
Great Victoria Des	✓			✓	✓	✓	✓
MacDonnell Ranges		✓	✓	✓		✓	
M–D Depression	✓	✓	✓				✓
Mulga Lands	✓	✓		✓	✓	✓	
Murchison			✓		✓	✓	
Naracoorte CP		✓					✓
Riverina	✓	✓	✓				✓
Tanami	✓	✓			✓	✓	

There are a number of desired management outcomes relating to biotic responses, such as (i) safe today and in the future, (ii) safe today, at risk in the future, (iii) at risk today and in the future, (iv) at risk today and newly safe in the future, (v) departing today, going extinct locally, so no future, (vi) not here today, returned in the future due to favourable environmental conditions, and (vii) new species due to novel environments. Although not an exhaustive list, it indicates the diversity of responses which can result in diverse management purposes, and some may be of a higher priority than others. If, as an example, we manage for (ii), then we may prioritise for invention the Eyre York Block and Murray–Darling Depression because environmental stress is severe, buffel grass invasion is high and landscape diversity is limited to one landform. If (vii) were the priority, then the Great Sandy Desert may warrant further attention because of the high level of environmental change and the diversity of landforms offering opportunities for new adaptations in species with short generation times.

In summary, there are a number of issues that can affect where to manage biodiversity for climate adaptation. Uncertainty can hamper management, but by adopting systematic conservation planning approaches underpinned by an adaptive management philosophy, it is possible to reduce the uncertainty and prioritise the multiple and sometime conflicting management options. We provide a crude introduction as to how this could be solved but recognise that more sophisticated work should be undertaken to demonstrate the best way forward for on-ground management, especially in how some of these approaches align with custodial management.

8 Conclusions

Multiple issues to do with the biome's climate zones, places of high environmental stress, environmental diversity, biogeography, adaptation capacity, ecological responses of biota and the unknown uncertainties will influence future management. As in the Savanna Woodlands and Grasslands biome, management capability is more limited due to the sparseness of human resources. In addition to other local land managers, there is a strong argument for engaging Aboriginal people in management.

The hummock grasslands biome is extensive, covering about 60% of Australia. The dry portion is relatively intact and has globally unique hummock growth forms in spinifex grasses and globally unique plant and lizard species that survive in the most extremely arid climates on the planet. It is socio-economically important for mining, ecotourism and Aboriginal culture. Not surprisingly its biota has some quirky adaptations to aridity. Rainfall and fire have been shaping the biome over 20 M years. However, its biodiversity is stressed by a number of threats which are compounded by climate change.

Physical factors driving the biome are energy from the sun, frequency and variability of rainfall and nutrients, and different soil types and quality. Combined, these factors sustain a multitude of ecological processes that influence environmental heterogeneity and ecosystem dynamics. Overlay the driving force of water and heat stress, CO₂ fertilisation, higher frequency of severe storms, flood, and longer dry periods with sustained impacts of existing threats, and biodiversity is faced with sustained environmental stress in the future.

Depending on the adaptation capacity of biota (via diversification and exploitation of refugia), extinction may be the only option for some organisms; others may thrive; and the population of others may fluctuate widely but overall not change much. Options for diversification and refugia where there are places with high environmental diversity exist in the long run for those species with short generation times. At an ecosystem level, community composition and structure as we know it today will change in the future, but how it will change is impossible to say because of the large amount of known and unknown uncertainties due to a lack of baseline information, especially about species interaction.

We can be reasonably confident that the existing NRS will play an important role in the long term but only if existing threats are eradicated and well-managed buffer zones are created and maintained. Unprotected areas will be equally important for biodiversity conservation. Nevertheless, biodiversity M&E will be essential for informing cost-effective management that reduces the uncertainty surrounding future climate change management.

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Appendix A Workshop summary

PARTICIPANT	AGENCY (NAME AT TIME OF WORKSHOP)
Justin Billings	Australian Government Department of Environment, Heritage and the Arts
Tim Bond	Australian Government Department of Environment, Heritage and the Arts
Robert Brandle	Department of Environment and Heritage, SA
Jayne Brim-Box	Department of Natural Resources, Environment and the Arts, NT
Graham Carpenter	SA Native Vegetation Council and Private Consultant
Sue Carthew	The University of Adelaide
Peter Copley	Department of Environment and Heritage, SA
Angus Duguid	Department of Natural Resources, Environment and the Arts, NT
Michael Dunlop	CSIRO Sustainable Ecosystems, ACT
Simon Ferrier	CSIRO Entomology, ACT
Jeff Foulkes	Department of Environment and Heritage, SA
Pauline Grierson	The University of Western Australia
Graham Griffin	Datasticians
Nerissa Haby	The University of Adelaide
Rohan Hamden	SA representative of Commonwealth CLAN (Climate Change and NRM Group)
Angas Hopkins	Australian Government Department of Climate Change
Peter Kendrick	Department of Environment and Conservation, WA
Stephen van Leeuwen	Department of Environment and Conservation, WA
Adrian Pinder	Department of Environment and Conservation, WA
Jolene Scoble	The University of Adelaide
Rick Southgate	Envisage Environmental Services
Anita Smyth	CSIRO Sustainable Ecosystems, SA
Glenda Wardle	The University of Sydney

Workshop program

TIME	THURSDAY, 5 MARCH
On arrival	Tea and coffee
11:15 – 11:30	Welcome and Introduction (Anita, Mike)
11:30 – 11:50	Introductions
11:50 – 12:30	Round table report back on homework (Participants)
12:30 – 1:30	Lunch
1:30 – 2:00	Round table report back on homework cont.
2:00 – 2:30	Presentation on environmental and biodiversity change (Mike)
2:30 – 3:00	Presentation on key ecosystem drivers of biome (Anita, Mike)
3:00 – 3:10	Presentation on contemporary climate variability (Jeff Foulkes)
3:10 - 3:20	Report on review – what’s changing (Anita)
3:20 – 3:45	Afternoon Tea
3:45 – 5:00	Update on biome and Open Discussion on likely changes (Mike facilitates)
5:00 – 6:00	Presentation and Open Discussion: Typology of big change phenomena (Mike)
FRIDAY, 6 MARCH	
On arrival	Tea and coffee

8:30 - 8:45	Update and housekeeping
8:45 – 9:45	Open Discussion: Modelling and detection of big changes (Dave/Simon facilitates)
9:45 – 10:45	Open Discussion: Implications for biodiversity, agencies, habitat protection and NRS (Mike facilitates)
10:45 – 11:15	Morning Tea
11:15 – 12:15	Open Discussion: Adaptation options (Mike facilitates)
12:15 – 1:15	Open Discussion: Information needs following on from adaptation options (Mike facilitates)
1: 15 – 2:15	Lunch
2:15 – 3:15	Round table on emerging issues, challenges, lessons (Anita?)
	Thank you

Definitional issues

- The biome was defined broader than NVIS Major Vegetation Group (Australian Government Department of Environment and Water Resources 2007). It's important to map where *Triodia* is the major functional component and where it is mixed with other major vegetation types but is a significant component for biodiversity especially under climate change.
- Map major and minor components to IBRA subregions.
- 'Habitat diversity' redefined in terms of environmental diversity – all of its components of diversity that lead to diverse vegetation types/communities referred to as habitats (excluding plants) occupied by organisms.
- Aspirational role of NRSs – Whatever on-ground management occurs, the aim must be to 'retain population structure' for 'susceptible' species and manage by removing the threatening processes (facilitating local adaptations) to maximise reproductive (ecological/ecosystem) processes and local adaptations whilst minimising genetic loss.

Key Guiding Principles

1. Biome characteristics and drivers

- Extensive biome and is influenced by a number of opposing climate systems at different times of the year.
- Need to consider 'rain years' as it changes for different locations in the biome.
- Long-term trends (~100 years) vary across the biome (need to divide the biome into climatic sub-zones within agri-climatic zones).
- Climate projections for rainfall for the biome inconclusive, so need to make projections for wetter and drier scenarios for each climatic sub-zone.
- Aridity in combination with other factors primarily explains mammalian extinctions in arid Australia.
- Soil moisture variability drives productivity and ecological processes, which stimulate animal responses. Relative humidity affects mammalian heat stress. Consequently, temperature and rainfall are reasonable surrogates for soil moisture and other climatic properties.
- Fire has been shaping the hummock grasslands for at least 20 Myr and it is intricately tied to climate, topography and vegetation productivity (e.g. lightning, rainfall seasonality, wind, relative humidity, topography, plant biomass and biomass connectivity).
- The daily, annual, decadal and centurial variability of temperature and rainfall mediates fire, plant productivity (summer vs. winter germinators), animal populations and other ecological processes at multiple spatial and temporal scales in the biome.
- Fire regimes, in turn, mediate local faunal persistence via the severity of introduced predators due to damage of shelter (vegetation architecture). 'Rainfall since time of fire' mediates the exposure to predation via vegetation restoration.

- The 'natural' fire–rainfall interactions drive species interactions locally (herbivory, carnivory, decomposition, reproduction, local extinctions) and not necessarily consistently throughout the whole biome. Overlay the interactive effects of threatening processes (climate change, feral herbivores, introduced predators, invasives – especially buffel grass, overgrazing, changed surface water expressions of groundwater) and shifts in environmental diversity will occur. Such changes could have beneficial, detrimental or neutral effects on biodiversity and ecosystem functionality.
- Subterranean termites are keystone ecosystem engineers of the hummock grasslands.

2. Typology of change

- Changes in the spatio-temporal dynamics of the rainfall–fire interaction will have beneficial, adverse or neutral effects on the spatio-temporal dynamics of species interactions.
- **Buffel grass** transforms native environments rapidly when disturbance levels are high enough and physical characteristics are suitable. CC will exacerbate its impact on biodiversity but we don't fully understand the complexity and dynamics sufficiently to predict a pattern. More important in the summer rainfall-dominated areas now, but that it can spread rapidly and dominate outside its bioclimatic envelope is critical.
- **Feral herbivores** (camels, donkeys) will increase under more mesic conditions (especially north) and so will species favouring a mesic climatic envelope. Where there is increasing aridity, ferals (and bats) will contract to waterpoints and these will become highly degraded. But under increasing relative humidity (temperature and rainfall interactive effects), larger mammals may suffer heat stress.
- Foxes and rabbits move south, tracking a mesic climatic envelope.
- **Heat stress.** Increasing variability in temperature extremes will increase mortality in ground mammals and some bird species that can't disperse in response. Refugia important.
- **Fire** characteristics are different in different parts of the landscape and not necessarily following a north–south pattern.
- Fire refugia occur in the sandstone ranges and rocky outcrops but the biomass lives on the hills and colluvial slopes.
- Information of fire regimes for HG are either lacking or inconclusive. Possible to predict probability of fire reoccurring with reasonable confidence.
- Biotic response to future changes in the dynamics of the fire–rainfall interaction are very complex to project under CC. May be better to develop a rating system for biotic responses.
- Adopt a shifting mosaic steady state. Dealing with an ecosystem as a whole and what you are trying to maintain is a % of the steady state (i.e. 10% of 'late successional', 20% 'early successional') but it keeps shifting around. Good broadscale management objective. But the difficulty is (i) how frequently, (ii) how big an area. A function of the place in the landscape (topography, ecological communities and organisms in it).
- Alternatively, manage for fixed properties i.e.. pick up naturally heterogeneous areas producing patchy burns (e.g. paleodrainage lines, rocky outcrops), so we manage for these 'fire-free refugia' with the mosaic. Accept the rest is unmanageable because of uncontrollable and changeable fire weather patterns. Manage for what you can keep. Have custodial management of threatening processes in 'fire-free refugia'.
- Fire management cannot be structured but must be flexible and allow for a range of environmental diversity. Need to manage for randomness at multiple spatio-temporal scales. Manage for priority places (NRS?) and broadscaled custodial management for fire and other processes.
- Fire is not benign on the landscape, it's just impossible to manage at a biome scale. Under CC. Fire linked with rainfall and is a major driver of the hummock grasslands and has been for millennia. Together they create opportunities for other threatening processes to have adverse interactive effects on biodiversity and ecological processes. Fire and weather dynamics difficult to manage so managed for heterogenous fire places in the landscape.
- In terms of **socio-economic trajectories**, may be a benefit to biodiversity for governments to continue to invest in socially driven conservation enterprises on Aboriginal lands as a mean of conserving biodiversity and being on country. Keep traditional knowledge on country and engage their management of broad

landscapes. Pushing TEK to manage for conservation outcomes but mindful there will be big economic incentives (via mining) not to manage for conservation. Societal issue to address.

- HGs are inseparable from Indigenous interests; key component and 99% Indigenous people to do management
- **Refuges and loss of aridity.** Fixed topographical features (ranges and rocky outcrops, GDEs, outlying bits of *Triodia*) are likely refugia but issues of connectivity due to big fires creating disconnectedness between refugia. Potentially important sources of radiation.
- **Plants vs animals.** *Triodia* will probably be a winner (spread more widely) under climate change.
- Aridity is the problem; greater variability increases with greater aridity. Loss of productivity and greater variability are due to rainfall patterns and that's why you see this difference between means. High rainfall mean leads to lower variability. If rainfall mean remains the same and greater variability occurs or mean decreases but with a greater variability, or both occur, then stress on biodiversity will be extreme. It will knock some species with life histories that don't match those linked patterns.
- Arid biota well adapted to present resources and functions but change the species interactions (seedbank and changed fire regime) then shifts (population, compositional) will occur. Plant–animal relationships have changed past 100 years, so what's there now is robust. But what's robust now, may not be robust under CC. Then need to look at the change in species interactions, but what will they be? Too speculative, we just don't know.
- Need to distinguish between adaptive and vicariance variation because they have different implications for CC management. But knowledge is poor.
- **Nutrient cycling.** Unclear about the impacts because difficult to measure due to extreme spatial variability and poor knowledge.
- **Spinifex and termites.** Hummocks structurally important for termites but they are more resilient than other invertebrates such as ants but overall poor knowledge about termite biology and response to rainfall, fire and climate change.

3. Policy and management guiding principles

- Biome is relatively intact and sparsely populated with land managers (Aboriginal people, mining enterprises and pastoralists).
- Management will need to be collaborative among land managers.
- Reserves are appropriate because of long-term security but must be managed with a 'whole of landscape' approach at a scale around 100,000 km² with indistinct boundaries.
- Alternative approach is to translocate biodiversity to 'islands' but recognising their different climates and unique biodiversity values.
- Whatever on-ground management occurs, the aim must be to 'retain population structure' for 'susceptible' species and manage by removing the threatening processes (facilitating local adaptations) to maximise reproductive (ecological/ecosystem) processes and local adaptations while minimising genetic loss (e.g. Casuarina seedling and rabbits).
- Detailed strategic planning with guiding principles in mind needs to occur before effective management actions can be identified. Follow up workshops will be needed.
- Available funding will need to increase to minimise conflicts (wicked issues – camels, dogs) in management among the biome's land managers.

4. Four targets/objectives for conservation

- Goal is to manage for maximal, collective diversity for the whole biome.
- The design of the NRS aims to capture as many places needed to maximise biological diversity and the custodial management aims to maintain ecosystem status.
- Use the 7 measures of ecosystem status to guide thinking on biodiversity values to prioritise for reserve design.

A.1 General conclusions

Some expected outcomes of the workshop were met more strongly than others:

- The characteristics of the biome as presented in the background document and the presentation were generally agreed.
- There was a shared understanding on the difficulty about the types of changes likely to affect the biomes. This was evidenced by the difficulty we had developing a typology of change. The thesis from the workshop was that the dynamics of the 'fire–rainfall' interactions drive the species dynamics locally and inconsistently throughout the biome. Environmental diversity unpredictable in space and time throughout the biome. Without a detailed empirical knowledge of how changes in 'fire–rainfall' interactions affect changes in species interactions, comments about the impacts of climate change will be highly speculative.
- No extra information about datasets was forthcoming in the workshop. Doubts were raised about the value of modelling when rainfall data are extremely sparse and unpredictable for the biome.
- No conclusive statements other than that *Triodia* could be a winner under climate change was made about its impacts on biodiversity. However, some guiding principles did emerge from discussions.

Appendix B Climate modelling in detail

B.1 Climate change scenarios

Two 1 km² resolution scenarios were considered, both using 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). 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; Fenner School of Environment and Society 2012), which incorporates three submodels: ESOCIM, which outputs raw climate variable grids; BIOCLIM (Busby 1986), which outputs grids of 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 landmass, 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 km²) 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.1.1 ECOSYSTEM CLASSES – ARTIFICIAL NEURAL NETWORKS (ANN)

Our approach 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 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 artificial neural networks 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 artificial neural network was used to classify 15 structural/physiognomic forest environments based on a range of climatic, edaphic and topographic variables (Hilbert and Van Den Muyzenberg 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 the biogeographic regionalisation for Australia (Thackway and Cresswell 1995). 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 and Ostendorf 2001; Hilbert et al. 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 as an appendix to the project synthesis document (Hilbert & Fletcher 2012).

B.1.2 SPECIES COMPOSITIONAL TURNOVER – GENERALISED DISSIMILARITY MODELLING (GDM)

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 km² grid resolution¹ 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 km² grid cells)
- 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 projected 'environmental stress' expected to be encountered 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 projected 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:

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.

- 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 point a. 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).

Appendix C Changes in the environments of spinifex and non-spinifex major vegetation groups of hummock grasslands biome

Areas (km²) of pre-1770 NVIS MVGs as currently mapped (descending order by mapped area) and as classified for present and 2070 climates under medium and high climate change scenarios, using the ANN model. (* MVGs with major and minor components of *Triodia* hummock grasslands. Accuracy - % accuracy of ANN classification, see Hilbert et al. 2012)

CODE	MAJOR VEGETATION GROUPS (MVGs) OF THE NATIONAL VEGETATION INFORMATION SYSTEM (NVIS), VERSION 3.0	CURRENT		CLIMATE CHANGE	
		MAPPED AREA (KM ²)	MODELLED AREA (KM ²) (ACCURACY, %)	2070 MEDIUM AREA (KM ²)	2070 HIGH AREA (KM ²)
MVG 20	*Hummock Grasslands	1184753	983891 (72)	1017896	978721
MVG 16	*Acacia Shrublands	611085	715733 (63)	703133	279512
MVG 6	*Acacia Forests and Woodlands	278368	276195 (54)	212688	227379
MVG 14	*Mallee Woodlands and Shrublands	275074	277938 (75)	190616	60437
MVG 13	*Acacia Open Woodlands	229329	234398 (54)	175030	172048
MVG 11	*Eucalypt Open Woodlands	152226	127425 (57)	259638	484677
MVG 22	Chenopod Shrublands etc.	131940	153943 (76)	265433	474552
MVG 8	*Casuarina Forests and Woodlands	128784	183412 (73)	144923	126330
MVG 19	Tussock Grasslands	117058	115995 (67)	187617	318779
MVG 21	Other Grasslands etc.	12067	25832 (61)	61953	105854
Total (% of biome)		3431512 (91)	3431512 (91)	3431512 (94)	3431512 (94)

Appendix D Relationship between CO₂ and daytime growing season temperature of C₃ and C₄ grasses

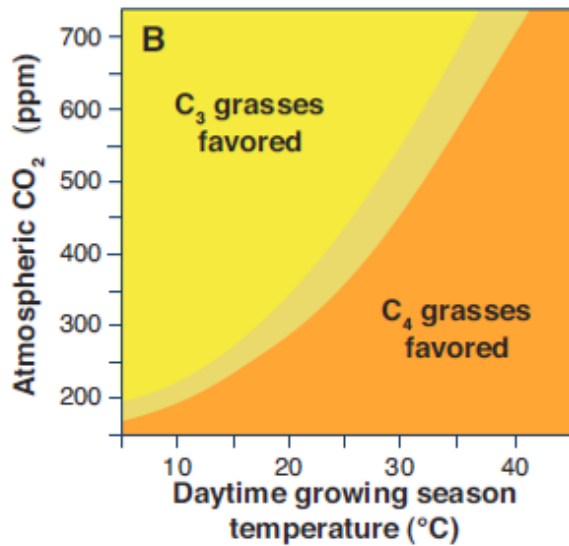


Figure D.1 Commonly reported prediction of atmospheric CO₂ and growing-season temperature conditions that favour the growth of C₃ and C₄ grasses, based on the quantum yield of photosynthesis, a measure of the inefficiency caused by photorespiration

Source: Edwards et al. 2010

Appendix E Projected mapping of major vegetation groups for dry hummock grasslands based on environmental change in 2070 for high emission scenario

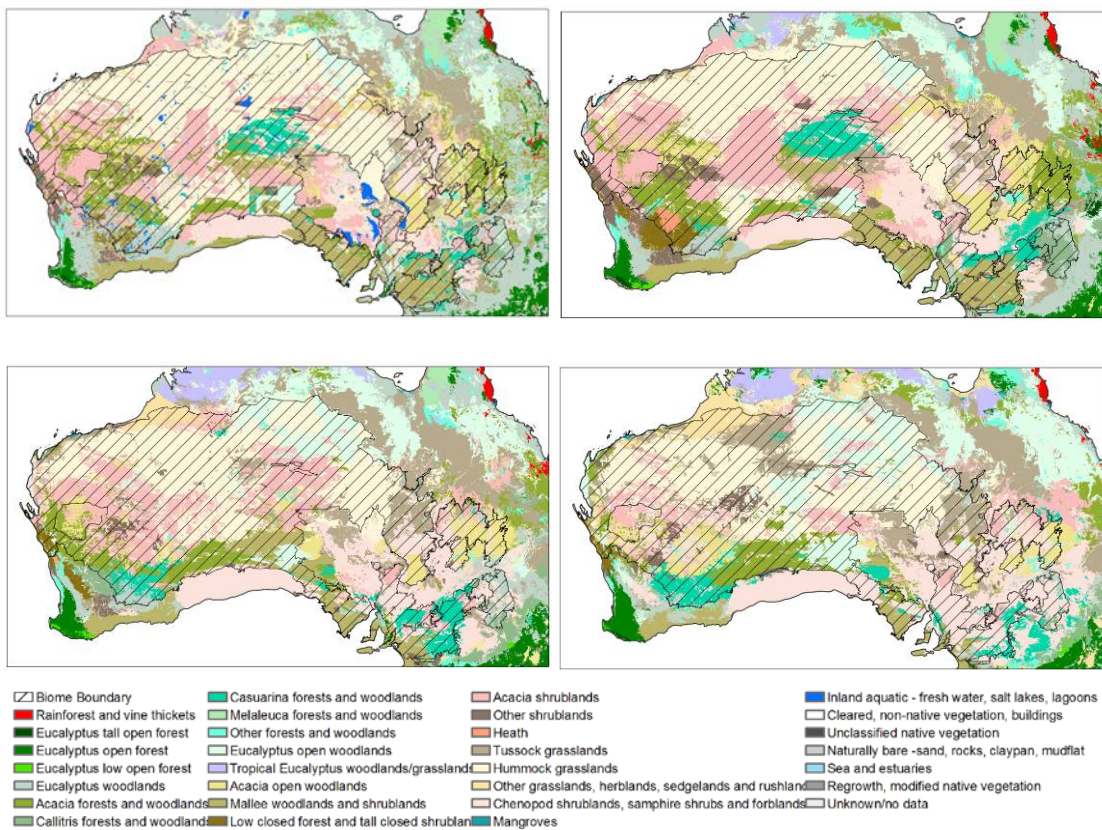
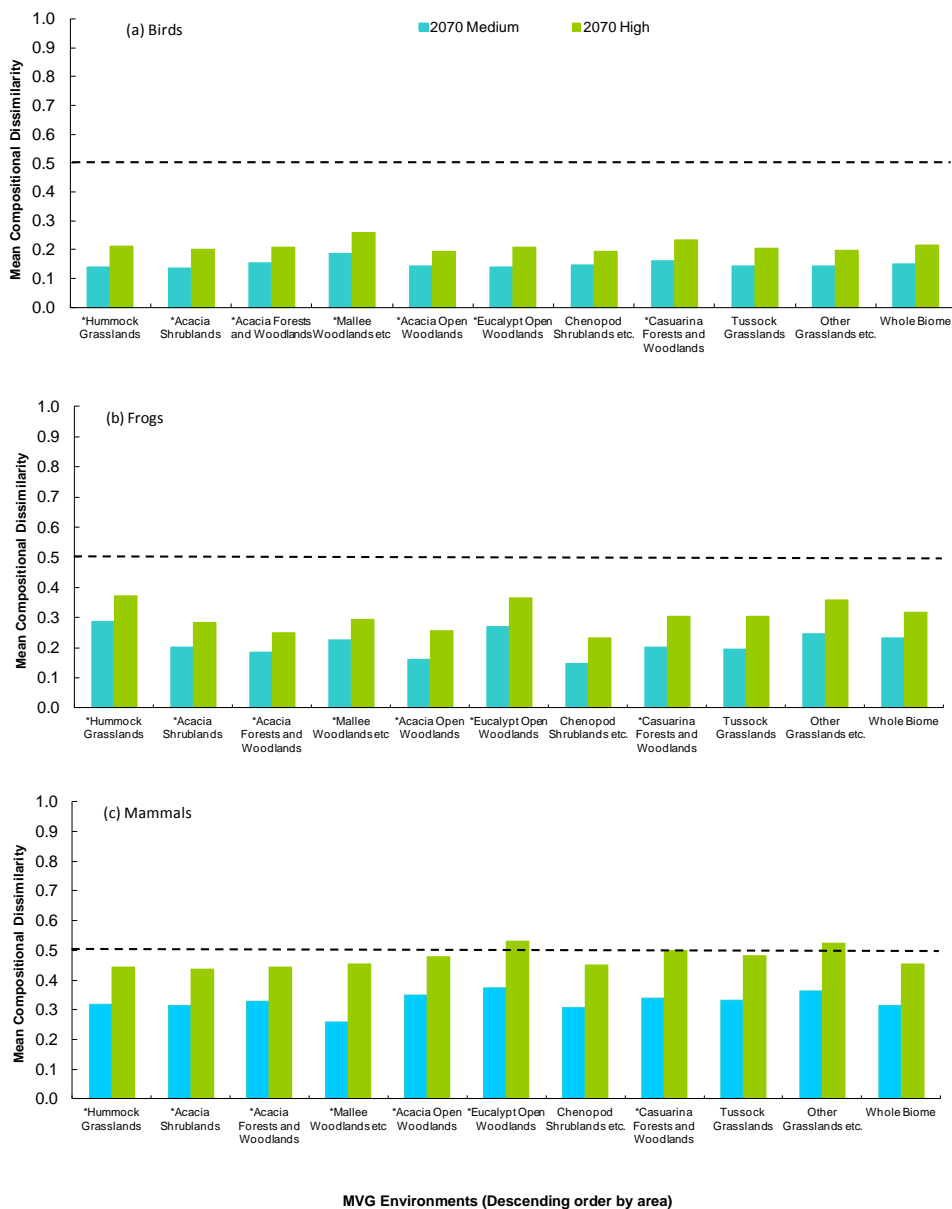


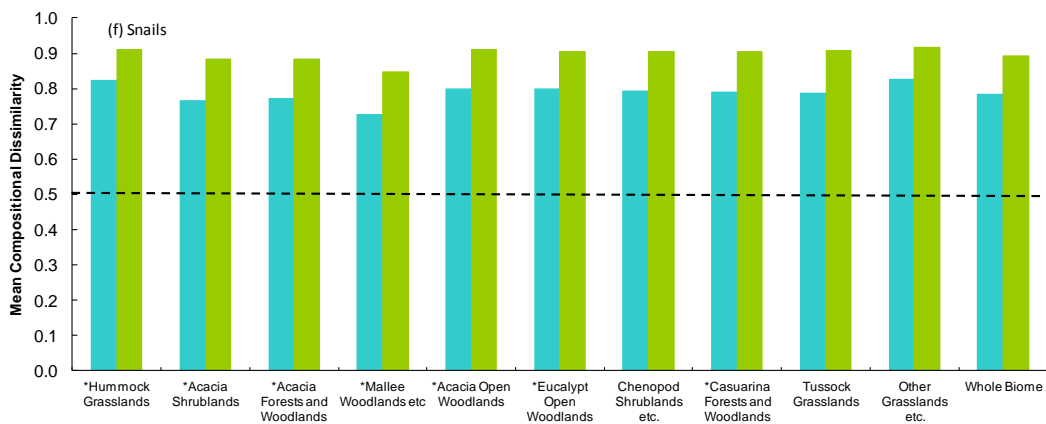
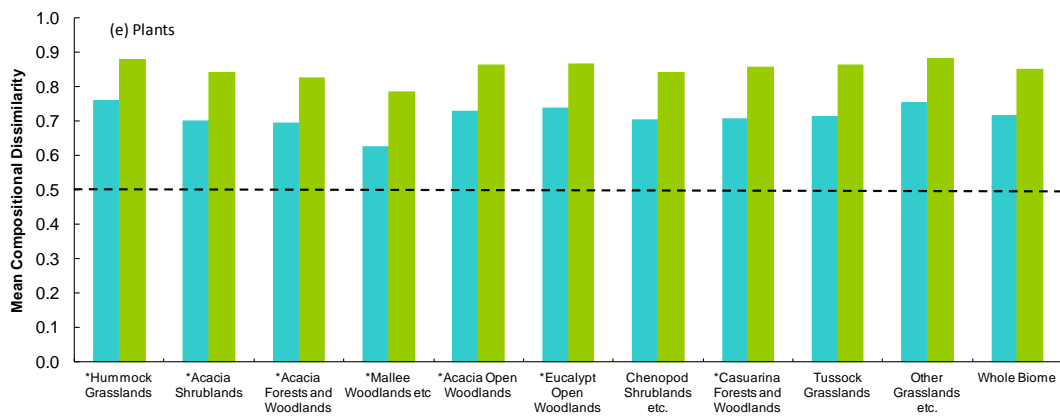
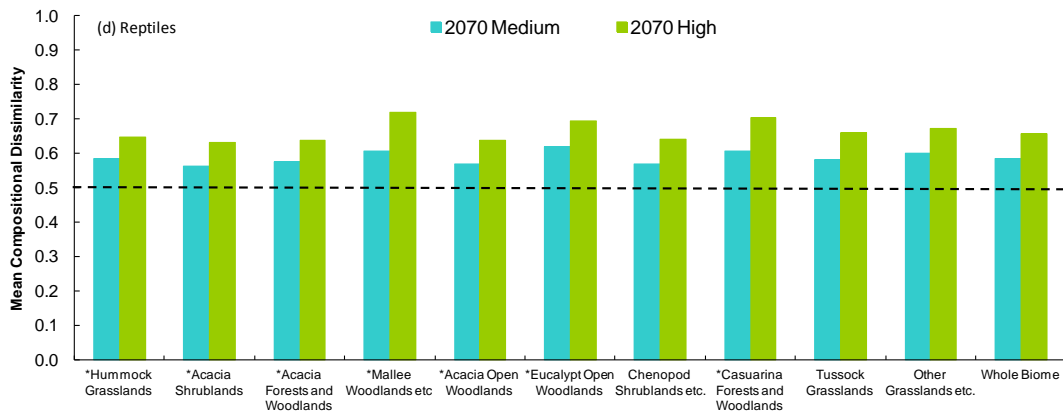
Figure E.1 (a) NVIS pre-clearing vegetation map, and ANN modelled distribution of environments for (b) current climate, (c) medium 2070, and (d) high 2070 emissions climate change scenarios. Hatched area indicates approximate biome boundary. (Note: Casuarina Forests and Woodlands in central Australia represents Desert Oak *Allocasuarina decaisneana* woodlands and *Casuarina pauper* (Black Oak) in the south)

Appendix F Compositional change in current taxon groups responding to environmental change under 2070 medium and high climate scenarios by major vegetation groups

(Taxa are depicted by increasing environmental stress; stress level: 0.1 = low, 0.5 = moderate, 1.0 = high. Standard error of the mean for MVGs and the whole biome are about 0.002)



APPENDIX F – CONTINUED



MVG Environments (Descending order by area)

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