Climate change, Variability and Conservation impacts in Australia

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Australian conservation scientists, managers and decision makers must come to grips with anthropogenic climate change, imposed upon an already variable regional climate system. Pre- and post-instrumental records and climate proxies indicate that Australia has experienced wet and dry cycles over intra-decadal to millennial time scales. Precipitation variation across Australia is correlated with different climate features but reliable tools for seasonal rainfall prediction are still some years away. Atmosphere-Ocean General Circulation Models predict a widening of the Hadley circulation and strengthening of the Southern Annular Mode, which should result in reduced cool season rainfall over southern Australia. Shifts in the Australian climate over the Holocene epoch, most notably increased ENSO variability after 5 000 years ago, are associated with substantial vegetation change and indicate the speed at which ecosystems may be altered. The CO_2 fertilization of plant biomes may mitigate increasing aridity to some extent but, in general, climate change is expected to negatively affect native vegetation and agricultural productivity. Sea-level rise is predicted to be substantial over this century and, when coupled with increased storm intensity, poses threats in the form of erosion, salinization and flooding. The best chance of building adaptable ecosystems and preserving ecosystem services requires the extension, integration and possibly optimization of reserve systems, in concert with improved management of other threatening processes (habitat loss, invasive species, overexploitation, pollution and disease). In addition, a price on carbon dioxide emissions would provide incentives for privately funded reforestation schemes, but additional incentives promoting mixed species over monoculture plantings would be required to assure maximum biodiversity benefits.

Key words: conservation management, drought, El Niño-Southern Oscillation, Southern Annular Mode, reserve system, carbon market, review

INTRODUCTION

AUSTRALIA'S climate is among the most variable of any country. Since current strategies of environmental management are based on instrumental (post-1900) records, natural climatic variation represents a significant challenge for responsible environmental management. For example, the Murray-Darling Basin in southeastern Australia has experienced multiple shifts in rainfall regime since European settlement. A wet phase in the late 1800s was followed by a dry regime extending into the 1940s and a subsequent wet regime reverted to a dry phase from the mid-1990s (e.g., Vivés and Jones 2005, Potter *et al.* 2010). If 1996 supply management rules had been implemented under these historical conditions, environmental flows would have been unacceptably low during the early 1900s (Jones and Pittock 2002). This illustrates the importance of understanding natural, long-term, climatic variation for natural resource management.

A further challenge is to come to grips with the effect of anthropogenic climate change, imposed upon an already variable climate system. Climate change negatively impacts biological systems by directly affecting species and the ecological processes that sustain them as well as additively and synergistically exacerbating the impacts of other stressors. Numerous threatening processes affect Australian ecosytems — habitat loss and degradation, invasive species, overharvesting, pollution, disease, modification of the hydrological cycle, and changed fire regimes are just some of the more important (Kingsford *et al.* 2009). Climate change interacts with all these processes in complex ways (e.g., Hughes 2003, Brook 2008, Steffen *et al.* 2009). Species physiology and phenology are affected, interactions between species are modified, species distributions are shifting (if they can), and entirely new ecosystems may result (Steffen *et al.* 2009). Although some climate change impacts are predictable, many outcomes remain unforeseen. Biodiversity conservation and maintenance of ecosystem services are best advanced by fostering ecological systems that are intrinsically resilient and retain sufficient variation to be able to adapt and preserve biodiversity (MEA 2005).

Thorough treatments of climate change attribution studies and the most recent climate change predictions for Australia are publically available (Suppiah *et al.* 2006, CSIRO 2007). Climate projections derived using different greenhouse-gas-emissions scenarios, coupled with 23 Atmosphere-Ocean General Circulation Models (AOGCMs), forecast a warming over the entire Australian continent and a rainfall decline, except in the tropical north (CSIRO 2007). Increased evapotranspiration accompanying higher temperatures may amplify the aridity caused by declining rainfall, leading to more severe droughts (Nicholls 2004). Regional precipitation variation is sensitive to small-scale topographic features that affect weather patterns

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(e.g., mountain ranges) as well as other large-scale climate features (e.g. the El Niño-Southern Oscillation), some of which are not well captured by the AOGCMs (CSIRO 2007, Sheridan and Lee 2010). In this review, we focus on the origins of natural climatic variation in Australia as well as recent research that advances our understanding of the major climate features related to precipitation variation across the continent. We consider insights from palaeo-climatic research and recent climate trends in Australia in the context of global change. Finally, we evaluate the impact of a changing climate on evapotranspiration, sea level rise, and future conservation strategies.

ATMOSPHERIC SYSTEMS OF THE AUSTRALIAN REGION

As global temperatures rise, large-scale atmospheric circulation patterns will change. At a global scale, the Hadley Cell is an overturning atmospheric circulation that redistributes heat from the equatorial region to the subtropics, affecting the Australian climate. Warm, moist air rises along the Intertropical Convergence Zone (ITCZ, Table 1), diverges polewards upon reaching the tropopause (the boundary of the troposphere and stratosphere), and sinks in the subtropics. The subsiding air is dry and warmed further by adiabatic heating, forming a belt of high pressure and low rainfall known as the sub-tropical ridge (STR, Table 1). Near the surface, the return flow, heading for the equator, is turned to the west by the Coriolis effect, resulting in south-easterly trade winds in the southern hemisphere. The ITCZ is south of the equator during the austral summer, shifting over the Australian continent during active phases of the monsoon. The STR is typically south of the Great Australian Bight (~37–38°S) during the warmer months but, in autumn, the ridge moves northwards and remains over the continent (~29–32°S) allowing moist, westerly winds to bring cool season rainfall to the southern continental areas.

Four additional climate features critically influence the Australian climate (Table 1): the El Niño-Southern Oscillation (ENSO), Inter-decadal Pacific Oscillation (IPO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). The meteorological and hydrological literature relies heavily on examining correlations between these features and regional climates (e.g., Larsen and Nicholls 2009, Risbey *et al.* 2009). Methodological issues and the physical processes underpinning these relationships continue to be debated (Nicholls 2010). Individual climate features typically account for less than 20% of the variation in monthly rainfall at a single location (Risbey *et al.* 2009). Regional Australian climates may vary out of phase due to complex interactions ("teleconnections") between features.

Understanding these teleconnections is central to developing predictions for regional climate variability and change (Trenberth *et al.* 2007). Consider the three most severe Australian droughts on record, each with a very different spatial signature (Verdon-Kidd and Kiem 2009a): the "Federation drought" (~1895–1902) covered most of the eastern two thirds of Australia; the "World War II (WWII) drought"

Table 1. Major climatic features influencing the Australian climate.

Climate feature	Acronym	Description/Effects
Intertropical Convergence zone	ITCZ	The ascending portion of the Hadley cell, where surface air originating from the subtropics is drawn in near the equator and rises due to convergence and convection, manifesting as an intense band of thunderstorms.
Sub-tropical ridge	STR	The descending portion of the Hadley cell, where warm, dry air sinks, forming a belt of high pressure and low rainfall at around 30 degrees of latitude.
El Niño-Southern Oscillation	ENSO	A coupled ocean-atmosphere variability whose oceanic component manifests as warm (El Niño) or cool (La Niña) sea surface temperatures of the tropical Pacific Ocean (Chiew *et al*. 1998, Neelin *et al*., 1998). The dry (El Niño) and wet (La Niña) phases of ENSO are predominantly during winter and spring over eastern Australia.
Inter-decadal Pacific Oscillation	IPO	A low frequency (~2–3 decades) variability, characterized by sea surface temperatures of the tropical and extra-tropical Pacific Ocean (Power *et al.* 1999). Its positive phase is associated with more frequent El Niño events and suppressed impacts of La Niña. Conversely, its negative phase is linked to more frequent, wetter La Niña events.
Indian Ocean Dipole	IOD	A coupled ocean-atmosphere climate mode whose eastern pole manifests as variation in sea surface temperature off northwest Australia (Saji *et al*. 1999). During winter and spring, warm (cool) sea surface temperatures here result in wet (dry) phases, predominantly throughout western to southeastern Australia, partially due to their influence on the formation of the northwest cloud bands (Evans *et al.* 2009).
Southern Annular Mode	SAM	The dominant climate mode for southern Australian regions below 30°S (Nicholls 2010), reflecting the difference in pressure between the mid and high latitudes (Thompson and Wallace 2000). The positive phase of the SAM is associated with reduced rainfall over southern Australia during winter but increased rainfall in southeastern Australia (excepting Tasmania) during summer (Hendon *et al.* 2007).

(~1937–1945) affected much of Australia, and; the "Big Dry" (~1996–2010) was a prolonged drought experienced by southwestern and southeastern Australia. The Federation drought occurred during positive-phase IPO and sustained El Niño activity, explaining its severity over eastern Australia (Verdon-Kidd and Kiem 2009a). During the WWII drought, the IOD was mostly locked into its positive phase, with cool sea surface temperatures off northwest Australia correlated with reduced winter-spring rainfall in the southeast (Ummenhofer *et al*. 2009). Finally, the Big Dry corresponded to three years of El Niño conditions (2002–2004) and a sustained period of positive-phase SAM which probably blocked the propagation of La Niña rainfall into southeast Australia (Verdon-Kidd and Kiem 2009a, Kiem and Verdon-Kidd 2010). Relationships between large-scale climate features and precipitation variation must be fully understood and utilized before reliable seasonal forecasting can be realized.

PALAEOCLIMATIC RESEARCH

Only palaeoclimatic research can provide a long-term view of natural climatic variability and the impact of variation in large-scale climate features (Harle *et al.* 2007). Reconstructions of Australia's climate during the Holocene (12 thousand years before present; ka BP) are particularly important because background conditions (i.e., sea level, global ice cover) changed little over this epoch. Palaeoclimatic proxies show a clear mid-Holocene optimum (~8–5 ka BP) during which climatic variability was lower, water availability was higher, the mid-latitude westerlies were stronger, and rainforests and wet-schlerophyll forests covered a larger area than at the time of European settlement (e.g., Jones *et al.* 1998, Donders *et al.* 2008). The ENSO system was probably relatively inactive during this period, with the STR further north than at present.

As the Holocene progressed, changes in solar irradiance due to the earth's orbit reduced the thermal gradient between low and high latitudes, leading to a more southerly ITCZ and STR and weaker westerlies than before (Donders *et al.* 2007). At ~5 ka BP, Australia rapidly shifted to a dry climate and more arid-adapted vegetation, probably due to increased ENSO activity associated with modification of the Hadley cell (Donders *et al.* 2007, Donders *et al.* 2008, Quigley *et al*. 2010). Climate proxies, dating back to the 1500s, record numerous ENSO events; however, the 20th century was a peak period of El Niño activity with the post-1940 period accounting for 30 % of extreme ENSO years (Gergis & Fowler 2009). Ground-surface temperature reconstruction from multiple sites around Australia indicates air temperatures were roughly constant 500–300 years ago, before warming over the last 200 years (Pollack *et al.* 2006). Hence palaeoclimatic research indicates that although substantial climate variability existed in the past, the last 200 years have trended towards a warmer, drier climate. Attribution of an anthropogenic contribution to this trend is currently limited to the rapid, post-1950s warming.

RECENT CLIMATIC TRENDS AND MODEL PROJECTIONS

Modification of climate features by climate change

The Hadley cell has widened by about 2–5° since the 1970s (Seidel *et al.* 2008, Hu *et al.* 2011). Climate models attribute some of this to global warming and forecast this trend to continue (Johanson and Fu 2009). This may lead to desertification poleward of ~30°S, with significant ramifications for the ecosystems and human populations of southern Australia, accustomed to higher rainfall. The SAM has a positive trend over 1979–2005, linked to decreased autumn-winter rainfall in southern Australia, through a reduction in rain-bearing frontal systems (Hendon *et al.* 2007, Verdon-Kidd and Kiem 2009b) and an increased intensity of the STR (Larsen and Nicholls 2009, Nicholls 2010). The SAM explains 10%–15% of weekly rainfall variability in southern areas during winter and on the southeast coast during spring–summer, comparable to the explanatory power of ENSO in these regions (Hendon *et al.* 2007). All GCMs forecast a continuing positive trend in the SAM associated with increased anthropogenic greenhouse gas emissions, representing one of the strongest signatures of climate change around the globe (CSIRO 2007). Although trends in the SAM and the Hadley cell are correlated (Previdi and Liepert 2007), these projections paint a worrying picture for water security in southern Australia. Although ENSO dynamics are likely to be modified by climate change, it is uncertain what form this modification will take (Collins *et al.* 2010).

Temperature and rainfall

Australian surface temperatures have increased by around 0.5°C since the 1950s, a warming most likely caused by anthropogenic increases in greenhouse gases (Nicholls 2003, Karoly and Braganza 2005, Timbal *et al.* 2006). Relative to 1990, best estimates (derived from multi-model averages) for 2070 indicate increased annual mean temperature from 1.8°C (the B1 emissions storyline from SRES; IPCC 2007) to 3.4°C (the A1F1 storyline), averaged across the Australian continent. Warming is projected to be greatest in inland areas but less severe in the south and northeast. In contrast, recent rainfall anomalies are not yet attributable to human activities. In southwest Western Australia, a step change decrease in annual rainfall of 15–20% occurred in the 1970s (IOCI 2002) and the new rainfall regime is now considered the norm (Murphy and Timbal 2008). Since the 1950s, precipitation has also decreased over eastern Australia (Chen *et al.* 2002, CSIRO 2007) and southern Australia, particularly in autumn (Larsen and Nicholls 2009, Nicholls 2010). Contrastingly, annual rainfall has increased in northwest Australia over the same period (Shi *et al.* 2008).

Best estimates for annual precipitation anomalies by 2070 indicate little change in the northern regions of Queensland and the Northern Territory, grading to a decline in the south ranging from 7.5 % (B1) to 10 % (A1F1). Precipitation is likely to decrease in the cool months in southern Australia, particularly in winter in southwest WA (CSIRO 2007). The latest climate models cannot simulate the observed rainfall increase over northwest Australia, which may be linked to higher regional aerosol loading due to increased burning activities in Southeast Asia (CSIRO 2007, Cai *et al.* in press). This deficiency reduces our confidence in the precipitation predictions for this region, where best estimates project rainfall to decline by 2070. The projected decline is now believed to result from an unrealistically strong modelled teleconnection between northwest Australian rainfall and ENSO dynamics (Shi *et al.* 2008, Cai *et al.* in press).

Snowfall and snowmelt

The snow season in the Australian Alps has shortened since the 1960s, with snow depths in spring decreasing by around 40% (Nicholls 2005). Relatively more precipitation may now be falling as rain rather than snow, but the spring decline is primarily driven by earlier snowmelt, probably due to anthropogenic warming (Nicholls 2005). Snow predictions for the Australian Alps are available for climate change scenarios of low impact (small temperature and precipitation increase) to high impact (large temperature increase and precipitation decrease) (CSIRO 2007, Hennessy *et al.* 2008). For the low-impact (high-impact) scenario, the total area with an average of at least 1 day of snow cover per year is projected to decrease by 10 % (39 %) by 2020, and by 22 % (85 %) by 2050. Peak snow depth is similarly expected to decrease and maximum snow depths to occur earlier in the season. Such changes are a significant hydrologic impact of climate change. Average winter runoff and peak runoff may increase (even if total precipitation declines) but peak runoff will be earlier, and spring runoff will end sooner than previously, reducing soil moisture. These changes will affect freshwater biodiversity dependent on river flows, although this will be mediated by the effects of dams.

Extreme events

As mean air temperature increases, the frequency of extreme hot weather events is expected to increase disproportionately (Stott *et al.* 2004). Across southern Australia, the ratio of the change in maximum to mean temperature is projected to exceed unity (CSIRO 2007) and frost frequency is predicted to decrease as warming progresses. The projected decrease in mean annual precipitation across southern regions is associated with more dry days (i.e., days where < 1 mm of rain falls) (CSIRO 2007). The frequency of extreme daily precipitation events (highest 1% of daily rainfall) over a year is predicted to increase in the north but decrease in the south where an expected reduction of subtropical cyclone frequency is linked to the projected trend in the SAM (Trenberth *et al.* 2007). In summary, current projections for Australia indicate more frequent extremes of heat and high rainfall in the far north and extremes of heat and low rainfall in the south (CSIRO 2007).

Given their natural rarity, extreme events are difficult to attribute to anthropogenic forcing (Trenberth *et al.* 2007). However, devastating floods throughout eastern Australia in 2010–2011 engendered public concern about possible links to climatic change. Enhanced precipitation intensity is consistent with climate change predictions, with increased sea surface temperatures inducing a feedback of increased water vapour in the atmosphere. However, the three-month SOI average for October-December 2010 was also the highest on record, indicating an intense La Niña event. There is considerable uncertainty regarding climate change impacts on tropical cyclone formation in the Australian region. Increasing sea surface temperatures potentially expand areas of storm formation but many other factors also influence cyclone generation (e.g., ENSO, wind shear, atmospheric structure) (Trenberth *et al.* 2007).

The "Big Dry": a taste of the future?

The Big Dry (~1996-2010) seriously affected water security and degraded environments throughout much of southern Australia, particularly the Murray-Darling Basin catchment. Given the short instrumental period, the severity, duration and spatial distribution of future droughts may be markedly different from historical ones. With ongoing and accelerating climate change, the arrival of the Big Dry was entirely consistent with model projections. Although not more severe in terms of precipitation (Nicholls 2005), this drought was unusual because of (Murphy and Timbal 2008, Verdon-Kidd and Kiem 2009a, Kiem and Verdon-Kidd 2010): (1) a marked decline in autumn rainfall; (2) unusually high maximum daily temperatures; and (3) very low interannual variability in rainfall. Runoff in the Murray-Darling Basin decreased by more than three times the rainfall decrease (Potter *et al.* 2010), a conversion significantly more severe than during the Federation or WWII droughts. Low autumn rainfall was the primary reason, leading to low soil moisture prior to the winter runoff period. Small interannual variation in rainfall (soil moisture was not reset with absent good years) as well as increased temperatures (and consequently evapotranspiration) were probably also important.

Changes in daily rainfall (i.e., frequency, intensity, and duration) have important hydrological implications, affecting soil moisture and runoff generated. During the Big Dry, the disproportionately large decline in autumn and early winter rainfall in the Murray-Darling Basin was due primarily to a decrease in rainfall intensity, magnifying decreased runoff because soil saturation was not occurring (Murphy and Timbal 2008, Verdon-Kidd and Kiem 2009a, Kiem and Verdon-Kidd 2010). This was due to the reduced frequency of mid-latitude storms and fronts moving across southeastern Australia in autumn (Pook *et al.* 2009, Verdon-Kidd and Kiem 2009b), which also explained the severity of the drought in southwest WA. This synoptic pattern is associated with an increased Hadley cell width and the positive phase of the SAM (Verdon-Kidd and Kiem 2009b).

EVAPOTRANSPIRATION

Net water availability for biota depends on rates of precipitation and water loss (through evapotranspiration and run-off). Climate change will influence evapotranspiration, the sum of evaporation from soil, plant canopies, water bodies and plant transpiration, affecting runoff into catchments and irrigation demand. Evapotranspiration depends partly on the atmospheric demand for water and water supply (Ragab and Prudhomme 2002). More water can be held by a warmer atmosphere as well as by moving air, so the atmospheric demand for water rises as temperatures and wind speeds increase (Roderick *et al.* 2009a). Potential evaporation (evaporation under water-unlimited conditions), as measured by pan evaporation (evaporation from a small dish of water at ground level), declined throughout the second half of the 20th century in Australia (Roderick and Farquhar 2004) and globally (Roderick *et al.* 2009a). These trends are at odds with the global increase in air temperature over the same period: the "pan evaporation paradox". Near-surface wind speeds have declined in mid-latitude regions including Australia (McVicar *et al.* 2008), possibly due to a stronger STR, and may explain this paradox (Roderick *et al.* 2007, Roderick *et al.* 2009b). Nevertheless, forecast increases in potential evapotranspiration across Australia are 3–6% by 2070 (CSIRO 2007).

It is not clear how potential evapotranspiration will relate to future actual evapotranspiration rates. Plant photosynthesis is not saturated at current atmospheric CO_2 concentrations (Leipprand and Gerten 2006) and so plants manipulate their stomatal conductivity to physiologically trade-off between maximizing CO_2 admission and minimizing transpirational water loss. In CO_2-enriched environments, smaller stomatal apertures permit enhanced rates of carbon assimilation with reduced transpirational losses (i.e., water use efficiency of plants is increased). This is known as "CO_2 fertilization" and it ubiquitously increases plant growth rates (Leipprand and Gerten 2006) for two reasons: (1) photosynthesis is stimulated directly by higher availability of carbon for carbohydrate synthesis, and (2) reduced transpiration rates improve soil moisture content (and thus nutrient bioavailability) (Volk *et al.* 2000).

This naturally leads us to ask whether improved water use efficiency will be offset by increased growth rates as atmospheric CO_2 concentration rise. Plant growth responses to CO_2 enrichment vary because of spatial variation in the supply of growth-limiting nutrients (Korner 2006). A common response to CO_2 fertilization is an increase in the leaf-area index (the ratio of total upper leaf area to the surface area of ground occupied) which tends to increase transpirational losses (Kergoat *et al.* 2002, Liu *et al.* 2010). Conflating this response, temperature increases will affect plant phenology and lengthen the growing season of many temperate plants, increasing their total water demand. Modified temperature regimes also impact on plant mortality rates with flow-on effects for evapotranspiration (Allen *et al.* 2010). Even under the assumption of a constant water supply, transpirational responses to climate change will depend critically on the species and ecosystem concerned.

SEA LEVEL RISE

Mean sea level rise (SLR) results from two main processes: the melting of land-based ice and a decrease in ocean density, primarily due to thermal expansion. Globally, sea level rose at 1.8 mm/yr (1961–2003), or 3 mm/yr if only recent years (1993–2003) are considered (CSIRO 2007). Up to 2095, the IPCC Fourth Assessment Report projects global SLR to be 18–59 cm (2.1–

6.7 mm/yr), with possible additional contributions from ice sheets allowing a maximum of 79 cm (9.0 mm/yr). Uncertainties in these estimates may lead to even larger changes. Recent statistical models forecast SLR of up to 1.4 m by 2100 (reviewed in Church *et al.* 2008) while up to 1.6 m may also be possible (AMAP; accessed August 4 2011).

The impacts of SLR will be inversely related to the shoreline gradient: low on steep rocky shores, moderate on sandy beaches and dune systems, and severe on low gradient, tide-dependent ecosystems (e.g., mangroves and salt marshes). The latter will be particularly affected by high tides, increasing salinization and more extreme and frequent flooding. Landward migration of mangroves and salt marshes will occur but in many places this will be impossible (due to topographical features or human development) so these habitats will be lost (Harvey and Woodroffe 2008, Soares 2009). Tide-dependent ecosystems such as mangroves are especially vulnerable. Mangroves provide many ecosystem services, including storm-surge protection, and their loss will mean increased erosion, loss of fish and crustacean nursery habitats, and reduced water quality (reviewed in Gilman *et al.* 2008).

Beaches will migrate landward and, where backed by coastal sand dune systems, SLR will increase erosion of frontal dunes. These processes have occurred in the past (Harvey 2006) and their impacts will be severe on human infrastructure and valuable habitat. Further, dune stability will be compromised by the negative impacts on dune vegetation of a warmer, drier climate (Greaver and Sternberg 2010). The effectiveness of dune re-vegetation programmes designed to counter erosion may be reduced. Where intertidal zones border human habitation, there are two long-term options in response to SLR: construct protective levees or permit loss to the sea (Hadley 2009). Over the short term (i.e. decades), metropolitan beaches may be successfully supplemented through dredging programmes. Given the numerous threats posed by SLR to ecosystems and human infrastructure, strategies for Australian coastline management must account for coastal processes, geomorphology, land use as well as future climate change projections (particularly wind speeds and storm frequency and intensity in our region) (Harvey and Woodroffe 2008).

CONSERVATION STRATEGIES UNDER A CHANGING AUSTRALIAN CLIMATE

Climate change will impact on Australian ecosystems and the services they provide, but uncertainty in climate projections hampers the development of tailored management strategies. The most commonly advocated response is a general one: to foster expansive, connected ecological systems that protect biodiversity now while retaining sufficient migratory potential and genetic diversity for future adaptation (Steffen *et al.* 2009). This goal can be promoted by optimising and/or extending the National Reserve System (NRS) and integrating this system within an off-reserve habitat network (Commonwealth of Australia 2005, Mackey *et al.* 2008, Taylor *et al.* 2011).

The NRS currently comprises about 9000 protected areas (incorporating several reserve types), covering 11.6 % of terrestrial Australia (Sattler and Taylor 2008). Since 1995, Australia has employed a systematic, threat-based framework for prioritizing investment in new protected areas (Commonwealth of Australia 2005). Nevertheless, the NRS has been criticized for failing to meet a range of conservation metrics; for example, it excludes 12.6 % of threatened species and meets conservative range protection targets for only 19.6 % of threatened species (Watson *et al.* 2011). Since funding restrictions will limit gains achievable through new protected areas, radical restructuring could delist the least-cost-effective reserves to finance the establishment of new ones (Fuller *et al.* 2010). The NRS must also recognize the importance of large, intact landscapes ("wilderness") that, although somewhat neglected by the threat-based prioritisation approach, may be critical for sustaining key ecological and evolutionary processes as climate changes (Watson *et al.* 2009).

Since the NRS necessarily protects discrete areas, a functional off-reserve habitat network is also crucial. It ensures that dispersal potential is high, intra-species genetic diversity is maintained, and populations of functionally significant species are sufficiently large to be ecologically effective (Mackey *et al.* 2008) and buffered against short-term environmental stochasticity (Akçakaya *et al.* 2006). Habitat restoration across private lands poses a significant challenge and, at present, most re-vegetation projects are funded publically because they are costly and generate no direct income for landowners. The Australian Government has recently sought to encourage further habitat restoration with a "Biodiversity Fund" that pledges $946 million over six years to support landholders in maintaining, enhancing and establishing tracts of native vegetation (Commonwealth of Australia 2011).

In August 2011, Australia seems destined to legislate a carbon price in the form of an initial tax for three years, followed by a cap-and-trade market system and related economic instruments

(Garnaut 2011; Commonwealth of Australia 2011). This will provide further incentives for landholders to fund (or sell or lease their land for) long-term reforestation schemes (Walsh 1999). Reforestation not only sequesters carbon but reduces recurrent wind and water erosion and reverses the salinization of land and water resources, with positive benefits for industry and biodiversity (Catterall *et al*. 2004, Harper *et al.* 2007). Furthermore, a price on carbon should provide a market-driven means to promote the development of a habitat network across private lands, with substantial biodiversity and connectivity gains (Hobbs *et al.* 2009). The biodiversity benefits achieved through such a scheme will largely depend on the types of forest cultivated. Monoculture plantations of regularly spaced trees, in large contiguous blocks, have small or negligible benefits to biodiversity (Kanowski *et al*. 2005, Harper *et al.* 2007, Sodhi *et al.* 2009). Conversely, the ecological value of forestry can be maximized by so-called "biodiversity plantings", comprising many species of different forms, located within small plots dispersed across the landscape. Monocultures are more economically viable, sequestering more carbon for the same unit cost (Hobbs *et al.* 2010). Monocultures or low-diversity plantations will also be favoured by increased demand for sustainable energy sources such as woody biomass crops (i.e. bioenergy production) (Hobbs *et al.* 2009). Such crops would be viable throughout much of southern Australia's low rainfall zone (Hobbs 2009, Hobbs *et al.* 2009).

For many species and ecosystems, the refinement and integration of the reserve system is not the only effective conservation strategy (Watson *et al*., 2011); rather, it is also critical to develop appropriate fire management regimes (Steffen *et al.* 2009, Driscoll *et al*. 2010) and reduce the impact of other threatening processes (Kingsford *et al*. 2009). Potential synergies between climate change and species' invasions are particularly concerning, but poorly studied (Brook 2008, Hellman *et al*. 2008). Invasive species often act as direct stressors to resident species, as competitors, predators or pathogens, and by drastically altering habitat structure and composition (Lockwood *et al*. 2007, Brook 2008). The indirect effects of invasives favoured by climate change may exceed the direct impacts of novel climates (Steffen *et al.* 2009). Climate change potentially affects every step along the invasion pathway, including the introduction, establishment and spread of exotic species (Brook 2008, Hellman *et al*. 2008). Many native and exotic species that are currently non-invasive may invade new areas due to favourable climatic conditions and/or local extinctions that indirectly facilitate their range expansion. The Australian quarantine and biosecurity network must plan for climate change effects on new transport and introduction mechanisms, improve the control of current exotic species, and increase investment in environmental monitoring and future control technologies (Steffen *et al.* 2009).

Substantial climate change in the coming decades will test historical conservation strategies. The rate of climate change seems certain to exceed the capacity of many species and ecosystems to adapt in their current range, but migration to more equable climatic regions may be impossible if dispersal is low or limited by natural or anthropogenic barriers. "Assisted migration" (i.e. translocation) is a controversial "last resort" that may be required to permit species persistence (Hoegh-Guldberg *et al*. 2008, Loss Scott *et al.* 2011) but raises further dilemmas, such as the difficulty of predicting regional climates and the risk of translocated species becoming invasive or introducing diseases at the new location (Mueller and Hellman 2008, Stone 2010). Another controversial notion is "conservation triage" which seeks to optimise conservation outcomes by efficient allocation of scarce resources, but necessarily implies that some conservation aims receive limited or no investment (Marris 2007, Bottrill *et al*. 2008). With severe climate change, triage may be unavoidable; for example, some vegetation types may disappear, regardless of human intervention. Such habitats may need to be triaged as focus shifts from preservation of historic species assemblages to maintaining functioning landscapes and future ecosystem services (Lawler *et al*. 2009, Hagerman *et al.* 2010).

CONCLUSION

The short instrumental period of climate measurements only permits a limited understanding of the amplitude and frequency of natural climatic events and long-term complexities of the climate system. Apart from the general temperature rise that the continent will share with rest of the world, climate change effects in Australia will depend critically upon the response of the Hadley cell and other large-scale climate features (ENSO, IPO, IOD, SAM). An improved understanding of the teleconnections between these climate modes is important for understanding natural climate variability and predicting future climatic change. Although recent declines in rainfall in southern Australia and the Murray-Darling Basin are not yet attributable to anthropogenic effects, a positive-phase SAM is correlated with reduced autumn-winter rainfall in these regions and climate models forecast that the SAM will become increasingly locked into this phase.

Climate change affects water loss from terrestrial systems by evapotranspiration, changing runoff into catchments and irrigation demand; the nature of these effects is complex, depending critically on the ecosystems concerned and local abiotic conditions. Although the CO_2 fertilization effect may mitigate some adverse effects of climate change, average crop and livestock production is likely to fall, if current climate projections are correct. Mean SLR of around one metre by the end of the century is possible, posing significant threats to coastal human infrastructure and natural ecosystems (particularly mangroves and salt marshes). Off-reserve reforestation, motivated by a price on carbon, could positively impact on environmentally degraded regions with negligible impacts on water security, if administered correctly. However, without a "biodiversity market", biodiversity gains resulting from reforestation schemes may be negligible unless incentive schemes through the markets are implemented to encourage revegetation with a mixture of native species of habitat value.

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