9 Management options for bird conservation in the face of climate change

DONALD C. FRANKLIN[1], APRIL E. RESIDE[2] AND STEPHEN T. GARNETT[1]

[1]*Research Institute for the Environment and Livelihoods, Charles Darwin University, Australia*
[2]*Centre for Tropical Biodiversity and Climate Change, James Cook University, Australia*

9.1 Introduction

The evidence is clear that recent climate change has already had an impact on birds and bird populations (Møller et al. 2010) as demonstrated both internationally (Thomas et al. 2006) and within Australia (e.g. Chambers and Keatley 2010; Chambers et al. 2011). Given that both climate change and the direct or indirect relationship between climate and bird ecology are pervasive, we should anticipate even greater impacts on the abundance and distribution of bird species with more extreme climate change in the foreseeable future (although there remains much uncertainty about the magnitude, direction and nature of these impacts; Pereira et al. 2010). Some of these impacts will doubtless be negative, threatening species with regional or global extinction (Maclean and Wilson 2011). Ecosystems may suffer loss of function as a result of the loss of species (Tomimatsu et al. 2013). Other bird species may benefit from change (Thomas et al. 2010). Still others may be impacted but in ways that do not affect populations. For example, mismatches between the timing of breeding and the timing of peak food availability induced by climate change may reduce reproductive success but sufficient young may still be produced to maintain the population at current levels (Chamberlain and Pearce-Higgins 2013; Reed et al. 2013). The response to these impacts may be gradual or abrupt, the latter being particularly unpredictable and the result of populations reaching demographic thresholds of stress.

For managers, the impacts of *ultimate* concern will mainly be regional or global extinction and loss of ecosystem function. More immediate concerns such as the spread of invasive or competitive species lead to ultimate concerns through their negative effects on species and ecosystems, and here we treat the spread of invasive species as one of many processes driving concern rather than the cause of concern itself. It is beyond the scope of this chapter for us to review such processes, which might include (but are far from restricted to): range shifts in response to shifts in climate envelopes (Parmesan and Yohe 2003); intolerance of extreme climatic events such as drought (e.g. MacNally et al. 2009); loss of habitat or resources (Cahill et al. 2013); mismatches in the timing of breeding or migration in relation to weather and

Applied Studies in Climate Adaptation, First Edition. Edited by Jean P. Palutikof, Sarah L. Boulter, Jon Barnett and David Rissik.

resources (Thackeray et al. 2010); and changes to the balance of interspecific competition (Urban et al. 2012).

Rapid and uncertain change presents an enormous challenge for wildlife managers. If we are to avoid widespread extinction and loss of ecosystem function then we must equip ourselves with new ways of thinking and a new and/or reinforced toolkit of management actions. This chapter builds on the Australian context to explore how we might deal with the challenges likely to face birds as a result of climate change over the next half-century. We first introduce some general management principles, then detail options for action and finally briefly explore issues surrounding the timing of management responses. A more detailed outline of management options is provided by Franklin et al. (2014). A comprehensive analysis of climate change adaptation and Australian birds is found in Garnett et al. (2013) and Garnett and Franklin (2014).

9.2 The purpose of management in the face of climate change

As climate changes, those goals of conservation that are implicitly based on the assumption that climate is static must be set aside (Hannah et al. 2002). The pre-European state of Australian ecosystems, often held as an aspirational goal for conservation, will become increasingly irrelevant. Protected areas may end up conserving something quite different to that which was originally intended (Monzon et al. 2011). Some species may need to be moved to new locations, challenging concepts of 'native' and 'invasive' (Webber and Scott 2012). Fundamental values embodied in current legislation, such as subspecies being the basic units of conservation, will be undermined by both natural and assisted movements. There will also be new human dimensions. What levels of assisted colonisation will the public tolerate? Will a species or subspecies that can persist only in captivity because its environmental envelope has disappeared continue to attract the necessary levels of expenditure for its survival?

9.3 General principles

Climate change is one among many threats (stressors) facing species, and the impact of climate change may be hidden by threats that seem more imminent. Negatively, the synergy of threats may well be worse than the sum of each (Brook et al. 2008); positively, it can mean that the mitigation of other threats is an appropriate (and more tractable) response to the threat posed by climate change (CCWAPWG 2009). This means that existing responses will need to be reinforced alongside the implementation of novel strategies (Lawler et al. 2010).

9.3.1 Strategies in the face of uncertainty

Types of uncertainty include unpredictable and often stochastic fluctuations in populations (Sinclair et al. 2006), ignorance about the relationship between a species' fundamental and realised climatic niche (Veloz et al. 2012), imprecision in climate projections at a local scale (Timbal et al. 2009), the likelihood that some climate components will change in abrupt steps as thresholds are breached (Lenton et al. 2008) and lack of a climatic benchmark (Head 2012). Possible management responses to ecological uncertainty include prioritising actions where current knowledge levels are high (Groves et al. 2012) and where detailed local projections of climate change and its impacts are not needed (Cross et al. 2012), and to practice adaptive management in a risk management framework (Conroy et al. 2011).

9.3.2 Three conceptual goals for conservation

Three conceptual goals for conservation are: avoiding the effects of climate change (resistance); promoting resilience to the impacts of climate change; and facilitating a response to it (Millar et al. 2007; Prober et al. 2012). Resistance

Table 9.1 Management options for the conservation of birds in a climate-change world (modified extensively from Mawdsley et al. 2009, see also Garnett et al. 2013, Shoo et al. 2013).

Management type	Practical options
Do nothing	–
Maintain and enhance habitat	Expand the protected area network; maintain and improve habitat quality; identify, protect and expand refugia; maintain and extend landscape connectivity; create new habitats
Facilitate the response of wild populations (intensive species management)	Assist colonisation by translocation; enhance the genetics of subspecies; manage other threatening processes (e.g. by predator control, habitat manipulation, captive breeding)
Preserve populations (the last resort)	Save species in captivity; store germplasm
Understand and prepare for what is happening	Monitor bird populations (general surveys e.g. Atlas; targeted species-specific monitoring); monitor habitats and threatening processes; investigate the ecology of species and communities; model habitat and climate envelopes in more detail; model management options

extends current management practice with climate change just another threat, and resilience combines current practice with new measures that increase population size or habitat area (Morecroft et al. 2012). The response goal acknowledges the need for inventive responses beyond current management.

9.3.3 Heirarchical adaptive management

A hierarchical approach to adaptive management is recommended in which steps increase in intensity, dollar cost, potential adverse environmental consequences and uncertainty as required (Table 9.1). The baseline is to do nothing. This should, however, only be considered where the consequences have been articulated, where monitoring is in place and where there is a commitment to institute management if circumstances change. As a second step, existing habitat can be maintained or enhanced by: expanding the protected area network; maintaining and improving habitat quality; identifying, protecting and expanding refugia; maintaining and extending landscape connectivity; and creating new habitats. Third, facilitating the response of wild populations through intensive species management would comprise actions such as: assisting colonisation by translocation; enhancing subspecies genetics; or targeted management of other threatening processes by, for example, predator control, habitat manipulation or supplementary captive breeding. Finally, and as a last resort, populations can be preserved in captivity or as germplasm. Informing all this is monitoring and research to identify trends and understand the processes underpinning them.

9.4 Actions

9.4.1 Maintaining and enhancing habitat

Enhancing protected areas

For many species, the retention of habitat through a network of public and private protected areas on both land and on sea will be even more critical in the face of climate change (Hannah et al. 2007). This must include both intact and fragmented landscapes (Van Teeffelen et al. 2012) and must anticipate geographic shifts in climate if they are to be effective into the future (Hole et al. 2011). A coastal drift of climate space for many birds of south-eastern Australia (VanDerWal et al. 2013) and global sea-level rises (e.g. Thorne et al. 2012) presages conflict with some intensive land uses which requires anticipatory management. Some opportunities for reservation may arise in settled districts where climate change renders farmland commercially unviable.

Enhancing habitat quality
An extensive body of research suggests that functional redundancy – in which more than one species serves a particular function within an ecosystem, e.g. dispersing fruit – and structural diversity provide strong support for species, so retaining or improving habitat quality will be an essential climate change adaptation strategy for many species. In an Australian context, weed and feral animal control and fire management will continue to be essential management goals, but may need to be intensified. Current prescriptions may well need to be tailored to new circumstances.

Refugia
A key management strategy will be the identification, protection and enhancement of places that will serve as climate refugia into the future. Refugia are places where the habitat and resources that a species needs are buffered against direct (e.g. temperature, moisture) and indirect (e.g. interactions, fire) impacts of climate change (Keppel et al. 2012). These might include, for example, mountain ranges, valleys, watercourses, springs and wetlands (Reside et al. in press). Refugia demonstrably facilitated the persistence of many species during the Ice Ages (e.g. Byrne 2008 for southern Australia). They need to be large enough for long enough to retain a genetically viable population (Ovaskainen 2002) and ideally be accessible for species to disperse to unaided. Three approaches can be taken to identify refugia (Ashcroft 2010): modelling of places where analogue climates will persist into the future independent of species (e.g. Mackey et al. 2012); identification of places where individual species are likely to persist; and identification of places where species have persisted in the past.

Ecological connectivity
Many bird species have already tracked geographical shifts in climate (Tingley et al. 2009; Brommer et al. 2012). For some, this movement will be prevented by a range of physical barriers. The 2000 km band of semi-arid vegetation may well prevent birds that inhabit the forests of south-western Australia from tracking their climate niche to forests in eastern Australia, for other species, however, barriers such as cleared land (e.g. Doerr et al. 2011), the ocean separating islands or even unsuitable habitat such as forests or rivers may operate at more local scales. The management response is to ensure that connectivity between current and potential habitat is retained or enhanced (Groves et al. 2012). Ecological connectivity also enhances the resilience of local populations through retention of metapopulation structure (Van Teeffelen et al. 2012). Planning for landscape corridors is well-advanced in Australia, enhancing the legacy of extensive tracts of uncleared habitat (DSEWPC 2012). In planning connectivity for birds, it is useful to characterise the species most likely to benefit from this form of management. Small species cross gaps less readily than large species (Lees and Peres 2009), and sedentary species and habitat specialists, especially those from closed vegetation, are often more reluctant to cross gaps than migrants, nomads or species of open habitats (Harris and Reed 2002). Birds with high dispersal capacity may not require connectivity (Mokany et al. 2013), whereas those with low dispersal capacity may not even be able to make use of corridors (Johst et al. 2011). With these qualifications in mind, investment in connectivity should be appraised carefully against other management options including assisted colonisation (see 'Assisted colonisation' in Section 9.4.2).

New habitats
Climates and communities with no previous analogue (Garcia-Lopez and Allue 2013 and Urban et al. 2012 respectively) may call for new habitats. Given time lags and expense, it is important to identify potential beneficiary species and have a clear understanding of the values underlying the management intent, especially where new habitats might be required to replace climate-change-induced degradation within existing natural areas. These issues have

already received some appraisal with respect to plants (Booth and Williams 2012).

9.4.2 Intensive management

Assisted colonisation
Moving species to places they have never been recorded in anticipation of climate shifts is a logical but controversial extension to existing management practices for threatened species of creating insurance populations and restoring those that have been lost (Hoegh-Guldberg et al. 2008; Thomas 2011). Assisted colonisation may also be employed to retain or restore ecosystem function (Lunt et al. 2013), for example to ensure that bird-pollinated plants have a bird capable of pollinating them present in the ecosystem. The process entails risks to source populations, founder individuals and the receiving ecosystem that require careful appraisal (Schwartz et al. 2012). Issues relating to timing (McDonald-Madden et al. 2011), genetics (Weeks et al. 2011), policy (for Australia, Burbidge et al. 2011) and the mixed success of previous reintroductions (for Australia, Sheean et al. 2012) have been reviewed.

Enhanced genetics
Many Australian bird subspecies are likely to lose their climate space over coming decades, but the new climate within their current range will often become suitable for another subspecies (Garnett et al. 2013). Assuming that subspecies have specific adaptations to their current climate spaces, this suggests that the survival of the population is likely to become maladapted over time may be enhanced by genetic augmentation from the other subspecies (Thomas et al. 2013). Deliberate enhancement also brings risks of outbreeding depression and disease transmission, but these seem relatively minor (Weeks et al. 2011).

9.4.3 Preserving populations

Captivity
Populations of some bird species already exist only in captivity, though nearly always there is hope of reintroduction to the wild. With climate change, reintroduction may not be possible in the foreseeable future so long-term or permanent *ex situ* conservation must be among the potential management tools as an alternative to extinction (Pritchard et al. 2012). This raises substantial ethical, technical and economic questions which have been explored in the context of captive breeding to enhance the conservation of wild populations, including: (1) captive populations are rarely self-sufficient; (2) captive breeding is often expensive; (3) captive populations often drift into domestication and inbreeding; (4) disease is common; and (5) administrative continuity is rare (Snyder et al. 1996; Araki et al. 2007; Christie et al. 2012). The considerable cost calls for prioritisation (Joseph et al. 2009) and strategic use of private as well as public resources (Cannon 1996). Conflict may also arise between the need to maximise the number of founders needed for genetic viability of a captive populations and attempts to save a species in the wild (McDonald-Madden et al. 2011).

Germplasm and code
The technologies for storage of the germplasm, embryos, blood products, tissue and DNA of birds, probably the very last option for biodiversity conservation (Wildt et al. 1997) are developing rapidly (Glover and McGrew 2012). Both semen and primordial germ cells can now be stored cryogenically and used to fertilise host embryos (Wernery et al. 2010). The technology may be the only practical way to preserve the exact genetic make-up of original forms that, in some unforeseeable future, could be re-established in the wild. The recreation of organisms from their DNA code is currently in the realm of science fiction, but coding technologies have improved exponentially in the last decade.

9.4.4 Monitoring and research

Monitoring
The appropriate timing of intervention in the face of climate change relies heavily on our understanding of population numbers and trends as well as change to habitat and ecological and threatening processes

(McDonald-Madden et al. 2011). Ecological surprises are inevitable (Doak et al. 2008) and require early detection if the response is to be adequate. Monitoring of Australian birds is patchy at best and absent at worst (Lindenmayer et al. 2012), although atlas schemes have provided baselines for all but the rare species (Blakers et al. 1984; Barrett et al. 2002, 2003). Monitoring of habitats and threatening processes may in some circumstances serve as adequate proxies (Lindenmayer and Likens 2010), but this monitoring too is currently of limited extent.

Research

Monitoring may identify trends but more detailed research is required to identify their drivers and thus optimal responses. Research will usually be required to identify the contribution of climate change to observed declines (though this in itself may not be productive; Parmesan et al. 2013) along with the demographic and ecological processes underlying it. For example, declines may be a direct response to climate-induced changes in resources or an indirect response via changes to interspecific interactions. Field research on species and communities should be complemented by modelling of habitat, climate envelopes and management options; Harris et al. (2012) provides an Australian avian example of this.

9.5 Timing and continuity

For successful climate change adaptation, some actions must begin immediately while others can wait for the results of monitoring; some actions will be one-off while others will need to be ongoing. This yields a four-way matrix of action categories. Immediate one-off actions might include land purchases, assisted colonisation of species already seriously threatened by climate change, surveys of little-known species or subspecies to create a baseline for future comparisons and the identification of refugia. Ongoing actions starting now include monitoring and management and captive breeding for species already seriously threatened (Garnett et al. 2011). Future one-off and ongoing actions will primarily be those identified as necessary in response to monitored trends.

9.6 Conclusion

Managers are not helpless in the face of climate change. However, the range of options available is not large and it cannot be stated strongly enough that mitigation is by far the cheapest and most effective way to retain our biodiversity. Even though the Australian avifauna has been winnowed by a tough environmental history, the combination of pressure from climate change and other anthropomorphic environmental change will make retention of all – or even most – bird species (and subspecies) exceptionally challenging. Substantially greater funds will be needed and, even then, strong prioritisation of actions will be essential (Wilson et al. 2006; Joseph et al. 2009). Society will need to debate difficult decisions about how it values biodiversity.

References

Araki, H., Cooper, B. and Blouin, M.S. (2007) Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science* 318, 100–103.

Ashcroft, M.B. (2010) Identifying refugia from climate change. *Journal of Biogeography* 37, 1407–1413.

Barrett, G., Silcocks, A. and Cunningham, R. (2002) *Australian Bird Atlas (1998–2001) Supplementary Report No. 1 - Comparison of Atlas 1 (1977–1981) and Atlas 2 (1998–2001)*. Birds Australia, Melbourne.

Barrett, G., Silcocks, A., Barry, S., Cunningham, R. and Poulter, R. (2003) *The New Atlas of Australian Birds*. Royal Australasian Ornithologists Union, Hawthorn East.

Blakers, M., Davies, S.J.J.F. and Reilly, P.N. (1984) *The Atlas of Australian Birds*. RAOU and Melbourne University Press, Melbourne.

Booth, T.H. and Williams, K.J. (2012) Developing biodiverse plantings suitable for changing climatic conditions 1: Underpinning scientific methods. *Ecological Management and Restoration* 13, 267–273.

Brommer, J.E., Lehikoinen, A. and Valkama, J. (2012) The breeding ranges of central European and Arctic bird species move poleward. *PLoS ONE* 7, e43648.

Brook, B.W., Sodhi, N.S. and Bradshaw, C.J.A. (2008) Synergies among extinction drivers under global change. *Trends in Ecology and Evolution* 23, 453–460.

Burbidge, A.A., Byrne, M., Coates, D. et al. (2011) Is Australia ready for assisted colonization? Policy changes required to facilitate translocations under climate change. *Pacific Conservation Biology* 17, 259–269.

Byrne, M. (2008) Evidence for multiple refugia at different time scales during Pleistocene climatic oscillations in southern Australia inferred from phylogeography. *Quaternary Science Reviews* 27, 2576–2585.

Cahill, A.E., Aiello-Lammens, M.E., Fisher-Reid, M.C. et al. (2013) How does climate change cause extinction? *Proceedings of the Royal Society B* 80, Art. no. 20121890.

Cannon, J.R. (1996) Whooping Crane recovery: A case study in public and private cooperation in the conservation of endangered species. *Conservation Biology* 10, 813–821.

Chamberlain, D. and Pearce-Higgins, J. (2013) Impacts of climate change on upland birds: complex interactions, compensatory mechanisms and the need for long-term data. *Ibis* 155, 451–455.

Chambers, L.E. and Keatley, M.R. (2010) Australian bird phenology: a search for climate signals. *Austral Ecology* 35, 969–979.

Chambers, L.E., Devney, C.A., Congdon, B.C., Dunlop, N., Woehler, E.J. and Dann, P. (2011) Observed and predicted effects of climate on Australian seabirds. *Emu* 111, 235–251.

Christie, M.R., Marinea, M.L., French, R.A. and Blouin, M.S. (2012) Genetic adaptation to captivity can occur in a single generation. *Proceedings of the National Academy of Sciences* 109, 238–242.

Climate Change Wildlife Action Plan Work Group (2009) *Voluntary Guidance for States to Incorporate Climate Change into State Wildlife Action Plans and Other Management Plans*. Association of Fish and Wildlife Agencies.

Conroy, M.J., Runge, M.C., Nichols, J.D., Stodola, K.W. and Cooper, R.J. (2011) Conservation in the face of climate change: The roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty. *Biological Conservation* 144, 1204–1213.

Cross, M.S., Zavaleta, E.S., Bachelet, D. et al. (2012) The Adaptation for Conservation Targets (ACT) framework: A tool for incorporating climate change into natural resource management. *Environmental Management* 50, 341–351.

Department of Sustainability Environment Water Population and Communities (2012) *National Wildlife Corridors Plan: A Framework for Landscape-scale Conservation 2012*. Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Doak, D.F., Estes, J.A., Halpern, B.S. et al. (2008) Understanding and predicting ecological dynamics: Are major surprises inevitable? *Ecology* 89, 952–961.

Doerr, V.A.J., Doerr, E.D. and Davies, M.J. (2011) Dispersal behaviour of Brown Treecreepers predicts functional connectivity for several other woodland birds. *Emu* 111, 71–83.

Franklin, D.C., Reside, A.E. and Garnett, S.T. (2014) Conserving Australian bird populations in the face of climate change. In: Garnett, S.T. and Franklin, D.C. (eds.) *Climate Change Adaptation Plan for Australian Birds*. CSIRO, Collingwood, pp. 53–78.

Garcia-Lopez, J.M. and Allue, C. (2013) Modelling future no-analogue climate distributions: A world-wide phytoclimatic niche-based survey. *Global and Planetary Change* 101, 1–11.

Garnett, S.T. and Franklin, D.C. (eds) (2014) *Climate Change Adaptation Plan for Australian Birds*. CSIRO, Collingwood.

Garnett, S.T., Szabo, J.K. and Dutson, G. (2011) *The Action Plan for Australian Birds 2010*. CSIRO, Collingwood.

Garnett, S.T., Franklin, D.C., Ehmke, G. et al. (2013) *Climate Change Adaptation Strategies for Australian Birds*. National Climate Change Adaptation Research Facility, Gold Coast.

Glover, J.D. and McGrew, M.J. (2012) Primordial germ cell technologies for avian germplasm cryopreservation and investigating germ cell development. *Journal of Poultry Science* 49, 155–162.

Groves, C.R., Game, E.T., Anderson, M.G. et al. (2012) Incorporating climate change into systematic conservation planning. *Biodiversity and Conservation* 21, 1651–1671.

Hannah, L., Midgley, G.F., Lovejoy, T. et al. (2002) Conservation of biodiversity in a changing climate. *Conservation Biology* 16, 264–268.

Hannah, L., Midgley, G., Andelman, S. et al. (2007) Protected area needs in a changing climate. *Frontiers in Ecology and the Environment* 5, 131–138.

Harris, R.J. and Reed, J.M. (2002) Behavioral barriers to non-migratory movements of birds. *Annales Zoologici Fennici* 39, 275–290.

Harris, J.B.C., Fordham, D.A., Mooney, P.A. et al. 2012. Managing the long-term persistence of a rare cockatoo under climate change. *Journal of Applied Ecology* 49, 785–794.

Head, L. (2012) Decentring 1788: Beyond biotic nativeness. *Geographical Research* 50, 166–178.

Hoegh-Guldberg, O., Hughes, L., McIntyre, S. et al. (2008) Assisted colonization and rapid climate change. *Science* 321, 345–346.

Hole, D.G., Huntley, B., Arinaitwe, J. et al. (2011) Toward a management framework for networks of protected areas in the face of climate change. *Conservation Biology* 25, 305–315.

Johst, K., Drechsler, M., van Teeffelen, A.J.A. et al. (2011) Biodiversity conservation in dynamic landscapes: trade-offs between number, connectivity and turnover of habitat patches. *Journal of Applied Ecology* 48, 1227–1235.

Joseph, L.N., Maloney, R.F. and Possingham, H.P. (2009) Optimal allocation of resources among threatened species: a project prioritization protocol. *Conservation Biology* 23, 328–338.

Keppel, G., Van Niel, K.P., Wardell-Johnson, G.W. et al. (2012) Refugia: identifying and understanding safe havens for biodiversity under climate change. *Global Ecology and Biogeography* 21, 393–404.

Lawler, J.J., Tear, T.H., Pyke, C. et al. (2010) Resource management in a changing and uncertain climate. *Frontiers in Ecology and the Environment* 8, 35–43.

Lees, A.C. and Peres, C.A. (2009) Gap-crossing movements predict species occupancy in Amazonian forest fragments. *Oikos* 118, 280–290.

Lenton, T.M., Held, H., Kriegler, E. et al. (2008) Tipping elements in the Earth's climate system. *Proceeding of the National Academy of Sciences* 105, 1786–1793.

Lindenmayer, D.B. and Likens, G.E. (2010) *Effective Ecological Monitoring*. CSIRO, Melbourne.

Lindenmayer, D.B., Gibbons, P., Bourke, M. et al. (2012) Improving biodiversity monitoring in Australia. *Austral Ecology* 37, 285–294.

Lunt, I.D., Byrne, M., Hellmann, J.J. et al. (2013) Using assisted colonisation to conserve biodiversity and restore ecosystem function under climate change. *Biological Conservation* 157, 172–177.

Mackey, B., Berry, S., Hugh, S., Ferrier, S., Harwood, T.D. and Williams, K.J. (2012) Ecosystem greenspots: identifying potential drought, fire, and climate-change micro-refuges. *Ecological Applications* 22, 1852–1864.

Maclean, I.M.D. and Wilson, R.J. (2011) Recent ecological responses to climate change support predictions of high extinction risk. *Proceeding of the National Academy of Sciences* 108, 12337–12342.

Mac Nally, R., Bennett, A.F., Thomson, J.R. et al. (2009) Collapse of an avifauna: climate change appears to exacerbate habitat loss and degradation. *Diversity and Distributions* 15, 720–730.

Mawdsley, J.R., O'Malley, R. and Ojima, D.S. (2009) A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology* 23, 1080–1089.

McDonald-Madden, E., Runge, M.C., Possingham, H.P. and Martin, T.G. (2011) Optimal timing for managed relocation of species faced with climate change. *Nature Climate Change* 1, 261–265.

Millar, C.I., Stephenson, N.L. and Stephens, S.L. (2007) Climate change and forests of the future: Managing in the face of uncertainty. *Ecological Applications* 17, 2145–2151.

Mokany, K., Harwood, T.D. and Ferrier, S. (2013) Comparing habitat configuration strategies for retaining biodiversity under climate change. *Journal of Applied Ecology* 50, 519–527.

Møller, A.P., Fiedler, W. and Berthold, P. (eds.) (2010) *Effects of Climate Change on Birds*. Oxford University Press, Oxford.

Monzón, J., Moyer-Horner, L. and Palamar, M.B. (2011) Climate change and species range dynamics in protected areas. *BioScience* 61, 752–761.

Morecroft, M.D., Crick, H.Q.P., Duffield, S.J. and Macgregor, N.A. (2012) Resilience to climate change: translating principles into practice. *Journal of Applied Ecology* 49, 547–551.

Ovaskainen, O. (2002) Long-term persistence of species and the SLOSS problem. *Journal of Theoretical Biology* 218, 419–433.

Parmesan, C. and Yohe, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421, 37–41.

Parmesan, C., Burrows, M.T., Duarte, C.M. et al. (2013) Beyond climate change attribution in conservation and ecological research. *Ecology Letters* 16, 58–71.

Pereira, H.M., Leadley, P.W., Proença, V. et al. (2010) Scenarios for global biodiversity in the 21st century. *Science* 330, 1496–1501.

Pritchard, D.J., Fa, J.E., Oldfield, S. and Harrop, S.R. (2012) Bring the captive closer to the wild: redefining the role of ex situ conservation. *Oryx* 46, 18–23.

Prober, S.M., Thiele, K.R., Rundel, P.W. et al. (2012) Facilitating adaptation of biodiversity to climate change: a conceptual framework applied to the world's largest Mediterranean-climate woodland. *Climatic Change* 110, 227–248.

Reed, T.E., Jenouvrier, S. and Visser, M.E. (2013) Phenological mismatch strongly affects individual fitness but not population demography in a woodland passerine. *Journal of Animal Ecology* 82, 131–144.

Reside, A.E., Welbergen, J.A., Phillips, B.L., Wardell-Johnson, G., Keppel, G., Ferrier, S., Williams, S.E., Storlie, C. and VanDerWal, J. (in press) Characteristics of climate change refugia for Australian biodiversity. *Austral Ecology.*

Schwartz, M.W., Hellmann, J.J., McLachlan, J.M. et al. (2012) Managed relocation: Integrating the scientific, regulatory, and ethical challenges. *BioScience* 62, 732–743.

Sheean, V.A., Manning, A.D. and Lindenmayer, D.B. (2012) An assessment of scientific approaches towards species relocations in Australia. *Austral Ecology* 37, 204–215.

Shoo, L.P., Hoffmann, A.A., Pressey, R.L. et al. (2013) Making decisions to conserve species under climate change. *Climatic Change* 199, 239–246.

Sinclair, A.R.E., Fryxell, J.M. and Caughley, G. (2006) *Wildlife Ecology, Conservation and Management. Second Edition*. Blackwell Publishing, Malden, Massachussetts.

Snyder, N.F.R., Derrickson, S.R., Beissinger, S.R. et al. (1996) Limitations of captive breeding in endangered species recovery. *Conservation Biology* 10, 338–348.

Thackeray, S.J., Sparks, T.H., Frederiksen, M. et al. (2010) Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology* 16, 3304–3313.

Thomas, C.D. (2011) Translocation of species, climate change, and the end of trying to recreate past ecological communities. *Trends in Ecology and Evolution* 26, 216–221.

Thomas, C.D., Franco, A.M.A. and Hill, J.K. (2006) Range retractions and extinction in the face of climate warming. *Trends in Ecology and Evolution* 21, 415–416.

Thomas, C.D., Hill, J.K., Anderson, B.J. et al. (2010) A framework for assessing threats and benefits to species responding to climate change. *Methods in Ecology and Evolution* 2, 125–142.

Thomas, M.A., Roemer, G.W., Donlan, C.J. et al. (2013) Gene tweaking for conservation. *Nature* 501, 485–486.

Thorne, K.M., Takekawa, J.Y. and Elliott-Fisk, D.L. (2012) Ecological effects of climate change on salt marsh wildlife: A case study from a highly urbanized estuary. *Journal of Coastal Research* 28, 1477–1487.

Timbal, B., Fernandez, E. and Li, Z. (2009) Generalization of a statistical downscaling model to provide local climate change projections for Australia. *Environmental Modelling and Software* 24, 341–358.

Tingley, M.W., Monahan, W.B., Beissinger, S.R. and Moritz, C. (2009) Birds track their Grinnellian niche through a century of climate change. *Proceedings of the National Academy of Science, USA* 106, 19637–19643.

Tomimatsu, H., Sasaki, T., Kurokawa, H. et al. (2013) Sustaining ecosystem functions in a changing world: a call for an integrated approach. *Journal of Applied Ecology* 50, 1124–1130.

Urban, M.C., Tewksbury, J.J. and Sheldon, K.S. (2012) On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society B: Biological Sciences* 279, 2072–2080.

Van Teeffelen, A.J.A., Vos, C.C. and Opdam, P. (2012) Species in a dynamic world: Consequences of habitat network dynamics on conservation planning. *Biological Conservation* 153, 239–253.

VanDerWal, J., Murphy, H.T., Kutt, A.S. et al. (2013) Focus on poleward shifts in species' distribution underestimates the fingerprint of climate change. *Nature Climate Change* 3, 239–243.

Veloz, S.D., Williams, J.W., Blois, J.L., He, F., Otto-Bliesner, B. and Liu, Z. (2012) No-analog climates and shifting realized niches during the late quaternary: implications for 21st-century predictions by species distribution models. *Global Change Biology* 18, 1698–1713.

Webber, B.L. and Scott, J.K. (2012) Rapid global change: implications for defining natives and aliens. *Global Ecology and Biogeography* 21, 305–311.

Weeks, A.R., Sgro, C.M., Young, A.G. et al. (2011) Assessing the benefits and risks of translocations in changing environments: a genetic perspective. *Evolutionary Applications* 4, 709–725.

Wernery, U., Liu, C., Baskar, V. et al. (2010) Primordial germ cell-mediated chimera technology produces viable pure-line Houbara bustard offspring: potential for repopulating an endangered species. *PLoS ONE* 5, e15824.

Wildt, D.E., Rall, W.F., Critser, J.K., Monfort, S.L. and Seal, U.S. (1997) Genome resource banks. *BioScience* 47, 689–698.

Wilson, K.A., McBride, M.F., Bode, M. and Possingham, H.P. (2006) Prioritizing global conservation efforts. *Nature* 440, 337–340.