

Protected Areas and Climate Change

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The study of protected areas and climate change has now spanned two decades. Pioneering work in the late 1980s recognized the potential implications of shifting species range boundaries for static protected areas. Many early recommendations for protected area design were general, emphasizing larger protected areas, buffer zones, and connectivity between reserves. There were limited practical tests of these suggestions. Development of modeling and conservation planning methods in the 1990s allowed more rigorous testing of concepts of reserve and connectivity function in a changing climate. These studies have shown decreasing species representation in existing reserves due to climate change, and the ability of new protected areas to help slow loss of representation in mid-century scenarios. Connectivity on protected area periphery seems more effective than corridors linking protected areas. However, corridors serving other purposes, such as large carnivore movement, may be useful for accommodating species range shifts as well. Assisted migration and *ex situ* management strategies to complement protected areas are being explored. Finally, in scenarios of the latter half of the century, protected areas and connectivity become increasingly expensive and decreasingly effective, indicating the importance of reducing human-induced climate change.

Key words: protected areas; climate change; biodiversity; reserves; connectivity; assisted migration

Introduction

Understanding of the role of protected areas as climate changes began in the late 1980s with a series of landmark journal articles and book chapters by Rob Peters, Thomas E. Lovejoy, and others (Peters & Darling 1985; Peters & Myers 1991; Peters & Lovejoy 1992). These authors pointed out that paleoecological evidence shows that range shifts were a predominant species response to climate change, suggesting that anthropogenic climate change would be likely to result in changing relationships between (dynamic) species range limits and (fixed) protected area boundaries. Peters illustrated this concept graphically in a figure that is reproduced below as Figure 1. This visual depiction has shaped much of the

subsequent debate about protected areas and climate change because it incorporates the major critical factors—mobile species range limits, fixed reserve boundaries, and land-use change.

In the decade following Peters's pioneering work, a small but growing number of authors addressed the impacts of climate change on protected areas. Most of these contributions were assessments of likely vegetation change or shifting species composition at global, national, and regional scales. Early modeling studies of species range shifts using software tools, such as BIOCLIM (Nix 1986) and DOMAIN (Carpenter *et al.* 1993) confirmed that changes in range boundaries are likely to affect spatial relationships between species and reserves. For instance, the range boundaries of some European plants have been projected to shift of tens or hundreds of kilometers in response to climate change (Huntley *et al.* 1995).

The early conservation and climate change literature made recommendations about

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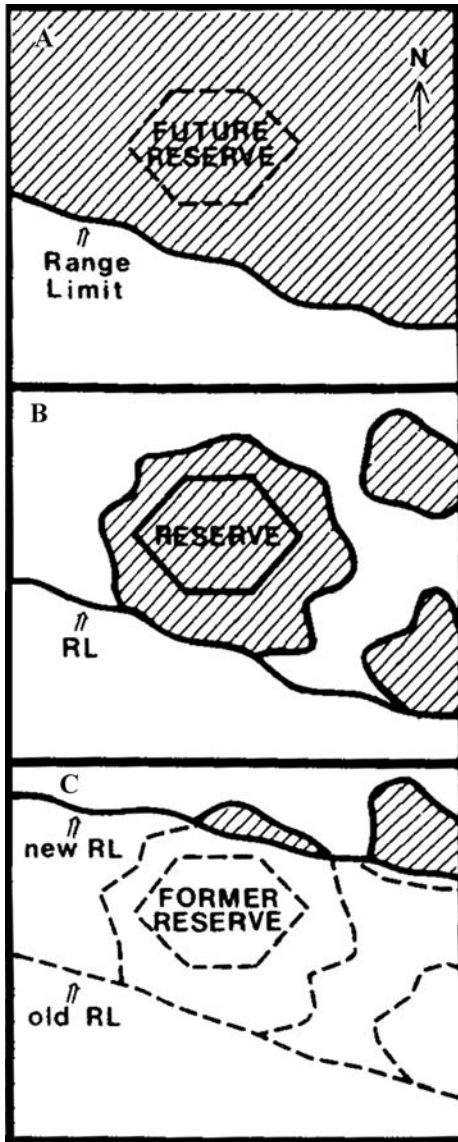


Figure 1. Illustration of relationships between species range limits, reserve boundaries, and land use change (from Peters & Lovejoy 1992). The hatched area in panel **A** represents the range limit of a species. The fragmentation of the hatched areas in panel **B** represents near-term habitat loss due to land-use change. Panel **C** illustrates the combined effect of habitat fragmentation and climate change-induced range shift on representation of the species' range within the reserve. (Note: This figure illustrates the loss of the reserve as the species' range retreats, which is unlikely in response to changes in only one species; the reserve would remain important for many species whose ranges don't shift, as well as for others that may experience range shifts that bring them into the reserve.)

protected areas, but few studies actively tested these notions. A useful review of the field (Halpin 1997) found five broad categories of management recommendation, which the author judged to be generic and in need of testing. These five protected area prescriptions were: redundant reserves; larger reserves; buffer zones around protected areas; landscape connectivity; and management of existing threats and disturbance regimes. The early calls for increased reserve area have been borne out in recent modeling studies. The term "buffer zone" has been partially displaced by discussions of connectivity and management of the matrix in the recent conservation literature, but the concept of multiple-use landscapes that permit both human use and species' responses to climate change remains current. Limiting other threats, such as habitat loss, is a major theme in climate change conservation writings today.

The late 1990s saw developments in conservation planning, species distribution modeling, and climate model downscaling that allowed more rigorous testing of the early recommendations. Reserve selection algorithms capable of testing the relative effectiveness of alternative protected area configurations became commonly available (Pressey & Cowling 2001). Models of species range shifts due to climate change moved from early envelope models, such as BIOCLIM, to better-performing statistical tools, such as Generalized Additive Modeling and MaxEntropy (Guisan & Zimmermann 2000; Elith *et al.* 2006). Finer-grain climate projections of 1–50 km were created for country studies, conservation assessments, and agricultural studies (Root & Schneider 1995). These fine-scale projections have been made widely available for biological modeling (see for instance www.worldclim.org). The convergence of improved modeling tools, reserve selection algorithms, and fine-scale climate projections combined to facilitate direct investigation of the effectiveness of protected areas and corridors in a modeled environment. A series of investigations in several parts of the world have

directly tested the relevance of protected area size, connectivity, and spatial configuration to conserving species whose ranges were shifting due to climate change.

These investigations have shown that protected areas can be an effective response to climate change–driven range dynamics, that limiting human-induced climate change is a critical counterpart to additional protected area, and that connectivity is essential for some species even in the early stages of anthropogenic climate change. Findings to date suggest elements important in the design of individual reserves, particularly for marine reserves in response to coral bleaching. Finally, new responses, such as temporally and spatially flexible reserves and assisted migration are now receiving attention.

This review summarizes this decade of progress, examining findings relating to design of:

- 1) Protected area networks
- 2) Connectivity and corridors
- 3) Individual protected areas
- 4) Mobile reserves
- 5) Measures needed when protection alone is not enough

Each section will summarize the peer-reviewed literature on the topic and mention select agency literature contributions. Challenges currently facing the field and in need of future investigation are highlighted. The review concludes with comments on the degree to which these findings are being, and can be, integrated into conservation practice.

Design of Protected Area Networks

The first conceptual element to be tested with models is the prediction that climate change might alter the species composition of reserves. Multispecies tests targeted at examining climate change effects on levels of species' representation in reserve networks were first conducted in South Africa (Rutherford *et al.*

1999) and Europe (Araújo *et al.* 2004). Representation is the amount of area of each species' range included within protected areas, a measure commonly used in conservation planning to assess adequacy of protection. These and other studies (e.g., Pearson & Dawson 2005) indicate that range shifts result in declines in species representation in some reserves, but, depending on assumptions about species' dispersal abilities, may result in increases in representation in other reserves. The net effect of movements on representation in individual reserves and across whole networks depends strongly on dispersal abilities and intervening land uses that may impede dispersal (Pearson 2006).

There is reason to believe that the net effect of climate change–induced range shifts will be reduction in ranges, which has implications for conservation and risk of extinction. Warming will cause species to migrate upslope and toward the poles to track suitable climatic conditions (Walther *et al.* 2002). Mountains have less area at higher elevation due to their geometry, while in the southern hemisphere, continents have less land area toward the poles due to their shape. While northern hemisphere land area increases poleward, species richness and endemism is lower in these areas due to Pleistocene glaciation.

Thomas and colleagues (2004) estimated the extinction risk associated with range shifts in six geographically diverse regions. They found that extinction risk increased in all cases, even under full dispersal assumptions, which suggests that there is an overall net trend toward smaller species ranges with climate change. Such a net reduction in average range size would favor net loss of representation in reserves. Modeling results examining this question directly have confirmed net reduction in species representation with climate change for specific regions (e.g., Hannah *et al.* 2005).

The creation of new reserves is a logical step to compensate for this loss of representation (Villers-Ruiz & Trejo-Vazquez 1998; Hannah *et al.* 2002; Hossell *et al.* 2003; Anderson & Martinez-Meyer 2004; Coulston & Riitters

2005). Additional protected areas have been suggested to compensate for loss of habitat representation in Canadian parks, where even gross vegetation type may be altered by climate change (Scott *et al.* 2002). Creation of new and larger reserves has been proposed as a response in marine systems because of their large extent and high degree of interconnectivity (Soto 2001). Improved coverage of important plant areas has been suggested in Africa and for dry forest worldwide based on modeling (McClean *et al.* 2006; Miles *et al.* 2006).

One method for systematically adding protected areas for climate change is to link species distribution models (SDMs) and reserve selection algorithms. The SDM is used to simulate the present and future ranges of a species, allowing the gain or loss of area protected to be calculated. Reserves are added to compensate for lost representation, using the algorithm, until no further improvement in representation can be achieved in the future (climate change) scenario. The improvement in representation achievable with additional protected areas can then be measured. The benchmark against which changes are gauged is a target level of representation (Pressey *et al.* 2007). In practice the amount of area to be protected should be tailored to each species, depending on their population sizes and habitat requirements. However, in these studies a simplifying assumption is made that all species must meet a minimal representation (area of species range protected) target.

An alternative response is to improve the climatic representation of a reserve network (Pyke *et al.* 2005; Pyke & Fischer 2005). This method adds area containing climates poorly represented in the reserve system. Reserves are added incrementally until climatic representation goals are met. Climatic representation is calculated using the climatic tolerances of target species, which is important because species response is the product of the amount of change in a particular climatic variable (e.g., precipitation) and species sensitivity to change in that variable (Pyke & Fischer 2005). The end

result of the climatic representation method may therefore be dependent on the number of species sampled, a trait it shares with species representation approaches.

No systematic test has been conducted comparing the climate-representation and species-representation approaches. Both approaches greatly increase the chance of all species being represented in a reserve network as climate changes, while only the species-representation approach can meet specific targets for the area under protection for each species. Since viable populations depend strongly on area conserved, the ability to set and meet area targets for priority species is a significant advantage.

The need for global coordination and expansion of protected areas to deal with climate change has been recognized (Hannah 2001). A key need is regionally or globally accepted representation targets for species. These would provide objective benchmarks, allowing new areas to be added to maintain targets as climate changes. Not all species are represented in protected areas in their current ranges, so an effort is needed to complete protected areas coverage globally. This provides an opportunity to meet climate-change and current protection needs simultaneously. A system of standards and timelines for completion of global coverage is therefore a key element in a global system of protected areas. Such a system would best function in a decentralized, voluntary fashion (Hannah 2001).

A crucial question about adding protected areas is whether sufficient viable range remains in future climates for new protection to make a difference. This issue has recently been addressed in a study which employed SDM and reserve selection algorithms in three regions (Hannah *et al.* 2007). This work built on the multispecies SDM efforts available in the Cape Floristic Region (Midgley *et al.* 2002), Mexico (Peterson *et al.* 2002), and Europe (Araújo *et al.* 2004) under climate changes projected for 2050. New protected areas were able to substantially restore species representation lost due to climate change in 2050 scenarios in all

three regions. New protected areas brought the number of species meeting the representation target to 78% (Cape), 89% (Europe), and 94% (Mexico). These results strongly confirmed the relevance of protected areas as a conservation response to climate change.

Strong performance of new protected areas in these midcentury scenarios does not indicate that protected areas are a panacea for climate change. On the contrary, the fact that up to 20% of species lost representation even with new protected areas in the 2050 scenarios is an indication that more severe climate change later in the century is highly likely to result in severe loss of representation. Variation between regions was high, indicating that performance of new protected areas is dependent on topography, characteristics of specific taxa, and other factors. In this study, the Cape and Europe analyses used plant taxa. In Mexico, vertebrate taxa were used and the protected area needs were far lower. Dispersal limits chosen by experts familiar with the species were included in the simulation, so the lower protected area need in Mexico may be related to the relatively higher dispersal abilities of vertebrates. Reanalysis of Mexico using plant taxa might show new protected area needs more similar to those found for the Cape and Europe.

Finally, early implementation of new protected areas for climate change paid dividends in all three regions. Area savings of 39–96% were realized when climate change and completing representation of current ranges were addressed at once. This is because protected area networks are not perfect in representation of current ranges—new protected areas must be added to meet a uniform representation goal for current ranges—and there are choices to be made as to which areas to add. If these choices are made in ways that favor areas needed to compensate for climate change, a head start on climate-change solutions is gained, reducing the amount of area needed to compensate for climate change losses later on. Even if anticipation of climate change is imperfect, explicit attempts to address climate change in selec-

tion of new protected area for current ranges will result in some area savings (Hannah *et al.* 2007).

Connectivity and Corridors

Early concepts of connectivity and corridors assumed that species moving in response to climate change would need pathways between one protected area that they were leaving and another, destination protected area. This simple conceptualization belied the complexity of multiple species, all moving simultaneously in response to climate change. The individualistic nature of species' responses to climate change is widely recognized in paleoecology, suggesting that future range changes will also find species moving each in their own characteristic way, depending on species-specific climatic tolerances. Such individualistic movements are not likely to align with one another closely or be readily captured in linear source-to-destination corridors.

The first modeling test of connectivity for climate change supported the individualistic view (Williams *et al.* 2005). This study used timestep models of plants (proteas) in the Cape region of South Africa to find “chains” of connectivity that would track suitable climate for moving species. SDMs were produced for 315 protea species each decade, from the present to 2050, in planning unit grids with dimensions of just under 2 km. A reserve selection algorithm was modified to search for chains of contiguous planning units that maintained suitable climate in all timesteps (Fig. 2). The shortest chain was one grid cell that maintained suitable climate from present to 2050. For species whose ranges moved considerably, 5–6 grid chains might be required. An estimate of dispersal limitation for each species excluded distant planning units from consideration. The algorithm selected chains within existing protected areas first, then selected new areas complementary to existing parks and reserves until the representation target was met. This final network of

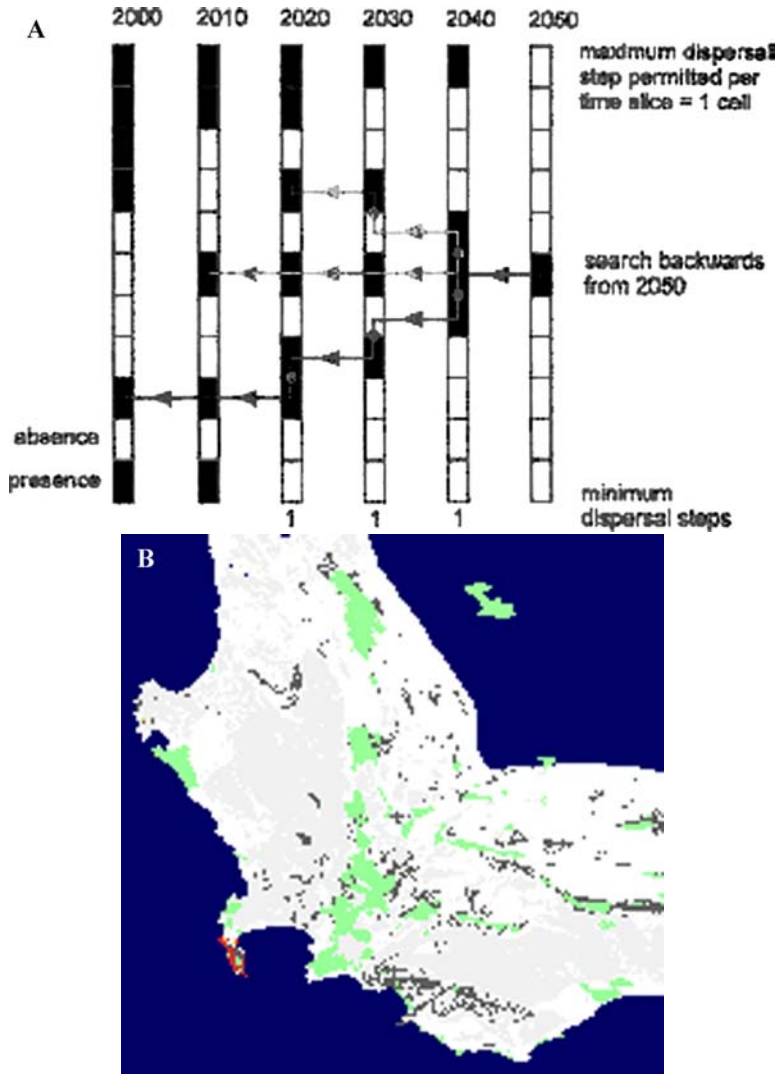


Figure 2. (A) Method for searching for "chains" of connectivity among planning units. When repeated over an entire protected area network, this procedure provides a basis for adding protected areas that will help accommodate range shifts due to climate change. In practice, searching backwards in time reduces nonproductive searches and search time, since it avoids "dead-end" chains that do not persist in the future (for instance the top row of cells in the figure). (From Williams *et al.* 2005.) (B) Example of additional areas selected by such a method for the Cape region of South Africa. Light green indicates existing protected areas, orange indicates protected area additions for climate change based on chains analysis. Light grey is land transformed to human use (e.g., agriculture), blue is ocean to the south and west, and non-fynbos vegetation to the North east. (Figure courtesy of Steven Phillips).

existing and new protected areas provided the best possible protection for all species as climate changes.

The most cost-effective connectivity linked a current protected area with unprotected habitat on its periphery. Few species actually moved from one protected area to another, and these

long-distance links would seldom be selected because shorter, less area-intensive links existed for most species. For smaller range shifts, cells that retained suitable climate could often be found within existing protected areas, or added to the network at relatively smaller cost. Many range shifts, both large and small, could be

accommodated by chains that lay entirely within existing protected areas.

The effectiveness of new protected lands to provide connectivity was eroding by 2050, as evidenced by the species with no suitable climate or need for long chains with little or no overlap with other chains. Further investigation is needed in this and other regions to determine the capacity for connectivity to compensate for the effects of climate change later in the century. It appears to be highly likely that connectivity and new protected areas will fail to maintain protection for many species past 2050 in at least some regions. This suggests that the next 50 years is the key timeframe in which climate change must be stopped to avoid large negative consequences for biodiversity.

The approach of Williams *et al.* (2005) has now been improved and modified using linear programming optimization techniques (Phillips, in press). Commercial linear programming softwares have been developed for industrial optimization problems such as airline routing. They provide better optimization results than the algorithms used in most conservation planning software, but are less often used in conservation due to the cost of the software and the longer time required to find a solution. These commercial optimization softwares have now been applied to the climate-change reserve-selection problem. Early results of these analyses suggest that connectivity may be achieved with even less area than in solutions developed with reserve-selection algorithms. The results do not, however, show much evidence of improved capacity to maintain representation past 2050, as the erosion of effectiveness in later timesteps is driven by shrinking suitable climate space for species rather than by problems of efficiency.

Design of Individual Protected Areas

A strong literature is evolving on the design of protected areas for climate change, particu-

larly with reference to marine protected areas (MPAs). Recommendations emphasize design concepts that promote either resilience or resistance to climate change (Salm *et al.* 2001; West & Salm 2003). Resistance is the ability of the ecosystems within a protected area to withstand climate change without substantial biological change. Resilience is the capacity of ecosystems (or species) to recover to a starting or reference condition after being damaged by climate change.

The climate change impact most addressed in the protected area literature is coral bleaching (West & Salm 2003). This emphasis arises because coral bleaching is an immediate threat from climate change to marine reserves (Salm *et al.* 2001). Bleaching has already affected most of the world's coral reefs and is expected to grow in severity as climate change accelerates (Hoegh-Guldberg 1999). MPAs may have an important role in slowing this process and ensuring that healthy coral reefs persist in some regions, with important implications for tourism and local fisheries.

Resistance to coral bleaching can be conferred by cool upwellings and by sites in which sedimentation and exposure to light are minimized (West & Salm 2003). Design elements that favor incorporation of these features therefore improve resistance within an MPA. Undamaged reefs in these resistant areas may serve as important sources of recolonization for areas damaged in bleaching events. However, under more extreme climate change, the combination of high water temperature and increasing acidity from the dissolution of atmospheric CO₂ in seawater may eradicate coral reefs on regional or global scales (Hoegh-Guldberg *et al.* 2007), outstripping the moderating effects of upwelling and making recolonization irrelevant.

Resilience is a biological property and is more difficult than resistance to incorporate into reserve design. Nonetheless, understanding of resilience is improving, and applications, particularly in MPAs, are evolving (Van Oppen & Gates 2006). Some species and some populations recover more quickly after

bleaching. Some coral reef ecosystems are more resilient than others (Bellwood *et al.* 2006). These resilient populations or ecosystems may be targeted in reserve design, for instance by placing boundaries to maximize area of resilient populations. Design for resilience may bias species composition (toward quicker-recovering species), so may have to be balanced against species representation goals. Zoning to reduce tourism use post-bleaching may reduce physical contact and damage to reefs, which may enhance recovery (Salm *et al.* 2001).

Sea-level rise is a second major concern addressed in the MPA design literature. Rising sea level over the coming centuries will alter the proportion of habitat types represented in MPAs. For example, some reserves in the Channel Islands of California will lose sea grass habitat as sea level rises, since shelf areas that currently harbor extensive sea grass beds will become submerged too deeply to support sea grass in the future. Individual sites can be selected or designed to incorporate areas that will lose less sea grass habitat under projected changes in bathymetry.

The terrestrial literature on reserve design for climate change is less well developed, but several important design considerations have been identified. Halpin (1997) has pointed out that changes in montane vegetation zones with warming are dependent on the topography of specific mountain chains. This effect parallels in principle the changes in marine habitat due to sea-level rise. Reserve configuration can help compensate for these changes. For example, using a watershed divide as a reserve boundary may be a good choice for ease of demarcation, but for climate change a better choice is to include high-elevation habitats on both sides of the divide, since these will be pushed upslope and consequently reduced in area by warming—setting a reserve limit along the divide would exclude half of these diminishing habitats from protection.

Sea-level rise is a concern in terrestrial reserve design as well as in marine settings. Coastal reserves will often be squeezed between

rising sea level and hard boundaries of inland human land use (Shirley & Battaglia 2006). Reserve design can help resolve this evolving conflict. For example, in the Albemarle Sound of North Carolina, acquisition of inland land is underway to allow migration of coastal communities as salt-water intrusion erodes peat soils (Pearsall 2005).

Protected area responses to ecosystem threshold changes is of growing concern. Vegetation type changes may be compensated for by adding protected area to compensate for vegetation types declining in protection. For example, in Canada, redesign of the entire protected area network has been recommended as boreal forests become rarer and temperate forests more common. Increased protection in the far north may be necessary to ensure the conservation of boreal forests that were formerly abundantly represented in protected areas further south (Scott & Suffling 2000). Other threshold changes may prove even more challenging. Pine bark beetle outbreaks are decimating dominant tree species across large areas of western North America and, due to climate change, are penetrating to latitudes and elevations previously immune to outbreak. Conservation responses to these events have been little examined, but protection of resistant stands may be critical in long-term conservation of these species.

Reserve management and design recommendations for major ecosystem types have been reviewed for several terrestrial and marine biomes for the NGO community in a volume by Hansen and Hoffman (2003). Among the suggestions of chapter authors of this volume were reduction in current stressors, maximizing habitat heterogeneity in reserves, and early and progressive implementation of protection and management actions.

Moveable Feast: Protection that Varies in Space and Time

Protected areas whose boundaries or level of protection vary in time or space are a logical

response to shifting species ranges due to climate change. If the target of protection (a species or ecosystem) is moving, why not have protection move with it? Altering protection in time is relatively common in current conservation practice, while protection that varies across geographic space has fewer analogs current. Both temporal and spatial variations may be adapted for improved conservation response to climate change (Scott 2007).

Protected areas that change are not unusual, particularly in sport hunting and fisheries. Temporally variable seasonal protection is common in these applications. Examples include closed seasons in hunting and seasonal fisheries closures. The level of protection may vary over time, for example in catch limits or bag limits that vary year to year depending on a regulatory agencies' assessment of population size.

Area closures are a management tool in many multiple-use protected areas such as National Forests. In fisheries, area closures are employed when seasonal closures are not sufficient to maintain a healthy population. Even within National Parks and nature reserves, area closures and zoning-related restrictions, for instance to allow vegetation to recover from overuse, are commonly employed. When closures rotate between adjacent management units, as they sometimes do in fisheries, forest reserves, or between zoning areas in parks, the effect is of a mobile protected area. These existing practices form a precedent for protected areas that vary in time and space to respond to climate change (Pressey *et al.* 2007). However, to be effective in management of climate change, such tools would need to be applied in coordinated ways over large areas. This requires advanced planning, monitoring, and coordination between parcels specifically for climate change.

Mobile protected areas to deal with climate change were first proposed for marine conservation (Soto 2001). Major areas of ocean current interaction, or "fronts," are associated with high concentrations of large marine predators

such as tuna and swordfish. Fronts are not fixed in space and may move over the course of a year or within a season in response to changes in patterns of circulation. Marine frontal zones are likely to shift with climate change as sea surface temperatures and global circulation patterns change. Geographically fixed protection for fronts would require huge areas to capture these present and future variations. Mobile protected areas would provide for the conservation of these variable features (Soto 2001).

Conservation easements are a final class of conservation tool that may be variable in time. Easements are bundles of use restrictions that can be reassessed, triggered, or removed as time passes. A coordinated system of landholder agreements has been proposed as a mechanism for providing mobile protection in response to climate change (Hannah & Hansen 2005). In this application, easements might be used to provide futures options to acquire land at a pre-specified price or to effect a specified land-use change (such as reversion to forest) based on future conservation action needed to respond to climate change.

When Protection Alone Fails: Assisted Migration

Assisted migration may be necessary when climate change is so rapid that the speed of a range shift exceeds a species' dispersal ability (McLachlan *et al.* 2007). It may also be required where human land uses make establishment of new protected area or connectivity impossible. Assisting dispersal may be as simple as transporting seeds from a plant to a new location or as difficult as maintaining viable populations of a top predator over several generations until newly suitable habitat is fully established.

There are numerous biological and policy issues that confront assisted migration, which are only beginning to be explored in the literature (McLachlan *et al.* 2007). In the short term, few species have suffered documented climate change-related declines which would

warrant assisted migration, so there is time to put technical and policy frameworks in place for decisions about appropriate application of assisted migration. One of the elements of a cost-effective policy will be preference for assisted migration in settings in which adequate protected areas are in place to ensure the survival of the translocated populations.

Other measures, such as captive breeding, may be necessary complements to *in situ* conservation in protected areas as well. For example, *ex situ* management may be a necessary complement to protection for conservation of genetic resources. Climate change, like habitat loss, may lead to genetic bottlenecks, inbreeding, and related genetic and population-level issues that may require monitoring and possibly captive-breeding efforts to supplement wild populations. A genetic issue unique to climate change is loss of local adaptation. Populations at the trailing edge of range shifts may be particularly important. These low-latitude limits of species' ranges have frequently been refugia during the predominantly cooler climates of the past 2 million years, making them unique stores of genetic diversity (Hewitt 2000). As climates continue to warm on today's relatively warm (in Pleistocene terms) climate, these low-latitude, trailing-edge populations may fragment and face extinction (Hampe & Petit 2005). Some gene banking and *ex situ* conservation of individuals from these populations may be warranted as climate change continues.

Conclusion

Protected areas have been generally under-recognized as a policy response for preventing extinctions due to climate change—no new protected areas have yet been established specifically to cope with climate change. Sufficient evidence now exists to indicate that early implementation of new protected areas is likely to substantially reduce the threat climate change poses to biodiversity. Connectivity and

corridors are much more frequently proposed as responses to climate change. Connectivity on the periphery of existing protected areas has been shown to be the most cost effective, since species move individually, making opportunities to establish multispecies corridors for climate change rare. Corridors for other purposes, such as large predator dispersal, may be valuable for climate change, however, and corridors can and should be designed to serve multiple purposes wherever possible.

Addition of protected areas to counter the effects of climate change on the natural world is complicated by the uneven coverage of current protected areas. Large gaps in representation exist, even for current ranges of relatively well-known taxa, such as mammals and birds (Rodrigues *et al.* 2004). This lack of maturity in global protection must be addressed in order for improvements for climate change to take place. It presents the opportunity, however, of closing both present and future (climate change-induced) gaps at the same time. Since climate change may be a motivating force to improve the consistency of global protected areas coverage, there is hope for meeting these dual goals.

Connectivity within and adjacent to protected areas is being found to be more cost effective and feasible than long-distance connectivity or connections between protected areas. The effectiveness of new connectivity is heavily influenced by the degree and extent of species range shifts. Assisted migration, captive breeding, and other intensive management options need to be implemented on a species-by-species basis and have the potential to become extremely expensive as communities disaggregate and reassemble as species follow individualistic range changes under severe climate change. Increasingly management-intensive options and decreasing species representation in protected areas can be expected if climate change continues unabated. Conservation strategies for the latter half of the century, and their cost and effectiveness, therefore depend in large part on action to bring climate change in check.

Conflicts of Interest

The author declares no conflicts of interest.

References

- Anderson, R.P. & E. Martinez-Meyer. 2004. Modeling species' geographic distributions for preliminary conservation assessments: an implementation with the spiny pocket mice (*Heteromys*) of Ecuador. *Biol. Conserv.* **116**: 167–179.
- Araújo, M.B., M. Cabeza, *et al.* 2004. Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. *Global Change Biol.* **10**: 1618–1626.
- Bellwood, D.R., A.S. Hoey, *et al.* 2006. Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. *Global Change Biol.* **12**: 1587–1594.
- Carpenter, G., A.N. Gillison, *et al.* 1993. DOMAIN—a flexible modeling procedure for mapping potential distributions of plants and animals. *Biodiversity Conserv.* **2**: 667–680.
- Coulston, J.W. & K.H. Riitters. 2005. Preserving biodiversity under current and future climates: a case study. *Global Ecol. Biogeogr.* **14**: 31–38.
- Elith, J., C.H. Graham, *et al.* 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* **29**: 129–151.
- Guisan, A. & N.E. Zimmermann. 2000. Predictive habitat distribution models in ecology. *Ecol. Modell.* **135**: 147–186.
- Halpin, P.N. 1997. Global climate change and natural-area protection: management responses and research directions. *Ecol. Appl.* **7**: 828–843.
- Hampe, A. & R.J. Petit. 2005. Conserving biodiversity under climate change: the rear edge matters. *Ecol. Lett.* **8**: 461–467.
- Hannah, L. 2001. The role of a global protected areas system in conserving biodiversity in the face of climate change. In *Climate Change and Protected Areas*. G. Visconti & M. Balaban. Kluwer. Dordrecht.
- Hannah, L. & L.A. Hansen. 2005. Designing landscapes and seascapes for change. In *Climate Change and Biodiversity*. T.E. Lovejoy & L. Hannah. Yale University Press. New Haven.
- Hannah, L., G. Midgley, *et al.* 2007. Protected area needs in a changing climate. *Front. Ecol. Environ.* **5**: 131–138.
- Hannah, L., G.F. Midgley, *et al.* 2005. The view from the Cape: Extinction risk, protected areas and climate change. *BioScience* **55**: 231–242.
- Hannah, L., G.F. Midgley, *et al.* 2002. Conservation of biodiversity in a changing climate. *Conserv. Biol.* **16**: 11–15.
- Hansen, L.B. & J. Hoffman. 2003. BUYING TIME: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems. http://assets.panda.org/downloads/buyingtime_unfe.pdf. (accessed Feb. 11, 2008).
- Hewitt, G. 2000. The genetic legacy of the Quaternary ice ages. *Nature* **405**: 907–913.
- Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshw. Res.* **50**: 839–866.
- Hoegh-Guldberg, O., P.J. Mumby, *et al.* 2007. Coral reefs under rapid climate change and ocean acidification. *Science* **318**: 1737–1742.
- Hossell, J.E., N.E. Ellis, *et al.* 2003. Climate change and nature conservation: implications for policy and practice in Britain and Ireland. *J. Nat. Conserv.* **11**: 67–73.
- Huntley, B., P.M. Berry, *et al.* 1995. Modelling present and potential future ranges of some European higher plants using climate response surfaces. *J. Biogeogr.* **22**: 967–1001.
- McClean, C.J., N. Doswald, *et al.* 2006. Potential impacts of climate change on Sub-Saharan African plant priority area selection. *Divers. Distrib.* **12**: 645–655.
- McLachlan, J.S., J.J. Hellmann, *et al.* 2007. A framework for debate of assisted migration in an era of climate change. *Conserv. Biol.* **21**: 297–302.
- Midgley, G.F., L. Hannah, *et al.* 2002. Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. *Global Ecol. Biogeogr.* **11**: 445–451.
- Miles, L., A.C. Newton, *et al.* 2006. A global overview of the conservation status of tropical dry forests. *J. Biogeogr.* **33**: 491–505.
- Nix, H.A. 1986. BIOCLIM—a bioclimatic analysis and prediction system. Pages 59–60. CSIRO Division of Land and Water Resources Annual Report. CSIRO, Canberra, Australia.
- Pearsall, S. 2005. Managing for future change on the Albemarle Sound. In *Climate Change and Biodiversity*. T.E. Lovejoy & L. Hannah, Eds. Yale University Press, New Haven.
- Pearson, R.G. 2006. Climate change and the migration capacity of species. *Trends Ecol. Evol.* **21**: 111–113.
- Pearson, R.G. & T.P. Dawson. 2005. Long-distance plant dispersal and habitat fragmentation: identifying conservation targets for spatial landscape planning under climate change. *Biol. Conserv.* **123**: 389–401.
- Peters, R.L. & J.D.S. Darling. 1985. The Greenhouse Effect and Nature Reserves. *BioScience* **35**: 707–717.
- Peters, R.L. & T.E. Lovejoy. 1992. *Global Warming and Biological Diversity*. Yale University Press. London.
- Peters, R.L. & J.P. Myers. 1991. Preserving biodiversity in a changing climate. *Issues Sci. Technol.* 66–72.

- Peterson, A.T., M.A. Ortega-Huerta, *et al.* 2002. Future projections for Mexican faunas under global climate change scenarios. *Nature* **416**: 626–629.
- Pressey, R.L. & R.M. Cowling. 2001. Reserve selection algorithms and the real world. *Conserv. Biol.* **15**: 275–277.
- Pressey, R.L., M. Cabeza, *et al.* 2007. Conservation planning in a changing world. *Trends Ecol. Evol.* **22**: 583–592.
- Pyke, C.R., S.J. Andelman, *et al.* 2005. Identifying priority areas for bioclimatic representation under climate change: a case study for Proteaceae in the Cape Floristic Region, South Africa. *Biol. Conserv.* **125**: 1–9.
- Pyke, C.R. & D.T. Fischer. 2005. Selection of bioclimatically representative biological reserve systems under climate change. *Biol. Conserv.* **121**: 429–441.
- Rodrigues, A.S.L., S.J. Andelman, *et al.* 2004. Effectiveness of the global protected area network in representing species diversity. *Nature* **428**: 640–643.
- Root, T.L. & S.H. Schneider. 1995. Ecology and climate: research strategies and implications. *Science* **269**: 334–341.
- Rutherford, M.C., L.W. Powrie, *et al.* 1999. Climate change in conservation areas of South Africa and its potential impact on floristic composition: a first assessment. *Divers. Distrib.* **5**: 253–262.
- Salm, R.V., S.L. Coles, *et al.* 2001. Coral Bleaching and Marine Protected Areas. Pp. 1–107. The Nature Conservatory. Honolulu, Hawaii.
- Scott, D., J.R. Malcolm, *et al.* 2002. Climate change and modelled biome representation in Canada's national park system: implications for system planning and park mandates. *Global Ecol. Biogeogr.* **11**: 475–484.
- Scott, D. & R. Suffling. 2000. *Climate Change and Canada's National Park System*. Environment Canada. Toronto, Canada.
- Scott, J.M. 2007. Presentation at the annual meeting of the Wildlife Society. Tucson, Arizona.
- Shirley, L.J. & L.L. Battaglia. 2006. Assessing vegetation change in coastal landscapes of the Northern Gulf of Mexico. *Wetlands* **26**: 1057–1070.
- Soto, C.G. 2001. The potential impacts of global climate change on marine protected areas. *Rev. Fish Biol. Fisheries* **11**: 181–195.
- Thomas, C.D., A. Cameron, *et al.* 2004. Extinction risk from climate change. *Nature* **427**: 145–148.
- Van Oppen, M.J.H. & R.D. Gates. 2006. Conservation genetics and the resilience of reef-building corals. *Mol. Ecol.* **15**: 3863–3883.
- Villers-Ruiz, L. & I. Trejo-Vazquez. 1998. Climate change on Mexican forests and natural protected areas. *Global Environ. Change Human Policy Dimensions* **8**: 141–157.
- Walther, G., E. Post, *et al.* 2002. Ecological responses to recent climate change. *Nature* **416**: 389–395.
- West, J.M. & R.V. Salm. 2003. Resistance and resilience to coral bleaching: implications for coral reef conservation and management. *Conserv. Biol.* **17**: 956–967.
- Williams, P., L. Hannah, *et al.* 2005. Planning for climate change: identifying minimum-dispersal corridors for the Cape proteaceae. *Conserv. Biol.* **19**: 1063–1074.