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Climate change-integrated conservation strategies

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ABSTRACT

Aim Conservation strategies currently include little consideration of climate change. Insights about the biotic impacts of climate change from biogeography and palaeoecology, therefore, have the potential to provide significant improvements in the effectiveness of conservation planning. We suggest a collaboration involving biogeography, ecology and applied conservation. The resulting Climate Change-integrated Conservation Strategies (CCS) apply available tools to respond to the conservation challenges posed by climate change.

Location The focus of this analysis is global, with special reference to high biodiversity areas vulnerable to climate change, particularly tropical montane settings.

Methods Current tools from climatology, biogeography and ecology applicable to conservation planning in response to climate change are reviewed. Conservation challenges posed by climate change are summarized. CCS elements are elaborated that use available tools to respond to these challenges.

Results Five elements of CCS are described: regional modelling; expanding protected areas; management of the matrix; regional coordination; and transfer of resources. Regional modelling uses regional climate models, biotic response models and sensitivity analysis to identify climate change impacts on biodiversity at a regional scale appropriate for conservation planning. Expansion of protected areas management and systems within the planning region are based on modelling results. Management of the matrix between protected areas provides continuity for processes and species range shifts outside of parks. Regional coordination of park and off-park efforts allows harmonization of conservation goals across provincial and national boundaries. Finally, implementation of these CCS elements in the most biodiverse regions of the world will require technical and financial transfer of resources on a global scale.

Main conclusions Collaboration across disciplines is necessary to plan conservation responses to climate change adequately. Biogeography and ecology provide insights into the effects of climate change on biodiversity that have not yet been fully integrated into conservation biology and applied conservation management. CCS provide a framework in which biogeographers, ecologists and conservation managers can collaborate to address this need. These planning exercises take place on a regional level, driven by regional climate models as well as general circulation models (GCMs), to ensure that regional climate drivers such as land use change and mesoscale topography are adequately represented. Sensitivity analysis can help address the substantial uncertainty inherent in projecting future climates and biodiversity response.

Key words biodiversity, climate change, conservation, matrix management, modelling, protected areas, range shifts.

INTRODUCTION

Mounting evidence indicates that global climate is changing, that biological responses to warming are under way, and that current conservation strategies will need to be revised to be effective in the face of future climate change (Hughes, 2000; Hannah, 2001; IPCC, 2001; Hannah *et al*., 2002). A new synthesis of biogeography and conservation biology is necessary to respond to the challenges posed by climate change to the conservation of biological diversity. This paper elaborates a framework for integrating biogeography, conservation biology and on-the-ground conservation management to produce Climate Change-integrated Conservation Strategies (CCS).

Conservation biology has explored the implications of reserve size, shape and location for the conservation of biodiversity, yet has developed little theory for the effects of climate change (Cowling, 1999). Biogeography has developed increasingly detailed understanding of past and future biotic responses to climate change, but the application of these results to reserve design, selection and management has been limited (Bush, 1996). New collaboration between these

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disciplines is urgently needed if the impending impacts of anthropogenic climate change are to be addressed in our strategies for conserving biodiversity.

Collaboration must include conservation managers, who are frequently faced with pressing day-to-day threats to biodiversity that make heavy investments of their time in impact assessments and risk management impractical, but who will need to make fundamental changes to their management programmes if climate change is to be addressed successfully. Synthesis is therefore needed not just across disciplines, but between theory and practice. Only a partnership based on adaptive management, in which field managers help to test and refine ideas progressively, can be expected to be effective given the uncertainties of the impacts of climate change on biodiversity.

A limited number of tools currently exist that can be utilized in this partnership. Understanding from biogeography and palaeoecology suggests several promising strategic directions. Ultimately, dynamic practical partnerships and assessments at the regional level are the best current hope for producing conservation strategies robust to climate change.

ASSESSMENT TOOLS

Several major types of tools are available for assessing the impact of climate change on biodiversity (Sulzman *et al.*, 1995). These include:

- global climate models;
- regional climate models;
- dynamic and equilibrium vegetation models;
- species bioclimatic envelope models; and
- site-specific sensitivity analysis.

Models of global climate, general circulation models (GCMs), provide broad resolution projections of future climate changes. A typical protected area occupies just a small fraction of a GCM grid cell, and there are substantial differences in projected climate changes among GCMs. None the less, GCMs are an essential entry point for conservation assessments of climate change, because they represent the only source for estimates of future climate changes due to global greenhouse-gas forcing. Global GCM projections for several models are available on the internet (e.g. http://www.meto.govt.uk/research/hadleycentre/models/modeldata.html). Software is available on CD-ROM for personal computers which allows the comparison of simulated results from several models, which is useful given the considerable inter-GCM uncertainty (Wigley *et al.*, 2000) [see citation for mailing address for CD/software requests].

GCM relevance to biodiversity assessment is improved by selecting results from transient (not equilibrium) simulations of CO_2 increase and from fully coupled ocean–atmosphere models appropriate to the region in question. Equilibrium simulations (i.e. a step increase in CO_2) show increasing temperature change poleward in both hemispheres, while more sophisticated transient simulations show temperature change decreasing with latitude in the southern hemisphere outside Antarctica (Sulzman *et al.*, 1995). Northern and southern hemisphere climate system dynamics are markedly different and GCM hemispheric coupling is problematic, so models developed with a southern hemisphere focus (e.g. several excellent modelling exercises in Australia) may be more appropriate in southern hemisphere applications (Grassl, 2000). Using inappropriate models or simulations may bias results, especially in the southern hemisphere.

Regional climate models may be embedded within GCMs to provide higher resolution results for use in assessments. Two major regional climate models in wide use are MM5 (Mesoscale Model version 5) and RAMS (Regional Atmospheric Modelling System) (Sulzman *et al.*, 1995). These models capture the regional influences that in some settings may be more important than global forcing in determining local climate changes. For instance, conversion of forest to pasture in the Amazon may produce local precipitation effects that overwhelm probable precipitation changes due to global greenhouse gas forcing (Pitman *et al.*, 2000). Regional models represent both the land-use changes and resultant cloud formation dynamics of this effect in ways impossible in a GCM. Regional models run at national or subcontinental scales useful in conservation planning. Their results are available less widely than those of GCMs, however, and they are not available for all regions. Biogeographers must typically work with atmospheric scientists to select appropriate global and regional modelling tools to drive biotic response models.

Dynamic vegetation models, forest 'gap' models, biome envelope (or 'correlative') models and species envelope models all use GCM and regional climate model results to provide insights into different aspects of the biogeography of future climate change. Dynamic global vegetation models (DGVMs) use first principles of photosynthesis, carbon processing and plant physiology to predict plant functional types (Cramer *et al.*, 2000). Forest 'gap' models simulate species-specific succession dynamics at the stand-level (< 1 ha), but have limited ability to represent landscape-level changes. They have data requirements that limit their application primarily, but not exclusively, to temperate forests (Shugart, 1990). Global biome models use the climatic limits of current vegetation to simulate future distributions in changed climates. Global biome models assume vegetation is in equilibrium with climate and so cannot model dynamic transitions, while DGVMs incorporate dynamics but do not yield species-specific results (Woodward & Beerling, 1997). Forest 'gap' models do both, but for only a small area and for only species for which growth and reproductive characteristics have been studied.

Species bioclimatic envelope models are the best available tool for producing the species-specific information necessary in conservation planning (Fig. 1). They are similar in principle

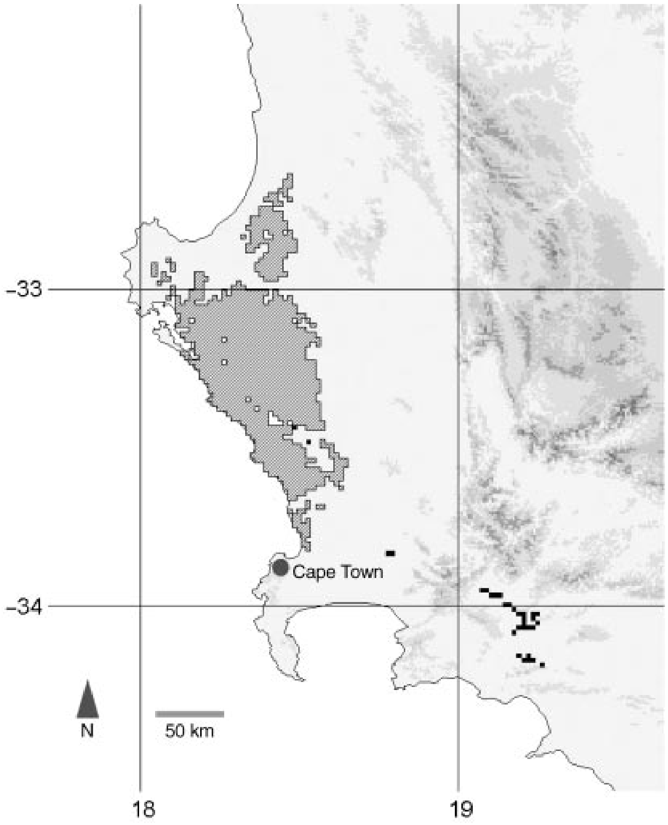

Fig. 1 Bioclimatic model of the range shift of *Leucospermum tomentosum* in a double CO_2 climate (approximately 2050) following the methods described in Midgley *et al.* (2002). The GCM projection used is CSM without sulphates. The modelled present range is indicated by cross-hatching. The modelled future range is indicated by black rectangles.

to biome envelope models, in that the present distribution of a species is used to 'train' a model to predict the climatic conditions in which the species may exist in the future. Envelope construction may be performed manually on a geographic information system (GIS) platform or through rule-based techniques such as genetic algorithms or general additive modelling (Peterson *et al.*, 2001; Berry *et al.*, 2002; Midgley *et al.*, 2002). Unfortunately, these models currently face numerous limitations, including the inability to model dynamic transitions, the effects of interspecific competition, herbivory, dispersal or other factors (e.g. soil type in some models).

To make the results of species bioclimatic envelope models most applicable to real-world conservation problems they must be coupled with land-use projection models. Land use projection models represent the current pattern of habitat fragmentation and model future patterns based on projections of parameters such as population and consumption levels (Sala *et al.*, 2000). The potential range shift of a species approximated by bioclimatic models is then reduced to the available habitat as projected by the land use model. For example, a species whose potential climate envelope shifts into an area entirely dominated by agriculture or urban development may be faced with extinction.

Integrative and sensitivity analysis based on the ecology of sites and individual species is an essential supplement to modelling, even if it may lack the attractive spatial specificity of models. Models cannot predict species composition at a landscape scale in a dynamic, competitive environment (dynamic vegetation models lack species-specificity, envelope models lack dynamic and competitive elements, 'gap' models lack spatial resolution) (Woodward & Beerling, 1997). Evidence of palaeoecological and palaeobiogeographical responses to climate change form a central element of integrative analysis.

Sensitivity analysis in a site assessment considers possible cooler climates, as well as anthropogenic warming. Palaeoclimatic evidence suggests that global climates may be capable of switching rapidly between states (Broecker, 1997). The possibility of reversal of current warming trends within centuries argues that sound conservation plans should be robust to both warming and possible cooling. An excellent introductory review of climate models, biogeographical models and sensitivity analysis in regional environmental assessment is given by (Sulzman *et al*., 1995).

CONSERVATION CHALLENGES

Palaeoecology, biogeography and emerging recent evidence indicates some of the challenges that will have to be overcome to conserve biodiversity successfully in a changing climate. In order to apply effectively the tools currently available for conservation planning in response to climate change, these disciplines must be considered. Major challenges include species range shifts, changes in abundance, and geographic variation in the magnitude of responses to climate change.

Range shifts are expected to impact many species in a changing climate (Huntley & Webb, 1989). Such shifts have been recorded in many taxa in the past (Graham & Grimm, 1990; Ashworth, 1995; Ponel, 1995; Webb, 1995). Palaeoecological evidence is dominated by individualistic species response to climate change. Current, probably anthropogenic, climate change is leading to similar shifts (Parmesan *et al*., 1999).

Peters & Darling (1985) first pointed out the conservation implications of shifts in species ranges relative to reserve boundaries. Losing some or all of a species-protected range are among the possible consequences. Adding new protected areas to maintain species representation targets is a major tool for addressing this problem (Hannah *et al*., 2002). Management of species within protected areas in reference to and in coordination with other protected areas (and not simply to maintain the site's *status quo*) is another strategic response to this problem.

Changes in abundance and patterns of abundance may occur in the absence of, or in tandem with, range shifts. Extensive pollen core data show shifting relative and absolute abundances of species (Huntley *et al*., 1995). This is most evident in temperate re-colonization after the last glacial maximum, but is well supported in tropical regions as well (Webb, 1995).

Conservation goals aimed at maintaining current population sizes will be challenged by climate-driven changes in abundance. For rare and endangered species, minimum population sizes may remain appropriate targets for genetic and recovery reasons, even where climatic conditions for the species are deteriorating. For site conservation plans, population size within the site may be less relevant than overall population size within the greater region or total population size. Regional coordination of goal-setting is necessary to reach viable targets in these situations.

Changes in ranges and abundance are particularly marked in montane areas. The climate gradients and microclimate variability associated with topography and elevation create a wider range of climate in montane regions, and thus greater opportunities for species to encounter range-limiting climatic conditions. In the tropics, species ranges and abundance may change in montane areas, even when neighbouring lowland taxa show little change (Flenley, 1998).

Early conservation theory suggested that montane zones might shift upward in warming climates (Peters & Darling, 1985; Peters, 1991). Halpin (1997) showed zonal shifts to be more complex — dependent on precipitation as well as temperature and subject to expansion and contraction as well as simple up- or down-slope movement (Halpin, 1997). Tropical montane palaeoecological studies are one of the strongest sources of evidence that species have moved individualistically in the past, suggesting that the concept of zonal movements itself should be called into question and perhaps replaced with a species individualistic view (Bush, 2002).

Fortunately, montane areas have generally proved less attractive for human settlement than lowlands. In many areas, natural habitat in high relief and high slope areas is relatively well preserved in nature reserves, forest reserves or on lands designated for watershed protection. Management of these areas for individualistic species range shifts will help reduce the possible detrimental effects of climate change on biodiversity. However, this pattern does not hold for many of the tropical montane areas in which biodiversity is exceptionally high (e.g. the tropical Andes, parts of New Guinea and Central America). Areas in tropical mid-elevation belts are often in intense agriculture for commodities such as dairy, coffee, tea, flowers and vegetables, and should be the focus of equally intense conservation efforts.

Species associations that have no current analogue are a major feature of palaeoecology (Roy *et al*., 1996). Combinations of plant and animal species have been found in the fossil and pollen records which are not found anywhere in the world today (Stafford *et al*., 1999). The development of these 'nonanalogue communities' has been closely linked to differing climatic conditions (Graham & Grimm, 1990). This suggests that future climate changes may produce new species assemblages with no counterpart in present communities.

Nonanalogue communities pose a problem for strategies based on conserving representative examples of community or vegetation types. If the palette for representation is current communities, many possible nonanalogue communities will be excluded. Because not all nonanalogue communities are known, representing all possible communities is unattainable. The strong evidence that species move individualistically suggests that communities are not discreet entities in most cases, making community 'representation' an impractical target overall.

Because not all species are known, constructing representational systems at the species level is also impossible in a comprehensive way. Conservationists must therefore incorporate uncertainty and surrogates into strategic planning. Among other tools, surrogates such as climate variables can be used in addition to biological variables to increase the likelihood of representation of future nonanalogue communities in a protected areas system (Pressey *et al*., 1997; Cowling, 1999).

The speed of biotic response to past climate change has often been remarkable. Re-colonization following glacial retreat often exceeds expected rates calculated from mean dispersal and growth time to reproductive maturity (King & Herstrom, 1995). Plant and animal species have tracked climate changes occurring on the scale of decades or centuries without major extinctions spasms (Roy *et al*., 1996). Outlier pockets of vegetation have been implicated in these rapid response rates. For example, forests on the South Island of New Zealand dominated the landscape within a few centuries following decline of the last glacial, despite the presence of a water barrier separating the known forest refugia on the North Island (McGlone, 1995). It has been suggested that microrefuges in complex montane relief on the South Island maintained small pockets of forest that subsequently expanded when suitable climatic conditions returned (McGlone, 1995).

Designing conservation responses to rapid range shifts will require additional information on rates and mechanisms of change. The possible importance of outlier pockets of vegetation suggests that protected areas managers should be concerned with managing outlier pockets of minority vegetation types as well as maintaining 'representative' vegetation. Rapid dispersal may also be dependent on rare long-distance dispersal events, so maintaining healthy populations of possible long-distance dispersal agents (such as bats, birds and large mammals) will increase the probability of maintaining natural capacity for range migration.

Extreme and periodic events may play an important role in determining patterns of biodiversity (Connell, 1978). High-intensity storms, El Niño events and droughts are examples. Changing frequency and intensity of these events have been associated with past climate changes (Easterling *et al*., 2000). Rapid temperature transitions in Northern European climate, for instance, are associated with increased dust storm intensity in Asia, indicating both a global signature to climate changes and changes in extreme events associated with variations in temperature (Broecker, 1999). Drought plays a major direct role in shaping species distributions and abundance in tropical forests (Condit, 1998). Drought is also associated with increased fire risk in temperate, mediterranean and tropical systems (Clark, 1990; Simmons & Cowling, 1996; Bond, 1997; Cochrane *et al*., 1999). The frequency of El Niño events may change with climate and create major regional changes in biodiversity through drought, fire and other factors (Trenberth & Hoar, 1997). Other extreme events have important consequences for biodiversity (Parmesan *et al*., 2000).

Conservation responses to changing frequency of extreme and periodic events can be accomplished only through monitoring and adaptive management. Analysis suggesting the possible effects of changes in frequency or intensity on target ecosystems must be gauged against observed patterns of occurrence. Because extreme events may cause a state-shift in some or all of the system, coordination with other protected areas in the region is essential to maintain representation and process targets.

Invasive exotic species may expand in range during climate change, as they are frequently opportunists adapted to a wide range of conditions (Macdonald, 1994). Modelling of invasive plants has shown that some may have expanded climate envelopes in the future, while others may have similar-sized or smaller climate envelopes (Dukes & Mooney, 2001). Substantial evidence supporting the theoretical notion of climate change enhancing success of invaders has not yet accumulated (Dukes & Mooney, 2001). Documenting and monitoring the areal extent of invasive species is an important first conservation step in response to this potential problem. Effective control strategies for invasives have substantial benefits that may be multiplied by climate change.

Finally, changes in phenology and resource asynchrony due to climate change are increasingly well established, but methods for assessing the impact of these changes on species distribution and abundance are largely lacking. Phenological changes have been demonstrated in plants, birds and other taxa in both Europe and North America (Farnsworth, 1995; Fitter *et al*., 1995; Forchhammer *et al*., 1998). Altered competitive interactions or resource asynchrony have been documented due to climate changes over the past 50 years, and greater problems are anticipated in the future (Hughes, 2000; Thomas *et al*., 2001). These effects are perhaps best incorporated into conservation strategies at present through monitoring of associated changes in species' populations.

CLIMATE CHANGE-INTEGRATED CONSERVATION STRATEGIES

Conservation responses to climate change that are anticipatory and systematic have been termed 'Climate Change-integrated Conservation Strategies' (CCS) (Hannah *et al*., 2002). CCS begin with regional modelling, which applies appropriate available assessment tools to provide an overview of possible climate change impacts on biodiversity. Regional modelling concludes with integrative sensitivity analysis based on local ecology. This analysis is used to design specific activities in three key spheres of activity: expansion of protected areas, managing the matrix land use outside of protected areas, and regional coordination of management actions.

Regional modelling

Regional modelling begins with an inventory of the assessment tools that are locally available, affordable and applicable. GCM, biome envelope and GDVM results are available at coarse scales for all areas at little or no cost. Regional climate models and biome envelope models are beyond the capacity of most protected areas to implement, and are best pursued in partnership with academic or private regional modelling efforts. Species envelope modelling may be within the means of protected areas that have a research staff and strong GIS capability. Sensitivity analysis at some level of complexity is possible in all areas. Choice of assessment tools will depend on available research budget, staff, and availability (e.g. for regional climate models) of partners.

The regional modelling phase of CCS development culminates in sensitivity analysis that incorporates as much site- and species-specific information as possible. Integrative sensitivity analysis examines the effects of climate change on individual species, especially rare, threatened and climate-sensitive species, and ecological processes. Processes include disturbance regimes that may impact vegetation dominance (e.g. fire, drought). Habitats that are sensitive to climate change (e.g. wetlands) and montane effects are other important assessment parameters. The result of a site-sensitivity analysis is a narrative exploring possible climate change effects and management options, and may include spatially explicit mapping of possible impacts if biotic response models are used.

Fifty years is the time horizon used in many climate change impact assessments, while a 100-year time horizon would be required to capture more dramatic effects of climate change. A typical temperature transition within a 50-year time horizon would be a 1–2 °C warming under most GCM projections for most areas outside the high northern latitudes. Analysis of the impact of comparable cooling, and positive and negative variation in several other climate variables is considered in sensitivity analysis. Because GCMs disagree on the sign of precipitation change in many areas, sensitivity analysis for both positive and negative change in precipitation-related variables (particularly plant–water balance) is especially important.

Most protected areas systems analysts will need to conduct sensitivity analysis in partnership with specialists in biogeography, ecology and climate change. It is most cost effective to link sensitivity analysis with management planning for protected areas and the land use matrix outside of core reserves (see below). While it is possible to conduct such an assessment for an individual reserve, the use of regional modelling and the necessity of consideration of regional shifts in species ranges suggests that a regional effort will be more cost-effective.

Regional modelling is used in CCS to generate practical conservation strategies. Expanding protected areas management and coverage is the most fundamental step in revising conservation strategy. It must be accompanied by increased management of the matrix of land uses outside of core reserves to accommodate range shifts and other biotic changes. Finally, these conservation responses must be coordinated regionally, to ensure that conservation objectives respond on the scale at which climate change impacts operate.

Expanding protected areas

Protected areas must be supplemented with additional coverage to allow for the effects of climate change, at the same time that management practices are expanded to respond to climate change impacts at individual sites (Hannah *et al*., 2002). For example, species range shifts may require supplemental protected areas to maintain biodiversity representation targets, at the same time that management practices are revised in individual sites to adjust to new population dynamics due to novel climate conditions.

Protected areas system design to accommodate climate change is in its infancy (Cowling, 1999). Conservation managers can employ a few early steps to help set the stage for refinements of siting methods in the future. First, the promotion of the use of rational planning systems to plan reserve systems (as opposed to *ad hoc* additions) is important. Pressey & Cowling (2001) identified four major stages of systematic reserve planning:

1 Identify conservation goals (e.g. at least one occurrence of all species).

2 Review existing conservation areas for contribution to the targets set in (1).

3 Select additional conservation areas.

4 Implement conservation actions.

Adjustments for climate change can be made at each of these four stages. Conservation goals can explicitly include maintaining representation and process (e.g. gene flow) targets in the face of climate change (Cowling, 1999). Species representation goals can be adjusted for range and abundance shifts predicted to take place with climate change (Fig. 2). For example, a systematic reserve plan should have multiple representations of each species as a goal, since single populations, especially small ones, are vulnerable to extinctions due to random events or loss of representation due to species range shifts with climate change (Williams & Araujo, 2000). Regional modelling results can be used to modify the estimate of the contribution of existing areas to conservation goals, based on possible species range shifts, changes in abundance and other factors. Adding protected areas on the fringes of species distributions may help maintain representation, as peripheral range may become increasingly important as climate changes, and recent evidence suggests that areas in the periphery of a species' range may persist longer in the face of human pressures (Channell & Lomolino, 2001). Many protected areas systems currently have no systematic planning process and will be especially vulnerable to climate change impacts.

Refinement of management practices in existing and future protected areas is a necessary complement to supplemental coverage in a CCS. Four elements make up a minimum revision of reserve management:

- scenario-building;
- enhanced monitoring;
- biological survey; and
- review and revision of management practices.

Scenario-building is an iterative process in which modelling is used to refine management and management revisions suggest further areas of enquiry for modelling. Scenarios

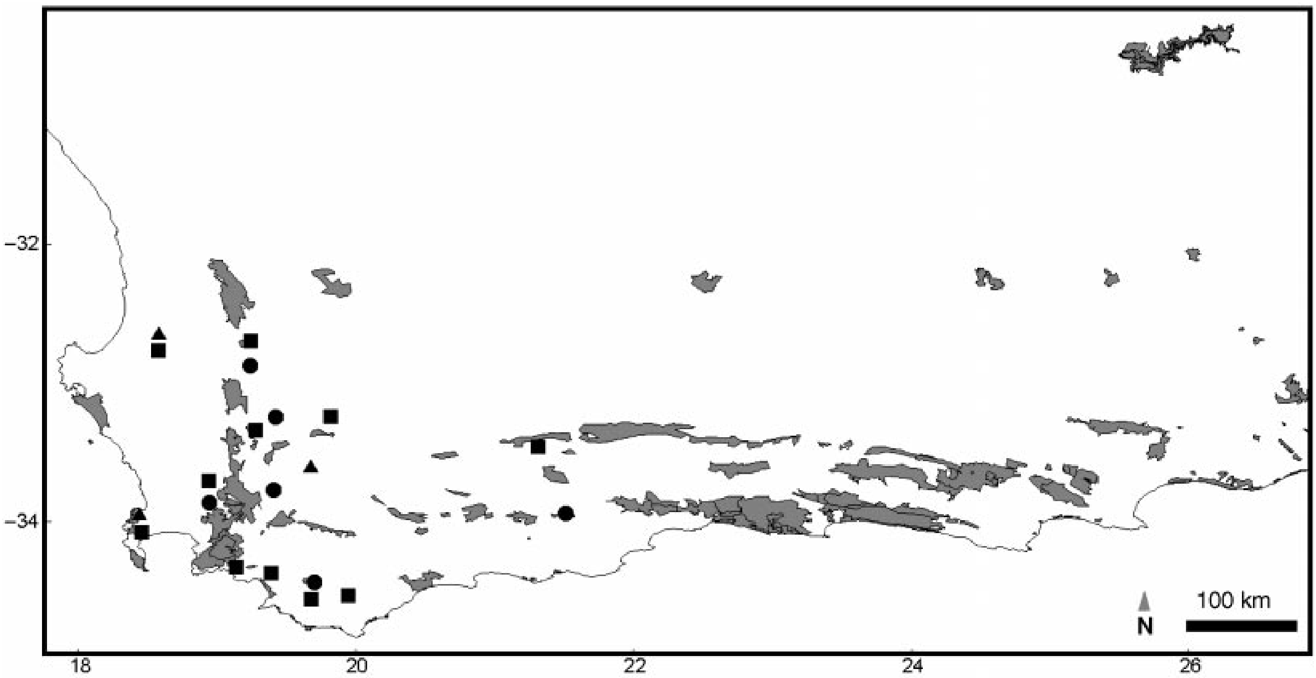

Fig. 2 Gap analysis for 343 species of the Proteaceae in the Cape Floristic Province. The present and future ranges of 343 species in the family Proteaceae were modelled using downscaled GCM projections as described in Midgley *et al.* (2002). Of the species modelled, 217 were found to have overlap between present and future ranges. Existing protected areas (shown in grey) protect these areas of overlap in most cases. Additional protected areas (solid shapes) are needed to protect all 217 species. Squares indicate irreplaceable areas, triangles indicate areas that may be substituted at no cost, and circles represent areas that may be substituted at the cost of adding additional areas. [Analysis and Worldmap figure courtesy of Paul Williams.]

are created that span the range of uncertainty in climate change and biotic response modelling, and that capture important management variables. Monitoring and management are tested repeatedly against the scenarios, and the scenarios themselves are revised repeatedly as more data become available and uncertainties change or decrease.

Scenarios should be created that capture possible major ecological events in the system being conserved. For instance, dynamic vegetation or envelope model results should be examined for biomes or habitats ‘on the edge’ — systems that are near a threshold for conversion to a different growth form, dominant vegetation or disturbance regime. Scenarios should also be constructed for rare, threatened and climate-sensitive species. Rare and threatened species may be vulnerable to further population reductions due to climate change, and these should be considered in management plans for these species. Climate-sensitive species include species with small ranges (even if abundant), species with limited (< 500–1000 m) elevational ranges, and upper elevation species whose habitat may be reduced with warming (Peters, 1991). Finally, scenarios should be constructed that describe the possible impact of climate change on ecosystem processes. Droughts and storms often limit plant functional types or open forest canopies for regeneration. Change in frequency of these events may therefore alter vegetation structure, succession and species diversity and composition.

An expanded monitoring programme is based on the scenarios developed. Testable scenario predictions monitored in the field permit adaptive management responses. Many parameters of enhanced modelling will be biological, including climate-sensitive species and processes. Installation or upgrading of weather data-gathering capability is a physical monitoring step to be considered. Collection of sound weather data has proven important in documenting climate correlates to species range changes, changes in abundance (amphibian decline) and even possible extinctions in the Monteverde cloud forests of Costa Rica (Pounds *et al.*, 1999). Remote sensing and regional modelling may help in the design of a monitoring system that focuses on variables that may be vulnerable to change, for instance lifting cloud bases in tropical montane settings such as Monteverde (Lawton *et al.*, 2001).

Biological survey work can complement monitoring and scenario refinement by providing key data. Detecting individualistic species range-shifts requires data on distribution and abundance generally not available nor previously considered necessary at most protected areas. Survey programmes can help fill this data need and provide baseline data for monitoring. For example, scenarios from modelling may show that a species not known from a reserve may find favourable climatic conditions there in the future (Rutherford *et al*., 1999). Such species may exist in the reserve but have escaped documentation. Survey work can help find outliers of the species or increase confidence that it does not exist in the reserve, information critical to the design of effective management and monitoring systems. Additional distributional data even on common species may be required for effective monitoring. Inexpensive GPS units make park staff on regular patrol or even tourists on remote trails potential data-gathering allies in this effort.

Review and revision of management practices is the final step in an iterative process of revision of management based on modelling, scenarios, monitoring and survey. Modelling results and management scenarios will suggest management practices to be reviewed and revised. Examples of management practices that will often qualify for review are management of fire or other disturbance regimes, classification of 'sensitive' areas, and management for 'representative' species. Management planning time horizons will need to be revised in almost all cases.

Fire and other disturbance regimes are often managed intensively in protected areas. These management practices will interact with climate change effects in ways that may not be apparent without careful monitoring. Fire may maintain certain vegetation types past their climatic optimum, or, if managed uncritically, suppress new vegetation types that are becoming climatically favoured. For example, in Central Canada, long-grass prairie is predicted to be climatically favoured over present forest types in future warmer climates (Scott & Suffling, 2000). Fire suppression may retard this transition. Fire management therefore has an effect that must be judged against regional conservation goals — either maintenance of forest or promotion of grassland in newly suitable climate space.

Sensitive areas form an important part of management in many protected areas. Climate change will introduce a new class of sensitive areas. Climate change-driven changes in range or abundance may render once common species sensitive. Rapid range shifts may make formerly robust systems sensitive. Changes in disturbance regime may create new or recovering vegetation sensitive to many types of use. Nonanalogue communities may arise with unknown sensitivity requiring conservative management until they are more fully understood. Heavy tourist traffic may facilitate the dispersal of invasive species into areas that are vulnerable because they are in transition to new vegetation types. These and other climate change sensitivities should be considered as sensitive areas are designated and managed.

Many protected areas are established or managed to conserve 'representative' ecosystems that may no longer exist in future climates. Minor vegetational elements or even outlier pockets may become dominant vegetation types in the future. Site goals will be difficult to set for changing vegetation without reference to regional trends and conservation goals. In the Central Canada example above, management for 'representative' forest is appropriate if the regional management goal is to retard biotic response to climate change, while promoting fire to stimulate transition to long grass prairie is appropriate if the regional goal is to allow natural transitions to take place while maintaining representation goals. Many other management issues will evolve from systematic modelling and management scenario analyses.

Finally, almost all protected areas management plans have 3–10-year time horizons, which are insufficient to allow for anticipatory management responses to climate change. A minimum appropriate planning time horizon for climate change is 30–50 years, while a 100-year horizon is necessary to capture many possible climate change effects. Incorporating sensitivity analysis and climate change management scenarios into a management plan will require that at least part of the management plan has a longer time horizon.

Management of the matrix

In a CCS, the matrix of land uses surrounding protected areas provides a biophysical framework that both impacts core reserves and maintains biodiversity in transition. For example, biodiversity-friendly land uses such as agroforestry may provide habitat for many species, increasing the chance for persistence when climate change affects populations in reserves. Conversely, the wrong mix of land uses in the matrix can increase light penetration and invasive weed invasion causing a retreating forest edge in reserves (Gascon *et al*., 2000).

The ability of species to exist and traverse the matrix becomes critical as climate change-driven range shifts (Fig. 3) occur. As changing conditions or extreme events alter vegetation in protected areas, the matrix may contain the only available habitat (either spatially or temporally) for some species. Predicting when the matrix would come into play is fraught with uncertainties, so one of the best strategies is to maximize biodiversity-friendly land uses in the matrix, including the option to revert human-orientated land uses to natural habitat.

Conservation managers can prepare for future need for matrix habitat by preparing conservation agreements with landholders outside parks. Options that do not break the soil are especially important, as they improve the possibility of future use of the land for biodiversity management. No-till agriculture, forestry, forest plantations, agroforestry and even low-density housing may be options.

Modelling and sensitivity analysis play key roles in determining probable alignments of climate-related changes in biodiversity. Climate envelope projections can be used to constrain possible agreement priorities, while knowledge of local ecology and biogeography can generate additional priorities and be used to compensate for model limitations. Conceptual tools such as 'corridors' can be used with

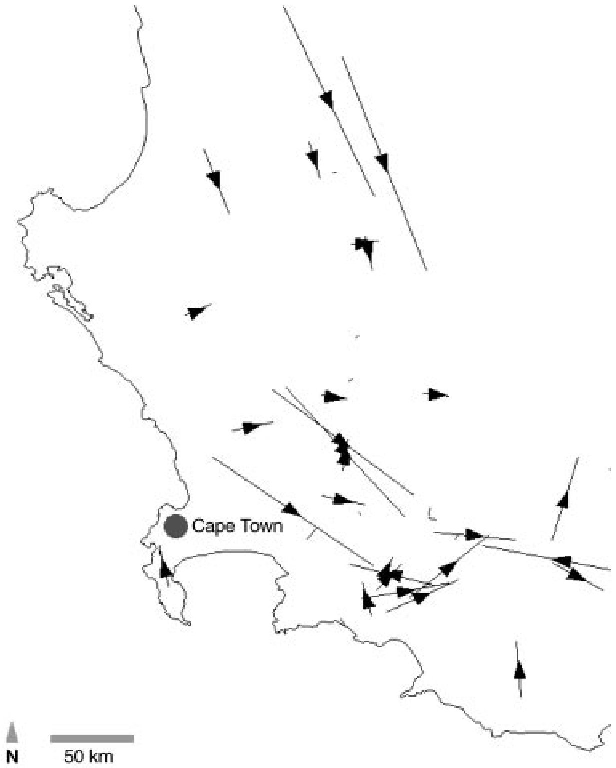

Fig. 3 Movement tracks of species of the genus *Serruria* (Proteaceae) in the Cape Floristic Province. Using the modelling techniques described in Midgley *et al.* (2002), centroids of present and future (2050) distribution for each species were connected to produce movement vectors. This technique helps in the visualization of range shifts in multiple species as landscape linkages are designed.

landowners and the public to promote the need to align matrix management with expected future climate change and other habitat connectivity values (Noss & Harris, 1986).

Part of matrix conservation agreements may include rights to future use for biodiversity management. In this way, a species experiencing a range shift out of a protected area might be conserved by invoking a conservation futures agreement that allows matrix land use to be converted to conservation. Landowners may favour such agreements, as they would represent additional income (for the futures right) against a limited chance of climate change.

Joint planning may work as effectively as formal contracts in some settings. For instance, in the Cape wine-growing region of South Africa, conservation organizations will use GIS to help vineyards plan future plantings while maximizing conservation. Because vines take years to mature, planning horizons for vineyards are on the order of decades, making them good partners for planning with climate change. The quality of their product is intimately linked to climatic conditions as well. Analysis of future consumer demand and possible climate changes will help identify directions (e.g. upslope) and scale of new plantings required, while GIS will be used to identify suitable areas for planting while conserving or restoring natural habitat.

Matrix management and options for land use conversion to conservation in an uncertain future are key elements of a CCS that are little developed in current practice. As CCS development progresses in different regions, lessons learned will permit expansion of the integration of climate change concerns into matrix management.

Regional coordination

Species range-shifts, impacts of extreme events and resource asynchronies often occur on regional scales, so an effective CCS includes mechanisms for coordinating conservation actions at the regional level across political boundaries and agency jurisdictions. Regional coordination is necessary for conservation goals and management to be coherent on the same scale at which climate change impacts will operate. Examples above show that managing for 'representative' vegetation is a relative term at the site level when climate is changing. Regional goals for representation can be maintained in a dynamic climate only when management at multiple protected areas is harmonized (Rutherford *et al.*, 1999). This coordinated management may require formal agreements, for instance when national boundaries are crossed, or may simply involve appropriate planning within existing protected areas systems and conservation agencies.

Modelling and monitoring will often be more effective when coordinated within a region. Monitoring must be undertaken in a way that is relevant to management goals, so regional goals require regionally coordinated monitoring. Sharing technical and financial inputs for modelling across multiple users on a regional basis increases cost-effectiveness as well.

Regional coordination will become increasingly important as climate change progresses. In the short term, identifying and establishing these collaborations is a priority. Peace Parks initiatives and other collaborative management efforts are already paving the way for these systems.

FUNDING AND IMPLEMENTATION

Creation of a CCS requires synergy among a novel set of actors and funding sources. Conservation managers, biogeographers, ecologists and climate change scientists are all needed to formulate an effective CCS. Funding from research sources will be required for modelling and assessment activities with clear connections to applied conservation. Conservation agencies will need to source funding for major new investments in monitoring and revision of management practices. Creation of this synergy will carry a cost, and responding to the new challenges of climate change to the conservation of biodiversity will require major new financial commitments.

In a world filled with conservation challenges, managers will not be able to undertake all the elements of climate change-integrated conservation strategies described here in the short term. What is important is that managers, biogeographers and ecologists begin to consider the impacts of climate change in their area, and adopt at least some elements of a CCS, progressively building capacity at the local level as the challenges posed by climate change mount.

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