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Special Section

Matching the Multiple Scales of Conservation with the Multiple Scales of Climate Change

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Abstract: *To anticipate the rapidly changing world resulting from global climate change, the projections of climate models must be incorporated into conservation. This requires that the scales of conservation be aligned with the scales of climate-change projections. We considered how conservation has incorporated spatial scale into protecting biodiversity, how the projections of climate-change models vary with scale, and how the two do or do not align. Conservation planners use information about past and current ecological conditions at multiple scales to identify conservation targets and threats and guide conservation actions. Projections of climate change are also made at multiple scales, from global and regional circulation models to projections downscaled to local scales. These downscaled projections carry with them the uncertainties associated with the broad-scale models from which they are derived; thus, their high resolution may be more apparent than real. Conservation at regional or global scales is about establishing priorities and influencing policy. At these scales, the coarseness and uncertainties of global and regional climate models may be less important than what they reveal about possible futures. At the ecoregional scale, the uncertainties associated with downscaling climate models become more critical because the distributions of conservation targets on which plans are founded may shift under future climates. At a local scale, variations in topography and land cover influence local climate, often overriding the projections of broad-scale climate models and increasing uncertainty. Despite the uncertainties, ecologists and conservationists must work with climate-change modelers to focus on the most likely projections. The future will be different from the past and full of surprises; judicious use of model projections at appropriate scales may help us prepare.*

Keywords: climate models, climate change, conservation planning, downscaling, scale, short-grass prairie, the nature conservancy

Adecuación de las Múltiples Escalas de Conservación con las Múltiples Escalas de Cambio Climático

Resumen: *Para anticipar el mundo rápidamente cambiante como resultado del cambio climático global, se deben incorporar modelos climáticos a la conservación. Esto requiere que las escalas de conservación sean alineadas con las escalas de proyecciones de cambio climático. Consideramos la forma en que la conservación ha incorporado la escala espacial en la protección de la biodiversidad, cómo varían con la escala las proyecciones de los modelos de cambio climático y cómo se alinean o no las dos. Los planificadores de la conservación utilizan la información sobre condiciones ecológicas pasadas y presentes en múltiples escalas para identificar amenazas y objetivos de conservación y orientar acciones de conservación. Las proyecciones de cambio climático también se hacen en múltiples escalas, desde modelos de circulación global y regional hasta proyecciones a escalas locales. Estas reducción en la escala de las proyecciones conlleva las incertidumbres asociadas con los modelos de escala amplia de donde se derivan; por lo tanto, su alta resolución puede ser más aparente que real. La conservación en escalas regionales o globales trata de establecer prioridades e influir en las políticas. En estas escalas, la granulosidad y las incertidumbres de los modelos climáticos globales y regionales pueden ser menos importantes que sus revelaciones sobre los futuros posibles. En la*

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escala ecoregional, las incertidumbres asociadas con la reducción de escala se vuelven más críticas porque las distribuciones de los objetivos de conservación, para los que están hechos los planes, pueden cambiar bajo climas futuros. En la escala local, las variaciones en la topografía y cobertura de suelo influyen en el clima local, lo cual a menudo invalida los modelos climáticos de mayor escala e incrementa la incertidumbre. A pesar de las incertidumbres, los ecólogos y conservacionistas deben trabajar con modeladores de cambio climático para concentrarse en las proyecciones más probables. El futuro será diferente del pasado y estará lleno de sorpresas; el uso juicioso de las proyecciones de modelos en escalas apropiadas puede ayudar a prepararnos.

Palabras Clave: cambio climático, escala, modelos climáticos, planificación de la conservación, praderas, reducción de escala, the nature conservancy

Introduction

During the past decade, global climate change has moved from the realm of theory and models to reality. Plants in England and North America are flowering earlier (Beaubien & Freeland 2000), coastal wetland marshes are suffering saltwater intrusion as sea levels creep upward (Gitay et al. 2001), migrant birds are arriving at breeding areas earlier (Both et al. 2006), tree zones are moving higher on mountainsides (Baker & Moseley 2007), and forest wildfires have increased in frequency and extent (Westerling et al. 2006). Unprecedented outbreaks of mountain pine beetles (*Dendroctonus ponderosae*) in western Canada have been associated with warmer winters at higher latitudes (Logan & Powell 2001; Carroll et al. 2004).

Projections of climate change over the coming decades portend even more dramatic impacts on biological systems. Ranges of some species may contract while others may expand (e.g., Iverson & Prasad 1998; Lawler et al. 2009; Wiens et al. 2009), causing massive community turnover and producing novel interactions between predators and prey, pathogens and hosts, and diseases and vectors. Habitat changes may threaten an increasing number of species with extinction (Thomas et al. 2004; Araújo et al. 2005*a*; Sekercioglu et al. 2008), whereas the spread of opportunistic and invasive species may be enhanced (Sutherst 2000). These changes may have cascading effects on the capacity of native ecosystems to provide the ecosystem services valued by people (e.g., Foley et al. 2007). The assumption that conservationists and resource managers can assess environmental variation by looking to the past (e.g., "historic range of variation" or "stationarity;" Milly et al. 2008) may not equip them to deal with a future that might be very different (e.g., Williams & Jackson 2007; Ruhl 2008; Seastedt et al. 2008). But ignoring the future, even with all its uncertainties, is not an option. Climate change must be integrated into conservation planning and management.

Part of the challenge in doing so is related to the issue of scale. Ecologists have written much about the scale-dependency of ecological patterns and processes (e.g., Wiens 1989; Root & Schneider 1993; Peterson & Parker 1998). Climate change also operates differently and has different effects at different scales. The process of climate change is driven chiefly by dynamics at global and continental scales, but its effects cascade to alter climate and weather at regional to local scales. The impacts on biological systems may ramify across the full range of spatial scales, but in quite different ways at different scales.

Here, we seek to initiate a discussion about meshing the scales of climate change and its environmental effects with the scales of impacts on and responses of biodiversity. We do this by considering how conservation has incorporated spatial scale into protecting biodiversity, how the projections (and the uncertainties) of climate-change models and analyses vary with scale, and how the two do or do not align.

Scaling Conservation

Conservation actions, particularly those focused on protecting habitats or managing species at risk of extinction, are usually carried out at local scales of a few hectares or km^2. At a regional scale, attempts have been made to link protected areas together in conservation networks (e.g., the U.S. National Wildlife Refuge System; Scott et al. 2004). On the other hand, conservation policies, such as the U.S. Endangered Species Act, CITES, or the Convention on Biological Diversity (CBD), are often developed at national, multinational, or global scales.

Conservation organizations have addressed these multiple scales through various conservation-planning or priority-setting approaches (Groves 2003). At a global scale, the emphasis is on the preservation of biodiversity writ large. For example, Conservation International (CI) has identified 34 hotspots of biodiversity (http://biodiversityhotspots.org), the World Wildlife Fund (WWF) has targeted a "Global 200" set of areas for conservation (http://wwf.panda.org/about_wwf/), and Birdlife International (BI) has identified over 7500 important bird areas for conservation throughout the world (http://www.birdlife.org). These and other prioritization approaches emphasize the irreplaceability (e.g., endemism) or vulnerability (e.g., rate of habitat loss) of components of biodiversity (Brooks et al. 2006). Because of differences in objectives and in the information used to establish priorities, different regions are given high conservation priority by the different approaches. For example, the prioritizations of CI and BI emphasize tropical and subtropical regions, whereas that of WWF includes temperate and high-latitude regions as well.

At the opposite end of the scale spectrum, local conservation often focuses on particular species of concern, especially those with restricted ranges or rare or declining populations. At this scale, conservation usually involves protection of areas that contain essential habitat (e.g., nature preserves, state parks) or agreements that restrict land uses (e.g., conservation easements). Although biological criteria may be important in targeting such areas for conservation, which places are actually protected is often determined by the opportunity to purchase property or establish a conservation easement. The objectives and scales of conservation prioritization and protection vary widely.

The conservation-planning process developed by The Nature Conservancy (TNC) illustrates the linkage of conservation efforts across a hierarchy of spatial scales. At the global scale, the 867 terrestrial ecoregions of the world (Olson et al. 2001) are stratified into major habitat types—groupings of ecoregions that share similar environmental conditions, habitat structure, and patterns of biological complexity. "Boreal forests/taiga" or "temperate grasslands, savannas, and shrublands" are examples (Fig. 1a). The major habitat types are in turn partitioned by biogeographic realms (e.g., Nearctic, Australasia). This stratification helps ensure broad representation of the Earth's biodiversity. Within this framework, information on species' richness and endemism, habitat loss, risks of future biodiversity loss, potential vulnerability to altered fire regimes or climate change, human economic or social conditions, and the like can be used to assess the overall conservation potential of ecoregions. For example, Hoekstra et al. (2005) used information on global land cover and protected-area networks to identify "crisis ecoregions" in which the disparity between habitat conversion (loss) and habitat under some form of conservation protection is great. Temperate grasslands, savannas, and shrublands and Mediterranean forests, woodlands, and scrub emerge as the major habitat types with the highest ratios of habitat conversion to protection, Boreal forests/taiga and Tundra the lowest. On the basis of this criterion, conservation efforts globally might best be focused on the former major habitat types.

Because ecoregions are defined by a combination of environmental and biological characteristics (Bailey et al. 1994), they provide a useful framework for conservation planning at a continental or regional scale. The process of ecoregional planning developed by TNC involves drawing together information on the distribution and conservation status of species, community types, and ecosystems in an ecoregion from an array of sources in an iterative reserve-selection process (e.g., SITES, MARXAN; Margules & Pressey 2000) to identify a set of conservation areas within the ecoregion that are thought collectively to represent the biodiversity and its spatial distribution for the ecoregion as a whole (Groves 2003). The process therefore emphasizes complementarity among the conservation areas (Margules & Pressey 2000).

The plan for the Central short-grass prairie ecoregion in the United States provides an example from the Nearctic temperate grassland/savanna/shrubland major habitat type. This ecoregion encompasses roughly 22.5 million ha in the western Great Plains. Grazing of domestic livestock dominates land use in much of the ecoregion, and the resulting land stewardship has left perhaps half of the ecoregion in a relatively natural state. The opportunities for conservation are therefore great, but can be realized only by establishing partnerships with the stakeholders who make their living off of the land, especially ranchers.

The ecoregional assessment for the Central short-grass prairie (Neely et al. 2006) identified a large number of conservation targets—features of biodiversity that warrant specific conservation attention (e.g., Mountain Plover, *Charadrius montanus*; sandhill goosefoot, *Chenopodium cycloids*; plains cottonwood riparian forest). Multiple sources of information were used to evaluate the current status of these targets and to estimate their importance to maintaining biodiversity in the region. That information was then used to identify conservation areas that would meet the conservation goals for as many of the targets as possible across the ecoregion as a whole with the lowest cost. This process resulted in the identification of 43 terrestrial conservation areas (Fig. 1b) over some 9.7 million ha (44% of the ecoregion) that would meet the goals for approximately 83% of the targeted ecological features. Ecoregional plans also identify general threats to biodiversity for the ecoregion as a whole. Within the Central short-grass prairie ecoregion, habitat conversion and degradation associated with housing and urban development, suppression of range fires, conversion of grasslands to agriculture, and incompatible grazing practices pose the greatest threats to the long-term integrity of the ecoregional conservation targets.

The conservation areas derived from an ecoregional plan identify places for action. The determination of what sorts of actions are needed to achieve conservation results within an area is guided by conservation action plans (Groves et al. 2002), which identify conservation targets for the area, the factors that threaten the long-term persistence of these targets, and the sources of those threats. This information is then used to develop conservation actions to enhance the viability of the targets or abate the threats. For example, conservation targets for the 199,395-ha Republican River Sand Hills Conservation Area within the Central short-grass prairie ecoregion (Fig. 1c) include several species of birds, amphibians, insects, and plants, and five plant communities, four terrestrial ecological systems, and one aquatic system. The underlying assumption of conservation action plans is that by focusing conservation efforts on a subset of targets that characterize the specific area, the overall biodiversity of the area and its contribution to the maintenance of biodiversity over the entire ecoregion will be maintained or enhanced. In some cases this will be accomplished by direct actions aimed at fostering the targets. In other cases, the conservation actions will be focused on reducing the major threats that occur within the conservation area, such as oil and gas drilling or conversion to cropland for the Republican River Sand Hills.

Multiscaled, hierarchical conservation planning enables prioritization of the places with the greatest conservation need where the most can be accomplished most efficiently. In such planning schemes, conservation efforts are applied strategically rather than opportunistically so that the results of local conservation actions can be used to assess progress toward reaching conservation objectives at broader scales (Parrish et al. 2003; Tear et al. 2005). The hierarchical nesting of conservation plans at multiple scales, for example, should allow one to assess how the conservation actions taken at the Republican River Sand Hills area help meet the specific goals for restoring or maintaining biodiversity in that area as well as the broader objectives for the Central short-grass prairie ecoregion and Nearctic Temperate Grasslands.

Scaling Climate-Change Models

Conservation planning uses information on past and current distributions and the status of species and ecological systems to establish priorities for current actions. Analyses of climate change, on the other hand, rely on models to project future conditions. The reliability of model projections varies with the scale at which they are used.

General circulation models (GCMs) were originally designed to simulate climate and ocean patterns and to provide projections of future trends at a global scale. Such models describe the world as three-dimensional grids with a horizontal resolution of 250–600 km, 10–20 vertical layers in the atmosphere, and up to 30 layers in the oceans. Many physical processes such as cloud formation occur at finer scales, however, and cannot be simulated properly in a GCM. Instead, physical properties are averaged to run at the global scale. Other sources of uncertainties in GCM simulations relate to feedbacks between the land surface and the atmosphere that involve water vapor and warming (Solomon et al. 2007), aerosols–cloud interactions (e.g., Spichtinger & Cziczo 2008), clouds and radiation (Soden & Held 2006), ocean circulation, and ice and snow albedo (Solomon et al. 2007). Because modeling teams represent these processes and feedbacks in various ways, different GCMs may project different responses to the same level of greenhouse gas emissions. Thus, for example, different models may project different patterns of future precipitation, ranging from very dry to very wet for the same region. Moreover, GCMs assume homogeneous elevation and cover for each pixel. Along coastlines, for example, coarse-scale projections assume either 100% land or 100% water configurations within a given pixel, which misrepresents the complexity of coastal and island areas and their climatic patterns. In the Pacific Northwest, GCMs do not simulate the Cascade snowpack, orographic precipitation along the Cascades, or the turning of winds along the coast, although they do simulate the global circulation patterns that drive these features (E. Salathé, personal communication).

To make the scales of the climate projections of GCMs relevant to multiple constituencies and to mobilize local policy makers to reduce future emissions, future global climate projections have been downscaled to national and regional scales (e.g., Wang et al. 2006) as inputs into models that project environmental impacts. Downscaling methods quickly evolved from simple interpolations to statistical methods (statistical downscaling) to better capture sub-grid-cell heterogeneity (Wilby et al. 1998). Regional climate is represented through a fine-grain, detrended, historical climate baseline consisting of interpolations of weather-station climate records that take into account local topography and climate anomalies calculated as the change from historical to future conditions in large-scale GCM projections (Neilson & Drapek 1998; Daly et al. 2000). Statistical downscaling uses various statistical methods (such as kriging or anuspline) that have been trained to empirical data to incorporate greater spatial variability into climate-change scenarios. Although these downscaling methods continue to be widely used for simulating climate-change impacts (Solomon et al. 2007), they have inherent weaknesses (Daly et al. 2007).

An alternative approach, "dynamic downscaling," uses a nesting approach and regional climate models (RCMs) (Hay & Clark 2003; Spak et al. 2007; Fowler et al. 2007) to simulate local conditions. An RCM takes the broad-scale circulation simulated by a GCM and simulates regional weather and climate patterns consistent with the broad-scale patterns at a finer resolution (e.g., 10–50 km) than GCMs with a more realistic representation of land cover (Wang et al. 2004). In addition to representing the average regional climate, RCMs can also simulate realistic variability at fine scales (e.g., climate variability associated with El Niño Southern Oscillation around the Cascade and Sierra Nevada mountains; Leung et al. 2003). Although RCMs yield greater spatial detail about climate, they are constrained at their boundaries by the coarse-scale output from a GCM and cannot correct for errors in the GCM. There may also be inconsistencies between the GCM and the derived RCM in representing how fine-scale processes affect local climate or the

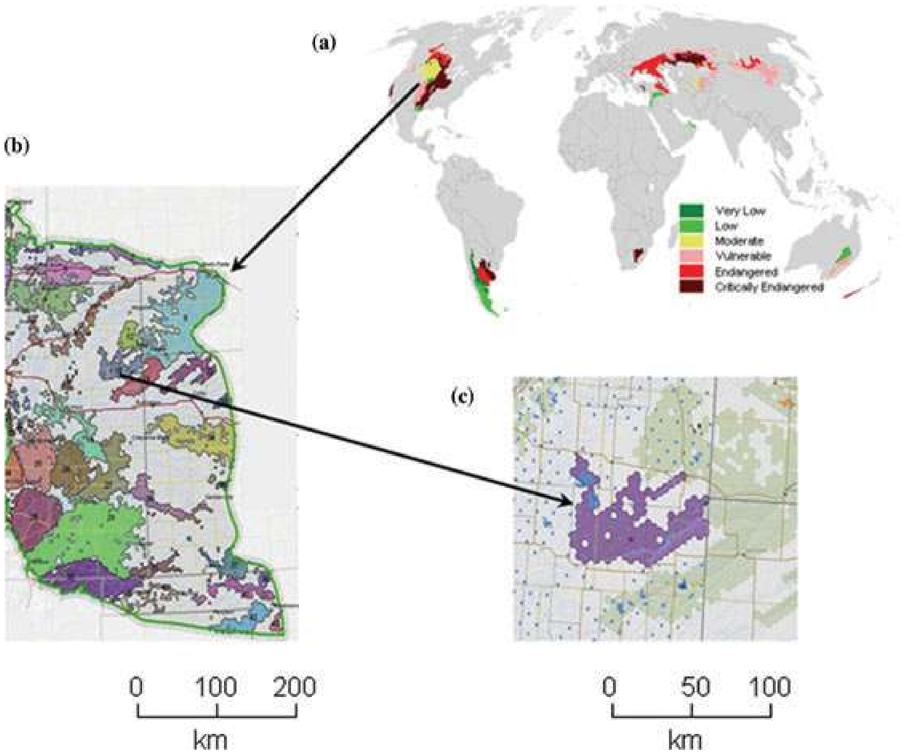

Figure 1. (a) Temperate grassland, savanna, and shrubland ecoregions of the world categorized by the amount of habitat conversion and the ratio of conversion to area under conservation protection (from Hoekstra et al. 2005). (b) The 43 terrestrial conservation areas of the Central short-grass prairie ecoregion identified by the ecoregional assessment process, and (c) 1 of the 43 areas, the Republican River Sand Hills Conservation Area in eastern Colorado. The irregular boundaries of the conservation areas reflect the hexagonal units used in the planning process.

coupling between the atmosphere and the ocean-land surface. Because there are errors, computational limitations, and biases introduced with each downscaling step, the modeling becomes more complex (and potentially more uncertain) as the scale becomes finer.

Complex topography, such as that in the mountainous areas of the western United States, creates an additional challenge. Deep valleys with narrow riparian corridors and tall summits often generate their own local climate conditions (Fig. 2). Such differences in local climate can translate into a greater demand for water by vegetation subjected to greater radiation at high elevations, ultimately reducing stream flow downstream. Lower in the valley, cloud layers, cold-air drainage, and thermal inversions may maintain cool temperatures and moist conditions along riparian corridors, possibly mitigating the

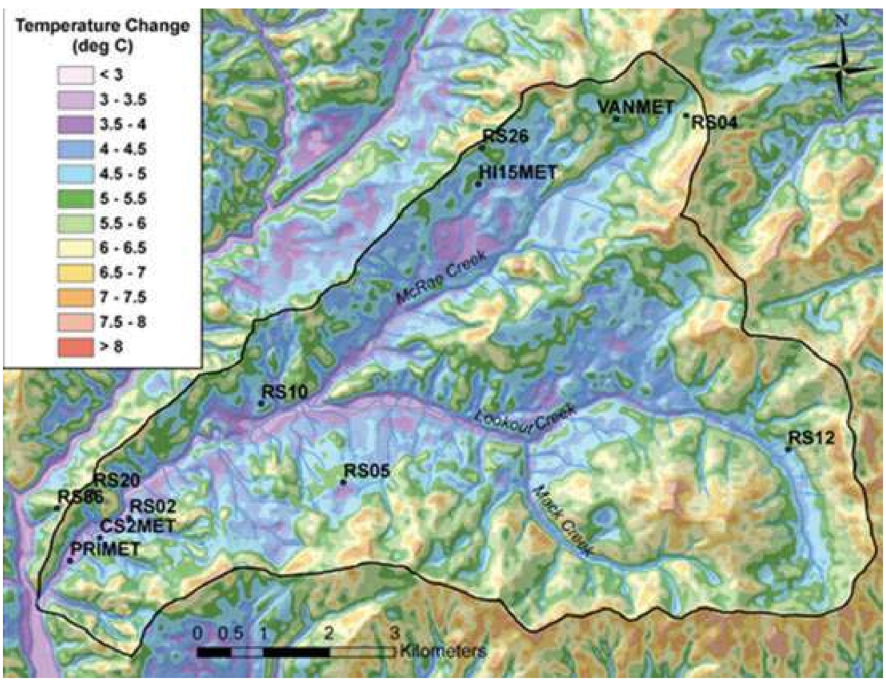

Figure 2. Complex topography and implications for climate change projections in the H.J. Andrews Experimental Forest, Oregon. The contours show projected change in January maximum temperature, under a model of +2.5 °C regional change in temperature and a +10 anticyclone-cyclone change. Points with alphanumeric codes show locations of meteorological stations. Source: Chris Daly, Oregon State University (unpublished).

increased water loss at mid-elevations. These differential effects of climate change due to complex terrain are not simulated by climate models (Daly et al. 2007).

Models are often chosen when their simulations of past climate compare well with observations, but care is needed when comparing downscaled data with point observations. There are several reasons why "scaling up" observed data to the same resolution as the GCM grid through the use of expert judgment is usually a more robust and defensible procedure than interpolating coarse-resolution data to a finer grid. First, the size of a region to be considered affects the evaluation of the performance of GCMs. For example, regions smaller than the GCM grid scale are less likely to be well described by downscaled GCM output than are large regions that include several grid cells.

Second, the characteristics of a region affect the perceived performance of GCMs. In less heterogeneous areas where boundary conditions are infrequent, such as the Great Plains, statistical downscaling may work well, but where topography or other boundary conditions are more complex, as in the Rocky Mountains, dynamic downscaling is necessary and the climate projections will still be less reliable than in more homogenous terrain. Even in topographically diverse regions, sensitivity to small changes in climate may differ. In the mountains of the Pacific Northwest and southern Sierras, for example, much of the snowpack occurs near the boundary of freezing winter temperatures, so a slight increase in temperature may have a huge effect on snowmelt and runoff. In the mountains of Colorado, on the other hand, most of the snowpack area is at higher elevations well above the freezing level, so the impact of a similar change in temperature will be much less.

Finally, the relative performance of the climate models that are downscaled depends on the variables that are simulated. The key climate variables almost always include temperature and precipitation, although the specific aspects of these variables that are important (e.g., annual minimum or maximum temperature, daily vs weekly precipitation) are likely to differ among regions. Regional precipitation is generally more variable and more difficult to model than regional temperature (Fig. 3). Moreover, most scenarios indicate that precipitation variability may change in the future, with more-extreme rainfall events but also more-frequent or severe drought periods. In the Great Plains, extensive droughts and localized extreme rain or hail events have occurred in the past, which suggests the probabilities of such fine-scale events should be included in future projections. Because the frequency and intensity of such events may change in the future, however, a model that best simulates the past or present will not necessarily provide the most reliable projections of the future. Practitioners who use simulated future scenarios should also discuss the probabilities associated with these extreme events and include in the analyses a range of likely future changes in their frequencies and intensities.

Selection of an appropriate spatial scale for model analyses is critical to evaluating the reliability of future projections and their applicability to particular conservation or management needs. Yet temporal scale should not be neglected. Assessments based on 10-year averages of precipitation or temperature, for example, may include such large climatic variability that it is difficult to separate the climate-change signal from background noise. Consequently, Solomon et al. (2007) recommend use of at least a 30-year average GCM output to dampen the effects of interdecadal variability. Conservation strategies should be designed for a temporal horizon that corresponds with the temporal scales of the projections used to determine the likely impacts of climate change.

Alignment of the Scales of Climate-Change Models and Conservation

Conservation at regional, national, or global scales is largely about establishing priorities and influencing policies that will advance these priorities. At these scales, the coarseness and uncertainties associated with GCMs and RCMs may be less important than what they say about possible futures. For example, much of the Great Plains is currently experiencing pervasive drought conditions (Cook et al. 2004, 2007). The most recent projections of future climate indicate that temperatures in the Great Plains will continue to increase (Fig. 3a). Nevertheless, future trends in precipitation are quite variable and model-dependent (Fig. 3b). The uncertainty arises from differences among climate models and from large differences in the expected rate of future anthropogenic CO_2 emissions, which depend on social and political decisions.

It is likely that the northern Great Plains will become hotter, which will increase evaporation rates and result in drier conditions. It is also likely there will be more extreme weather events, such as longer and more-intense droughts that could lead to new Dust Bowls or more intense rain events that increase the potential for erosion. Projected vegetation shifts such as the expansion of eastern deciduous forests westward and the increase in woody life forms in the Great Plains depend on the effect of increased atmospheric CO_2 concentration that would enhance the water-use capacity of trees, which could mitigate drought stress. Unlike grasses, deeper-rooted trees under drought conditions would also depend for their survival on the persistence of the deep aquifer, which would be even more severely taxed by human activities in the region as rainfall becomes scarce.

Because the Great Plains have a fairly homogenous terrain, downscaling techniques should work well or may not be needed. Consequently, climate models can be used effectively to illustrate the climate vulnerability of the area and the likely shifts in vegetation and habitat suitability due, for example, to the reduction in water resources. With this information, managers can focus on reducing water losses by maintaining soil-surface integrity to ensure resilience during Dust Bowl-like droughts; protecting riparian corridors to keep stream temperatures low and reduce evaporation; limiting the use of deep-rooted exotics; protecting drought-adapted ecosystems, such as natural grasslands, to reduce erosion from heavy rainfall events; reducing unsustainable use of water; and supporting legislation to reduce irrigation, well-drilling, and urban and industrial expansion (Brikowski 2008). In this situation, broad-scale climate-change projections may suffice to indicate how warming and restricted water availability might alter the conservation priority of an area.

At the scale of ecoregional planning, however, the uncertainties associated with downscaling GCMs or RCMs can become important, especially in complex terrain. Ecoregional plans consider variations within an ecoregion in the distributions of targeted species, plant communities, and ecological systems in order to identify areas that complement one another in their contributions to ecoregional biodiversity. To be useful, climate-change projections should correspond at least roughly to the scales of the biological data. The level of resolution of GCMs and RCMs is generally coarser (e.g., 50 × 50 km pixels). Downscaling may produce projections that more closely match the scales used in ecoregional planning, but such projections may produce a false sense of security unless one acknowledges the compounding uncertainties as downscaling proceeds to finer and finer scales. Of course, there are also uncertainties in the distributional data on which ecoregional plans are based. In some cases, assessments are based on generalized range maps that may be decades old, whereas in other situations the occurrences of taxa are based on interpolations from widely scattered observations.

Climate change may have other, more complex effects on how conservationists plan at the ecoregional scale. The distributions of many species may be altered as they respond to local and regional climate changes (Lawler et al. 2009; Wiens et al. 2009). At some point, the compositional criteria used to define ecoregions and ecoregional boundaries may become blurred. Dealing with such distributional shifts adds another layer of uncertainty to that contained in the climate models. So-called bioclimatic envelope or species-distribution models have been used to describe potential distributional shifts of species (Thuiller 2004; Araújo et al. 2005*b*; Lawler et al. 2009). Modeling the potential future distribution of a species on the basis of its present distribution assumes that current conditions experienced by a species correspond to its optimal (fundamental) niche. Nevertheless, the realized niche (which is what one observes) is almost always fraught with uncertainties associated with, for example, present or past competition, disturbances, human land use, and dispersal barriers (Wiens et al. 2009). Conservationists might do well to focus on ecosystem functions that should be maintained even if species assemblages change, rather than (or as well as) considering the impacts of climate change on individual species.

Matching the scales of climate-change projections to the scales of conservation and management may be more problematic in some regions than in others. For example, evaluating the potential impacts of climate change on wetlands, as in the Prairie Pothole Region of North America, may be especially challenging. Such wetlands may change dramatically in response to annual variations in precipitation and temperature. Their seasonality supports a rich food web that is essential to migratory birds. Because wetland locations are often determined by local topography and soil type, they are not represented easily in dynamic global vegetation models (DGVMs) that use downscaled climate and regional soil type with biogeography rules to identify the locations of plant functional types. This is why global models have mostly ignored wet-soil processes and methane production and release. Similarly, riparian habitats are often natural corridors for species migration and refugia for heat-intolerant species, yet they are not simulated in DGVMs. For conservationists working on landscapes where rivers and streams are major features, future climate projections should be used primarily to focus on water flow in the rivers rather than on how rivers affect the surrounding vegetation and associated fauna. This means it will be essential to incorporate the outputs of landscape-scale hydrological models into projections of future climate-change impacts. Such efforts should aim to link hydrological models with global vegetation models, including climate-driven vegetation shifts that may act to modify water dynamics.

In coastal zones the situation may be simpler because the most apparent effects of climate change may be through sea-level rise. Projections of sea-level rise under different climate-change scenarios are increasingly used to assess potential impacts on coastal ecosystems and protected areas (e.g., Fig. 4; Poulter & Halpin 2008). There may be substantial differences, however, between global projections of sea-level rise and the rise that is projected to occur on particular coastlines given local subsidence (e.g., parts of Florida and Louisiana) or uplift due to regional tectonics (e.g., Vancouver Island). Coastal zones are complex ecosystems that are affected by storms that can erode their boundaries, bring new sedimentation patterns, or change the nutrient status of coastal water through upwelling or shifts in currents. Estuaries are affected by these factors and by river discharge, which integrates environmental conditions over the entire watershed. The combination of changes in river discharge with sea-level rise may create complex patterns of

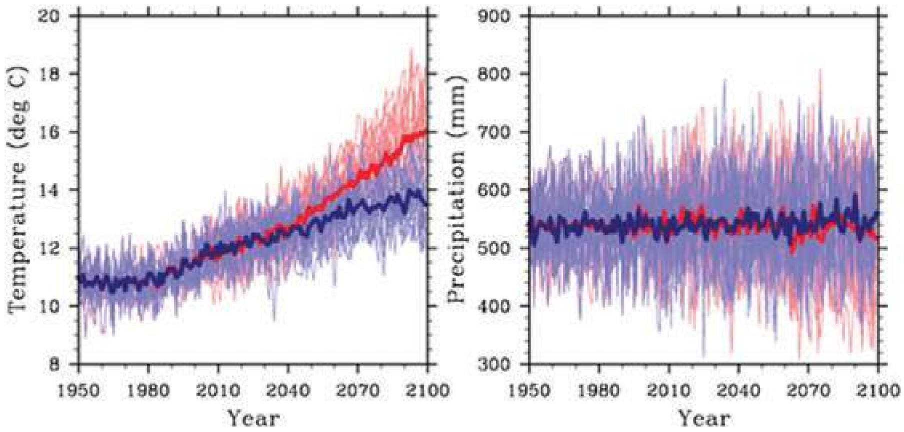

Figure 3. Projections of historic and future (a) temperature and (b) precipitation for the Great Plains from 16 atmosphere–ocean general circulation models and the ensemble mean value (thick lines) under two emission scenarios (A2, high emissions, in red; B1, low emissions, in blue). Data were obtained from CMIP3 multimodel data set, stored and served at the Lawrence Livermore National Laboratory Green Data Oasis. Analysis by Barry Baker, The Nature Conservancy (unpublished).

salinity changes in estuarine ecosystems. The effects of climate change are therefore much more complicated than a simple rise in sea level (Caldwell & Segall 2007). In the Albemarle Peninsula of North Carolina, for example, the effects of sea-level rise are exacerbated by the loss of coastal peat due to salt-water intrusion and the attendant subsidence of shoreline (Fig. 4) (Pearsall & Poulter 2005). In the delta of the Sacramento and San Joaquin rivers in California, agricultural land use has diminished soil carbon content and contributed to the sinking of islands below sea level, rendering the area vulnerable to storm surges and sea-level rise.

Incorporating the effects of climate change may not be possible or appropriate at all scales, however. At very local scales, the projections of downscaled models may contain so much uncertainty as to render them useless, particularly in varied terrain or where special circumstances determine conservation priorities. For example, local conservation often emphasizes small preserves with unique characteristics (e.g., serpentine soils, occurrences of rare or endemic species; Wiens et al. 2008). Because local conditions drive the uniqueness of such preserves, regional climate projections may be irrelevant. Climate may not be the limiting factor if soils

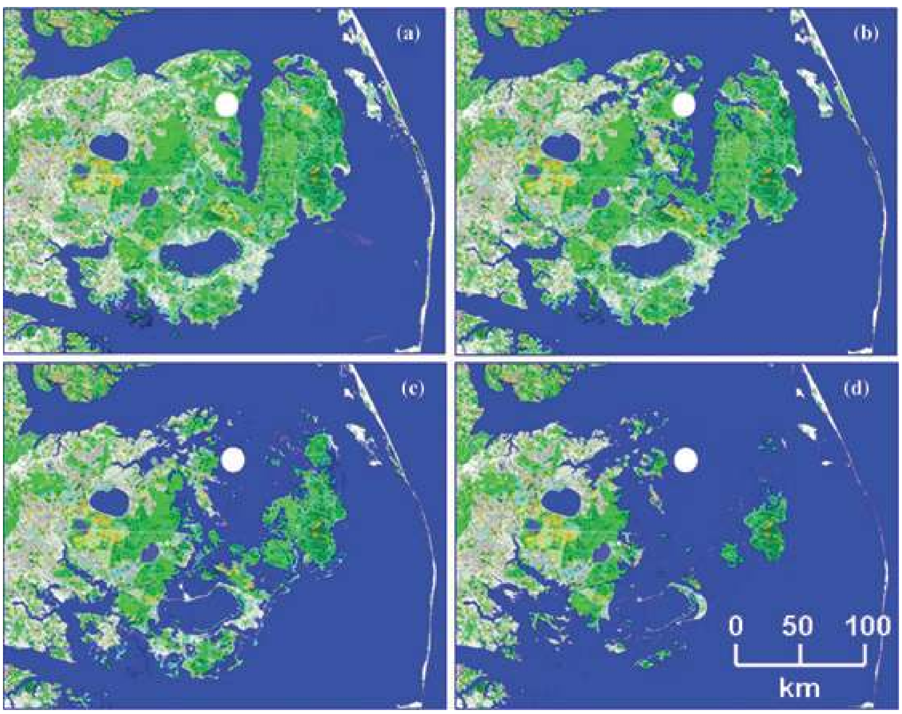

Figure 4. Projected sea-level rise impacts on the Albemarle Peninsula, North Carolina. The circle indicates the location of a site targeted for conservation through The Nature Conservancy's conservation planning process: (a) current situation; (b) projected sea-level rise of 10 cm; (c) projected rise of 40 cm; (d) projected rise of 82 cm. Sea-level rise projections are from Poulter and Halpin (2008) and were obtained through a grant from The Nature Conservancy.

are poor, microclimate constrains growing conditions, or climate change is a less imminent threat than, say, land conversion to intensive agriculture as energy and food resources for human populations become increasingly scarce.

Importance of Variance

Most climate-change models project changes in global or regional average climatic conditions, such as temperature or precipitation. Increases in the frequency and intensity of extreme events are likely, however, even if climate models cannot predict them accurately. Future monsoons could bring more intense and devastating rain. Droughts could become more intense or last longer, as they have in the past (paleoecological records indicate megadroughts lasting a century or more; Woodhouse & Overpeck 1998; Stahle et al. 2000). Episodic extreme events such as blowdowns (e.g., in March 2008 on the coast of Washington or January 2009 in France and Spain) or extensive stand-replacing fires (e.g., in Siberia, Canada, California, and Brazil in 2003; Australia in 2009) alter landscape cover and ecosystem processes and thus reset successional trajectories or shift systems to alternative states (as visualized in state-and-transition models; Bestelmeyer et al. 2004; Peters et al. 2004). Although climatologists may warn of general patterns of change in the frequency and intensity of extreme events, they do not provide the specific information needed to anticipate the consequences of such events. This limits the usefulness of climate projections where landscapes will be dramatically altered by such events.

In some cases extreme variations in systems are linked to cycles of natural variability. The frequency of large fires in western United States, for example, is associated with El Niño Southern Oscillation and Pacific Decadal Oscillation cycles (Westerling et al. 2006). Detecting such relationships or the occurrence of past extreme events that may have lingering effects requires long-term data. Even with widely distributed data sources, such as weather stations, complete and reliable long-term data on such things as wildfire frequencies, vegetation cover, or abundances of key species are generally scarce. Monitoring networks, such as long-term ecological research (LTER) sites, the U.S. Forest Service Forest Inventory and Analysis (FIA) Program, or remotely sensed records of land-use change, are relatively recent developments (Goward et al. 2008). To run climate models to project potential impacts, however, requires a time series of historical climatology to initialize model parameters and another set of long-term data to test the model and verify whether the simulations are satisfactory before projecting the future (Neilson & Drapek 1998). Although such data sets exist for some locations, complete data sets of climate and land cover for long periods and multiple scales are scarce and inconsistent.

Next Steps

Despite all the difficulties of developing climate models that address the needs of conservation practitioners at relevant scales and of making the data and information of conservation useful to modelers, models are the only way to peer into the future to see what it might hold. Developing better ways of downscaling climate-change projections, with known uncertainties, is important. Although it would be nice to have high-resolution climate data and finer resolution climate models, it is unlikely they will be reliable and accurate at the finest scales. Using fine-grain baseline information to bring global climate projections to a local scale through downscaling can produce maps that have high apparent spatial resolution, but appearances are misleading. The climate projections actually have not been produced at the fine spatial scale, and the apparent high resolution of the output masks the uncertainties that expand at the finer scales. These realities of modeling should not discourage the use of climate models in conservation, however; rather, the climate projections that are currently available should be judiciously incorporated into conservation planning and prioritization *now*, but at the scales at which the GCMs and RCMs have been designed to apply.

Although it does not solve downscaling issues, one solution to the problem of uncertainty is to use an ensemble model or consensus method approach (Thuiller 2004; Marmion et al. 2009) in which several models are used with various emission pathways to examine a range of likely projections. Examining more than a few model and scenario combinations, however, quickly becomes an intractable problem when interpreting results. Therefore, the most common approach is to calculate a median or mean value from the ensemble of models. Unfortunately, this method dampens the potential impacts by removing the projections of models that simulate more extreme conditions. To avoid this problem, probabilistic forecasts of habitat change from the ensemble models under different scenarios of atmospheric CO_2 emission are being developed.

Another way to deal with the uncertainty of climate projections is to incorporate stochastic climate events into the models and project the response of the system to test the validity of current conservation strategies. With long-term data, knowledge of historical events, and information about how ecological systems have responded to past changes, modelers can extend their models to incorporate disturbances such as fire or drought by calibrating the model parameters with the data and expert knowledge. Modelers will not develop the sorts of projections that are needed, however, unless they work in tandem with conservationists to understand how systems are likely to respond to future stresses. The models can then be used to assess the system vulnerability under scenarios that incorporate extreme events with different intensity, duration, or seasonality. Although such analyses may be compromised if future stresses are different from those in the past, they may nonetheless help direct efforts to increase the resilience of systems most at risk. Climate-change models project the future, but they depend on historical ecology to establish the foundation for those projections.

Decisions are being made about where, globally, conservation organizations should target their activities and investments. Will today's biodiversity hotspots be only lukewarm in the future? Will the major habitat types that are most threatened now retain that status as the climate and vulnerabilities and distributions of key species and ecosystem components change? Current model projections may help answer such questions. Yet most conservation action is carried out at relatively fine scales, where current climate-change projections are uncertain. It may be unrealistic to hope for model projections that tell one what to expect in different parts of a wildlife refuge or conservation area, but having some notion of the likelihood that, say, the Republican River Sand Hills Conservation Area will be cooler, unchanged, or much warmer would be useful in framing management strategies now.

Even with downscaling, conservationists should not expect climate-change models to provide accurate, fine-scale predictions and should not require such guidance to move ahead. Climate-change modeling is about probabilities, and at some scales, regions, or ecosystems the probability envelope will be wide. But it is not infinitely wide. The regions that are likely to get warmer or drier can already be identified. Conservationists need to incorporate what the current models say into planning and action. Because the future will always be uncertain no matter how good the models, conservationists should hedge their bets and be prepared to adjust priorities and actions quickly if it becomes apparent that the future is not playing out as expected. This is the essence of adaptive management.

The challenges to conservation and management in the face of climate change are formidable (Hulme 2005; Kostyack & Rohlf 2008). Considerable attention is being given to incorporating climate change into conservation planning, adjusting policy to address potential climate impacts (e.g., Ruhl 2008), and developing new management tactics (McLachlan et al. 2007). As these and other efforts develop, it will be imperative to consider the scales of climate-model projections and the scales of biological responses and make sure they align. Mismatches of scale can lead to misguided management.

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