

Adaptation Approaches for Conserving Ecosystems Services and Biodiversity in Dynamic Landscapes Caused By Climate Change

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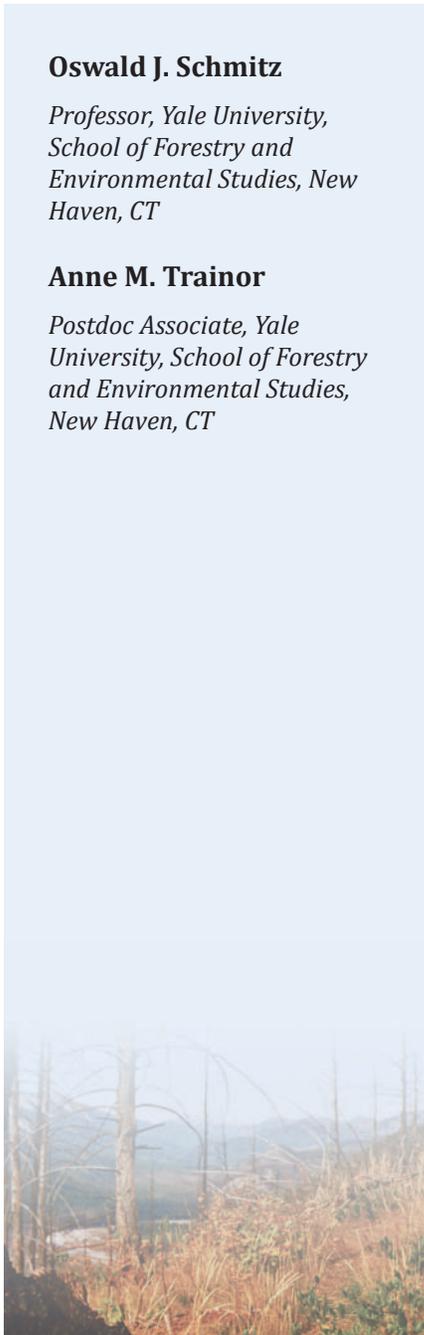
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Abstract: Climate change stands to cause animal species to shift their geographic ranges. This will cause ecosystems to become reorganized across landscapes as species migrate into and out of specific locations with attendant impacts on values and services that ecosystems provide to humans. Conservation in an era of climate change needs to ensure that landscapes are resilient by devising adaptation strategies to deal with such dynamism. This requires anticipating the future fate of species and ecosystems as well as implementing spatially explicit adaptation that enables species, ecosystems and their services to persist across vast landscapes. This paper describes a framework that highlights six spatially explicit adaptation approaches that emulate natural ecological resilience in support of landscape-scale adaptation planning. These include understanding and better sustaining concentrations of current biodiversity on landscapes and ecosystems services; anticipating where species will migrate so as not to develop landscapes in ways that impede their movement; and establish landscape connectivity between habitats and geophysical settings to ensure species can reach thermally favorable new environments as they are displaced by climate change. We discuss how to deploy the adaptation approaches in conservation assessments aimed at supporting land use planning for conservation and compatible land uses, highlighting the importance of using multiple approaches to develop coherent plans that address multiple stakeholder interests.

INTRODUCTION

Forest management is faced with the significant challenge of maintaining the integrity and functioning of forest ecosystems in the face of changing climate. This is a particularly formidable challenge because on-the-ground management activities are generally associated with specific geographic locations within fixed political jurisdictions. Yet species comprising ecosystems are expected to shift their geographic ranges toward more favorable climatic (i.e., temperature, precipitation) conditions (Hansen and others 2001; Iverson and Prasad 2001). Moreover,



these shifts may happen at differential rates depending on species' abilities or capacities to move (Hansen and others 2001; Malcolm and others 2002). Consequently, species that comprise forest ecosystems stand to become disassembled and reassemble into new configurations elsewhere (Hansen and others 2001; Malcolm and others 2002; Iverson and Prasad 2001; Zavaleta and others 2009), with attendant impacts on ecological processes and related ecosystem services (Schmitz and others 2003; Walther 2010).

To keep pace with this change, and maintain ecological integrity, management aimed at addressing the impacts of climate change must extend its purview. It has to shift from a traditional emphasis on local parcels of land with fixed boundaries to a more regional focus that strategically considers those local parcels of land as part of a larger portfolio of places that are integrated to build landscape-scale resilience as species and ecosystems move to adjust their geographic locations (Spittlehouse and Stewart 2003; Schmitz and others 2013). This further requires developing and implementing adaptation plans aimed at adjusting both natural and human systems in order to minimize the adverse effects of climate change on biodiversity (Spittlehouse and Stewart 2003; IPCC 2007; Mawdsley and others 2009). Such regional planning requires: (1) knowing what we have today; (2) understanding what a climate future might look like; and (3) adopting adaptation approaches that respond to current conditions and anticipated future change (Spittlehouse and Stewart 2003; Schmitz and others 2013). We present here a framework that addresses these three points to assist regional planning conserving biodiversity within dynamic landscapes caused by climate change.

The framework is the result of yearlong-deliberations by a scientific working group (see <http://yale.databasin.org/pages/panelmembers>) comprised of conservation biologists, modelers, and policy-makers charged with developing practical guidance for integrating climate adaptation approaches into conservation planning and policymaking. At the outset, the working group recognized that the conservation science community has made great strides in developing adaptation approaches to address climate change: there are upwards of 42 of them (Vos and others 2008; Galatowitsch and others 2009; Game and others 2011; Heller and Zavaleta 2009; Mawdsley and others 2009; Poianni and others 2011). But, in many cases, these approaches are presented merely as a menu of options. It was the working group's experience that such wide range of choices makes it difficult to decide which options should be implemented or to know which ones lead to complementary or contradictory outcomes for a given adaptation plan. Accordingly, in the face of such uncertainty important decisions and actions may be put off or avoided altogether, at the very time when action is critically needed (Spittlehouse and Stewart 2003; Brooke 2008; Poianni and others 2011).

The working group therefore distilled the choices down to seven promising adaptation approaches that are robust to uncertainty and can help maintain the functional integrity of biotic systems that are being managed (Schmitz and others 2014). The six approaches were chosen because they emulate natural ecological resilience; and they are spatially explicit to support action that must contextualize place-based action within regional, landscape contexts (Schmitz and others 2014). They are organized to address three levels of ecological organization (i.e., species, ecosystems and landscapes) and consider the need to consider existing as well as future conditions (Figure 1).

The six approaches are themselves complementary and broadly applicable to adaptation planning for a broad range of natural resource and biodiversity management concerns. As such, the framework complements and builds on existing climate adaptation frameworks (e.g., that developed by

Ecological Level			
Adaptation Approach	Species & Population	Ecosystem	Landscape
A. Strengthen current conservation efforts			
1) Protect current patterns of biodiversity	<ul style="list-style-type: none"> Assess population sizes, viability, conservation status, and phenological trends Map species occurrences 	<ul style="list-style-type: none"> Map terrestrial and aquatic ecosystems 	<ul style="list-style-type: none"> Map genetic pattern across the landscape Map beta and gamma diversity Map biodiversity hotspots
2) Protect large, intact, natural landscapes and ecological processes	<ul style="list-style-type: none"> Identify and map extent of species occurrences in relation to their thermal tolerances, habitats and food resources 	<ul style="list-style-type: none"> Map potential future patterns of fire, hydrology, carbon sequestration, and ecological integrity Map locations where ecosystem services provide human value 	<ul style="list-style-type: none"> Map factors related to ecological integrity (e.g., fragmentation, distance from disturbance)
3) Protect the geophysical setting	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Map areas of high ecological integrity Map land facets in relation to current climate patterns Map areas of high topographic complexity 	
B. Anticipating and responding to future conditions			
4) Identify and appropriately manage areas that will provide future climate space for species expected to be displaced by climate change.	<ul style="list-style-type: none"> Forecast species and rare community vulnerability to climate change based on their capacity to adapt biologically Map future climate envelopes that will constrain distributions 	<ul style="list-style-type: none"> Forecast ecosystem vulnerability to climate change Map locations that would support shifts in vegetation types and biomes 	<ul style="list-style-type: none"> Forecast land use change Project sea level rise Analyze projected trends in climate variables (precipitation, temperature, etc). Project climate change Map potential future biodiversity hotspots
5) Identify and protect climate refugia	<ul style="list-style-type: none"> Identify areas that could harbor current species into the future Identify where species populations remain stable 	<ul style="list-style-type: none"> Map habitats with high natural resilience to climate change (e.g. spring-fed streams) Map areas projected to experience little change in vegetation 	<ul style="list-style-type: none"> Map drought refugia Map areas projected to maintain stable climate
6) Maintain and restore ecological connectivity	<ul style="list-style-type: none"> Identify areas critical to species movements in a changing climate Map movement corridors for species life-history and migration 	<ul style="list-style-type: none"> Map connections between current and projected future locations Anticipate species invasions along planned corridors 	<ul style="list-style-type: none"> Map connections between land facets, ecological land units, refugia or areas of high ecological integrity

Figure 1. Six key climate change adaptation approaches for conservation planning at three levels of ecological analysis. The cells within the matrix list the kinds of scientific assessment needed to support adaptation planning and action.

the U.S. Forest Service www.forestadaptation.org and the Nature Conservancy [Cross and others 2012, Groves and others 2012]) that are more focused to meet specific agency goals or specific resource planning needs. In presenting the framework here, we recognize that ultimately decisions about which adaptation approaches to implement depend also on the socio-economic and political context of the management issue (Spittlehouse and Steward 2003; Heller and Zavaleta 2009). Nevertheless, these decisions require first understanding the biophysical conditions determining the fate of the biotic systems being managed. To this end, we discuss here how to derive this understanding by describing how the different adaptation approaches can be used in conservation assessments to support regional planning for biodiversity conservation.

FRAMEWORK FOR CONSERVING AND ADAPTING BIODIVERSITY

The adaptation approaches featured in the framework address three levels of ecological organization (i.e., species, ecosystems and landscapes) and consider the need to protect the integrity of existing conditions (i.e., ensure that current environmental conditions are maintained or improved) as well as anticipate future conditions to develop appropriate adaptation actions (Schmitz and others 2014). While the different approaches can be considered individually, we juxtapose them within a matrix that reveals the complementarity among ecological organization (Figure 1).

Doing this has tactical value. The framework is designed to simultaneously consider different approaches and organizational scales, thus encouraging the use of multiple approaches. This is based on the consensus that “climate-adaptive” conservation plans should be geared toward conserving not only species and their habitats, but should ensure that ecological and evolutionary processes can continue to operate across landscapes over the coming decades of changing climate (Zavaleta and others 2009; Zarnetsky and others 2012; Schmitz and others 2014). By contrast, most assessments that inform biodiversity conservation planning today continue to focus somewhat more narrowly on the upper-left section of this matrix (i.e., they map current and/or future species geographic ranges). Choosing and implementing several adaptation approaches from the matrix can help to ensure that there is coherence across ecological scales and organizational levels. For example, it helps to appreciate that conserving species may not only require maintaining existing habitats, reserves and protected areas but further appreciating the need for connectivity among those locations to facilitate species movements across landscapes. It further encourages anticipating locations where species may move in the future to identify and conserve those candidate locations and connect them with current locations inhabited by the species.

The framework also has strategic value by helping to foster collaboration and coordination among conservation and management agencies. Various conservation and management agencies have distinctive goals and expertise and as such often operate at different spatial scales or operate at diverse levels of ecological organization. The framework can help to envision how each agency’s efforts can be aligned to encourage inter-agency complementarity and synergism when developing regional adaptation policy and action. For example, coordinating the adaptation efforts of the U.S. Fish and Wildlife Service (USFWS)—a species-centric organization—with adaptation efforts of the U.S. Forest Service (USFS)—an ecosystem-centric organization—or the Bureau of Land Management (BLM)—a landscape-centric organization—can help to ensure that essential habitats are available for forest wildlife species (USFWS & USFS) or ensure that working landscapes designed to be resilient to climate change maintain or enhance the capacity for species of conservation concern to move across broad regions as they shift their geographic.

Ecological scales of consideration

The adaptation approaches apply to any or all of the following three levels of ecological organizations routinely considered in conservation and management (Schmitz and others 2014). (1) The species and population level focuses on spatial occurrences, population sizes, viability and conservation status and conservation concern. Adaptation at this level involves understanding current and future species geographic range distributions as well as population dynamics and movement patterns. (2) The ecosystem level recognizes that species and their habitats are integral components of ecosystems and, as such, influence ecological processes that provide services

to humankind and habitat for other species. This level begins to consider biodiversity in terms of its functional role and associated services in addition to more classical preservation values. (3) The landscape level recognizes that there are important patterns across multiple ecosystems that are determined by a combination of geographical features such as topography and soils (land facets and ecological land units), as well as by the degree to which species sort themselves into communities that comprise different ecosystems.

Adaptation approaches

The adaptation approaches fall into two broad categories. The first are those that enhance current conservation and management efforts, and the second are those that anticipate and respond to future conditions.

Strengthen current conservation efforts

The first three approaches build on conservation actions that are already in place. Once implemented, these approaches may also buy time to formulate adaptation actions once better understanding of future conditions is developed for any region of conservation or management concern. The first two approaches (Figure 1) are perhaps most familiar because they are used widely in conservation; the third is an emerging new approach that considers an additional suite of environmental variables that determine species distribution and diversity.

1. Protect current patterns of biodiversity. This represents a baseline objective reflecting Aldo Leopold's admonition that "the first rule of intelligent tinkering is to keep all of the parts." Even as climate change redistributes species, conservation will still need to ensure that species can persist where they are today. Without such protection, coexisting species may have little chance of persisting until other adaptation approaches can be implemented. Ensuring that critical natural habitat is maintained or enhanced across a landscape is key to such protection. This also helps to foster management actions that connect the places where species currently are to future locations with more favorable climatic conditions, using corridors, steppingstones, or working lands permeable to plant and animal movement (Thomas and others 2012).

2. Protect large, intact, natural landscapes and ecological processes. Shifts in the geographic range of species stand to reorganize species compositions of communities because they may become disassembled over time and space. This in turn may alter ecosystem functioning and the provisioning of environmental services (Schmitz and others 2003; Zavaleta and others 2009). Maintaining large areas reduces the potential for community disassembly because it helps to ensure that trophic interactions, disturbance regimes, intra-specific and inter-specific competition, and other large-scale processes can continue to generate and maintain high levels of biodiversity. As species move in response to changing climates, it will be more difficult to manage for species composition directly. Maintaining large spaces that can support the kinds of ecological and evolutionary processes offers a better way to protect a wide range of species moving at different rates. These areas are likely to contain a large complement of native species, including densities of top carnivores large enough to affect community structure. Such intact systems can also accommodate large-scale disturbance regimes (flood, fire, and windthrow). This adaptation objective thus considers the functional roles of species and takes a more dynamic perspective than the previous adaptation approach. It also recognizes that

species within communities are interdependent with each other and may provide important ecological services through those interdependencies. For example, native insect pollinator species diversity may be a key determinant of the success of high-value fruit and vegetable farming, especially when commercial species of pollinators such as European honeybees are in short supply. Plant species comprising coastal ecosystems buffer coastlines from flooding and erosion during storm surges and upland forest in watersheds control surface runoff and erosion while reserving drinking water quality. Conserving predators may be important not only to protect species with charismatic value but also to prevent loss of trees needed for watershed protection because predator species may prevent prey population outbreaks thereby protecting ecosystems from herbivore damage. The human-built environment may constrain the ability to protect single large areas, and so assembling a connected portfolio of smaller, undeveloped spaces may also protect many of the remaining natural landscapes as possible. In practical terms, this calls for considerably enlarging areas that are under active management for management or conservation (Sinclair and others 1995) combined with targeted restoration activities (e.g., reintroducing apex predators).

3. Protect geophysical settings. Species presence in a location can depend on a suite of factors including soil types, upslope drainage area, slope, elevation, aspect, and solar insolation (Hunter and others 1988). Such biophysical attributes—called land facets or geophysical settings—can sometimes account for spatial variation in biodiversity better than spatial variation in habitat attributes (Anderson and Ferree 2010). Even while climate changes, these locations are enduring features because soil types and geology are unlikely to change, and local climate gradients that are driven by topography will likely not change as quickly (Currie and Paquin 1987; Davies and others 2007; Anderson and Ferree 2010). Maintaining areas that contain a diversity of geophysical settings may help to conserve a diverse complement of species associated with these features under current and future climate regimes (Schloss and others 2011).

Anticipating and responding to future conditions

This set of approaches (Figure 1) address changing climate futures. Through scenario analyses (Galatowitsch and others 2009) one can explore what influence climate change might have on species distributions and ecosystem functions and services. Anticipating geographic range shifts and alteration of ecosystem functions and services requires the use of models to project what areas may become suitable for species under future climates. Modeling helps locate areas on the landscape to protect for the future and areas needed to support range shifts between current and future locations (Lawler and others 2009).

4. Identify and protect areas that will provide future climate space for species expected to be displaced by climate change. Ample evidence shows that species are already undergoing shifts in their geographic ranges (Parmesan 2006; Barnosky 2009). While many shifts are comparatively small forays (e.g. 50-150 mile range extensions) arising from small (0.5°C) temperature increases over the last 50-100 years, larger range extensions can be expected if projections of even 1-3°C rise in mean temperature (IPCC 2007) come to pass over the next century. This approach identifies candidate locations to which species may migrate; and thus provides the impetus to determine if those locations are currently managed in ways that ensure species persistence after their migrations.

5. *Identify and protect climate refugia.* This adaptation approach recognizes that many species may have limited capacities to evolve tolerances quickly enough to match the rate of future climate change or have the capacity to migrate to new locations. One way to prevent potential losses of these species is to identify and protect climate refugia into which species can retreat. Refugia (e.g., mountain ranges, high plateaus, or areas of cold air drainage) are effectively safe havens on the landscape because climatic changes are expected to be relatively small there.

6. *Maintain and establish ecological connectivity.* Even if we succeed in conserving today's portfolio of large natural and semi-natural landscapes (Adaptation approaches 1-3) and have connected these areas with corridor networks some species will need to shift their range beyond those locations as climates change. Consequently, the connectivity network that was designed for current conditions may not be completely suitable for adapting to future conditions. Climate change induced species range shifts can be facilitated by anticipating where species will move (Adaptation approach 4), and connecting these new areas also with corridors. This approach thus identifies where species movement will likely take place across the landscape and accordingly identifies current and potential future travel routes and impediments (such as terrain, vegetation, human land use, and geological barriers) to movement. The connected areas can support gene flow among species populations, promote demographic flows that can prevent local extinction (demographic rescue), and facilitate recolonization after local extinction.

Steps to applying the framework

The framework (Figure 1) presents a suite of approaches that collectively support management to build climate resilient landscapes. It provides a systematic way to reason how different adaptation approaches and ecological levels may complement each other spatially. But, it is intentionally not prescriptive in order to accommodate the diversity of goals and objectives among different conservation and management agencies. It also helps identify critical information needs to characterize the current state-of-play as well as envision future outcomes through scenario analysis.

Scientific assessments in support of natural resource conservation and management gather and depict spatially explicit information about species and their habitats within ecosystems, and ecosystems across landscapes. This information is most effectively displayed through the use of maps. Developing maps as a product of assessments is a very useful way to foster scenario-building exercises and reveal decision options. The information in maps help policy-makers and managers visualize not only current but importantly potential future consequences of particular decisions that may be conflated or confounded by climate change.

Modern geographic information systems (GIS) technology is capable of providing the integrative environment needed for storing, accessing, and processing spatial data from such assessments by representing data from a broad range of sources into a single display. Maps can represent large volumes of disparate information in visual form where they would otherwise be buried in vast unconnected data sets, thus facilitating geospatial analyses among variables and features to produce a composite picture across landscapes.

Fundamentally, any assessment should be motivated by a clear articulation of the conservation problem and goal *before* choosing the adaptation strategy, analysis approaches, tools, and

data. Oftentimes, assessments are motivated simply because data and tools are readily available. Specifying goals and ensuring that the data and tools align with the goals ensures that assessment outcomes will meet the needs of planners; and hence reduces risks that inappropriate adaptation actions will be recommended. Once the goal is chosen, we suggest that a scientific assessment process supporting climate adaptation involves 5 steps: (1) Choose one or more adaptation strategy(ies) (the left column of Table 1) that may be appropriate depending on conservation planning goals. (2) Choose the level(s) of ecological organization (the top row of Figure 1). Ideally, more than just the species level of ecological analysis should be considered in assessments, for reasons explained above. The choice of adaptation strategy and level of ecological analysis then triangulate to a particular cell of the matrix, which in turn, leads to identifying appropriate analysis tools. (3) Choose the analysis tool(s). A menu of available tools for the different matrix cells, their description and explanation of their benefits and drawbacks can be found at <http://www.databasin.org/yale/using/matrix/lc/approaches>. (4) Choose the data sets. The choice of assessment tool dictates critical data needs, including deciding on the spatial extent and spatial resolution of the data. Assessments typically require the use of disparate abiotic, biotic and cultural datasets originating from multiple sources, and while numerous such datasets are available (see <http://databasin.org/yale/using/matrix>), integrating data from disparate sources to provide coherence is one of the toughest challenges in any assessment process. This step may require rescaling and reinterpreting datasets to a common spatial scale and development of common variable definitions. It further offers a way to identify and rectify data gaps. It also forces understanding and explication of uncertainties, which is among the most critical *aspect* of conservation planning (Lawler and others 2010). For example, data that are measured directly in the field or based on expert opinion may be more certain than data from satellite imagery that is not ground-truthed, or data outputs from models (e.g. projections of future climate). (5) Specify the assessment time horizon. The major effects of climate change on species and ecosystems are likely to be realized within the next 50 to 100 years (IPCC 2007). Yet, land-use planning for human systems often focuses on shorter (5-10 year) time horizons, although forest management planning may occur on somewhat longer time horizons. Regardless, any mismatch in the time horizon of climate change effects and management decisions can create irreversible, path-dependent land allocation outcomes (e.g., urban sprawl) because sequential short-term land-use plans often build upon existing land allocations that in turn may preclude land use options for management and conservation needed 20 or 30 years hence. For this reason, scientific assessments for future land management and conservation should be conducted for at least a 50-year time horizon. We encourage consideration of potential future scenarios over even longer time horizons in addition to the 50-year time frame, with the recognition that projections about future geographic range distributions of species as well as human demographics and land-use patterns become increasingly uncertain as the time horizon becomes longer than 50 years.

Strengthen current conservation efforts

Assessments in support of strengthening current conservation efforts include characterizing and inventorying the state of current conservation efforts. This can range from mapping the occurrence of single species of conservation concern, to mapping intact ecosystem types within a region (e.g., fir-hemlock forests, alpine, tallgrass prairie, riparian and associated riverine systems) or identifying geographic patterns and gradients in biodiversity concentrations across a landscape (biodiversity hotspots, beta and gamma diversity). Delineating the size and location of such large spaces involves different assessments for the different ecological levels (Figure 1). At

the species and population level, assessments identify and map species occurrences in relation to their needs (also called species distribution or niche modeling), such as their thermal tolerances, habitat requirements and prey species distributions. At the ecosystem level, assessments include mapping the spatial extents of disturbance regimes and ecological functions such as the spatial pattern in levels of production or carbon sequestration, watershed and hydrological regimes, and location and extent of wildfires. At the landscape level, assessments would include identifying and mapping landscape features such as high-elevation, low insolation slopes on calcareous soils, that can be strong surrogates for species diversity (Anderson and Ferree 2010) locations and extent of the human built environment, or degree of habitat fragmentation (e.g., Sanderson and others 2002; Theobald 2010).

Anticipating and responding to future conditions

Assessments to envision and respond to future conditions require the use of scenario analyses (Galatowitsch and others 2009) to explore what influence climate change might have on species distributions and ecosystem functions and services. Scenario analysis involves the use of predictive modeling and expert opinion. Generating future scenarios typically involves the sequential use of several or all of five kinds of models that project 1) future emissions of greenhouse gases, 2) how global atmosphere and oceans respond to these emissions, 3) how atmospheric processes affects habitats and biomes at smaller spatial extents, 4) species' responses to climate change (e.g., climate envelope models, physiological models) and 5) species movement and colonization (Pearson and Dawson 2003; Phillips and others 2008). Each of the models carries uncertainties because they employ uncertain data and assumptions to drive model projections. The sequential application of the models can compound these uncertainties because the output of each model is a crucial input into the next one. Nevertheless, one may still use scenario generation as a heuristic tool that, when combined with expert opinion, provides the means to envision and appropriately act in response to plausible future outcomes (Galatowitsch and others 2009; Lawler and others 2009; see also ***Coping with uncertainty***, below for more detail). Assessments enlist statistical modeling to project future locations with suitable biophysical conditions (niche modeling, climate envelope modeling), or enlist process-based models (physiological models) to identify locations that have climatically tolerable future environmental conditions, aka future niche space. Such single species models will provide the most robust insights for conservation planning especially if multiple scenarios are generated to cover a wide range of model uncertainty. This approach can also be used to make predictions for multiple species. Outputs for each species should be combined to generate a spatially coherent depiction of areas that will support future biodiversity concentrations. Because of the potential to compound uncertainties a more practical approach may be to consider ecological organization broader than individual species (i.e., ecosystems and landscapes; Figure 1) within each adaptation approach. Assessments in support of ecosystem level planning involve mapping future geographic locations of the dominant vegetation types or biomes that comprise different ecosystems (e.g., Neilson 1995; Iverson and Prasad 2001). This assumes that such vegetation provides critical habitat for animal diversity. One confounding factor is that biophysical conditions across broader landscapes may limit or preclude geographic range shifts of species. These constraining conditions include sea level rise and inundation, changes in land use regimes, and changes in the intensity and frequency of disturbances like fires and hurricanes. This requires contextualizing species and ecosystem assessments within anticipated biophysical landscape change. Assessments would also model the shifting climate space of individual species and overlay the individual species' projected

movements to identify landscape locations that may support range shift (Phillips and others 2008). Because this involves the same five kinds of models discussed above, it carries the same kinds of uncertainties. Newer coarse filter approaches can help reduce uncertainty by identifying potential corridors and connectivity areas on the basis of “natural blocks” or the degree of human modification (e.g., Spencer and others 2010; WHCWG 2010; Theobald and others 2012), geophysical settings (Brost and Beier 2012), or present-day climate gradients (Nuñez and others 2013). These approaches have their own uncertainties and assumptions (e.g. that areas of low human modification provide for movement of species and processes, or that future climate gradients will occur in the same locations as present day climate gradients—Nuñez and others 2013). Although these uncertainties are undoubtedly smaller than those involved in emission scenarios and general circulation models, the impact of such uncertainty needs to be quantified.

Coping with uncertainty

The six adaptation approaches carry uncertainty stemming from quantifiable errors in the measured or modeled data, assumptions of models used to project future climate change, and effects of climate change on species and ecosystems. It is easy to be paralyzed by uncertainty or invoke uncertainty to avoid making difficult decisions. We nevertheless advocate moving forward amidst uncertainty. Indeed, the first three proposed approaches (Figure 1) build on existing conservation approaches for which outcomes are known or relationships to biodiversity are well established empirically. So, they are likely to be good actions to take whether or not changes in climate play out as projected (Groves and others 2012). For those cases requiring greater use of modeling to conduct assessments (those projecting climate futures), several techniques can be employed to help reduce uncertainties. These include simulation analyses that account for the range of variability in the data, sensitivity analyses that explore robustness of models or adaptation approaches to various assumptions, and scenario analyses that examine a range of possible outcomes (Galatowitsch and others 2009; Glick and others 2011). Insights from modeling are extremely useful, especially when tempered by good expert judgment and opinion. One strategy to alleviate some uncertainty is to cross-walk between multiple adaptation strategies and ecological levels to evaluate when identification of priority conservation opportunities or future management actions are congruent or divergent. Indeed, those kinds of insights form the basis of many vulnerability assessments. Moreover, by providing vivid examples of the impacts of climate change, such assessments (e.g., Lawler and others 2009; Beever and others 2011) have motivated many managers and decision makers to treat climate adaptation as an urgent priority. Nevertheless, even with the best available data and models, uncertainties will always remain. Therefore, we recommend the use of adaptive management approaches that monitor and evaluate the performance of any implemented adaptation approaches (Lawler and others 2010; Cross and others 2012). This provides the kind of critical feedback needed to make continual amendments as new information and uncertainty arises.

CONCLUSIONS

The framework provides a vision on how to build resilient landscapes by establishing strategic partnerships to align institutional capacity, data and analysis tools in a concerted effort to take action to protect biodiversity in an era of climate change. The Framework provides guidance on implementing any combination of six adaptation approaches at three distinct levels of ecological organization and the scientific assessments that are needed in support of their implementation.

This guidance helps to establish a baseline understanding of current environmental conditions; identify which ecological features will likely be most vulnerable to climate change; and visualize an act to meet the future needs species, ecosystems, and landscapes.

ACKNOWLEDGEMENTS

We thank the Doris Duke Charitable Foundation, the Kresge Foundation, and the Wilburforce Foundation for providing financial support of this work.

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This paper received peer technical review. The content of the paper reflects the views of the authors, who are responsible for the facts and accuracy of the information herein.