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Conserving Biodiversity: Practical Guidance about Climate Change Adaptation Approaches in Support of Land- use Planning

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ABSTRACT: As species' geographic ranges and ecosystem functions are altered in response to climate change, there is a need to integrate biodiversity conservation approaches that promote natural adaptation into land use planning. Successful conservation will need to embrace multiple climate adaptation approaches, but to date they have not been conveyed in an integrated way to help support immediate conservation planning and action in the face of inherent spatial uncertainty about future conditions. Instead, these multiple approaches are often conveyed as competing or contradictory alternatives, when in fact, they are complementary. We present a framework that synthesizes six promising spatially explicit adaptation approaches for conserving biodiversity. We provide guidance on implementing these adaptation approaches and include case studies that highlight how biodiversity conservation can be used in planning. We conclude with general guidance on choosing appropriate climate adaptation approaches to amend for conservation planning.

Index terms: biodiversity, climate adaptation, conservation planning, land use planning

INTRODUCTION

As the impacts of climate change on biodiversity are becoming more evident, federal, state, local government agencies, conservation groups, and land trusts are increasingly faced with anticipating and integrating adaptation approaches and natural resilience into resource and land use plans. Such change is requiring a shift from using classic, place-based strategies that maintain the integrity of local protected areas and reserves within fixed boundaries to more dynamic strategies that develop and implement approaches that foster the ability of species to move across landscapes in order that they, and the ecosystems they comprise, may persist (Hannah et al. 2002; Brooke 2008; Heller and Zavaleta 2009; Mawdsley et al. 2009; Game et al. 2011; Poiani et al. 2011).

Conservation science has offered at least 42 approaches to climate adaptation (Vos et al. 2008; Galatowitsch et al. 2009; Heller and Zavaleta 2009; Mawdsley et al. 2009; Game et al. 2011; Poianni et al. 2011). But, with such a cornucopia of approaches, managers may have difficulty determining if they are complementary, competing, or even contradictory options. This tends to cause confusion, leading to debate about appropriate choices, thereby creating a proverbial "tower of babel" rather than a coherent context for making decisions. As a result, important conservation decisions and actions are delayed or avoided altogether because of a perceived risk that any particular action may be misguided (Spittlehouse and Stewart 2003; Brooke 2008; Poianni et al. 2011). But, in a multi-objective land use planning setting, critical

decisions for alternative land uses will go forward without a solid biodiversity conservation approach included in the planning process. Thus, land use options that may be critical for future species or ecosystem persistence are not included and subsequently precluded as possibilities once land is allocated for alternative uses. This leads to a failure to achieve agreement on the kinds of compatible future land uses that are appropriate across a broad spectrum of geographic scales and stakeholder interests at the very time when action is critically needed.

To overcome inaction, we offer here guidance, in the form of a Climate Adaptation Framework (hereafter, simply Framework), that presents a flexible portfolio of six adaptation options that support thoughtful trade-off decisions about species and ecosystem protection with alternative human land uses such as energy development and siting, and infrastructure development. These adaptation approaches range from leveraging areas already dedicated to conserving species and ecosystems, to creating a broader network of conservation areas and strategies that protect biodiversity, to anticipating and connecting locations of future species assemblages across the landscape. We illustrate how the Framework can be used to determine how the approaches complement one another across different scales of organization, thereby providing coherence for conservation planning and action that will be robust to uncertainties about a climate future. Using the Framework to determine a complementary set of approaches can also help to foster a new and critically needed spirit of regional partnership and collaboration among conservation

agencies that have traditionally operated on their own within their local jurisdictions. Thus, the portfolio of options represented by the Framework provides flexibility to support thoughtful and context-dependent trade-off decisions about species and ecosystem protection with alternative human land uses across those regions.

The Framework is the result of deliberations of a consensus-based scientific working group charged with developing practical guidance for integrating climate adaptation approaches into conservation planning and policymaking (see <http://yale.databasin.org>). The working group (authors of this paper) is comprised of individuals from federal land management agencies, state fish and wildlife agencies, the private sector, and academia. The Framework guidance has been tested through six pilot projects, two of which are highlighted in this paper.

THE FRAMEWORK

We distilled the six approaches from 42 proposed by the conservation science community broadly. Most of these support conservation action across three levels of ecological organization (i.e., species, ecosystems, and landscapes). Although each approach can be considered individually, we present them as a matrix to reveal their complementarity among the levels of ecological organizations (Table 1).

Emphasizing complementarity has two advantages. First, the Framework spurs simultaneous consideration of different adaptation approaches and organizational scales to encourage integrating multiple approaches and to identify gaps in data and/or strategies. We believe climate-adaptive conservation plans should conserve not only species and their habitats, but also the biophysical features and processes of ecosystems and landscapes because they provide unique opportunities for species persistence and resilience. By contrast, most conservation planning focuses narrowly on the upper-left section of this matrix (i.e., they map current and/or future species geographic ranges). Considering the full matrix strengthens conservation plans and actions and stimulates new

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

	Ecological Level				
	Adaptation Approach	Species and Population	Ecosystem	Landscape	
<p style="text-align: center;">Strengthen current conservation efforts</p>	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 and their associated services 	<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	<ul style="list-style-type: none"> • Forecast climate change effect on species viability • Forecast climate change effect on pests, diseases, or invasive species 	<ul style="list-style-type: none"> • Map potential future patterns of fire, hydrology, carbon sequestration and ecological integrity • Map locations where ecosystem services operate and provide human value 	<ul style="list-style-type: none"> • Analyze projected trends in climatic variables (precipitation, temperature, etc.) • 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 		
	<p style="text-align: center;">Anticipate and respond to future conditions</p>	4) Maintain and restore ecological connectivity	<ul style="list-style-type: none"> • Identify areas critical to species movements in current conditions and 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
		5) 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 range distributions of species 	<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 • Project climate change • Map future biodiversity hotspots
		6) Identify and protect climate refugia	<ul style="list-style-type: none"> • Identify areas that would harbor current species into the future • Identify where species populations remain stable or increase with climate change 	<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

ways of thinking about adapting to future changes. This helps reduce inefficient or ineffective decisions about actions to promote adaptation. Second, the Framework creates a common language and overarching vision to foster collaboration and policy coordination among government agencies and nongovernment organizations with different political jurisdictions and purviews. Different conservation organizations and agencies often operate at varying spatial scales with goals that pertain to different levels of ecological organization (i.e., species, ecosystem, and landscape). The Framework matrix can help envision how an entity's efforts can be aligned to encourage inter-agency complementarity and synergism when developing regional adaptation policy and action. The Framework facilitates working at varying scales, landscape or continental scales, and also facilitates cooperation among multiple levels of government and ownership, as each entity can recognize its own expertise and prerogatives in the Framework.

The approaches (descending down the left column of the Framework matrix) fall along a continuum between strengthening current conservation actions and anticipating and responding to future conditions (Table 1). The first three approaches build on classic conservation actions that already take place. As such, they readily help to amend and strengthen ongoing conservation efforts. Once implemented, these approaches may also buy valuable time to formulate plans addressing adaptation that anticipates long-term, broader geographic changes as we obtain a better understanding of future conditions. The remaining three approaches address climate futures and require scenario analyses (Galatowitsch et al. 2009) to explore what influence climate change might have on species distributions and ecosystem functions and services. 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 the global atmosphere and oceans respond to these emissions; (3) how atmospheric processes affect 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 et al. 2008). Each carries uncertainties because they employ uncertain data and assumptions to drive model projections. The sequential application of models can compound 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 et al. 2009; Lawler et al. 2009; see also *Coping with Uncertainty*, subheading below, for more detail).

The information needed to support effective decisions about which adaptation approach(es) to implement is most effectively gathered by conducting scientific assessments and displaying the information using maps (Figure 1). Modern geographic information systems (GIS) technology is capable of providing the integrative environment needed for storing, accessing, and processing spatial data in support of conducting assessments. GIS tools can represent data from a broad range of sources in layers of single images.

Maps are ideal for representing large volumes of disparate information in visual form where they would otherwise be buried in vast unconnected data sets. Maps allow easier analyses of association among numerous variables and features to produce a composite picture of the landscape (Figure 1). For example, by combining data on species point locations, vegetation, precipitation, and temperature, one can estimate spatially explicit statistical relationships among variables (a.k.a. bioclimatic niche modeling) to produce a composite map depicting concentrations or hotspots of species diversity across a landscape (Figure 1). Combining data layers for soils, topography, and parent geological material produces a composite map identifying the diversity of geophysical attributes or land facets comprising the geophysical settings of landscapes. Modeled future environmental conditions can be used to help project where species and ecosystems may end up (Figure 1). For example, bioclimatic models are useful

in projecting biodiversity hotspots on a landscape (Figure 1, 1st column) because they combine information from climate modeling on how vegetation, temperature, and precipitation might change in a climate future to produce a composite map depicting landscape-scale changes to biodiversity concentrations (Figure 1, 4th column). Other biophysical data can be added to produce composite maps to identify climate refugia or important topographic and habitat conditions that best connect landscape locations to support species movements (Figure 1). We next introduce the six adaptation approaches and discuss the kinds of scientific assessments needed to support their consideration in land use planning.

1. Protect current patterns of biodiversity.

Even as climate change redistributes species, conservation still needs to protect species where they are today. Without protection, species, especially those that are rare and threatened, will have little chance of persisting until other adaptation approaches are possible or effective. Furthermore, this can help to ensure that critical "stepping stones" exist across landscapes as species adjust their geographic ranges in response to climate change (Thomas et al. 2012). Conservation can further enhance the effectiveness of such protection by connecting currently occupied areas with corridors, stepping stones, or working lands permeable to plant and animal movement.

Assessments in support of this approach characterize and inventory the state of current conservation efforts. They 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 (e.g., biodiversity hotspots, beta and gamma diversity).

2. Protect large, intact, natural landscapes and ecological processes.

Protecting large areas reduces the potential for community disassembly because it helps to ensure that trophic interactions, disturbance regimes,

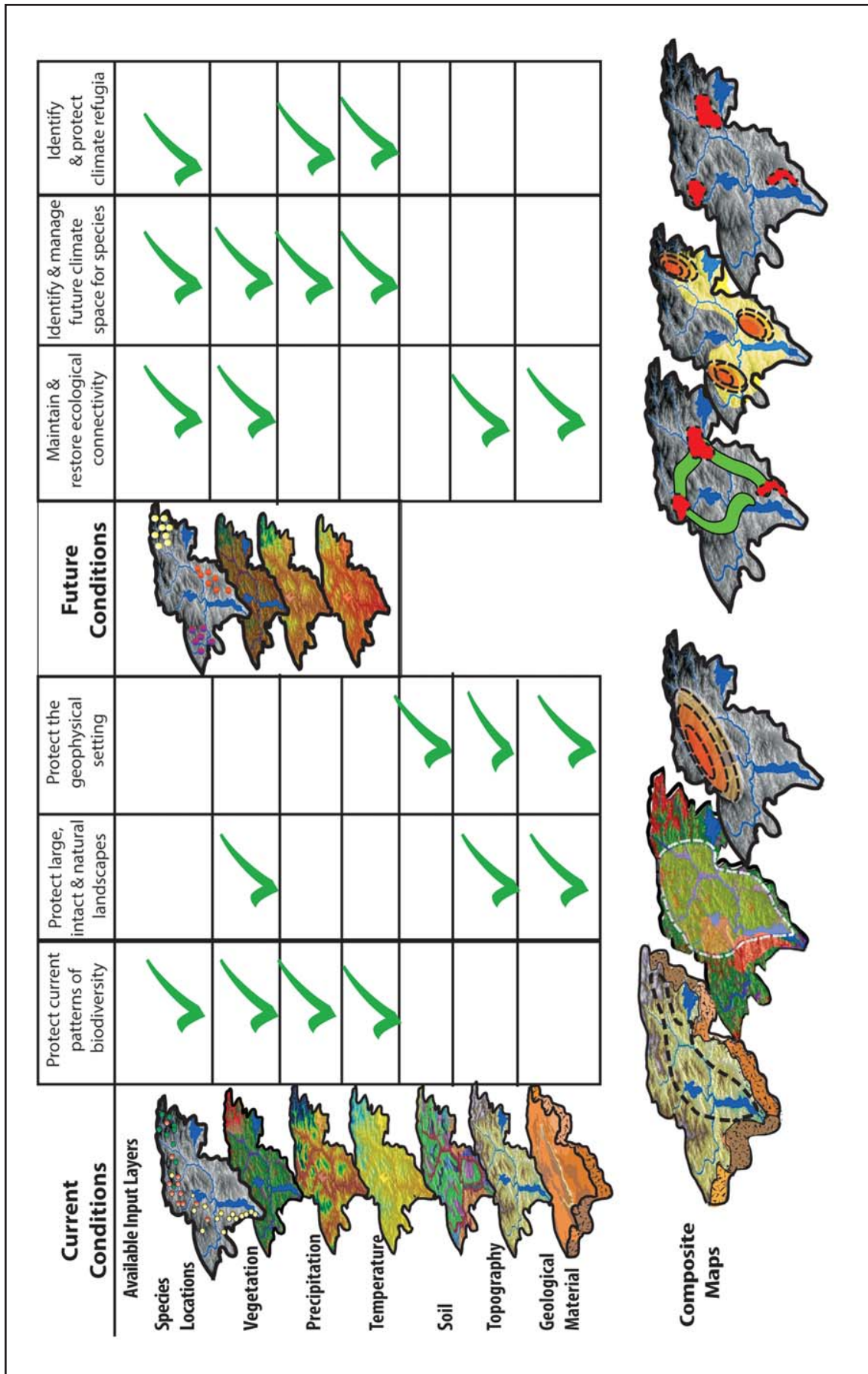


Figure 1. A hypothetical example of how different data layers could be combined to generate composite maps for different adaptation approaches. Such composite maps can be used to support land use planning for biodiversity conservation in an era of climate change. Data range from baseline information on attributes like geology, topography, and soils, to climatic attributes like temperature and precipitation, to biotic attributes like vegetation and point locations depicting spatial occurrences of different animal species. The composite maps depict biodiversity hotspots, large intact natural landscapes (area surrounded by dashed white line), geophysical settings that provide the greatest heterogeneity (area outlined by dashed black line), climate refugia (red areas), and conservation corridors that maintain and restore ecological connectivity (green bands).

intra-specific and inter-specific competition, and other large-scale processes continue to generate and maintain high levels of biodiversity and endemism. As species move, it will be increasingly hard to manage for species composition directly. A more successful approach may be to preserve large spaces that can support the kinds of ecological and evolutionary processes that generate and maintain biodiversity. Even if these areas lack exceptional endemism (Kareiva and Marvier 2003), they likely contain a large complement of native species, including densities of top carnivores large enough to affect community structure. Such intact systems exhibit redundancy and are resilient to large-scale disturbance regimes (e.g., flood, fire, and windthrow). They have spatially complex settings needed to support speciation and will likely provide these functions regardless of future climate. The human-built environment reduces resiliency of large areas. A strategy of assembling a connected portfolio of smaller, undeveloped spaces may also protect many of the remaining natural landscapes. In practical terms, this calls for expanding areas that are under active management for conservation (Sinclair et al. 1995) combined with targeted restoration activities (e.g., reintroducing apex predators).

Delineating the size and location of large spaces involves different assessments for the different ecological levels (Table 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 the locations and extent of the human built environment or degree of habitat fragmentation (e.g., Sanderson et al. 2002; Theobald 2010).

3. Protect geophysical settings. Species presence depends on a suite of factors including soil chemistry, upslope drainage area, topographic positions, slope, elevation, aspect, and solar insolation (Hunter et al. 1988). Such geophysical attributes—called land facets, ecological land units, or geophysical settings—can sometimes account for spatial variation in biodiversity better than spatial variation in habitat attributes (Anderson and Ferree 2010). The basic premise of this approach is that even while climate changes, these locations are enduring features because soils and geology will not change (Currie and Paquin 1987; Davies et al. 2007; Anderson and Ferree 2010). Thus, prioritizing and protecting areas that contain a diversity of geophysical settings should help to maintain a diverse complement of species associated with these features under current and future climate regimes (Beier and Brost 2010; Schloss et al. 2011).

Assessments delineate those geophysical landscape attributes into units called land facets or ecological land units such as high-elevation, low insolation slopes on calcareous soils, for example, that can be strong surrogates for species diversity (Anderson and Ferree 2010). Alternatively, one could assess geophysical diversity by considering it as a continuum, rather than in discrete bins (Faith and Walker 1996).

4. 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 habitat connecting corridors, species will shift their range within those landscapes as climates change. Connecting areas with corridors, stepping stones, or working lands creates landscape permeability for plant and animal movement. The connected areas sustain gene flow among species populations that can prevent local extinction (demographic rescue), and facilitate recolonization after local extinction. Most existing connectivity plans were based on maps of current vegetation community locations, which may not reflect their distributions in the future climate. Phillips et al. (2008), Beier (2012), and Nuñez et al. (2013) suggest how corridor plans should be reevaluated

and might support range shifts for species whose climate space will shift.

Assessments model shifts in species climate space by overlaying the projected movements of species to landscape locations supporting range shifts (Phillips et al. 2008). Because this involves the five kinds of scenario-generating models discussed above, it carries uncertainties. Recently described coarse-filter approaches help reduce uncertainty by identifying potential corridors between landscape locations where human land use is less constraining (e.g., Spencer et al. 2010; WHCWG 2010; Theobald et al. 2012), where there may be acceptable geophysical settings (Brost and Beier 2012), or that encompass present-day climate gradients (Nuñez et al. 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 et al. 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 (Beier 2012).

5. Identify and protect areas providing future climate space for species expected to be displaced by climate change. Ample evidence shows that species are undergoing shifts in their geographic ranges (Parmesan 2006; Barnosky 2009). While many shifts are comparatively short (<240 km range extensions) arising from small (0.5 °C) mean temperature increases over the last 50–100 years, larger range extensions can be expected if mean temperature projections of even a 1–3 °C rise (IPCC 2007) occur over the next century. The fundamental questions become (1) where will species likely end up, and (2) are those locations managed to ensure species persistence upon their arrival? Questions about the future can be addressed using information on species' current biophysical conditions (e.g., temperature, precipitation) or habitats (included in Adaptation Approach 1) coupled with downscaled projections of how regional climate change will geo-

graphically shift biophysical conditions and habitats. Modeling helps anticipate the future locations of suitable areas on the landscape for species (Lawler et al. 2009). It also facilitates an assessment of existing management policies to determine if they are adequate to protect species range shifts between current and future locations (Lawler et al. 2009).

Assessments use statistical modeling to project future locations with suitable biophysical conditions (niche modeling, climate envelope modeling), or enlist processed-based models (physiological models) to identify locations that have thermally tolerable future environmental conditions (a.k.a future niche space (Johnston and Schmitz 1997)). This approach is perhaps the most sensitive to model uncertainty. When such models are used for single species, their effectiveness for conservation planning increases if multiple scenarios are generated that encompass the range of model uncertainty and include measures of model agreement. This approach can also be used to make predictions for multiple species. Outputs for each species 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 (e.g., biomes shifting across the landscape (Rehfeldt et al. 2012)).

Assessments supporting ecosystem-level planning involve mapping future geographic locations of the dominant vegetation types or biomes (building on assessments for the first adaptation approach “Protect current patterns of biodiversity”) that comprise different ecosystems (e.g., Neilson 1995; Iverson and Prasad 2001). This assumes that vegetation provides critical habitat for animal diversity. One confounding factor inhibiting planning for future ecosystem locations is that biophysical conditions across broader landscapes may preclude geographic range shifts of species and ecosystems or impair them owing to constraining biophysical factors such as sea level rise and inundation, changes in land use regimes, and changes in the intensity

and frequency of disturbances like fires and hurricanes. Contextualizing species and ecosystem assessments within anticipated biophysical landscape change will strengthen conservation assessments. This requires using assessments that draw on models of future emissions of greenhouse gases, models of how global atmosphere and oceans respond to these emissions, models to downscale global climate projections to smaller spatial extents, and models of land use change.

6. Identify and protect climate refugia.

Climate refugia can be defined in at least two ways. First, they can be specific places where climate and associated biophysical conditions are likely to remain stable, having little impact on biodiversity, while other locations experience regional climate change. Second, they can be areas in which the climate will change, but nonetheless they will host climates that are suitable to species in the surrounding region. Examples of these latter types of refugia include mountain ranges, high plateaus, and cold-air drainages.

Assessments can enlist niche modeling to identify macrorefugia where species habitat may persist (Ashcroft 2010). Some cold-adapted species (e.g., red fir (*Abies magnifica* Murray), marten (*Martes americana* Linnaeus), wolverine (*Gulo gulo* Linnaeus), and pika (*Ochotona princeps* Richardson)) are already restricted to their interglacial macrorefugia. Macrorefugia for these species will be compromised under climate warming more so than in previous interglacials in the last 600,000 years. Therefore, small, local microrefugia (e.g., cold valleys, areas with springs, or other small areas) will be increasingly important, especially if their climate is more stable than the regional climate (Dobrowski 2010). At the ecosystem level, dynamic global vegetation models (DGVM) can help locate climatically stable regional macrorefugia, (areas of hundreds of square kilometers) where biomes (broad plant physiognomic classes such as tundra, forest, shrubland, or grassland) are expected to be stable during the coming century. The potential exists also to locate refugia by identifying areas where primary productivity (inferred from

satellite imagery) remained stable through several recent cycles of extreme climate shifts (Klein et al. 2009). At the landscape level, assessments identify future regional patterns of temperature and precipitation (i.e., drought) to partition landscapes into areas likely to undergo change from those that should remain more stable.

Coping with Uncertainty

All approaches carry levels of 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, or invoke uncertainty, to avoid making difficult decisions. There is no option but to move forward. We believe by utilizing the Framework to combine approaches, the negative effects of uncertainty can be reduced. The first four conservation approaches (Table 1) are likely to be good actions to take whether or not changes in climate play out as projected (Groves et al. 2012). For assessments requiring greater use of modeling (those projecting climate futures), several techniques can help reduce uncertainties, including: simulation analyses that account for 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 et al. 2009; Glick et al. 2011). Insights from modeling are extremely useful, especially when tempered by good expert judgment and opinion. Indeed, those kinds of insights form the basis of many vulnerability assessments. Moreover, by providing vivid examples of climate change impacts, such assessments (e.g., Lawler et al. 2009; Beever et al. 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 remain. Therefore, we recommend monitoring and evaluating the performance of adaptation approaches once they have been implemented (Lawler et al. 2010; Cross et al. 2012). This critical feedback is needed to make continual amendments as new information and uncertainty arise.

Evaluating the Guidance: Case Examples

Case example 1: an assessment in support of climate adaptation in Florida

Anticipating effects of climate change is important to ensure the efficacy of well established, existing conservation efforts. In Florida, sea-level rise is projected to be 0.75–1.9 meters by the end of this century (Vermeer and Rahmstorf 2009), submerging 15% of the state within 90 years and jeopardizing considerable conservation actions that have already occurred. But predicting the individual response of hundreds of species and communities to sea-level rise involves impractical degrees of complexity and uncertainty. Thus, scaling up to consider a landscape perspective provides a practical alternative.

The Florida Natural Areas Inventory (FNAI) (www.fnai.org) has conducted extensive landscape-level conservation planning but used the Framework and the approaches outlined in this paper to assess how well climate adaptation is integrated into Florida's current conservation planning efforts. Current planning adequately implements approaches 1, 2, and 4 (Table 1) across all three levels of ecological analysis (see Figure 2). However, adaptation approaches that focus on using geophysical settings as a surrogate of biodiversity (3, Table 1), or those focused directly on assessing climate change effects (5 and 6, Table 1), had not been considered. FNAI thus gathered further data to assess and prioritize areas of land cover heterogeneity in relation to projected sea-level rise. Areas of high land cover heterogeneity were considered better adapted for sea-level rise, as these locations should support a greater diversity of species than more homogenous locations. By identifying habitat heterogeneity hotspots (defined as 25 hectare units with 6 or more habitat types) in relation to connectivity, habitat fragmentation, and ecological integrity, FNAI was able to develop a dataset that prioritizes coastal landscapes and habitats in terms of sea-level rise adaptation potential (Figure 3).

Their analysis addressed the three climate adaptation approaches identified in Table 1 previously missing in Florida conservation planning: (1) protect the geophysical setting, (Adaptation Approach 3); (2) identify and appropriately manage areas that will provide future climate space for species expected to be displaced by climate change, (Adaptation Approach 5); and (3) protect climate refugia (Adaptation Approach 6). Habitat heterogeneity was used as a surrogate for geophysical setting in this analysis because the low topographic relief and limited resolution of soils data within the planning area were insufficient to differentiate geophysical setting at a meaningful scale.

Although the results of the habitat heterogeneity analysis have not been fully integrated into FNAI's overarching evaluation of environmental land acquisition projects, it is apparent even from casual observation that areas identified as having high value for protecting current patterns of biodiversity, or as having high value for providing ecological connectivity, are not necessarily co-located with areas having high value for habitat heterogeneity. Thus, while there often appears to be relative agreement in conservation priorities for current conservation efforts, this may not hold true for efforts focused on future conditions resulting from climate change.

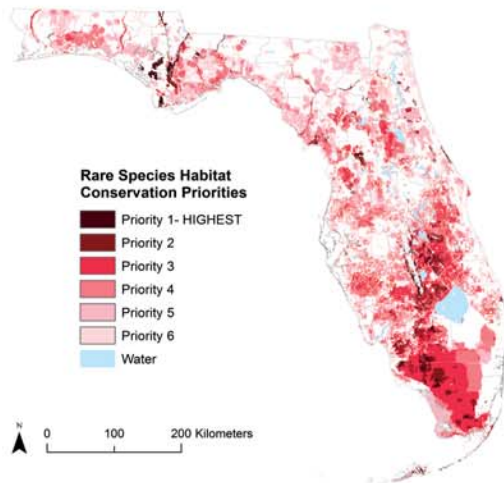
The integration of the habitat heterogeneity analysis, an approach that anticipates future conditions and is distinguished by an inherently greater level of uncertainty, with existing conservation analyses focused on current conservation values is challenging, especially when applied to the practical problem of ranking environmental land acquisition projects. FNAI anticipates that for areas where the conservation value of the habitat heterogeneity analysis corresponds with values from existing analyses, whether high or low, the conservation value of these areas will be reinforced. The results are a first step at a statewide account for sea-level rise associated with climate change and its effects on biodiversity.

Case example 2: cross-walking the Framework matrix to develop coherent adaptation plans

In general, a conservation planning process

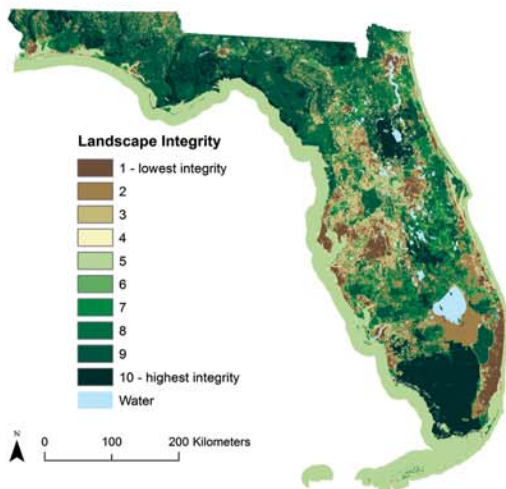
can be partitioned into three stages: (1) selecting a suite of important resources in a region; (2) assessing the vulnerability of those resources to climate change (which includes a priori specification of data requirements for the assessment); and (3) conducting spatial analysis and mapping to inform and guide the implementation of adaptation approaches. The Framework is designed to offer guidance on all three stages to help ensure buy-in by managers throughout the design and implementation stages. This value can be realized by engaging managers and planners in workshop exercises that involve cross-walking the matrix. Cross-walking is the process of using composite maps produced for one matrix cell in synergy with composite maps from other cells in the matrix (e.g., see stylized composite maps in Figure 1) when creating management plans. Cross-walking between multiple adaptation approaches and ecological levels provides complementary insight to help practitioners cope with uncertainty. For example, the California Landscape Conservation Cooperative (CA LCC) recently identified critical resources in the Sierra Nevada region. The Framework matrix was presented to members of the Sierra Nevada LCC to assess the vulnerability of those resources to climate change and then examine appropriate actions to reduce current and future stressors. Members identified which cells in the matrix are already being addressed in ongoing projects, identified cells for which data were available but not yet used in assessments in support of the adaptation approach, and cells for which data were unavailable. While this group was familiar with most of the adaptation approaches independently, the Framework provided a structure to foster dialogue about key adaptation approaches and ecological levels that could be implemented, and identified gaps in spatial analysis and mapping needs and opportunities for future projects and collaboration.

A second workshop convened a group of regional and local US Bureau of Land Management staff that undertook a cross-walk exercise to illustrate the value of considering multiple adaptation approaches in order to provide complementarity among the different ecological levels and

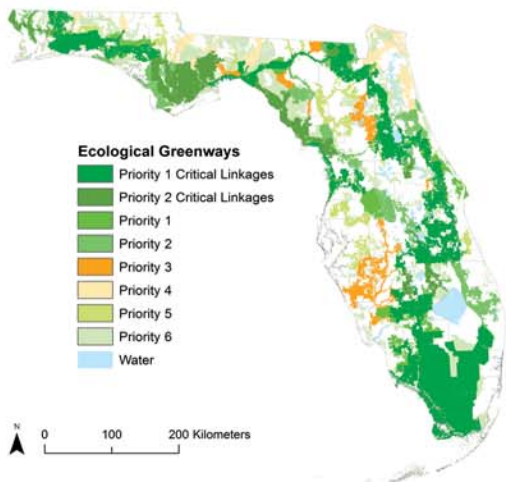


Protect current patterns of biodiversity. This Rare Species Habitat conservation Priorities analysis includes occurrence-based habitat for 248 species with a high conservation need including plants, invertebrates, and vertebrates. Individual species maps are weighted according to conservation need and overlaid to reflect values for both rarity and richness. The final layer prioritizes places on the landscape that would protect both the greatest number of rare species and those species with the greatest conservation need.

See: www.fnai.org/FIForever.cfm



Protect large intact natural landscapes and ecological functions and processes. This analysis uses two models to evaluate landscape integrity: natural land cover patches size and land use intensity. Higher values indicate large expanses of remote, intact natural and semi-natural areas such as the Everglades or the Apalachicola and Ocala National Forests. Lower values indicate more fragmented landscapes with increasingly intensive land uses ranging from agriculture to urban development. See: www.fnai.org/clip.cfm



Maintain and restore connectivity. The Ecological Greenways Network is a statewide system of landscape hubs, linkages, and conservation corridors. Prioritization is based on importance for wide-ranging species, importance for maintaining a connected reserve network, and riparian corridors. Critical Linkages are considered most important for completing a statewide ecological network of public and private conservation lands. See: www.state.fl.us/gwt/network/network.htm

Figure 2. Examples of conservation planning maps generated by considering three different adaptation approaches within the state of Florida.

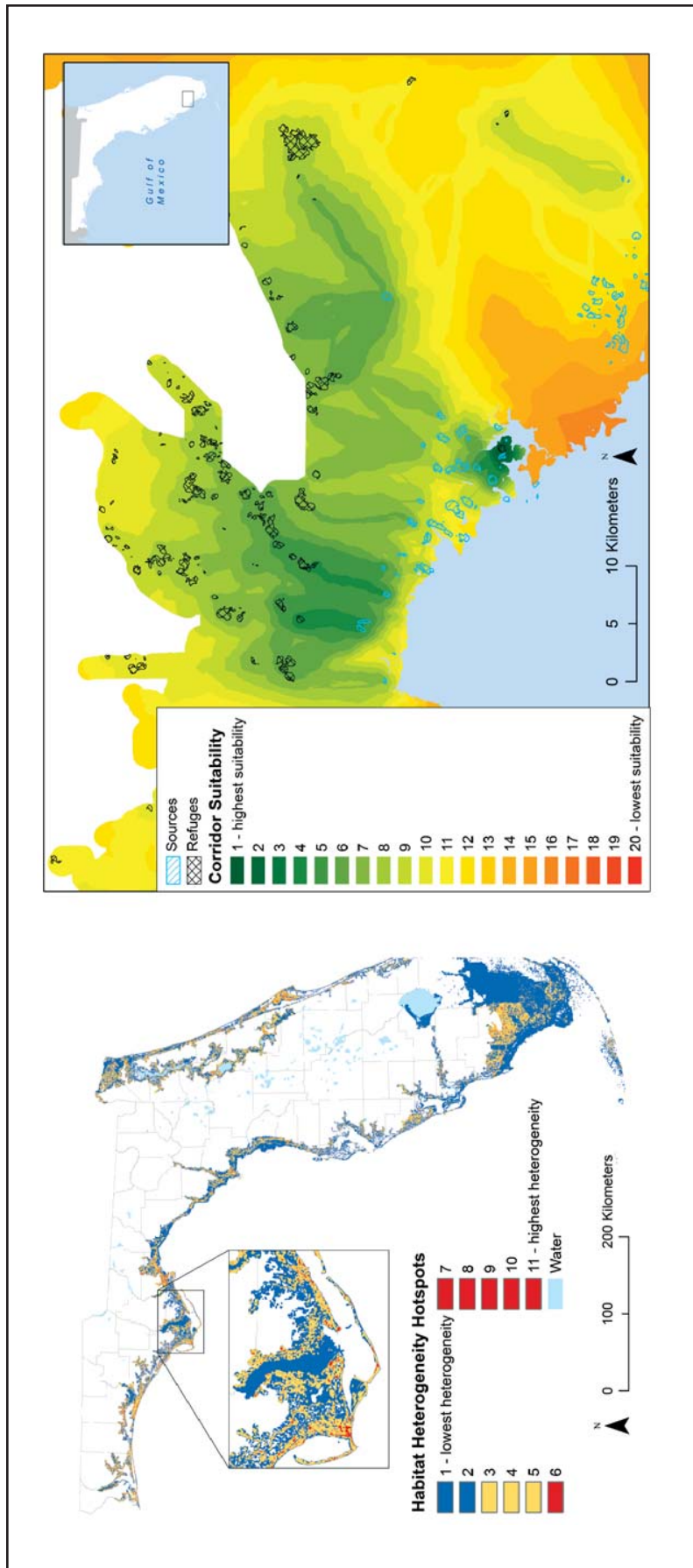


Figure 3. Habitat heterogeneity hotspots for sea-level rise mitigation planning. This analysis identifies planning units with six or more landcover types per 25 hectare unit along the Florida coast 0–3 meters above sea level. Corridor suitability surface (1 = highest suitability), linking habitat heterogeneity hotspots less than 1 meter in elevation (but not intersecting areas of 3 meters or more in elevation (sources)) with habitat heterogeneity hotspots greater than 3 meters in elevation.

local and regional spatial scales at which the different staff operated. This exercise began by presenting maps derived from assessments for the different adaptation approaches to demonstrate how they can be integrated with one another to address both climate and non-climate stressors in management plans. Workshop participants felt that the Framework offered a strategic way to organize data at multiple ecological levels. The Framework could also guide the drafting of a revised conservation plan by using the matrix as a cross-check to ensure all relevant adaptation approaches and ecological levels were included in the plan.

In both workshops, participants were able to use the Framework to enhance the organizational capacity and identify resources needed to achieve a coherent adaptation plan. The matrix also encouraged participants to be more specific about what they wanted to achieve and to assess alternative approaches in order to stay on task and budget. The structure of the matrix also provided a succinct way to assemble and evaluate all of the mapping products from different assessments *before* prioritizing conservation opportunities for adaptation. Overall, cross-walking through the Framework matrix helped practitioners emphasize conservation planning at multiple scales, address uncertainty, and integrate core elements of conservation science into adaptation planning.

DISCUSSION: THE FRAMEWORK'S STRATEGIC AND TACTICAL VALUE

Tactically, the Framework is designed to spur deliberate consideration of the different approaches and scales of analyses prior to conducting an assessment. Many assessments focus on a subset of the adaptation approaches. For example, one may choose to conduct assessments that support the maintenance or restoration of ecological connectivity when dealing with species that are expected to undergo major shifts in geographic range in response to climate change (Adaptation Approach 4). One may choose to conduct assessments that identify parcels of land within a watershed or along a seacoast that will support biodiversity in the future as sea level rises (Adaptation Ap-

proach 5). 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, data and tools that are already in hand drive assessments. This can then lead to assessment outcomes that will fail to meet the needs of planners, and hence risks inappropriate adaptation action.

Most importantly, the Framework can help reason through the mechanics of aligning results of conservation assessments with the landscape-scale planning. This is predicated on the assumption that any assessment for biodiversity and climate adaptation has undertaken the normal preliminary steps to ensure that the assessment output will be aligned with the needs of planners. These steps include: (1) understanding the goals and the information needs of the planning process; (2) understanding how different stakeholder values are incorporated into the project plan; (3) understanding the methodology and approaches used by planners to reach decisions about land allocation for compatible uses; and (4) understanding how stakeholder values are weighted to reach final decisions about actions and how the final decision is reached. Developing maps as a product of assessments is a very useful way to foster scenario-building exercises, through iterated processing of maps and information, thus enabling policy-makers and managers to visualize not only current, but also potential future consequences of particular decisions that may be conflated or confounded by climate change.

As an example, consider a hypothetical trade-off decision about two laudable actions to protect the environment: conserving endangered species now and into the future on the one hand, and siting power lines that potentially transmit energy from renewable generation sources like wind or solar to urban centers (Figure 4). We recognize that such trade-off decisions can be complex, requiring the optimization of multiple objectives. The highly oversimplified example we presented here is merely to illustrate how assessments in support of trade-off decisions could work.

According to the Framework guidance, one would need to assess the current and future spatial locations of the species' populations across a landscape, based on the species' habitat needs and biophysical conditions that it can tolerate. This information is used to identify crucial landscape locations that need to be conserved to support the species' persistence. This information can complement maps depicting proposed transmission corridors to generate a combined map that helps identify potential conflicts between the two proposed land uses (Figure 4). But, the decisions about what land to conserve and what to dedicate for energy transmission can differ, depending on the time horizon of the conservation assessment. Under current conditions, the optimal transmission route would be the middle corridor, as the other two would impact critical habitat locations of two of the three species' populations (Figure 4). But choosing the middle corridor could jeopardize the species if future climate caused the species' populations to shift their geographic range. In the hypothetical example, climate change is expected to cause one population to move out of the focal landscape region, making it no longer of conservation concern for the specific case of planning transmission routes. But the other two populations are expected to shift northeastward and converge into the middle of the landscape, squarely into the optimal transmission corridor identified for current conditions. The better corridor, considering current and future climate together, would be the upper route. Even though that route might impact a small part of one population's habitat in the near-term, it is least likely to impact the viability of all of the populations over the longer-term. The lesson here is that failing to consider a climate future—i.e., a dynamic landscape—could result in misguided outcomes if the siting decision impeded movement of the species' populations or destroyed habitat locations that would otherwise have become future climate spaces for the species.

Strategically, the Framework creates a common language and overarching vision to foster collaboration and policy coordination among government and nongovernment organizations and agencies that

routinely have different political jurisdictions and purviews. Indeed, this is a key socio-political adaptation strategy (Heller and Zavaletta 2009). For example, many national governments are committing to develop coherent climate adaptation policy (Game et al. 2011), yet they are often comprised of multiple agencies whose efforts may be overlapping or conflicting.

Agencies and organizations often operate at different spatial scales and have goals that pertain to different levels of ecological organization (i.e., species, ecosystem, landscape), and conservation/adaptation strategy can help to envision how each entity's efforts can be realigned to encourage inter-agency complementarity and synergism when developing national adaptation policy. The Framework can encourage consideration of the implications of specific adaptation actions within a broader geographic context. For instance, many local municipalities, land trusts, and NGOs (nongovernmental organizations) undertake their planning within geographic scales defined by their political jurisdictions. But these are often embedded within larger landscapes. So, while a decision to reallocate a small parcel of habitat or enduring feature within a local planning jurisdiction might seem appropriate given local stakeholder values, that habitat or feature may be a critical part of an ecological process taking place across the broader landscape. Failure to consider the broader context could jeopardize species viability if the habitat belonged to a larger constellation spread across a landscape and that is occupied only during part of a species' life cycle. Moreover, given that climate change is likely to cause long-range movements by species, it will become increasingly important to consider the strategic value of individual habitat units or enduring features as part of a larger network within entire ecological regions (e.g., forest ecoregion when considering a forested tract of land; a watershed when considering a series of freshwater streams or lakes; a state's coastal zone when considering a salt-marsh estuary). Finally, the Framework can identify deficiencies or even key gaps in our scientific knowledge. At the species level, we know a lot about current and future patterns of biodiversity and how to

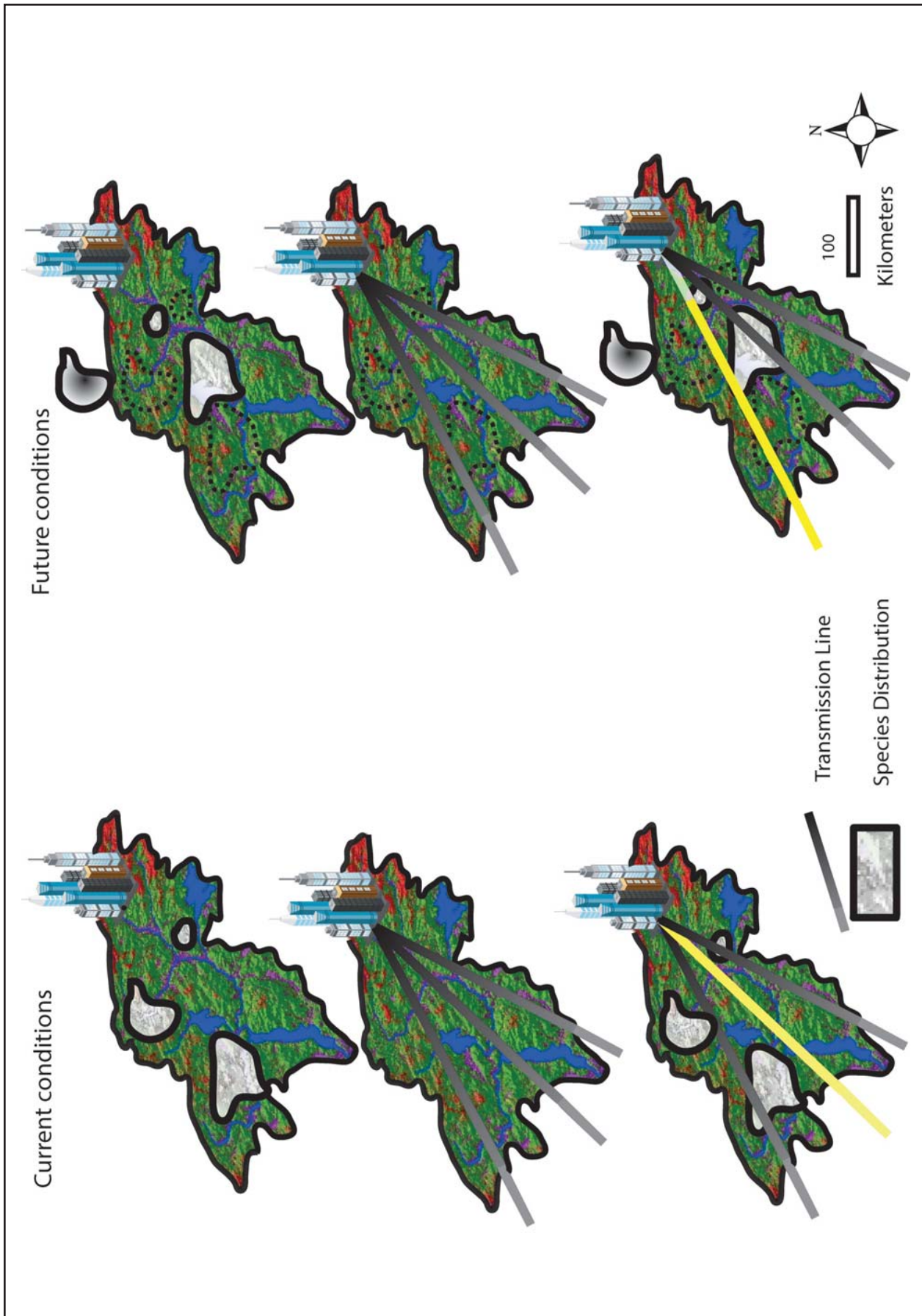


Figure 4. A hypothetical example depicting the tactical value of considering both current and future climatic conditions when planning for competing uses of land. The case example pits protection of three populations of an endangered species against three options for siting a power line corridor. Under current conditions, the optimal power line corridor (depicted in yellow) would run through the center of the landscape because it minimizes the impact on the species populations. However, building along the middle corridor could lead to the demise of two species populations in a climate future. The better option, after considering where the species populations are expected to shift as climate changes, is the upper corridor (depicted in yellow) because it has a lower impact on all three populations.

carry out appropriate assessments, possibly a holdover of a very species-centric tradition in conservation. By contrast, we know much less about assessing and implementing adaptation approaches at the more critical ecosystem and landscape levels, especially as regards to climate refugia and enduring features, approaches that are increasingly touted as being key to maintaining resistance and resilience under climate warming (Game et al. 2011; Groves et al. 2012).

CONCLUSIONS

The Framework provides a vision on how to enlist and align institutional capacity, and analytical tools to protect biodiversity in an era of climate change. Operationally, it provides guidance on whether and how to systematically consider which combination of six adaptation approaches at three distinct levels of ecological organization should be used in conservation assessments. The Framework offers insights on how to establish a baseline of current environmental conditions, identify which ecological features will likely be most vulnerable to climate change, and visualize the future needs of the most vulnerable species, ecosystems, and landscapes.

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LITERATURE CITED

Anderson, M., and C. Ferree. 2010. Conserving the stage: climate change and the geophysical underpinnings of species diversity. *PLoS One* 5:e11554.

Ashcroft, M. 2010. Identifying refugia from climate change. *Journal of Biogeography* 37:1407-1413.

Barnosky, A.D. 2009. Heatstroke: Nature in an Age of Global Warming. Island Press, Washington, DC.

Beever, E.A., C. Ray, J. Wilkening, P.F. Brusard, and P.W. Mote. 2011. Contemporary climate change alters the pace and drivers of extinction. *Global Change Biology* 17:2054-2070.

Beier, P. 2012. Conceptualizing and designing corridors for climate change. *Ecological Restoration* 30:312-319.

Beier, P., and B. Brost. 2010. Use of land facets to plan for climate change: Conserving the arenas, not the actors. *Conservation Biology* 24:701-710.

Brooke, C. 2008. Conservation and adaptation to climate change. *Conservation Biology* 22:1471-1476.

Brost, B.M., and P. Beier. 2012. Use of land facets to design linkages for climate change. *Ecological Applications* 22:87-103.

Cross, M.S., E.S. Zavaleta, D. Bachelet, M.L. Brooks, C.A.F. Enquist, E. Fleishman, L.J. Graumlich, C.R. Groves, L. Hannah, L. Hansen, G. Hayward, M. Koopman, J.J. Lawler, J. Malcolm, J. Nordgren, B. Petersen, E.L. Rowland, D. Scott, S.L. Shafer, M.R. Shaw, G.M. Tabor. 2012. The Adaptation for Conservation Targets (ACT) framework: a tool for incorporating climate change into natural resource management. *Environmental Management* 50:341-351.

Currie, D.J., and V. Paquin. 1987. Large scale biogeographical patterns of species richness of trees. *Nature* 329:326-327.

Davies, R.G., C.D.L. Orme, D. Storch, V.A. Olson, G.H. Thomas, S.G. Ross, T.S. Ding, P.C. Rasumussen, P.M. Barnett, I.P.F. Owens, T.M. Blackburn, and K.J. Gaston. 2007. Topography, energy and the global distribution of bird species richness. *Proceedings of the Royal Society of London B* 164:1189-1197.

Dobrowski, S.Z. 2010. A climatic basis for microrefugia: the influence of terrain on climate. *Global Change Biology* 17:1022-1035.

Faith, D.P., and P.A. Walker. 1996. How do indicator groups provide information about relative biodiversity of different sets of areas? On hotspots, complementarity, and pattern-based approaches. *Biodiversity Letters* 3:18-25.

Galatowitsch, S., L. Frelich, and L. Philips-Mao. 2009. Regional climate change adaptation strategies for biodiversity conservation in a midcontinental region of North America. *Biological Conservation* 142:2012-2022.

Game, E.T., G. Lipsett-Moore, E. Saxon, N. Peterson, and S. Sheppard. 2011. Incorporating climate change adaptation into national conservation assessments. *Global Change Biology* 17:3150-3160.

Glick, P., B.A. Stein, and N.A. Edelson. 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, DC.

Groves, C.R., E.T. Game, M.G. Anderson, M. Cross, C. Enquist, Z. Ferdana, E. Girvetz, A. Gondor, K.R. Hall, J. Higgins, R. Marshall, K. Popper, S. Schill, and S.L. Shafer. 2012. Incorporating climate change into systematic conservation planning. *Biodiversity Conservation* 21:1651-1671.

Hannah, L., G.F. Midgley, T. Lovejoy, W.J. Bond, M. Bush, J.C. Lovett, D. Scott, and F.I. Woodward. 2002. Conservation of biodiversity in a changing climate. *Conservation Biology* 16:264-268.

Heller, N.E., and E.S. Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation* 142:14-32.

Hunter, M.L., G.L. Jacobson Jr., and T. Webb III. 1988. Paleoecology and the coarse-filter approach to maintaining biological diversity. *Conservation Biology* 2:375-385.

[IPCC] Intergovernmental Panel on Climate Change. 2007. *Climate change 2007: Synthesis Report*. IPCC, Geneva, Switzerland.

Iverson, L.R., and A.M. Prasad. 2001. Potential changes in tree species richness and forest community types following climate change. *Ecosystems* 3:186-199.

Johnston, K.M., and O.J. Schmitz. 1997. Wildlife and climate change: Assessing the sensitivity of selected species to simulated doubling of atmospheric CO₂. *Global Change Biology* 3:531-544.

Kareiva, P., and M. Marvier. 2003. Conserving biodiversity coldspots. *American Scientist* 91:344-351.

Klein, C., K. Wilson, M. Watts, M.J. Stein, S. Berry, J. Caewardine, M.S. Smith, B. Mackey, and H. Possingham. 2009. Incorporating ecological and evolutionary processes into continental-scale conservation planning. *Ecological Applications* 19:206-217.

Lawler, J.J., S.L. Shafer, D. White, P. Kareiva, E.P. Maurer, A.R. Blaustein, and P.J. Bartlein. 2009. Projected climate-induced faunal change in the Western Hemisphere. *Ecology* 90:588-597.

Lawler, J.J., T.H. Tear, C. Pyke, M.R. Shaw, P. Gonzalez, P. Kareiva, L. Hansen, L. Hannah, K. Klausmeier, A. Aldous, C. Bienz, and S. Pearsall. 2010. Resource management in a changing and uncertain climate. *Frontiers in Ecology and the Environment* 8:35-43.

Mawdsley, J.R., R. O'Malley, and D.S. Ojima. 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology* 2:1080-1089.

Neilson R.P. 1995. A model for predicting continental-scale vegetation distribution and water balance. *Ecological Applications* 5:362-385.

- Núñez T.A., J.J. Lawler, B. McRae, D.J. Pierce, M. Kavanagh, P.H. Singleton, and J.J. Tewksbury. 2013. Connectivity planning to address climate change. *Conservation Biology* 27:407-416.
- Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology and Systematics* 37:637-669.
- Pearson, R.G., and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Change Biology* 12:361-371.
- Phillips, S.J., P. Williams, G. Midgley, and A. Archer. 2008. Optimizing dispersal corridors for the Cape Proteaceae using network flow. *Ecological Applications* 18:1200-1211.
- Poiani, K.A., R.L. Goldman, J. Hobson, J.M. Hoekstra, and K.S. Nelson. 2011. Redesigning biodiversity conservation projects for climate change: Examples from the field. *Biodiversity Conservation* 20:185-201.
- Rehfeldt, G.E., N.L. Crookston, C. Saenz-Romero, and E.M. Campbell. 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. *Ecological Applications* 22:119-141.
- Sanderson, E.W., K.H. Reford, A. Vedder, P.B. Coppolillo, and S.E. Ward. 2002. A conceptual model for conservation planning based on landscape species requirements. *Landscape and Urban Planning* 58:41-56.
- Schloss, C.A., J.J. Lawler, E.R. Larson, H. Papendick, M.J. Case, D.M. Evans, J.H. Delap, J.G.R. Langdon, S.A. Hall, and B.H. McRae. 2011. Systematic conservation planning in the face of climate change: Bet-hedging on the Columbia Plateau. *PLoS ONE* 12:e28788.
- Sinclair, A.R.E., D.S. Hik, O.J. Schmitz, G.G.E. Scudder, D.H. Turpin, and N.C. Larter. 1995. Biodiversity and the need for habitat renewal. *Ecological Applications* 5:579-587.
- Spencer W.D., P. Beier, K. Penrod, M. Parisi, A. Pettler, K. Winters, J. Strittholt, C. Paulman, and H. Rustigian-Romsos. 2010. California Essential Habitat Connectivity Project: A strategy for conserving a connected California. Report prepared for California Department of Transportation and California Department of Fish and Game. <<http://www.dfg.ca.gov/habcon/connectivity/>>.
- Spittlehouse, D.L., and R.B. Stewart. 2003. Adaptation to climate change in forest management. *BC Journal of Ecosystems and Management* 4:1-11.
- Theobald, D.M. 2010. Estimating natural landscape changes from 1992 to 2030 in the conterminous USA. *Landscape Ecology* 25:999-1011.
- Theobald, D.M., S.E. Reed, K. Fields, and M. Soule. 2012. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. *Conservation Letters* 5:123-133.
- Thomas, C.D., P.K. Gillingham, R.M. Bradbury, D.B. Roy, B.J. Anderson, J.M. Baxter, N.A.D. Bourn, H.Q.P. Crick, R.A. Findon, R. Fox, J.A. Hodgson, A.R. Holt, M.D. Morecroft, N.J. O'Hanlon, T.H. Oliver, J.W. Pearce-Higgins, D.A. Proctor, J.A. Thomas, K.J. Walker, C.A. Walmsley, R.J. Wilson, and J.K. Hill. 2012. Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Science USA* 109:14063-14068.
- Vermeer, M., and S. Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences USA* 106:21527-21532.
- Vos, C.C., P. Berry, P. Opdam, H. Baveco, B. Nijhof, J. O'Hanley, C. Bell, and H. Kuipers. 2008. Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. *Journal of Applied Ecology* 45:1722-1731.
- [WHCWG] Washington Habitat Connectivity Work Group. 2010. Connected Landscapes Project. WHCWG, Seattle. <<http://wacnected.org/>>.