A Framework and Guidance for Integrating Climate Adaptation and Landscape Conservation Planning

This document is the product of a collaboration of nationally recognized scientists and policy experts, and is intended to provide a description of the tools that can be used to implement and achieve a "climate-smart" ***ecological assessment****. The general purpose of this document is to help resource planners identify areas that are important to allow plant and wildlife species (biodiversity) to adapt to a changing climate, independent of any social or economic factors that are associated with* ***conservation planning****. The intended audience of this document is the highly informed, technical practitioner who seeks to integrate climate-smart ecological assessments into* ***planning for land and water use****. Additional documents are available for other audiences interested in this work, such as policy-makers and high-level decision-makers.*

Introduction

Debates about anthropogenic origins aside, scientific evidence demonstrates that the Earth's climate is changing. Many species are responding to this changing climate by shifting their geographic ranges. In response to climate change, we should expect both an influx of new species to geographic locations and a concomitant loss of species that have historically thrived within those locations. The differential rates at which species will shift their ranges will also result in a reshuffling of species relationships, **ecological processes**, and related **ecosystem services**.

Can visitors still expect to see mountain goats in National Parks within the Rocky Mountains? What **invasive species** may arise inside **protected areas** or across the **landscape**? Which species are particularly sensitive to climate stresses because of their narrow range of thermal and hydrologic tolerances or because they are restricted to disappearing **habitats**? Do we need to protect potential areas that represent **refugia**? Do we need to identify and manage corridors that could facilitate movements, or is it sufficient to identify and attend to barriers to movement that are limiting species range shifts across a landscape or watershed?

Conservation planners are now faced with the challenge of developing and implementing assessments for land allocation that supports biodiversity conservation in the face of climate change. While many spatial approaches and datasets supporting assessments are available for **climate adaptation**, there is considerable confusion about which approaches are best to ensure that **biodiversity** is appropriately considered in planning for land and water use.

This document presents a framework—the Yale framework—that offers a menu of approaches appropriate for ecological assessments to support conservation planning in a changing climate. It is not a step-by-step "cookbook." It does not replace existing approaches and it does not develop new approaches. Rather, it offers guidance on appropriate strategies for **climate-smart** ecological assessments and the tools to implement them. The intention is to help identify effective and scientifically defensible climate adaptation strategies based on the best current approaches to ecological assessments, with the general purpose being to enhance the effectiveness of policy decisions related to biodiversity preservation, climate change adaptation, and compatible land use. This is not a conservation prioritization exercise, instead, once conservation goals and priorities have been identified, this framework is intended to provide guidance on what analyses to undertake when developing climate-smart conservation planning.

Climate-smart plans are applicable to a wide range of planning situations. At one end of the spectrum, plans of non-profit conservation organizations like The Nature Conservancy or plans for National Parks or wilderness areas, may focus entirely or nearly so on conservation. In many cases, natural resource agencies at the state and federal level are required to prepare plans that have multiple objectives, including extractive uses of resources such as grazing or timber harvest as well as more conservation-oriented objectives. At the other end of the spectrum, conservation objectives may play an important but minor role in land-use plans prepared for local governments. The Yale Framework should prove useful to some degree to planners and planning processes in all of these different contexts.

Key examples of how the Yale Framework might be useful include the identification of important wildlife habitat and corridors to assist in a more strategic placement of renewable energy sites, and the development of a portfolio of potential conservation lands that could be acquired in anticipation of future sea level rise or loss of existing habitat.

The Yale Framework is being developed by a science panel drawn from state and federal government agencies, universities, and from the for-profit and non-profit private sectors.

The members were chosen for diverse and complementary expertise. The thirteen members are:

- Paul Beier, Professor of Conservation Biology and Wildlife Ecology, Northern Arizona University School of Forestry
- Douglas (Sandy) Boyce, National Wildlife Ecologist, USDA Forest Service
- Jason Bulluck, National Heritage Information Manager, Virginia Department of Conservation and Recreation
- Craig Groves, Director of the Conservation Methods Team, The Nature Conservancy
- Kevin M. Johnston, Product Engineer, Environmental Systems Research Institute
- Mary Klein, President & CEO, NatureServe
- Gary Knight, Director, Florida Natural Areas Inventory
- Joshua Lawler, Associate Professor, University of Washington School of Forest Resources
- Kit Muller, Strategic Planner, Bureau of Land Management
- John Pierce, Chief Wildlife Scientist, Washington Department of Fish and Wildlife
- James Strittholt, President and Executive Director, Conservation Biology Institute
- David M. Theobald, Research Scientist and Assistant Professor, Colorado State University Department of Fish, Wildlife, and Conservation Biology
- Stephen C. Trombulak, Professor of Biology and Environmental Studies, Middlebury College

Dr. Oswald Schmitz of the Yale School of Forestry and Environmental Studies is the project lead. William Singleton of Singleton Strategies LLC has worked with Dr. Schmitz to plan and oversee the process and help guide the Science Panel in its deliberations.

Objectives and Process

The goals of the Science Panel are to: (1) recommend strategies and associated tools and data to conduct assessments for biodiversity conservation in an era of climate change; (2) develop a broad framework to identify important areas needed to conserve biodiversity in a changing climate; (3) evaluate the Framework by funding independent teams to apply the Framework and by inviting peer review.

Thus far, the Science Panel has spent approximately six months building consensus around assessment approaches and data that can be applied to a broad range of planning contexts. This effort led to a Framework comprised of a matrix (see Table 1 below) and associated narrative intended to provide guidance and advice on how best to navigate through the different approaches, tools, and data to conduct an appropriate ecological assessment.

The Yale Framework will be evaluated through a process of grants to regional mapping and analysis teams that reflect the wide diversity of planning needs and challenges across the United States. These teams will use the Framework guidelines to implement geospatial analysis approaches pertinent to their respective regional planning contexts and objectives. After implementing and evaluating the Yale Framework, these teams will then provide feedback on the utility of its guidelines and the strengths and weaknesses in relation to each team's specific approach, objectives, scales, and planning timeframe. Teams will also identify improvements to the guidelines that are delineated in the Yale Framework. During this time the Science Panel will continue to refine the Framework as input from outside experts and policy makers is sought through a peer review process (Box 2).

Following this evaluation period, the Yale Framework will be finalized based on products and feedback provided by mapping and analysis teams during the re-grant process to better enable its potential to overcome obstacles confronted in the critical steps of the planning process. Finally, a process will be recommended for improving the Framework over time. This process will identify new tools and approaches to be developed to address future conservation planning needs, and will determine the most critical datasets for frequent and ongoing updates.

The tested and refined Framework will then be made available to the wider community of government and private actors, in order to help integrate climate adaptation strategies into efforts to plan for land and water use at the federal, state, county, and private-sector levels throughout the United States.

Framework Description

The Framework is intended to offer coherence on appropriate application of myriad approaches, tools, and data when conducting climate smart ecological assessments. Its development was guided by four requirements. (1) The Framework should not be overly prescriptive. Stakeholders and potential users should be provided with a clear overview of the major steps in an ecological assessment intended to develop climate adaptation strategies. At the same time, it should present options rather than a single prescription. (2) Emphasis should be placed on assessment approaches that are, whenever possible, based on empirical data rather than modeled data, which tend to have greater certainties, or more robust to uncertainty. Where uncertainty does exist, it should be clearly identified. (3) Recognizing the large body of scientific literature on conservation planning to meet goals related to representation, species coverage, and maintenance of ecological functions under current conditions, the Framework should focus solely on practical steps to add climate adaptation to such conservation planning efforts. (4) The Framework should focus on **spatially explicit** strategies. Some climate adaptation strategies are not spatially explicit – examples include increasing connectivity, establishing new reserves, and expand existing reserves without specifying where those should be done. The Framework focuses on spatially explicit approaches to such conservation assessments.

The Framework is based on the Science Panel's consensus about assessment approaches, tools and data that offer the greatest potential to provide insights about climate adaptation as a part of conservation planning in all terrestrial and aquatic **ecosystems**. The summary matrix (Table 1) provides an overview of six different adaptation objectives that one may employ in an assessment. This matrix is intended to encourage deliberate consideration of the different approaches and tools *prior to* conducting an assessment and to foster agility in their use during the assessment process. The information provided in the matrix is focused on guidance for identifying areas of importance for biodiversity in the face of climate change. At the same time, the Science Panel recognizes that most planning efforts at a landscape or watershed scale likely will consider other objectives and resource uses that influence the conservation and management of biodiversity and natural resources. For example, some lands and waters have multiple use objectives intended to benefit society at large, such as commercial development, road building, timber harvest, grazing management, energy development, and fisheries harvest . These activities have the potential to interact synergistically with environmental impacts related to climate change. And through habitat degradation, habitat loss, and fragmentation of landscapes and watersheds, these activities can, by themselves, result in losses of biodiversity that this framework is intended to abate and mitigate. More importantly, these sorts of land-use activities will often result in additional challenges to implementing the adaptation strategies outlined below. To the degree that these sorts of landscape and watershed stressors can be addressed in a landscape plan, the adaptation strategies outlined below will have a greater probability of succeeding.

Human communities are responding to climate change impacts in a number of ways that planners will need to confront. For example, sea walls and dikes are being established to combat sea-level rise, biofuels are being developed in part to reduce carbon emissions, communities surrounded by forests are being "fire-proofed" in response to increasing frequency and severity of climate-induced changes in wildfire regimes, and new dams and reservoirs are being proposed in areas expected to experience long-term declines in precipitation. Although it is beyond the scope of this framework to consider how adaptation strategies may best be implemented in all of these varied circumstances, some segments of the biodiversity conservation community are increasingly focused on adaptation solutions that represent "win-win" scenarios for both ecological and human communities. In many cases, using ecosystem-based solutions to reduce climate-related hazards to humans reduce costs because they are less reliant on expensive and repeated engineering and management interventions. Such solutions are referred to as Ecosystem-based Adaptation under the auspices of the United Nations Convention on Biological Diversity. Examples of these are highlighted below in the section of this framework on consideration of adaptation objectives.

An important consideration for any landscape planning context in which human communities are responding or need to respond to climate change is whether there is sufficient adaptive capacity within the local communities. Two factors tend to shape the adaptation responses of human communities: 1) the existing capacity of the affected community, and 2) the level of information about projected climate impacts and potential ways to minimize and adapt to those impacts. To the extent that use of the framework provides relevant information, it contributes to the adaptive capacity of human communities.

Table 1. Overview of different combinations of adaptation objectives and levels of ecological analyses that could be the focus of assessments of climate effects on biodiversity and habitat. Each cell of the matrix lists examples of appropriate approaches one would use to carry out an assessment. There may be approaches that we have not listed. Appendices are provided at the end of the document with detailed methodologies.

	Levels of Ecological Analysis		
Adaptation Objectives:	A. Landscapes	B. Ecosystems	C. Species and populations
1) Protect current patterns of biodiversity (baseline)	• Map genetic patterns across the landscape • Map **beta and gamma diversity** • Map **biodiversity hotspots**	• Map terrestrial and aquatic ecosystems and their associated services	• Assess population sizes and dynamics and phenological trends, or use existing status assessments (e.g., conservation status ranks) • Map occurrences of rare species and plant communities • Map distributions of more common species
2) Project future patterns of biodiversity	• Forecast land-use change • Project sea-level rise • Analyze climate-change	• Forecast vulnerability of ecosystems to climate change • Map areas that would support shifts in vegetation	• Forecast vulnerability of species and rare communities to climate change based on their capacity to adapt to environmental change • Map areas that would

	Levels of Ecological Analysis		
Adaptation Objectives:	A. Landscapes	B. Ecosystems	C. Species and populations
	projections • Map projected future biodiversity hotspots	types and/or biomes	support shifts in species distributions of vulnerable and/or indicator species or community types
3) Maintain ecological processes	• Analyze projected precipitation and temperature trends • Analyze projected extreme weather events • Map fragmentation and other factors related to **ecological integrity** (e.g., distance from disturbance)	• Map potential future patterns of fire, hydrology, carbon sequestration, and ecological integrity • Map where ecosystem services operate and, thus, provide human value	• Forecast how climate change factors may impact the viability of particular species populations or function of rare plant communities • Forecast climate change effects on pests, diseases, and invasive species • Forecast changes in animal behavior • Forecast climate change effects in phenology
4) Maintain and restore **ecological connectivity**	• Map connections between land facets, ecological land units, refugia, or areas of high ecological integrity	• Map connections between current and projected future locations • Anticipate species invasions along planned corridors	• Identify areas that are critical for species movements in a changing climate • Map movement corridors important for species life history and migration
5) Protect climate refugia	• Map recent drought refugia • Map areas of high topographic complexity • Map locations projected to maintain stable climates	• Map habitats with high natural resilience to climate change (e.g., spring-fed streams) • Map areas projected to experience little change in vegetation	• Identify areas that would continue to harbor species in the future or areas where populations would be stable or increase with climate change
6) Protect the ecological stage (enduring features)	• Map ecological land units or land facets • Map areas of high ecological integrity	• Map ecological land units or land facets • Map areas of high ecological integrity • Map climate facets based on current	N/A

	Levels of Ecological Analysis		
Adaptation Objectives:	A. Landscapes	B. Ecosystems	C. Species and populations
	• Map climate facets based on current climate patterns	climate patterns	

The matrix is organized according to three levels of ecological analysis (landscape; ecosystems; and species and populations) that could be considered for each of six adaptation objectives. This is based on the consensus that "climate-adaptive" conservation plans should be geared toward conserving not only species and their habitats, but should also ensure that ecological and evolutionary processes can continue to operate across landscapes over the coming decades of climate change. By contrast, most assessments that inform planning today continue to focus somewhat more narrowly on the upper-right section of this matrix (i.e., they map current and/or future species geographic ranges).

Box 2: Regional case studies implementing and evaluating the Framework guidelines.

Climate change adaptation strategies for the Bureau of Land Management resource management in southern Nevada. (Nature Serve): NatureServe will test several aspects of the Yale Framework by integrating and or downscaling assessment results from two BLM Rapid Ecoregional Assessments (REAs) with core recommendations from the Framework along the ecotone between the Central Great Basin and Mojave Desert Ecoregions. Results will be used to develop adaptation strategies for integration into state and field office planning by BLM Nevada to manage public land in a scientifically-defensible and effective way under rapid climate change conditions.

Protecting the ecological stage: applying and testing a land-facet-based approach to conservation planning in a changing climate (University of Washington): The University of Washington will explore the concept of protecting a diversity of abiotic conditions (land facets) as a means of protecting biodiversity in a changing climate. Research will be conducted across 14 ecoregions in the northwestern US and will result in mapped land facets that feed into an ongoing climate-change vulnerability assessment serving three state wildlife agencies, the National Park Service, and a regional conservation planning effort lead by The Nature Conservancy.

Rapid Assessment of the Framework and adaption blueprint for the Pacific Coastal Rainforest (Geos Institute): The **Geos Institute** will apply elements of the Yale Framework to Pacific coastal rainforests. Objectives are to: (1) compare baseline to future climate scenarios; (2) identify key processes likely to shift in response to climate change; and (3) identify relatively stable climatic areas that might function as microrefugia. Climate change models will be used to project potential shifts at regional, subregional, focal species, and microsite levels. The results will have application to forest planning, landscape conservation cooperatives of the US Fish & Wildlife Service, and high profile species.

Box 2 (continued):

Re-evaluating Florida Ecological Conservation Priorities in the Face of Sea-level Rise (Florida Natural Areas Inventory & Florida State University): Florida Natural Areas Inventory & Florida State University will incorporate a key element identified in the Yale Framework that is currently missing from Florida conservation planning—protecting the ecological stage. This project will evaluate habitat heterogeneity and available geophysical data to define the ecological stage in areas likely to be affected by sea-level rise by the end of this century. The resulting conservation value layer will be further refined to consider connectivity, habitat fragmentation, and ecological integrity, with results incorporated into ongoing statewide conservation planning efforts.

From the mountains to the sea: applying the Yale framework in western Washington for holistic adaptation (EcoAdapt): EcoAdapt will use the Framework to provide an integrated assessment of spatially explicit adaptation opportunities that address and link watershed function from terrestrial to freshwater to coastal systems in the Puget Sound Basin. The goal is to support climate savvy integrated watershed management action across ecosystem types.

Comparing alternative approaches for predicting future habitat conditions and distribution patterns for two forest carnivores of conservation concern in the sierra Nevada, California (Conservation Biology Institute): The **Conservation Biology Institute** has developed a project that compares and integrates alternative climate change analytical approaches at several spatial resolutions to address climate impacts on two rare forest-dependent carnivores – fisher *(Martes pennanti*) and marten (*M. americana* [*caurina*]). The integrated results on future habitat suitability for these two species will be used to advance our knowledge about how to best apply existing climate models and tools to support wildlife conservation, and will inform ongoing forest policy and management throughout the region.

A. General recommendations for an ecological assessment process that focuses on climate change

The following set of recommendations 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: understanding the goals and the information needs of the planning process; understanding how different stakeholder values are incorporated into the project plan; understanding the methodology and approaches used by planners in reaching decisions about land allocation for compatible uses; and understanding how stakeholder values are weighted in reaching final decisions about actions and how the final decision is reached. These general recommendations are:

(1) Assessments should be at a **resolution** that matches those at which decisions are made, and **spatial extent** should extend beyond the main jurisdictional area of interest, so that important ecological links to the larger landscape are considered. Given that climate change is likely to cause long-range movements by species, it will become increasingly important to conduct ecological assessments at spatial extents that represent entire **ecoregions**.

(2) More than just the species level of ecological analysis should be considered in assessments (hence the consideration of three levels of ecological analysis in Table 1).

(3) An assessment or prioritization for climate adaptation should be conducted for a 50 to 100 year time horizon. The major effects of climate change are likely to occur within this time horizon, even if humans stopped emitting greenhouse gasses today. Climate change cannot reliably be predicted farther into the future. If resources and time permits, it is encouraged to conduct a temporally explicit trajectory analysis (e.g., 15, 30, 60, and 100 years).

B. Consideration of adaptation objectives and levels of ecological analysis for the assessment

The Framework is built around the consideration of six major adaptation objectives for biodiversity conservation and climate adaptation and three levels of ecological analysis (see Table 1).

Users of the framework are encouraged to assess as many of the adaptation objectives and levels of ecological analysis as is feasible based on their planning context and the resources available. These objectives include:

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." Most plans will benefit from including this objective because it has the least uncertainty in the short term, and other adaptation strategies require it as a baseline state for future projections. The intent is to identify current patterns of biodiversity

across landscapes and reduce stressors as a way to increase the probability that key components of biodiversity (e.g., vulnerable species, habitat cores, and high value ecological processes) persist or improve into the future. This objective 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. Predator species may prevent prey population outbreaks thereby protecting ecosystems from damaging pests. Forest tree species within watersheds help to protect water quantity and quality.

2) *Forecast future patterns of biodiversity*. This adaptation strategy anticipates and protects the locations that will meet the habitat needs of biodiversity under future conditions. Many species and their habitats may respond to changing climate (especially temperature and hydrology) by undergoing shifts in their geographic ranges. Other climate-induced changes like sea-level rise or altered precipitation patterns may conflate these shifts in geographic ranges. Closely related to forecasting future patterns of biodiversity is the ability to forecast impacts of climate change such as sea-level rise and storm surges. Models and tools that make such predictions in combination with data on current patterns of biodiversity may help human communities develop plans that can capitalize on conserving ecosystems that provide natural solutions for reducing vulnerability.

3) *Maintain ecological processes*. This adaptation objective considers the functional roles of species and takes a more dynamic perspective than the previous two adaptation objectives. In addition, many ecological processes are not species-specific. Thus, processes such as fire and flooding, which have a strong biophysical component, also come into play. It also recognizes that species abundance and persistence may not simply be products of available habitat within an ecosystem, but that species may also be integral and active players determining how the ecosystem functions. Not only are ecosystems defined by their geographic location and spatial extent, they also reflect associated ecosystem services. For example, coastal ecosystems buffer coastlines from flooding and erosion during storm surges and upland forest in watersheds controlling surface runoff and erosion while reserving drinking water quality. Projects that focus on restoration of mangroves and coral reefs, for example, represent the "win-win" natural solutions to climate adaptation that help safeguard vulnerable human communities from storm surges and conserve and restore important ecological communities (see Ecosystem-based Adaptation in introductory section of this framework). The functions of such ecosystems are also maintained by food web interactions. Thus, conserving predators may be important not only to protect species with charismatic value but also to prevent loss of trees needed for watershed protection.

4) *Maintain and restore ecological connectivity*. This objective complements Adaptation Objective 2 by recognizing that species and their habitats could shift their distributions in response to climate change. It takes the further step to identify where that 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 goal is to ensure that species will be able to reach new locations that can support their populations as climate changes. While increasing habitat connectivity to facilitate gene flow and decrease the incidence of local extinction is usually the focus of conservation efforts, climate change could also create corridors that reduce wildlife populations by increasing disease transmission, colonization of exotic species, or lead to non-analog communities.

5) *Protect climate refugia.* This adaptation objective recognizes that many species may have limited capacities to evolve tolerances at a rate that is commensurate with the rate of future climate change. Consequently, there are risks that species may become extirpated throughout parts of their geographic ranges. One way to prevent some of these losses is to identify and protect climate refugia. Refugia are effectively safe havens on the landscape that provide the diversity of habitats and stability needed to promote persistence of biodiversity as regional biotic and abiotic environmental conditions change. In essence, they are locations that biodiversity can retreat to, persist in, and can potentially expand from under changing climate.

6) *Protect the ecological stage.* This adaptation objective effectively identifies and protects the current variety of landscape topography, geology/soils and associated abiotic conditions (including temperature and moisture) needed to support diversity of species that have different thermal, moisture etc. requirements for survival.

Assessments frequently focus on a subset of the adaptation objectives. The choice of adaptation objectives should be steered by the biological characteristics of the species of concern (Box 3). For example, one may choose to conduct assessments that support the maintenance or restoration of ecological connectivity if one is dealing with species that are expected to undergo major shifts in geographic range in response to climate change (Adaptation Objective 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 Objective 2). As a matter of sound practice, any assessment should be systematically motivated by a clear understanding and articulation of the conservation problem and associated ecological conditions *before* choosing the analysis approaches, tools, and data for the assessment. That is, let the conservation issue define what approaches, tools, and data are needed for the assessment. Oftentimes, assessments are driven by availability of data and tools rather than by clear problem definition, which can lead to assessment outcomes that will fail to meet the needs of planners.

Box 3: Example questions that could help to identify the biological characteristics of species in order to choose an appropriate adaptation strategy and level of ecological analysis for a climate assessment.

Identifying species needs

What are the vegetation types a species needs? What does it use each type for?

How much area does the species need to survive? Does the species require contiguous habitat, or can its habitat be fragmented? Does the species have specialized habitat or resource requirements? What are the ecological conditions a species desires? Are those conditions provided (will they be provided) on the landscape? What is the relative importance of each condition. Does the species undergo source/sink population dynamics? Does the species have different needs for different seasons? Is the species social? How does the species interact with humans or human-built environments? If the species is a predator, is its prey also being protected? Is the species competing with invasive species? If considering multiple species, what things do the species have in common? What do they have that are unique?

Identifying the nature of species movement
Does the species migrate or disperse seasonally? How far does the species travel in a year? What is the yearly movement pattern like? Do the criteria for identifying the best ecological conditions for movement complement the criteria for identifying the best conditions for feeding and reproducing?

Things to consider relative to climate change
How tolerant to heat or drought is the species? How does the species respond to changes in abiotic conditions like rainfall, snowfall, flooding etc.? How does the species fare at different elevations?

Once the adaptation objectives are chosen, the assessment can proceed with any of three levels of ecological analysis:

A. *Landscape level.* This level recognizes that there are important patterns across landscapes that are determined by a combination of geographical features such a topography and soils (land facets and ecological land units), as well as by the degree to which species assort themselves into communities.

B. *Ecosystem level.* This level recognizes that species and their habitats are components of ecosystems and, as such, species 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.

C. *Species, population, and highly restricted plant community level.* This level targets species or populations of conservation concern. For greatest efficiency, an assessment should only develop species-specific information for those species that are not adequately assessed at the ecosystem level either because they are rare, or have very specific or limited habitat requirements. Some plant communities with limited distributions and a small spatial footprint (e.g., fens) are usually better handled at this level. Assessments can be geared to understand current and future species distributions as well as population dynamics and movement patterns.

Ideally, assessments should be conducted for all three levels of analysis in order to be ecologically complete. However, this may not be feasible because of limitations imposed by available data or cost, or may not be desired because of stakeholder values and planning information needs. Nevertheless, it is recommended that assessments that focus on one level of analysis at least be placed into the context of the next higher level. For example, planners may only wish to understand the fate of focal species (e.g., desert tortoise, prairie chickens, sage grouse, pikas) under climate change. But considering the community context for these species' distributions (e.g., the species' food and habitat) would strengthen the species level assessment by providing insights about the fate of important resources supporting the species. Regardless, the approaches, tools, and data used to conduct assessments will differ between the levels of ecological analysis.

C. Navigating the assessment approaches and tools

The matrix (Table 1) is structured to provide a systematic way to arrive at an appropriate assessment approach and related tools. The first step is to select the desired adaptation objectives. Once the user has selected the appropriate adaptation objectives, he/she would select the desired level of ecological analyses. Most planning projects, unless they cover a very small spatial extent, will benefit from addressing all three levels of ecological analysis.

1) Protect current patterns of biodiversity

A. Landscape level: The landscape-level assessment aims to identify extant patterns of species and ecosystem distributions across large areas. This assessment can build on information gathered for the species and populations level by generating maps that present the aggregate of individual species distributions (i.e., provide a composite map built on individual species data layers). This composite map can be used to delineate biodiversity hotspots or quantify changes in the number and identity of species across a landscape.

B. Ecosystem level: Ecosystems – recognizable and consistent patterns of vegetation – are typically differentiated through a statistical analysis of abiotic features (e.g., soils) and vegetation observations via satellite and/or vegetation plots sampled in the field. Because a wealth of existing spatial data in this category is readily available (e.g., LANDFIRE, GAP vegetation maps, NatureServe ecosystem maps), most users can avoid developing their own classification systems and maps. A more efficient process is to use existing data on ecosystems in the focal planning jurisdiction and the surrounding landscape. Ecosystems often form the basis for evaluating potential mitigation sites, especially for wetlands.

A list of widely-used datasets portraying current ecosystems is provided in Appendix 3.

Building an accompanying data layer that identifies the major plant and animal species that comprise the community belonging to the suite of ecosystems within the planning area can enhance an appreciation of the level of biodiversity contained within it. Ecosystem maps can also provide an important foundation for understanding ecological processes and their associated ecosystem services, if those are also part of the assessment objectives.

C. Species, population, and highly restricted plant community level: Assessments at this level typically focus on delineating the current geographic ranges of species and highly restricted vegetation communities such as fens. Mapped information is typically based on geo-referenced data and insights on species presence gathered during scientific surveys and through the opinions of experts (e.g., natural heritage element occurrences, USGS-GAP distribution models, state wildlife agency maps). Because a wealth of existing spatial data is available in this category, most users can avoid creating their own distribution maps. A more efficient process is to establish priorities for which species to assess, then use existing distribution data to visualize the current situation or as input for predicting future distributions.

A list of widely-used datasets portraying current distributions for species and highly-restricted habitats is provided in Appendix 3.

If adequate data on current distributions are not already available for the planning area, there are a wide range of approaches and tools that quantify species geographic distributions, ranging from statistical regression that relates environmental variables and species presence and absence at particular geographic coordinates, to models and algorithms that quantify likelihoods of occurrence across a landscape. An overview of each of these approaches and tools, their data requirements, their strengths and weaknesses, and the required technical capacity of the user is provided in Appendix 1.

The species-level assessment may be enhanced to provide a more dynamic representation of current conditions by using population abundance and demographic data to estimate species or population viability. Population viability can be estimated for the landscape as a whole or in relation to different plant communities or land uses. This approach is often limited by the availability of spatially explicit data on population demography (e.g., age and sex structure, age-specific birth and death rates, migration rates, etc.) and abundance.

2) Forecast future patterns of biodiversity

A. Landscape level: The landscape-level assessment aims to identify future patterns in landscape conditions. An assessment can examine changes in biophysical conditions (e.g., sea level rise, changes in precipitation patterns) using outputs from climate assessments like the IPCC. They can also build on information gathered for the species and populations level by generating maps that present the future aggregate of individual species distributions (i.e., provide a composite map built on individual species data layers). This composite map can be used to delineate biodiversity hotspots or quantify changes in the number and identity of species across landscapes.

B. Ecosystem level: Assessments at this level aim to forecast future locations of plant communities. They employ modeling approaches that can map the geographic distribution of vegetation based on biophysical processes (e.g., nutrient cycling, moisture patterns, fire regimes). The models can project potential future locations of vegetation using biophysical data from global climate models such as those used in the IPCC process.

C. Species, population, and highly restricted plant community level: Assessments of future conditions involve models to forecast the geographic distribution and fate of species. These assessments use climate data generated by a host of different global climate models that each address different assumptions about future CO_2 emissions (summarized in IPCC Assessment Reports: http://www.ipcc.ch/publications_and_data/publications_and_data.shtml).

Two basic modeling approaches – both representing types of correlative bioclimatic envelope models – have been used to forecast the potential effects of climate change on species distributions: correlative models and mechanistic models. Correlative models generally link the current distributions of species with current climate using statistical models or machine-learning techniques. These models are often called species distribution models, niche models, climate-envelope models, and more generally, bioclimatic models. Mechanistic models attempt to simulate the distribution of a species based on understood mechanisms (e.g., moisture requirements, competitive interactions, experimentally-derived temperature tolerances). Theoretically, mechanistic models should be more robust for the purpose of projecting potential climate-change impacts; however, the data to build such models is often lacking. Substantial uncertainties are associated with both approaches due to uncertainties in the climate-change projections as well as in the empirical and theoretical relationships upon which the models are founded. Nonetheless, these models have been shown to capture recent range shifts for some species and provide projections that correspond with expected shifts in species distributions.

It is important to be mindful when using any of these approaches that future projections will be based on statistical associations, so that they cannot be used to infer cause-effect relationships. This is a limitation of any current approach to assess future consequences of climate change. Global climate models are built on uncertainties about the likelihood of different CO_2 emissions scenarios, as well as how different atmospheric CO_2 levels affect the climate system and the biophysical conditions determined by climate. Moreover, future projections based on statistical associations are inherently dependent upon the underlying assumptions of the specific model used to generate the climate and vegetation data. Consequently, decision-makers should be reluctant to use assessments based on data from a single global climate model if small changes in assumptions of any one model produce radically different projections about the future. It is therefore recommended that any of the above assessments should be repeated using input data that bracket the range of climate sensitivity projected by different global climate models. That is, it is recommended that assessments consider using worst-case change scenarios, average-change scenarios and minimal-change scenarios.

3) Maintain ecological processes

A. Landscape level: An assessment at this level of analysis aims to understand how biophysical gradients could change across landscapes. This involves mapping current and potential future climate patterns. Future climate gradients and spatial patterns in climate variability can be mapped using data from global climate models. Mapping climate patterns, especially temperature and precipitation gradients, represents a way to predict shifts in climate zones (e.g., plant hardiness zones, Holdridge life zones). These shifting climate zones can help predict distribution the distribution of species with varying climatic needs and tolerances. These changes may also stress large areas, creating the potential for catastrophic change. In addition, mapping the degree of variability in temperature and precipitation can be used to identify areas of potential climate stability across the landscape that can help to inform assessment 5 below.

B. Ecosystem level: Climate warming stands to reorganize communities and associated ecosystems across landscapes through species losses and gains, as well as differential rates of movement. This process of community disassembly and reassembly also means that assessment approaches may need to examine collections of species more directly and explicitly and determine how changing species composition influences ecological processes.

Assessments at this level can also draw on projected shifts in the distribution of plant communities. Similar to the modeling of species distributions, both mechanistic and correlative models have been used to model shifts in the distribution of suites of plant species. In general, correlative models project changes in the areas that are climatically suitable for today's flora, although some take into account dispersal abilities as well. Mechanistic models include dynamic global vegetation models, forest gap models, and other approaches that simulate vegetation growth and competition and provide projections of how general vegetation types will likely change with changes in climate.

Assessments at this level of analysis may determine how changing biophysical conditions affect the components of ecosystems that drive processes (e.g., increase in fuel for fires, change in canopy cover, increase in nutrient loading, etc.). Climate warming is expected to alter chemical and biophysical conditions of ecosystems. Thus, mapping the spatial extent of biophysical change offers insight about the level that different areas of an ecosystem might be impacted. For example, sea-level rise is expected to cause the loss of habitat for coastal and estuarian species. Mapping the extent and topographic height of sea-level rise can inform which areas might be affected. Also, one could model and map change to ecological processes. Many ecosystem services (e.g., primary production, provisioning of freshwater) are dependent upon biophysical conditions like temperature, rainfall, and snowpack, which will be altered by climate change. Spatial data for these biophysical conditions can be obtained from global climate change models. These data can be used as inputs to process based models (e.g., models of primary production and hydrological flow) in order to provide spatially explicit projections of changes in the levels of ecosystem services.

Mapping ecosystem services provides important complementary insights about the value of a land area and water sources to the welfare of humans. In as much as plant and wildlife species provide these services, such a mapping approach provides a way to articulate important human dependencies on plant and wildlife species. For example, a grassland and associated riverine ecosystem that together comprise a watershed could provide several important services, including forage production for cattle and native ungulates, carbon sequestration, and water provisioning. Understanding of the rates at which these services are provisioned across the landscape can be developed using combinations of measured and modeled data. Measured data might include stream flow, primary production of different grassland plant species, and soil carbon levels. Modeled data may come from processed-based modeling of soil carbon sequestration rate based on primary production and plant species data or changes in stream flows based on hydrological modeling. Such data can provide a spatial representation of different levels of the services within the ecosystem. One can further illuminate the link between the provisioning of services and human dependency by mapping the locations of service beneficiaries (e.g., locations of ranches or agricultural communities) across the landscape.

C. Species, population, and highly restricted plant community level: An assessment at this level of analysis requires data on species attributes such as behavior in relation to climate, population demography (e.g., birth and death rates, migration) in relation to climatic conditions, and the timing of life-cycle events in relation to climatic conditions.

These data can then be used in combination with mathematical models to project how changing climatic conditions and species relationships will influence movement behavior or population growth. The degree of population growth can then be mapped in relation to climate gradients expected on landscapes under future climate change. This kind of analysis will likely not be feasible for many species because vital data on species behavior and demography in relation to climate are currently unavailable.

4) Maintain and restore ecological connectivity

A. Landscape level: Given that animal and plant species are expected to shift their geographic ranges in response to changing climate, we recommend that assessments also explicitly identify land facets or ecological land units, refugia, and/or areas of high ecological integrity, and then map connections among these areas using circuit theory or graph theory models (see Appendix 2).

B. Ecosystem level: Climate warming stands to reorganize communities and associated ecosystems across landscapes because species existing within a community will not all respond in the same way to this stressor. Some species may tolerate changes in particular climatic conditions, while others may shift their geographic ranges—although they may not necessarily move in identical directions.

Assessments for this level of analysis aim to determine where the habitats for species will move and identify important conduits on the landscape that facilitate such movement. Such assessments can build on insights gained from the ecosystem assessment for Adaptation Objective 2. Essentially, one uses maps of current and future vegetation in conjunction with movement models applied to a variety of species.

C. Species, population, and highly restricted plant community level: An assessment approach at this level aims to identify areas or features of landscapes that are important for species movement across landscapes in order to maintain viable populations and gene flow in the face of climate change. A variety of approaches and tools are available to conduct such analyses. An overview of each of these approaches and tools, their data requirements, their strengths and weaknesses, and the required technical capacity of the user is provided in Appendix 2.

These approaches essentially identify or simulate potential movement pathways for species across a landscape using data on biophysical attributes of the landscape (such as terrain, vegetation, land use, geological barrier, etc.) in conjunction with data on species habitat needs. This approach estimates the relative ease of travel, in terms of relative resistance to or cost of travel between two locations. The input data of physical geographic characteristics and species-specific habitat requirements may be highly certain, but the output, or least-cost path, may be highly uncertain unless it is validated through monitoring of species movements.

The approaches can be extended to identify areas needed to facilitate future movement in response to climate change by using existing landscape features combined with data on changes in landscape attributes derived from assessment at the ecosystem level of analysis for Adaptation Objective 2. This kind of assessment can help to inform how species might move through the landscape beyond their current distribution. One can also use predicted shifts in species distributions to map corridors and connections.

5) ***Protect climate refugia***

A. Landscape level: Landscape level assessments of refugia can be mapped in several ways. One could map places associated with Pleistocene climate refugia. Pleistocene refugia are landscape units that, due to topographic features, enabled species to survive glaciation processes. These are also locations from where modern species expanded their ranges when the glaciers receded. Thus, they represent locations of potential evolutionary origin of many modern plant and animal taxa. One could map areas of high physiographic or topographic complexity. Studies have shown that areas with a high degree of variability in landscape topography and geology/soils have associated variability in climatic conditions (especially temperature and moisture) that then supports a diversity of species that have different thermal and moisture requirements for survival.

B. Ecosystem level: An assessment at this level focuses on identifying ecosystems that provide environmental conditions that are expected to undergo limited change under climate warming. These could be areas that are expected to have little change in vegetation, as determined by the kinds of vegetation assessments described above. They may also involve identifying and mapping geographic locations that are expected to undergo limited changes in biophysical conditions as determined by climate models.

C. Species, population, and highly restricted plant community level: Many species may have limited capacities to evolve tolerances to changing climate at a rate that is commensurate with the rate of future climate change. Consequently, such species may become extirpated in large parts of their geographic ranges. One way to prevent some of these potential losses is to identify and protect climate refugia. Refugia are effectively safe havens on the landscape that provide the diversity of habitats and stability needed to ensure species persistence as regional biotic and abiotic environmental conditions change. In essence, they are places that species can retreat to, persist in, and can potentially expand from under changing environmental conditions. Places that served as refugia during past climatic shifts offer good chances for survival under future climate change for many species because they are locations that have facilitated the survival of species under changing environmental conditions for millennia, thus making their identification important for conservation.

An assessment at this level involves identifying areas that will likely be suitable for species into the future or areas where species may be able to move to as climates change. Such species-specific assessments will likely rely on the models and approaches used to project the responses of species and populations to changes in climate. These models may allow researchers to identify areas that will continue to have suitable climates for a given species into the future.

6) Protect the ecological stage

A. Landscape level: Protecting the ecological stage could allow biodiversity to maintain its evolutionary potential. Assessments for this adaptation strategy are conducted exclusively at the landscape level. The aim is to identify and map current land facets or ecological land units and areas of high ecological integrity. The approach effectively provides a broader representation of fixed landscape features than landscape level assessments for Adaptation Objective 5.

Data Needs

A list of databases and their web links is provided in Appendix 3.

Analysis and Synthesis

Any assessment will invariably have the potential to produce numerous maps and data. This information needs to be synthesized in ways that can help inform planners about needs of and risks to biodiversity under potential changing climate. Given the uncertainty on how species and ecosystems may respond to climate change, we provide a solid approach for conservation planners to move forward by applying the Framework in combination with adaptive management and carefully developed monitoring programs.

At a minimum, maps may need to be combined as data layers. But the combined maps may need to be interpreted using statistics or indices.

Below we provide a short list of common ways to combine multiple maps together, though there are a variety of additional ways to do this. However, the following principles should be followed (largely drawn from Schultz 2001):

1. Normalize or standardize the values (e.g., 0.0 → 1.0, -1 to 1, or 0 to 100), and examine the distribution of values for each factor
2. Be clear what data type is represented by the various factors -- interval and ratio types can be averaged using various statistics (e.g., mean, geometric mean), but nominal (classes) data should be combined using logical rules.
3. Specify whether the individual factors are exclusive or compensatory.
4. Integrate based on empirically-based model. Develop a regression-based model using empirical data to estimate the weighting factors.
5. Integrate using ecological process. Combine factors based on the dominate ecological processes, based on a conceptual model. For example, three main factors control riparian dynamics: longitudinal hydrologic regime, upland watershed sedimentation, and lateral constraints imposed by land uses in the valley bottom.
6. Using multi-criteria analysis. Factors are often combined using weighted additive (or product) overlays, where the weights sum to 1.0. Weights should be developed and specified prior to producing an output map to avoid potential "tweaking" of weights to get a desired pattern. Rather, a formal process such as Delphi or Analytical Hierarchy Process (Saaty 1980) should be used to specify the weights, using a measure of internal logical consistency. Marxan with Zones (Watts et al. 2009) and Zonation (Moilanen 2007) are examples of widely-used tools in conservation that can help land-use planners achieve a range of social and conservation objectives.
7. Optimization. By specifying an objective function, apply an optimization algorithm (e.g., heuristic, linear programming, simulated annealing, genetic algorithm, etc.) to identify the optimal (or near optimal) solution.
8. Scenarios. Scenario planning develops a series of alternatives that are expressed

in terms of logical, explicit assumptions about future system conditions, and uses a series of indicators to compare across them. Web mapping tools such as *Coastal Resilience* (http://coastalresilience.org) can compare the social, economic, and ecological conditions under future coastal hazard scenarios, thereby providing stakeholders and decision-makers with information they can utilize in their local planning processes.

9.

Assessments that aim to project future conditions should conduct analyses that quantify the degree to which future projections change with changes in model assumptions or parameter values. These analyses can take two forms. The first is called uncertainty analysis; the second is called sensitivity analysis.

Uncertainty analysis. This involves scenario-generating simulation exercises using data outputs from several different global climate models that are built on different sets of assumptions. Such an analysis can boost confidence if projections of species range shifts based on data from different models are congruent. Moreover, the degree to which the data from the global climate models produce congruent projections (i.e., the quantitative variation in spatial extent of range shifts produced by different models) can help to infer whether or not a future outcome is more or less likely.

Sensitivity analysis: This involves systematically changing assumptions or parameter values in a single global change model to generate new sets of environmental data. It then uses those data sets to determine which assumptions or parameters produce the greatest change in projections for the future. Assumptions or parameters that lead to large changes in projections are said to be more sensitive than assumptions or parameters that produce less change.

Summary

The work of the Science Panel has produced, for the first time, a Framework that provides systematic and comprehensive guidance on the choice and application of climate adaptation objectives and assessment strategies for protecting biodiversity in an era of climate change. The utility of the Framework must still be assessed and such assessment will likely lead to refinements. With such refinements, the goal is to disseminate a state-of-the-art Framework that facilitates the integration of climate smart adaptation strategies for biodiversity conservation into efforts to plan for land and water use at the federal, state, county, and private-sector levels throughout the United States.

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Glossary

Adaptive Capacity: the ability of a system (including natural and human systems and communities) to adjust to climate change including climate variability and extremes to moderate potential damages, to take advantage of opportunities, or to cope with consequences

Analytical unit – The area unit of analysis or description used for an **ecological assessment** (e.g., watersheds, ownership parcels, or regular polygon array). These units typically are intermediate in size between the **spatial resolution** of a map and the **extent** of the entire assessment area. For example, the spatial resolution of land use/land cover data for an ecological assessment of a state might be 30 x 30 m, but the analysis of those data and how they are ultimately described and reported might be done only at the level of watersheds.

Beta diversity – The change in species composition between ecosystems or along an ecosystem gradient.

Biodiversity – Life in all of its forms – plants, animals, fungi, and microbes – and at all levels of organization from the organism to **ecosystems** and **landscapes**.

Biodiversity hotspots – Geographic locations with high numbers of species.

Climate adaptation strategies – Strategies to adjust to or cope with the social and ecological changes caused by climate change. Such strategies are intended to moderate the harm caused by climate change or to take advantage of resulting beneficial opportunities.

Climate-smart – Policies and practices that incorporate consideration of the effects of climate change with respect to both mitigation and adaptation.

Connectivity – see **Ecological connectivity**.

Conservation plan – A description of a proposed course of action intended to achieve one or more conservation goals. Optimally, such plans are the result of a planning process that specifies ecological features – such as species, ecosystems, or such geophysical elements as **land facets** or **ecological land units** – that are the focus of conservation efforts, identifies important places to protect those features and threats to them, and describes specific strategies to be taken to achieve the conservation goals (Groves et al. 2002). Conservation plans can be developed by any number of planning processes, such as **systematic conservation planning**, but at a minimum should involve detailed **ecological assessments** so that the full scope of current and projected ecological conditions can be taken into account as plans are developed.

Conservation target – A concept central to conservation planning. The term "conservation target" is used in two distinct but related ways in different conservation planning processes. One process, developed by The Nature Conservancy, uses the term conservation target to refer to an ecological feature – such as a species, ecosystem, or **ecological land unit** – that is part of an **ecological assessment** or **conservation plan**. The other process, characterized by most decision support tools for **systematic conservation planning**, uses the term conservation target to refer to the minimum number or amount of an ecological feature that is considered acceptable for a preferred conservation plan. Thus, conservation target can refer to either the minimum amount of a feature or the feature itself.

Ecological assessment – An ecological assessment identifies important patterns and trends of ecological features, which provide foundational information on which conservation objectives and strategies would be most effective to implement. Assessments can be accomplished both by direct field measurements and predictive modeling, through which responses of ecosystems to human-induced changes can be more fully understood and management options developed.

Ecological connectivity – The degree to which a landscape facilitates movement among resource patches, from ecological to evolutionary time scales (Taylor et al. 1993). Two types of connectivity can be assessed. First, structural connectivity measures the spatial arrangement of different types of habitat or ecological systems in a landscape without reference to the likelihood of movement of particular organisms through the landscape. Second, functional connectivity incorporates at least some aspects of the behavioral response of individuals, species, or ecological processes to the physical structure of the landscape (Baudry & Merriam 1988; Crooks & Sanjayan 2006).

Ecological integrity – The ability of an ecosystem to maintain an assemblage of organisms that has a composition, structure, and function that is comparable to that of natural conditions in the region.

Ecological land units – A characterization of locations based on topography, elevation, and bedrock geology. This concept is similar to **land facets**.

Ecological processes – The dynamic actions and interactions that place within any level of biological organization. Ecological processes of interest to conservation planners can take place at the species level, such as predation and pollination, or at the ecosystem and landscape levels, such as nutrient cycling and moderation of hydrological flow. This concept is the same as ecological functions.

Ecoregion – A large area within which suites of specific **ecosystems** reoccur in a frequent or predictable pattern.

Ecosystem – A community of organisms and the abiotic components that affect or exchange materials with the organisms.

Ecosystem-based Adaptation: the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change**.** Ecosystem-based adaptation uses the range of opportunities for the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change.

Ecosystem services – Ecological processes perceived in terms that relate directly to human values and benefits. For example, the ecological process of pollination is related to the ecosystem service of pollination of agricultural crops, and the process of moderating hydrological flow relates to the service of reducing flooding and the loss of property.

Enduring features – Geological and geographical characteristics of the environment that are not likely to change quickly as a result of climate change, such as soil type, elevation, and aspect.

Extent – Extent can be used to describe either spatial (or area) extent or temporal (or time) extent. Spatial extent is the region on the Earth's surface that is the focus of an **ecological assessment** or **conservation plan**. It is often represented as a defined rectangle just large enough to include all mapped features that are of interest, but it can also be defined by a political boundary (e.g., state) or ecological region (e.g., Southern Rockies ecoregion). Temporal extent is the duration of time a plan or assessment is concerned with, which generally must take into account the duration of important or relevant ecological processes.

Gamma diversity – The total diversity of species across a large region or within a large **landscape**. It is a function both of the diversity of species at each location within the landscape (alpha diversity) and the diversity across ecosystems within the landscape (**beta diversity**).

Habitat – The area occupied by a species and/or the biophysical conditions needed to support a species.

Intensity – The precision or level of differentiation of values that are depicted on a map – such as the number of land cover classes that are contained in a dataset (e.g., 7 classes vs. 21 classes).

Invasive species – An exotic species (one that is present at a location through human action) that causes ecological or economic harm.

Land facets – A characterization of locations typically based on elevation, topography, and soil characteristics (Wessels et al. 1999, Beier and Brost 2010). This concept is similar to **ecological land units**.

Landscape – A central concept to describing geographic regions that are the focus of **ecological assessments** or **conservation plans.** Some authors use the term to refer to a mosaic of ecosystems, although most use the term simply to represent a large expanse of land and water.

Map scale – The ratio of a distance on the map to the corresponding distance on the ground. A large-scale map (e.g. 1:24,000) shows greater detail because the scale is a larger fraction than that of a small-scale map (e.g. 1:250,000). The concept of map scale differs from **spatial scale**, which describes altogether different characteristics of a mapped area.

Minimum mapping unit (MMU) – This is the size of the smallest feature that (a) can be mapped at a given map scale or (b) is selected to be displayed on a given map. An example of the former is that of land use/land cover maps created from satellite-based remote-sensing technology, where the smallest area that can be characterized, and therefore can be uniquely described on a map, is 30 x 30 m. An example of the latter is the choice to display major roads but not minor roads when map scale is less than 1:100,000.

Planning for land and water use – A phrase intended to be more inclusive than simply "land-use planning." In its simplest form, land-use planning is the process of making decisions on how to use land and its associated resources to achieve one or more goals, such as providing food for people and maintaining **ecosystem services**. It is well recognized, however, that conservation planning requires attention to aquatic ecosystems as well, hence the expansion of the concept to include water, as well.

Protected areas – Areas that are, for the most part, permanently protected from conversion to development.

Refugia (singular: **refugium**) **–** Locations that historically or currently protect conservation elements that are eliminated or significant degraded elsewhere.

Resolution – Resolution can be used to describe either spatial (or area) resolution or temporal (or time) resolution. Spatial resolution (or grain) is the size of the smallest amount of detail depicted on a map. It can be thought of as the pixel (or cell) on a digital image or as the smallest mapping unit on a feature-based map. For example, the highest (or finest) resolution on a land use/land cover map created by satellite-based remote-sensing technology is 30 x 30 m, so that each 30 x 30 m cell is described by one value, and all variation within that cell is ignored. Temporal resolution describes the smallest unit of time described by data (e.g., daily average, yearly minimum). Variation within that smallest unit of time can be characterized by a statistical measure of variation (e.g., standard deviation), but the actual data associated with shorter increments of time are ignored.

Scale – A general concept that can be applied to both spatial (or area) and temporal (or time) domains as **spatial scale** and **temporal scale**. Scale, whether spatial or temporal, represents a combination of separate characterizations of area or time, particularly **extent**, **resolution**, and **intensity**.

Scale matrix – A visual representation of the general ecological relationship that exists between **spatial scale** and **temporal scale**. At one extreme are those processes that operate only over small areas and require short periods of time. At the other extreme, certain ecological processes take place over large areas and require hundreds or even thousands of years to operate.

Spatial extent – see **Extent**.

Spatial scale – A general concept used to characterize aspects of an area that is the focus of an **ecological assessment** or **conservation plan**. Spatial scale includes three important descriptions of how the area is characterized: **extent**, **resolution, and intensity**. In conducting ecological assessments, it is important to explore the appropriate spatial scale(s) needed to adequately address the conservation needs of particular species, ecosystems, or ecological processes. Some ecological processes and species life histories take place over very small areas (e.g., a vernal pool, a rotting log, or a rock outcrop). These are said to operate at a "small" spatial scale (i.e. *plot or stand scale*; 1 m^2 – 1 km^2). Other species and processes (e.g., grizzly bears and forest fires) occur over broader (or "larger") *regional scales* (1 km^2 – 10,000 km^2), while still others (e.g., climate and some species migrations) operate at even greater the *continental* (10,000 km^2 – 100,000 km^2) or even *global scales* (>100,000,000 km^2). Note that this is the opposite of the usage of **map scale**. It is generally felt that a general ecological relationship exists between spatial and temporal scales, described by a **scale matrix**.

Spatially explicit – Referring to the condition of having the specific location of something – ecological feature, process, or conservation action – specified.

Systematic conservation planning – A specific framework for developing a **conservation plan** intended to identify conservation goals, locations where conservation actions are priorities for achieving the goals, and strategies that will improve the chances that actions taken at those locations will succeed (cf., Margules & Pressey 2000). **Ecological assessments** are a critical part of such a framework.

Target – see **Conservation target**.

Temporal scale – A general concept used to characterize aspects of time, especially as they relate to the goals or process of **conservation planning**. As with **spatial scale**, temporal scale includes two important descriptions of how time is characterized: **extent** and **resolution**. In conducting **ecological assessments**, it is important to explore the appropriate temporal scale(s) needed to adequately address particular species, ecosystems, or ecological processes. Some ecological processes and species life histories take place over very short periods of time (e.g., storms, seed germination, mating, and nesting). Other processes, however, operate over longer durations (e.g., climate change, speciation, and extinction). It is generally felt that a general ecological relationship exists between spatial and temporal scales, described by a **scale matrix**.

Bibliography of suggested supplemental readings

Anderson, M. G., and C. E. Ferree. 2010. Conserving the stage: climate change and the geophysical underpinnings of species diversity. Public Library of Science ONE 5 DOI: 10.1371/journal.pone.0011554

Beier, P, DR Majka, and SL Newell. 2009. Uncertainty analysis of least-cost modeling for designing wildlife linkages. *Ecological Applications* 19:2067-2077.

Beier, P, WD Spencer, R Baldwin, and B McRae. 2011. Toward best practices for developing regional connectivity maps. Conservation Biology: in press.

Beier, P., and B. Brost. 2010. Use of land facets in planning for climate change: conserving the arenas not the actors. Conservation Biology 24:701-710.

Brost, BM, and P Beier. 2011. Use of land facets to design linkages for climate change. Ecological Applications: in press.

Colls, A, N. Ash, and N. Ikkala (2009). Ecosystem-based Adaptation: a natural response to climate change. Gland, Switzerland: IUCN. 16pp. Available from: http://data.iucn.org/dbtw-wpd/edocs/2009-049.pdf

Dudley, N., S. Stolton, A. Belokurov, L. Krueger, N. Lopoukhine, K. MacKinnon, T. Sandwith and N. Sekhran [editors] (2010); Natural Solutions: Protected areas helping people cope with climate change, IUCNWCPA, TNC, UNDP, WCS, The World Bank and WWF,Gland, Switzerland, Washington DC and New York, USA

Eeley, H. A.C., M. J. Lawes, and S. E. Piper. 1999. The influence of climate on the distribution of indigenous forest in KwaZulu-Natal, South Africa. Journal of Biogeography **26**:595-617.

Hajkowicz, S., and K. Collins. 2007. A review of multi-criteria analysis for water resource planning and management. Water Resources Management **21**:1553–1566

Hewitt. G. 2000. The genetic legacy of the Quaternary ice ages. Nature **405**:464-475.

Klein, C., K. Wilson, M. Watts, J. Stein, S. Berry, J. Carwardine, 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. 2009. Climate change adaptation strategies for resource management and conservation planning. Annals of the New York Academy of Science **1162**: 79–98

Malczewski, J. 1999. GIS and Multicriteria Decision Analysis. John Wiley & Sons.

Moilanen, A. 2007. Landscape zonation, benefit functions and target-based planning: unifying reserve selection. *Biological Conservation* 134: 571-579.

Noss R. F. 2001. Beyond Kyoto: forest management in a time of rapid climate change. Conservation Biology **15**:578-590.

Pearson, R.G. and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species:Are climate envelope models useful? Global Ecology and Biogeography **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.

Rouget, M., R. M. Cowling, R. L. Pressey, and D. M. Richardson. 2003. Identifying spatial components of ecological and evolutionary processes for regional conservation planning in the Cape Floristic Region, South Africa. Diversity and Distributions **9**:191-210.

Saaty, TL. 1980. The Analytical Hierarchy Process. McGraw Hill, NY, NY.

Schultz MT (2001) A critique of EPA's index of watershed indicators. Journal of Environmental Management **62**:429–442

Spencer, W. D., P. Beier, K. Penrod, M. Parisi, A. Pettler, K. Winters, J. Strittholt, C. Paulman, H. Rustigian-Romsos. 2010. California Essential Habitat Connectivity Project: a strategy for conserving a connected California. Report. California Department of Transportation and California Department of Fish & Game, Sacramento, California. Available from http://www.dfg.ca.gov/habcon/connectivity/ (accessed November 2010).

Theobald, D. 2010. Estimating natural landscape changes from 1992 to 2030 in the conterminous US. Landscape Ecology **25**:999-1011.

Tracey, J. A. 2006. Individual-based modeling as a tool for conserving connectivity. Pages 343-368 (Chapter 14) in KR Crooks and MA Sanjayan. Connectivity Conservation. Cambridge University Press.

Washington Habitat Connectivity Work Group (WHCWG). 2010. Connected landscapes project. WHCWG, location. Available from http://waconnected.org/ (accessed November 2010).

Watts citation?

Williams, P., L. Hannah, S. Andelman, G. Midgley, M. Araujo, G. Hughes, L. Manne, E. Martinez-Meyer, and R. Pearson. Planning for climate change: identifying minimum-dispersal corridors for the Cape Protaceae. Conservation Biology **19**:1063-1074.

Appendix 1

Approaches and Tools for Conducting Assessments of Species Distributions

Appendix 1 describes a sample of modeling approaches commonly used to estimate and map species distribution. Practitioners are also encouraged to search for and use existing species distribution maps. However, when using currently available species distribution maps it is important for the practitioners to understand and report the data and methods used to generate the maps.

A) Generalized linear model and logistic regression model

Overview

Generalized linear model (GLM) approaches use least squares methods to fit the relationship between the mean of the response variable and the linear combination of the explanatory variables. The response variables for distribution models are usually represented with simple species presence, presence–absence or abundance observations at geographic locations based on random or stratified field sampling, expert opinion, or observations obtained opportunistically. Explanatory variables in this approach represent environmental data that are assumed to directly or indirectly effect on species (Austin, 2007). The assumed relationship between the response and explanatory variables are defined with one of several link functions describing the probability distributions (e.g., normal, Poisson, negative binomial, or gamma distribution) (Guisan et al., 2002).

Logistic regression is a special kind of GLM used to evaluate how a suite of environmental variables predict the presence of a species. The species data are summarized into binomial response (presence or absence) for each sampled area. The logistic regression model constrains the probability of presence and absence between zero and 1 with a logit link function and assumes the error term has a binomial distribution.

Data Requirements

Both GLM and logistic regression model require field observations and measurements of environmental factors expected to influence organism's distribution. The environmental data can be collected with in situ field sampling methods or with remote sensing methods.

Strengths

GLM (and logistic regression) has long been used in biological research for a wide breath of studies to estimate species' distribution (Guisan and Thuiller, 2005). The approach allows much flexibility in selecting the environmental data. This approach allows researchers to test several working hypotheses by using maximum likelihood methods to determining the most parsimonious model that best fits the observed data.

Weaknesses/Assumptions

GLM models are dependent upon the quality of data and the structure of the candidate models developed by the researcher. The logistic regression analysis is dependent upon the assumption that a species does not occur where it is deemed absent (as opposed to being present but undetected). There may be uncertainty about the whether or not locations were sampled extensively enough to verify that individuals are not present. Also, spurious results can occur if the environmental variables that have little or no influence on the response variable (Burnham and Anderson, 2002).

Linear regressions are parametric statistical analysis limited by the following four main assumptions

- Each environmental variable's error is assumed to be identically and independently distributed;
- The variance of the response variable is constant across observations;
- Each environmental variable's error are assumed to follow the selected link functions describing the probability distribution;
- The regression function is linear in the predictors.

Capacity Needed (construct and run model)

Regression models are relatively easy to construct, run, and interpret with the help of many statistical packages (e.g., SAS and R).

B) Occupancy models

Overview

An occupancy modeling approach estimates the distribution or proportion of geographical locations occupied by a species (MacKenzie et al., 2002). Since the probability of observing a species can be < 1 when the species is present, the occupancy model also incorporates the probability of detecting the species within a site along with allowing the probability to vary as a function of site characteristics, time, or environmental variables (MacKenzie et al., 2002). With multiple site visits to detect the species, this approach estimates the probability that a species will be detected at site given a likelihood that it is present (Mackenzie et al., 2005).

Data Requirements

A species' occupancy within a site and distribution between sites involves multiple visits to sites when a species may be detectable (MacKenzie et al. 2002). For this approach sites may represent discrete habitat patches or sampling units (e.g., quadrats) regularly visited as part of a large-scale monitoring program. Each survey is conducted on discrete time periods where an investigator records if the species was present or absent at each occasion. The set of detection histories for each site is used to estimate the proportion of sites occupied by the species. Investigators can also collect site-level characteristics (e.g., area and dominant vegetation) and environmental variables expected to influence probability of detecting organisms (e.g., weather conditions and time of sampling).

Strengths

The occupancy modeling approach can be implemented more easily and less expensively than the methods used for abundance estimation. In addition, occupancy modeling can be applied to large-spatial extent monitoring programs to determine a species spatial distribution throughout a region. Covariates expected to influence detection or occupancy can be easily included in the occupancy model to account for the heterogeneity in probability detection and varied occupancy by site. Missed sampling events can be adjusted for by slightly modifying the maximum likelihood model that estimates likelihood of presence.

Weaknesses/Assumptions

One of the main weaknesses in this method is the requirement of many visits to a single site. For some study systems it may be logistically difficult and time consuming. Habitat patches need to be delineated by the investigator. But, increasing the number of visits per site improves the precision of the estimated occupancy rate, and the resulting increase in information improves the accuracy of the estimate when detection probabilities are low (MacKenzie et al., 2002). This approach only provides information on occupancy of a patch and no information about the population dynamics or abundance of the species in the patch. Therefore, it is difficult to use these data to speculate on the viability of the population.

Key assumptions for the occupancy modeling approach include (MacKenzie et al., 2002):

- Sites are closed to changes in occupancy during sampling (i.e., closed system). Sites are occupied by the species of interest for the duration of the survey period, with no new sites becoming occupied after surveying has begun, and no sites abandoned before the cessation of surveying
- Detection of the species at a site is also assumed to be independent of detecting the species at all other sites.
- Species are never falsely detected at a site when absent, and a species may or may not be detected at a site when present.

Capacity needed

The development of the occupancy modeling approach has lead to detailed documentation describing sampling procedures and analysis (Mackenzie et al., 2005). In addition, a freely downloadable program PRESENCE is available to analyze the data (version 3.1 at http://137.227.242.23/software/presence.html)

C) Maximum entropy models

Overview

A maximum entropy (MaxEnt) modeling approach using a machine-learning algorithm to predict a species' geographic distribution based on locations of known occurrences and layers of environmental data (Elith et al., 2006; Phillips et al., 2006). The maximum entropy modeling approach estimates the species distribution by finding the maximum entropy (i.e., closest to uniform) distribution, constrained by the environmental data associated with species known locations (Phillips et al., 2006).

Data Requirements

Maximum entropy modeling requires two types of input data, the geographic coordinates of species occurrences and geographically explicit environmental variables likely to influence the distribution of a species at the relevant spatial and temporal scale (Phillips et al., 2006). Occurrence locations only need to represent presence only records (e.g., natural history museum or herbarium) records and at least 50 to 100 occurrence locations are recommended to obtain predictions close to optimal distribution (Phillips et al., 2006).

Strengths

There are many advantages to using the Maximum entropy approach when modeling species distribution (Phillips et al. (2006)):

1) Presence only data are required for species occurrences
2) Environmental grids can contain continuous and categorical information
3) There is an efficient deterministic algorithm for obtaining the optimal probability distribution, obviating the need for uncertainty analyses
4) Over fitting features can be avoided by adjusting the regularization parameter
5) One of the output products is a continuous map allowing fine distinctions between the species distribution throughout the entire region
6) Provides insight into relative importance and relationship of each environmental feature predicting species distribution

Weaknesses/Assumptions

Maps (geo-referenced data) of the environmental variables or covariates representing environmental conditions need to be available for the entire landscape. In addition, the environmental variables and the species occurrence locations should be measured for similar time periods (Phillips et al., 2006). The number of environmental variable used in conjunction with the occurrence locations may not be sufficient to describe the species distribution. The occurrence locations may be biased, spatially auto-correlated, or sampling intensity/methods may have widely varied across the study area (Phillips et al., 2006). For example, museum samples may have been collected near roads and within a small segment of the population. There could also be errors when recording the occurrence locations or the species may have been misidentified during field observations.

Capacity needed

Basic knowledge of GIS is needed to ensure that all environmental data have the same format (projection, extent, and resolution). A freely downloadable program Maxent is available to analyze the occurrence locations and environmental grids (http://www.cs.princeton.edu/~schapire/maxent).

D) Resource selection probability functions

Overview

A resource selection probability function (RSPF) is a mathematical function that predicts a species use of resources or habitats relative to availability of the resources or habitats (Manly et al., 2002)—hence a habitat suitability measure. The approach uses species occurrence location data to estimate where habitat use exceeds availability. RSPF can take many mathematical forms (Manly et al., 2002) but logistic regression is the most common form used to estimate habitat suitability.

Data Requirements

There are three data requirements to estimate RSPF.

1) Coordinates of species observations, known as used locations
2) Coordinates of locations where the species may occur within the study area to define potential habitat, known as available locations. These are typically defined as random subset of points within an individual's home range.
3) Environmental data expected to influence the species distribution.

Strengths

RSPF are flexible enough to parameterize the environmental data with a wide range of functional relationships (e.g., polynomial terms and interactions). This approach easily fits into maximum likelihood framework with model selection to determine which environmental variables influence species distribution. A RSPF approach allows researchers to easily interpret environmental variables estimated in the "best" model. The analysis can be conducted at multiple ecological levels (individual, populations, or species).

Weaknesses

Model output can be sensitive to sampling of available locations in relation to observed used locations.

Capacity needed

Basic knowledge of GIS. A GIS tool to execute RSPF has been developed by Yellowstone Ecological Research Center (http://www.yellowstoneresearch.org/projects_rspf-down.html).

F) Multivariate Models

Overview

A commonly used multivariate modeling approach to estimate species distribution is Mahalanobis distance (MD). MD is a dimensionless measure of dissimilarity by representing the standard squared distance between a set of environmental variables and ideal habitat quality (Clark et al., 1993). A distance threshold is then used to define the boundary of the species distribution (Tsoar et al., 2007). When mapping species distribution in relation to habitat quality, the MD metric can be used to rank each cell in the habitat map relative to a statistical description of habitats used by a species. Each cell on the MD habitat map is relative to the vector describing the multivariate characteristics of habitats at cells where the species was located.

Data Requirements

Species occurrence data. Environmental data expected to influence species distribution.

Strengths

Environmental variables can be correlated and the assumption of multivariate normality does not have to be met because MD creates new and uncorrelated variables (Clark et al., 1993; Knick and Dyer, 1997). Environmental data can be continuous or categorical.

Weaknesses/Assumptions

The MD approach assumes that the species is distributed optimally at the mean environmental conditions, and that any deviation from the mean (optimal) conditions is associated with lower suitability (Farber and Kadmon, 2003). Similar to many multivariate analysis, it may be difficult to interpret how the environmental variables directly relate to species distribution.

Capacity needed

A surface representing Mahalanobis distance for species distribution can be calculated with statistical software (e.g., R or SAS). This analysis can also be conducted using multivariate statistical software such as PCord (http://home.centurytel.net/~mjm/)

E) Expert opinion

Overview

When data are limited investigators may consult groups of experts to subjectively delineate species distributions or define environmental features that influence species distributions. Expert opinion can be incorporated into species distribution modeling by providing input into data preparation, identifying suspect records of species occurrences, selecting relevant environmental features influencing species distribution, developing various models, or by grouping vegetation into habitat suitability classes (Pearce et al., 2001).

Data Requirements

This approach requires limited field data collection. However, it is a time consuming process of identifying and interviewing experts for various ecosystems or species. Published literature (peer-reviewed articles and reports) should also be reviewed to supplement expert opinion information. If expert opinion models are displayed spatially then all relevant environmental features are needed in a spatial data layers such as grids or vectors.

Strengths

Since there is little or no field data collection this method is relatively inexpensive. For a few species and ecosystems, experts are available with extensive knowledge based on decades of field experience.

Weaknesses

There is limited publishing information or available expert knowledge for many rare and federally protected species. When experts are available, the degree of their expertise may be difficult to evaluate and it can be difficult to standardize interview techniques. While it is a cost-effective approach with regard to limited field data collection, incorporating expert opinion into distribution modeling can be a slow and tedious process and is usually performed on a species-by-species basis (Seoane et al., 2005). Distribution models created from expert opinion are rarely validated with independent data. Therefore, a high level of uncertainty is present in the model until observations confirm the presence of the species in relation to environment.

To address some of the uncertainties with varying expert opinions, species distribution models created with expert opinion can be subject to a pairwise comparison technique (Analytic Hierarchy Process) developed by Saaty (1980), whereby experts rank the relative importance of each variable in a pair using a continuous scale. For example, each expert selects the variable deemed to be more important in each of pairwise comparisons and rank how important the selected variable is, compared with the others, on a scale of 1 (equally important) to 9 (extremely more important). The pairwise comparisons are transformed into a matrix of ranks based on the Analytic Hierarchy Process model. Those ranks can be calculated by averaging the survey scores of all respondents for each pairwise comparison to represent the relative importance of each variable against another variable.

Capacity needed

Beyond locating and interviewing experts, modeling species distribution with expert opinion usually requires GIS knowledge to compile a map overlaying relevant environmental features expected to influence species distribution.

References

Adriaensen, F., Chardon, J.P., De Blust, G., Swinnen, E., Villalba, S., Gulinck, H., Matthysen, E., 2003. The application of 'least-cost' modelling as a functional landscape model. Landscape and Urban Planning 64, 233-247. .

Austin, M., 2007. Species distribution models and ecological theory: A critical assessment and some possible new approaches. Ecological Modelling, 200, 1-19. .

Belisle, M., Desrochers, A., 2002. Gap-crossing decisions by forest birds: an empirical basis for parameterizing spatially-explicit, individual-based models. Landscape Ecology 17, 219-231. .

Bunn, A.G., Urban, D.L., Keitt, T.H., 2000. Landscape connectivity: A conservation application of graph theory. Journal of Environmental Management 59, 265-278. .

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: A practical information-theoretic approach, second edn. Springer-Verlag, Inc., New York, New York, USA.

Calabrese, J.M., Fagan, W.F., 2004. A comparison-shopper's guide to connectivity metrics. Frontiers in Ecology and the Environment 2, 529-536. .

Clark, J.D., Dunn, J.E., Smith, K.G., 1993. A Multivariate Model of Female Black Bear Habitat Use for a Geographic Information System. The Journal of Wildlife Management 57, 519-526. .

DeAngelis, D.L., Mooij, W.M., 2005. Individual-Basedmodeling of Ecological and Evolutionary Processes. Annual Review of Ecology, Evolution, & Systematics 36, 147-C-2. .

Elith, J., Graham, C.H., Anderson, R.P., Dudík, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., and others, 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129-151. 10.1111/j.2006.0906-7590.04596.x.

Farber, O., Kadmon, R., 2003. Assessment of alternative approaches for bioclimatic modeling with special emphasis on the Mahalanobis distance. Ecol. Model. 160, 115-130. DOI: 10.1016/S0304-3800(02)00327-7.

Grimm, V., Railsback, S.F., 2005. Individual-based modeling and ecology, Princeton University Press, Princeton, NJ, USA.

Guisan, A., Thuiller, W., 2005. Predicting species distribution: offering more than simple habitat models. Ecol. Lett. 8, 993-1009. 10.1111/j.1461-0248.2005.00792.x.

Guisan, A., Edwards, T.C., Hastie, T., 2002. Generalized linear and generalized additive models in studies of species distributions: setting the scene. Ecol. Model. 157, 89-100. DOI: 10.1016/S0304-3800(02)00204-1.

Johnson, A.R., Wiens, J.A., Milne, B.T., Crist, T.O., 1992. Animal movements and population-dynamics in heterogeneous landscapes. Landscape Ecology 7, 63-75. .

Keitt, T.H., Urban, D.L., Milne, B.T., 1997. Detecting critical scales in fragmented landscapes. Conserv. Ecol. 1, 4. .

Knick, S.T., Dyer, D.L., 1997. Distribution of Black-Tailed Jackrabbit Habitat Determined by GIS in Southwestern Idaho. The Journal of Wildlife Management 61, pp. 75-85. .

Lookingbill, T.R., Elmore, A.J., Engelhardt, K.A.M., Churchill, J.B., Edward Gates, J., Johnson, J.B., 2010. Influence of wetland networks on bat activity in mixed-use landscapes. Biol. Conserv. 143, 974-983. DOI: 10.1016/j.biocon.2010.01.011.

Mackenzie, D.I., Nichols, J.D., Royle, J.A., Pollock, K.H., Bailey, L.L., Hines, J.E., 2005. Occupancy Estimation and Modeling - Inferring patterns and dynamics of species occurrence, Elsevier, Boston.

MacKenzie, D.I., Nichols, J.D., Lachman, G.B., Droege, S., Royle, J.A., Langtimm, C.A., 2002. Estimating site occupancy rates when detection probabilities are less than one. Ecology 83, 2248-2255. .

Manly, B.F.J., McDonald, L.L., Thomas, D.L., McDonald, T.L., Erickson, W.P., 2002. Resource selection by animals : statistical design and analysis for field studies, Second edn. Kluwer Academic Publishers, Boston.

McRae, B.H., Dickson, B.G., Keitt, T.H., Shah, V.B., 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology 89, 2712-2724. .

Minor, E.S., Urban, D.L., 2007. Graph theory as a proxy for spatially explicit population models in conservation planning. Ecological Applications 17, 1771-1782. .

Minor, E.S., Urban, D.L., 2008. A Graph-Theory Framework for Evaluating Landscape Connectivity and Conservation Planning. Conserv. Biol. 22, 297-307. .

Palomares, F., Delibes, M., Ferreras, P., Fedriani, J.M., Calzada, J., Revilla, E., 2000. Iberian Lynx in a Fragmented Landscape: Predispersal, Dispersal, and Postdispersal Habitats. Conserv. Biol. 14, 809-818. .

Pearce, J.L., Cherry, K., M., D., S., F., Whish, G., 2001. Incorporating expert opinion and fine-scale vegetation mapping into statistical models of faunal distribution. J. Appl. Ecol. 38, 412-424. 10.1046/j.1365-2664.2001.00608.x.

Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling, 190, 231-259. .

Roshier, D.A., Robertson, A.I., Kingsford, R.T., Green, D.G., 2001. Continental-scale interactions with temporary resources may explain the paradox of large populations of desert waterbirds in Australia. Landscape Ecology 16, 547-556. .

Saaty, T.L., 1980. The Analytic Hierarchy Process: planning, setting priorities, resource allocation. McGraw-Hill, New York, NY.

Schadt, S., Knauer, F., Kaczensky, P., Revilla, E., Wiegand, T., Trepl, L., 2002. Rule-Based Assessment of Suitable Habitat and Patch Connectivity for the Eurasian Lynx. Ecol. Appl. 12, 1469-1483. .

Schultz, C.B., Crone, E.E., 2001. Edge-Mediated Dispersal Behavior in a Prairie Butterfly. Ecology 82, 1879-1892. .

Seoane, J., Bustamante, J., Diaz-Delgado, R., 2005. Effect of Expert Opinion on the Predictive Ability of Environmental Models of Bird Distribution. Conserv. Biol. 19, 512-522. 10.1111/j.1523-1739.2005.00364.x.

Tsoar, A.A., Allouche, O., Steinitz, O., Rotem, D., Kadmon, R., 2007. A comparative evaluation of presence-only methods for modelling species distribution A comparative evaluation of presence-only methods for modelling species distribution. Diversity & Distributions 13, 397-405. .

Turchin, P., 1998. Quantitative Analysis of Movement: Measuring and Modeling Population Redistribution in Animals and Plants, Sinauer Associates, Inc. Publishers, Sunderland, MA.

Urban, D.L., Keitt, T.H., 2001. Landscape connectivity: A graph-theoretic perspective. Ecology 82, 1205-1218. .

West, D.B., 1996. Introduction to graph theory, Prentice Hall, Upper Saddle River, NJ.

Appendix 2

Approaches and Tools for Conducting Assessments of Species Landscape Movement

Appendix 2 describes a sample of tools commonly used to assess and map species ability and willingness to traverse among natural and human-modified landscape features. When assessing and predicting species movement on a landscape, practitioners should build off existing information on the species movement behavior in the literature and expert opinions. For example, if information on species ability or inability to traverse steep terrain has been previously determined to be an important factor influencing movements then an elevation raster and slope model should be used when mapping species movements.

A) Least-cost Path Models

Overview

Least-cost distance accounts for the affects of landscape structure on movement by depicting the relative resistance of different land-cover types or land uses encountered during species' movements. In other words, each land-use characteristic thought to influence movements is assigned a friction value, which approximates how much that feature impedes or facilitates movement (Adriaensen et al., 2003). The minimum cumulative cost between resource patches based on the resistance surface is known as the least-cost path (Adriaensen et al., 2003). The least-cost path can be associated landscape connectivity through a two step process; 1) calculate the least-cost distance from a source over a cost surface and 2) perform a connectivity analysis with the least-cost surface. Within GIS there are two options for connectivity analysis. The first option is to estimate the least-cost path which requires a set of possible destinations to calculate the back link in the cost distance analysis. The other, more computational option to estimate connectivity is to run a corridor analysis where a second cost-distance is calculated from the destination. This surface is then combined with cost distance from the source and destination at a set threshold value.

Data Requirements

This approach requires two types of data

- Spatial distribution of habitat patches, and
- Resistance surface containing friction values representing how environmental features influence movement ability.

The most important step when creating a resistance surface for this method is estimating biologically relevant friction values (Adriaensen et al., 2003). Due to the lack of detailed information about dispersal and movement behavior, friction values for most species are usually defined subjectively based on expert opinion, or are converted from species habitat preferences during common daily activities, and therefore not representative of dispersal behavior (Schultz and Crone, 2001; Schadt et al., 2002).

Strengths

Due to the limited data requirements it is relatively easy to calculate least-cost path between habitat patches with minimal animal movement data.

Weaknesses/Assumptions

Friction values derived from these routine movements may not accurately depict an individual's reaction to landscape features outside their habitat because behavior may differ during dispersal through non-habitat (Palomares et al., 2000). Studies rarely validate friction values and resistance surface derived from expert opinion or daily activities with independent movement data. Therefore, surfaces are not confirmed in relation to observed movements. Resistance surfaces require continuous land-cover maps spanning large spatial extents.

The least-cost distance approach has two improbable assumptions

- Individuals have complete knowledge of their surroundings
- Individual select the global optimum least-cost path between patches

Capacity Needed (construct and run model)

Least-cost distance can be calculated in GIS software.

B) Circuit Theory Models

Overview

Circuit theory models assume that species movements are analogous to electrical current flowing over a landscape composed of conductors with various amounts of resistance, represented by a raster dataset. Circuit theory models can be considered an efficient analytical equivalent to simple individual-based models known as "biased random walk" models (McRae et al., 2008), and allow dispersal corridors and "pinch points", where animal movements are constricted to only a few possible paths, to be mapped quickly and effectively. This model also allows the investigator to quantify the relative strength of connections between all habitat patches, based on their distance and the quality of intervening habitat.

Data Requirements

Circuit theory models require two inputs.

- A raster where valued cells represent occurrences of the focal species.
- A raster of resistances that represent the relative impermeability of different landscape features to dispersing organisms.

Strengths

Every grid cell in a landscape receives a relative movement ability estimate in Circuit theory models. One is able to identify pinch-points and landscape corridors a species has a high likelihood of passing through when moving between patches (McRae et al., 2008).

Weaknesses/Assumptions

The modeling outcome is based on resistance surface supplied by the investigator. Therefore, there will always be uncertainty in selecting biologically relevant friction values for the resistance surface and appropriate cell resolution. Edges of maps (i.e., landscape features data) limit estimation of the potential movement route. Movement is assumed to occur with the same ease in forward and backward directions. Therefore, species movements influenced by directional features like elevation or water currents may not be appropriate for this approach (McRae et al., 2008).

Circuit theory models are restricted to Markovian random walks with no ''memory'' between steps. This framework cannot incorporate correlated random walks, changes in movement behavior with time, or mortality rates that increase with an organism's age (McRae et al., 2008). Barriers to movement need to be identified and delineated.

Capacity Needed (construct and run model)

The investigator will have to know basic GIS processing to prepare grids. The model can be processed in freely available software Circuitscape (http://www.circuitscape.org).

C) Graph Network Models

Overview

Graph network models are able to summarize the spatial relationship between points of interest and estimate the optimal flow patterns or connectivity through a network (West, 1996). A graph network data structure is a set of nodes (points) connected to some degree by links or edges. Nodes in the graph networks are typically denoted as habitat patches and edges usually represent the movement ability between pairs of patches. Potential connections between habitat patches exist if the focal species movement ability is greater than the edge's distance. Once a network is created, several network-level and patch-level graph metrics can be calculated to evaluate the topology of the network and centrality or juxtaposition of each habitat patch.

For many habitat connectivity studies, the flow of individuals between habitat patches is estimated for a wide range of distinct edge threshold distances (Bunn et al., 2000; e.g., Urban and Keitt, 2001). Habitat patches within the threshold distance are defined as connected while patches beyond the distance threshold are defined as disconnected (Keitt et al., 1997; Minor and Urban, 2008). This approach evaluates connectivity to movement ability and can reveal a sharp transition between connected and disconnected landscapes (Urban and Keitt, 2001). This sharp transition is then compared to a fixed distance that represents typical or maximum dispersal distance and that is based on literature review (Roshier et al., 2001; e.g., Lookingbill et al., 2010).

Data Requirements

The only data required to create the simplest graph networks for landscape connectivity model is the location of habitat patches. The simplest graph networks are based solely on the spatial distribution of the habitat patches and assume that connectivity is only a function of distance between patches. More complex network models account for varying ability to move through the environment (Calabrese and Fagan, 2004; Minor and Urban, 2007). These more complex models replace the Euclidean distance matrix that is populated with all pairwise combination of habitat patches with least-cost distances. The distance matrix is then converted into a directed or unidirected graph network.

Strengths

Graph networks are able to incorporate spatial arrangement of habitat patches and attributes of the habitat patch (Keitt et al., 1997; Bunn et al., 2000; Urban and Keitt, 2001). Graph networks do not require knowledge of behavior, fecundity, or mortality parameters. However, as data on a species become available they can be incorporated and used to create an ecologically rich graph model. For example, as mark-recapture data become more available for a species the estimated probability of long-distance dispersal events can be included in graph network model.

Weaknesses/Assumptions

Habitat patches need to be identified and delineated and are simplified into a single point with little or no habitat quality information. Therefore, gradient of habitat quality within a patch is usually not represented in graph networks.

Capacity Needed (construct and run model)

Graph networks can be created within R software with separate packages such as igraph, network, or sna. Free software called Pajek is also available to download (http://vlado.fmf.uni-lj.si/pub/networks/pajek).

D) Agent-based Models

Overview

Agent-based model (also known as individual-based models) is a spatially-explicit simulation modeling approach that attempts to capture the variation among individual movements in order to understand landscape-level movement behavior. Individuals are discrete agents with various properties that change during the life cycle (e.g., age, weight, and reproductive status) (Grimm and Railsback, 2005). For every time step (e.g., year or season) dynamic movement behavior for each agent or individual is governed by local rules (JOHNSON et al., 1992). As a result each individual has a unique history of interactions with its environment and other agents (DeAngelis and Mooij, 2005).

Random walk in a homogeneous environment is one of the simplest agent-based models. This model assumes that step directions are random and independent of each other and movement from a source is similar to diffusion model (Turchin, 1998). The investigator can increase the complexity of the model by correlating species movements with heterogeneous environments. This is accomplished by adjusting the probability of moving into a cell based on the species preference/ability to traverse through that land-cover feature and a correlation between previous step and the next step can be adjusted for each land-cover to mimic straight or curved movements.

Data Requirements

Detailed individual-level movement data (e.g., radio-telemetry) throughout various land-cover types are required to accurately parameterize species movements (Belisle and

Desrochers, 2002). When modeling movements in different environments, continuous raster of all environmental data are required.

Strengths

Very flexible modeling approach where many different types of information regarding species biology, environmental interactions, and intra/inter species interactions can be incorporated into the model. Once the simulation model is constructed, it can be easily altered to account for different behavior rules between species or landscape features. This approach allows models constructed with movement data from a short temporal scale to represent the population or system at wider temporal scale.

Weaknesses/Assumptions

This approach can be data intensive. Many movement studies are needed to inform the local rules needed to mimic a species movement behavior. Each movement decision is based on the immediate surrounding cells. Therefore, this approach is very sensitive to the raster resolution selected by the modeler. The simulated patterns are rarely compared with independent movement data to determine closeness of fit between model predictions and observed movements.

Capacity Needed (construct and run model)

This approach requires a high skill level in computer programming.

References

Adriaensen F., J. P. Chardon, G. De Blust, E. Swinnen, S. Villalba, H. Gulinck, and E. Matthysen. 2003. The application of 'least-cost' modelling as a functional landscape model. Landscape and Urban Planning 64:233-247.

Belisle M., A. Desrochers. 2002. Gap-crossing decisions by forest birds: An empirical basis for parameterizing spatially-explicit, individual-based models. Landscape Ecology 17:219-231.

Bunn A. G., D. L. Urban, and T. H. Keitt. 2000. Landscape connectivity: A conservation application of graph theory. Journal of Environmental Management 59:265-278.

Calabrese J. M., W. F. Fagan. 2004. A comparison-shopper's guide to connectivity metrics. Frontiers in Ecology and the Environment 2:529-536.

DeAngelis D. L., W. M. Mooij. 2005. Individual-basedmodeling of ecological and evolutionary processes. Annual Review of Ecology, Evolution, & Systematics 36:147-C-2.

Grimm V., S. F. Railsback. 2005. Individual-based modeling and ecology. Princeton University Press, Princeton, NJ, USA.

Johnson A. R., J. A. Wiens, B. T. Milne, and T. O. Crist. 1992. Animal movements and population-dynamics in heterogeneous landscapes. Landscape Ecology 7:63-75.

Keitt T. H., D. L. Urban, and B. T. Milne. 1997. Detecting critical scales in fragmented landscapes. Conservation Ecology 1:4.

Lookingbill T. R., A. J. Elmore, K. A. M. Engelhardt, J. B. Churchill, J. Edward Gates, and J. B. Johnson. 2010. Influence of wetland networks on bat activity in mixed-use landscapes. Biological Conservation 143:974-983.

McRae B. H., B. G. Dickson, T. H. Keitt, and V. B. Shah. 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology 89:2712-2724.

Minor E. S., D. L. Urban. 2007. Graph theory as a proxy for spatially explicit population models in conservation planning. Ecological Applications 17:1771-1782.

Minor E. S., D. L. Urban. 2008. A graph-theory framework for evaluating landscape connectivity and conservation planning. Conservation Biology 22:297-307.

Palomares F., M. Delibes, P. Ferreras, J. M. Fedriani, J. Calzada, and E. Revilla. 2000. Iberian lynx in a fragmented landscape: Predispersal, dispersal, and postdispersal habitats. Conservation Biology 14:809-818.

Roshier D. A., A. I. Robertson, R. T. Kingsford, and D. G. Green. 2001. Continental-scale interactions with temporary resources may explain the paradox of large populations of desert waterbirds in australia. Landscape Ecology 16:547-556.

Schadt S., F. Knauer, P. Kaczensky, E. Revilla, T. Wiegand, and L. Trepl. 2002. Rule-based assessment of suitable habitat and patch connectivity for the eurasian lynx. Ecological Applications 12:1469-1483.

Schultz C. B., E. E. Crone. 2001. Edge-mediated dispersal behavior in a prairie butterfly. Ecology 82:1879-1892.

Turchin P. 1998. Quantitative Analysis of Movement: Measuring and Modeling Population Redistribution in Animals and Plants. Sinauer Associates, Inc. Publishers, Sunderland, MA.

Urban D. L., T. H. Keitt. 2001. Landscape connectivity: A graph-theoretic perspective. Ecology 82:1205-1218.

West D. B. 1996. Introduction to graph theory. Prentice Hall, Upper Saddle River, NJ.

Appendix 3

Data Types to Consider

Foundational Datasets These datasets can form the basis of assessments that are comparable across jurisdictions and regions. In some cases state or regional entities may have improved upon these data locally. Providing links to those locally-relevant data sets is beyond the scope of this data table. Criteria for inclusion in the table include:

- Dataset is widely available across most, if not all of the U.S.
- Dataset is of known quality and utility
- Metadata and/or online guidance provide adequate information about appropriate uses of the data
- For composite datasets, documentation provide a complete description of how the data were derived

Matrix Element	Data Type	Information/Examples	Level of Synthesis *	Scope (Global, National, Regional, State)	Maintenance Status
Abiotic					
	Bathymetry Surveys	Example datasets	DO, SR-2	N	Regular Updates
	Climate Change Uncertainty	Example datasets	CO	G,N,R	Active Research
	Elevation – DEM, 30m	Information Example datasets	SR-1	N	Regular Updates
	Elevation – DEM, 10m	Information	SR-1	N	Regular Updates
	Elevation – DEM, 3m	Information	SR-1	R,S	Regular Updates
	Fire Fuel	Information Example datasets	CO	N	Regular Updates
	Fire Regimes	Information Example datasets	CO	N	Regular Updates
	Floodplain	Information	DO, SR-2	N	Regular Updates
	Geology	Example datasets	SR-2	N,R, S	Irregular Updates
	Historic Precipitation (1950-2000) 1km	Example datasets	CO	N	Complete

	Historic Temperature (1950-2000) 1km	Example datasets	CO	N	Complete
	Hydrology – lakes	Example datasets	SR-1,SR-2	N,R,S	Irregular Updates
	Hydrology – streams	Example datasets	SR-1,SR-2	N,R,S	Irregular Updates
	Hydrology – Stream Reach	Example datasets	SR-1,SR-2	N,R,S	Irregular Updates
	Physical Habitats	Example datasets	CO		Active Research
	Predicted Future Precipitation	Example datasets	CO	N	Active Research
	Predicted Future Temperature	Example datasets	CO	N	Active Research
	Sea Level Rise	Example datasets	CO	R	Active Research
	Slope and Aspect	Information Example datasets	SR-1	N	Regular Updates
	Soils – SSURGO	Example datasets	SR-2	R	Regular Updates
	Soils – STATSGO2	Information Example datasets	SR-2	N	Regular Updates
	Storm Surge	Information	CO	N,R	Active Research
	Watersheds (Hydrologic Units)	Information Example datasets	SR-2	N	Complete

**** Level of Synthesis***

DO – Direct Observation
SR-1 – Spatial Representation, based on continuous data (e.g., satellite imagery)
SR-2 – Spatial Representation, based on interpolation between observed points
CO – Composite synthesis of multiple types of data, (e.g., the Human Footprint)

Matrix Element	Data Type	Information/Examples	Level of Synthesis *	Scope (Global, National, Regional, State)	Maintenance Status
Cultural					

	Agricultural Land	Example datasets	SR-1	S	Regular Updates
	Cities & Towns	Example datasets	DO	G,N,S	Regular Updates
	Conservation Easements, NCED Partnership	Example dataset	DO	N	Regular Updates
	Crucial Habitat	Information Example datasets	CO	N,R,S	Active Research
	Dams & Reservoirs	Example datasets	DO, SR-1	N,S	Regular Updates
	Designated Critical Habitat	Information Example datasets	DO	N,R	Irregular Updates
	Designated Roadless Areas	Example datasets	DO	N	Complete
	Energy – Biomass	Example datasets	CO	N,R,S	Regular Updates
	Energy – Coal	Example datasets	CO	N,R,S	Irregular Updates
	Energy – Oil & Gas	Example datasets	DO	N,R,S	Regular Updates
	Energy – Solar Energy Study Areas	Example datasets	DO, CO	N,R	Regular Updates
	Energy – Wind	Example datasets	DO, CO	N,R,S	Regular Updates
	Forest Harvest History and Forecast, CROP	Information	DO	N/S/R	Regular Updates
	Human Footprint	Example datasets	CO	N/R	Active Research

	Human Population	Example datasets	DO	N	Regular Updates
	Impervious Surface – National Land Cover Data	Information Example datasets	CO	N	Regular Updates
	Livestock Grazing Allotments	Example datasets	SR-2	S/R	Regular Updates
	Mine Locations	Example datasets	DO	N	Irregular Updates
	National Cultural Landmarks	Example datasets	DO	N	Irregular Updates
	Power Lines & Pipelines	Example datasets	DO	R	Regular Updates
	Place Names	Information		N	Regular Updates
	Public Land Survey (PLS)	Information Example datasets	DO	N,R,S	Regular Updates
	Protected Areas	Example datasets	DO	N,R,S	Regular Updates
	Railway Network	Example datasets	DO	N	Irregular Updates
	Recreational Facilities	Example datasets	DO	N	Irregular Updates
	Rights-of-Way	Example datasets	DO	N	Regular Updates
	Roads	Information Example datasets	DO	N	Regular Updates
	Trails	Example datasets	CO	R	Irregular Updates
	Urban Boundaries	Example datasets	SR-1	G	Regular Updates
	Water Use by County	Example datasets	CO	N	Irregular Updates

	Wood Mills	Example datasets	DO	R	Irregular Updates

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Matrix Element	Data Type	Information/Examples	Level of Synthesis *	Scope (Global, National, Regional, State)	Maintenance Status
Biological					
	Atlas of Bird, Mammal and Fish Distributions	Information	SR-2	R	Regular Updates
	Biome Shifts				
	Breeding Bird Survey	Information	DO	N	Regular Updates
	Connectivity	Example datasets	CO	R,S	Active Research
	Ecological Systems – NatureServe	Information		N	Active Research
	Ecological Systems – USGS ReGAP	Information	CO	N,R,S	Regular Updates
	Ecoregions – WWF	Example datasets	CO	G,N,R,S	Complete
	Ecoregions – EPA	Example datasets	CO	G,N,S	Complete
	Element Occurrences	Information	DO	N,S	Regular Updates

	Ecoregions – USFS	Example datasets	CO	N	Irregular Updates
	Existing Vegetation (cover, height, type)	Information	CO	N	Regular Updates
	Fish Distributions	Information Example datasets	DO	R	Regular Updates
	Fish Habitat	Information	SR-2	N	Irregular Updates
	Forest Cover 1930 – PNW	Example datasets	SR-2	R	Complete
	Forest Fragmentation	Example datasets	CO	N	Regular Updates
	Forest Insect & Disease Damage and Risk	Information Example datasets	CO	N	Regular Updates
	Forest Inventories / Statewide Forest Plans	Information	CO	S	Irregular Updates
	USFS FIA Plots	Information	DO	N	Regular Updates
	General Land Cover – National Land Cover Database	Example datasets	CO	N	Regular Updates
	Important Bird Areas (IBAs)	Information	DO,CO	N,S	Regular Updates
	Intact Natural Landscapes	Example datasets	CO	G,N,R	Irregular Updates
	Invasive Species	Information Example datasets	DO,CO	N,R,S	Regular Updates
	Landscape Condition	Information Example datasets	CO	R,S	Active Research

	Old-growth Forests	Example datasets	DO,SR-1	R,S	Active Research
	Pre-settlement Vegetation	Information	CO	N	Complete
	Salmon ESUs	Information Example datasets	SR-2	R	Irregular Updates
	Species Distributions	Information Example datasets	SR-2	N,R,S	Active Research
	Species Mortality – Roadkill	Information	DO	S	Regular Updates
	Species range maps	Information Example datasets	SR-2	G,N,R	Active Research
	State Wildlife Action Plan priorities	Information	CO	S	Irregular Updates
	TNC ERA Portfolio	Example datasets	CO	N	Irregular Updates
	Vertebrate Habitat Models	Information Example datasets	CO	R	Active Research
	Wetlands	Example datasets	CO	N	Irregular Updates

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Home pages for most-cited data aggregation sites:

DataBasin http://databasin.org/

ESRI ArcGIS Online Data http://www.esri.com/products/index.html#data_panel

National Atlas http://www.nationalatlas.gov/

NPScape http://science.nature.nps.gov/im/monitor/npscape/index.cfm