Climate Change Vulnerability Assessment for Natural Resources Management: Toolbox of Methods with Case Studies

Version 2.0

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1.0 Introduction

The toolbox of methods for climate change vulnerability assessment (CCVA) for natural resources—from individual species to habitats to places (e.g., protected areas, watersheds, landscapes)—continues to grow as new approaches are developed, tested, and applied. The purpose of this document is to provide a non-comprehensive survey of some of the principal CCVA methods in use today for: (1) species; (2) habitats; (3) places (protected areas, watersheds, landscapes); (4) ecosystem processes; (5) ecosystem services; (6) water resources; and (7) coastal resources. Case study examples are presented for as many of the methods as possible. Most of the text is taken directly from the abstract or methods section of the article/report cited.

This toolbox does not provide an evaluation of the pros and cons of methods, but simply provides a description of each method and case study to provide the reader with sufficient information to: (1) decide if further investigation of a tool or case study is warranted; and (2) find additional resources about that tool/case study.

Deciding which tool to use is not always simple or straightforward, and depends on factors including the management question being asked, the target natural resource or resources, the staff and financial resources available, the level of stakeholder participation desired, the desired level of confidence in the results, and other factors. Readers should consult the comprehensive publication *Scanning the Conservation Horizon* (Glick et al. 2011; http://www.habitat.noaa.gov/pdf/scanning_the_conservation_horizon.pdf), for an introduction to climate change vulnerability assessment and questions to ask in deciding which tool to use.

The goal is to regularly update the Toolbox as new methods and case studies are published. To be effective, this needs to be a living document. We welcome input from readers regarding different methods and case studies, as well as any published evaluations of methods.

Please send information on additional tools and case studies to Kurt A. Johnson (kurt_johnson@fws.gov).

2.0 Species Approaches

CCVAs at the species level are generally categorized into "coarse-filter" approaches that use indices to develop a qualitative categorization of vulnerability, and "fine-filter" approaches that use models, often spatially-explicit, to determine where and how species may be vulnerable to climate change. Each approach has strengths and limitations. Using the two together can be a fruitful approach, especially if a large suite of species is under consideration. In such an analysis, a coarse-filter approach would first be used to identify a suite of species considered vulnerable to climate change. Then a fine-filter, modeling approach would be used to identify species-specific vulnerabilities and responses in greater detail. One such approach is being used by Lawler and associates in the Pacific Northwest (http://www.climatevulnerability.org/).

In recent decades, more and more field data have been collected that demonstrate actual species responses to changing temperatures and/or precipitation regimes (e.g., through changing distribution, timing of migration, reproduction, etc.), providing direct evidence of their vulnerability to climate change. We have highlighted a few such studies to indicate the breadth of direct evidence to be found in the published literature.

2.1 Coarse-filter Species Approaches -- Indices

A number of coarse-filter approaches to assessing species climate change vulnerability have been developed and applied in the United States. Perhaps the most widely used to date is NatureServe's Climate Change Vulnerability Index (CCVI), which has been applied to a number of state-level analyses. In the southwestern United States, the US Forest Service System for Assessing Vulnerability of Species (SAVS) has been used to assess species vulnerability in several large protected areas. The US Environmental Protection Agency Framework for Categorizing the Relative Vulnerability of Threatened & Endangered Species to Climate Change was circulated in draft form, but never finalized. It has not been widely applied. A new approach, termed the Standardized Index of Vulnerability and Value (SIVVA) was developed by Florida researchers. It has been applied to a large suite of species in Florida that may be threatened by sea level rise, land use, and climate change. Other indices have been developed and applied for specific locations or taxa. A brief synopsis and case studies of each approach follow.

2.1.1 Climate Change Vulnerability Index, CCVI (NatureServe)

The Climate Change Vulnerability Index (CCVI; Young et al. 2011) uses a scoring system that integrates a species' projected exposure to climate change in an assessment area with three factors associated with climate change sensitivity: (1) indirect exposure to climate change; (2) species-specific factors (including dispersal ability, temperature and precipitation sensitivity, etc.); and (3) documented response to climate change. The CCVI is intended for use with terrestrial and aquatic (but not marine) animals and plant species. According to NatureServe: "Assessing species with this Index facilitates grouping taxa by their relative risk to climate change, and by sensitivity factors, which we expect will help users to identify adaptation options that could benefit multiple species." Interpretation of the results involves using the outcomes in conjunction with the NatureServe status ranks since CCVI does not consider some key factors that influence vulnerability.
Developer: NatureServe
http://www.natureserve.org/prodServices/climatechange/pdfs/Guidelines_NatureServeClimateChangeVulnerabilityIndex_r2.1_Apr2011.pdf

CCVI Case Studies:

- **Climate-Change Vulnerability Assessment for Priority Wildlife Species (of the Navajo Nation) (Mawdsley and Lamb 2013)**
  The primary methodology for assessing high and low vulnerability in this report is adapted from the NatureServe CCVI, a spreadsheet-based tool that estimates a species' relative vulnerability to climate change. There are three possible generalized outcomes (high, moderate and low) obtained under this method of evaluation. After a review of the primary scientific literature for each of the animal species, a Climate Change Vulnerability Worksheet was completed for each species. This worksheet contains a questions designed to illuminate areas of vulnerability by assessing categories of potential exposure and sensitivity. The information from this worksheet was then used to complete a species-assessment table to further index and classify the species' overall vulnerability. Each species-assessment table contains nine categories including: Man-made barriers, Dispersal Ability, Temperature, Precipitation, Habitat Requirements, Interspecies Interactions, Diet, Population/Genetics, and Human Interactions.
  http://itepsrv1.itep.nau.edu/itep_course_downloads/ClimateAdaptation_Resources/ExamplePlansReports/NavajoNation/Navajo%20Nation%20Climate%20Change%20Vulnerability%20Assessment%20Report.pdf

- **Vulnerability of 70 Plant Species of Greatest Conservation Need to Climate Change in New Jersey (Ring et al. 2013)**
  In order to better integrate the conservation of plant species into the New Jersey State Wildlife Action Plan, this analysis of the vulnerability to climate change of seventy plant Species of Greatest Conservation Need (SGCN) in New Jersey was undertaken. The 70 state endangered plant species were selected from two distinct Landscape Regions of New Jersey; Skylands (40 species) and Pinelands (30 species; see Table 1 below). We used Natureserve's Climate Change Vulnerability Index (CCVI), release 2.1.

https://connect.natureserve.org/sites/default/files/documents/NJ-SWAP-Plants-CCVI-FINAL_0.pdf

- **Changing Climate, Changing Wildlife: A Vulnerability Assessment of 400 Species of Greatest Conservation Need and Game Species in Michigan (Hoving et al. 2013)**
  The Michigan Natural Features Inventory (MNFI) assessed the vulnerability of 198 animal and plant species in the coastal zone using the Climate Change Vulnerability Index (CCVI) developed by NatureServe. The Michigan Department of Natural Resources (DNR) Wildlife Division assessed the vulnerability of 281 animal species using the same methods. Twelve animal species were assessed by both MNFI and the Michigan DNR. All resident terrestrial game species and all Species of Greatest Conservation Need (SGCN) (with enough life history data) were assessed.
  http://www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf

- **Climate Change Vulnerability Assessments for Terrestrial and Freshwater Vertebrates in the Mediterranean Coast Network of National Parks (Bova et al. 2012)**
  Authors examined 68 randomly selected species distributed across five taxonomic groups. The species we studied match the proportions that correspond with the ecological communities of the Santa Monica Mountains National Recreation Area, Channel Islands National Park, and Cabrillo National Monument. Using NatureServe's Climate Change Vulnerability Index—which incorporates modeled future temperature and moisture change and species life history data—they scored each species' vulnerability to climate change.
  http://www.environment.ucla.edu/perch/resources/files/mednclimatechangevulnerabilityassessments.pdf

- **Climate Change Vulnerability Assessment of Rare Plants in California (Anacker et al. 2012)**
  The California Department of Fish and Game, Biogeographic Data Branch used the CCVI to assess the 'vulnerability' of roughly 10% of California's rare plant species (156 of 1625 total rare plants) representing a range of species characteristics. Due to the large number of rare plants in California, authors sought to determine whether the level of climate change vulnerability could be inferred for certain groups of rare plants based on characteristics such as level of rarity, habitat specificity, or other life history traits.
  http://climate.calcommons.org/sites/default/files/final_report_oct_29_2012%281%29.pdf

- **Assessing Climate Change Vulnerability of Breeding Birds in Arctic Alaska (Liebezeit et al. 2012)**
  The Wildlife Conservation Society assessed the climate change vulnerability of 54 Arctic Alaskan breeding bird species using the CCVI. In addition, the assessment was intended to: (1) evaluate the relative contribution of specific sensitivity and exposure factors to individual species rankings; (2) consider how this assessment may be integrated with other approaches; and (3) appraise the effectiveness of the CCVI tool.
  http://www.wcsnorthamerica.org/WildPlaces/ArcticAlaska.aspx

- **Vulnerability of At-risk Species to Climate Change in New York (Schlesinger et al. 2011)**
  The New York Natural Heritage Program calculated the relative vulnerability of 119 of New York's Species of Greatest Conservation Need using the CCVI. They selected species spanning taxonomic groups that were thought (1) might be susceptible to climate change; (2) would be good indicators of vulnerability of species in similar habitats; and (3) would have sufficient data to allow conducting the assessment.
  https://adapt.nd.edu/resources/309/download/CCVI_report_Mar2011_final.pdf

- **Integrating Climate Change Vulnerability Assessments into Adaptation Planning: A Case Study for Species in Florida (Dubois et al. 2011)**
  Defenders of Wildlife assessed 21 species that reflected diverse ecological and management attributes of interest using the NatureServe CCVI, for potential use in the Florida State Wildlife Action Plan. Defenders writes: "By using a facilitated process with species experts, we were able to use the CCVI as a framework to (1) identify factors contributing to vulnerability, (2) elucidate hypothesized relationships among these factors and the potential impacts on species and their habitats, and (3) differentiate among sources of uncertainty."
  http://www.defenders.org/publications/integrating_climate_change_vulnerability_into_adaption_planning.pdf

- **Climate Change Vulnerability Assessment of Species of Concern in West Virginia (Byers and Norris 2011)**
  The West Virginia Division of Natural Resources used the CCVI to assess and rank the relative climate change vulnerability of 185 animal and plant species in West Virginia. Most species were selected based on their status as Species of Greatest Conservation Need within the West Virginia Wildlife Conservation Action Plan.
  http://wvdnr.gov/publications/PDFFiles/ClimateChangeVulnerability.pdf

- **Updating the Illinois Wildlife Action Plan: Using a vulnerability assessment to inform conservation priorities (Walk et al. 2011)**
  The Illinois Chapter of The Nature Conservancy used the CCVI to assess the climate change vulnerability of 162 Species in Greatest Need of Conservation for use in Illinois Wildlife Action Plan.
  http://www.nature.org/ourinitiatives/regions/northamerica/areas/greatlakes/explore/climate-change-il-case-study.pdf

- **Identifying Species in Pennsylvania Potentially Vulnerable to Climate Change (Furedi et al. 2011)**
  The Pennsylvania Natural Heritage Program completed climate change vulnerability assessments for 85 priority species from Pennsylvania's State Wildlife Action Plan using the CCVI.
  http://www.naturalheritage.state.pa.us/ccvi/ccvi_final_report.pdf

- **Use of a Climate Change Vulnerability Index for Assessing Species at Risk on Military Lands (Sperry and Hayden 2011)**
  The Construction Engineering Research Laboratory of the U.S. Army Engineer Research and Development Center evaluated the CCVI as a tool for military land managers by applying it to three high priority Species at Risk: (1) the Mohave ground squirrel (*Spermophilus mohavensis*) on Fort Irwin, CA; (2) the Columbia Basin distinct population segment of the greater sage-grouse (*Centrocercus urophasianus*) on the Yakima Training Center, WA; and (3) the gopher tortoise (*Gopherus polyphemis*) on Fort Stewart, GA.
  http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA559189

- **Climate change planning for the Great Plains: Wildlife vulnerability assessment & recommendations for land and grazing management (Zack et al. 2010)**
  The Wildlife Conservation Society used the CCVI tool to conduct an assessment for a set of 30 grassland species, focusing primarily on the species of concern listed in the wildlife action plans of the states within the Great Plains LCC.
  http://www.southernclimate.org/documents/resources/Climate_Change_Planning_for_Great_Plains_Wildlife_Conservation_Society.pdf

- **Assessing Species and Area Vulnerability to Climate Change for the Oregon Conservation Strategy: Willamette Valley Ecoregion (Steel et al. 2011)**
  The Conservation Management Program at the University of California, Davis, used the CCVI to conduct a vulnerability assessment of 46 focal species across seven broad taxonomic groups within the Willamette Valley Ecoregion of Oregon.
  http://www.defenders.org/publications/assessing_species_and_area_vulnerability_to_climate_change_for_the_oregon_conservation_strategy_willamette_valley_ecoregion.pdf

2.1.2 A System for Assessing Vulnerability of Species to Climate Change, SAVS (US Forest Service)

The System for Assessing Vulnerability of Species (SAVS; Bagne et al. 2011) identifies the relative vulnerability of terrestrial vertebrate species to climate change. Designed for managers, the SAVS tool uses a questionnaire of 22 predictive criteria to create vulnerability scores. The user scores species' attributes relating to potential vulnerability or resilience associated with projections for their region. Six scores are produced: an overall score denoting level of vulnerability or resilience, four categorical scores (habitat, physiology, phenology, and biotic interactions) indicating source of vulnerability, and an uncertainty score, which reflects user confidence in the predicted response.
Developer: US Forest Service, Rocky Mountain Research Station
http://www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/

SAVS Case Studies:

- **Vulnerability of species to climate change in the Southwest: terrestrial species of the Middle Rio Grande (Friggens et al. 2013)**

Authors used the SAVS vulnerability scoring system to assess the vulnerability of 117 vertebrate species that occur in the Middle Rio Grande Bosque (MRGB) in New Mexico to expected climate change. The purpose of this project was to guide wildlife managers on options and considerations for climate change adaptation. The 117 species occur regularly in the MRGB during the breeding season, winter, or year-round.
http://www.fs.fed.us/rm/pubs/rmrs_gtr306.pdf

- **Species Vulnerability in Coronado National Forest (Coe et al. 2012; Davison et al. 2012)**
  US Forest Service staff, led by Rocky Mountain Research Station, assessed the vulnerability of a selection of terrestrial vertebrates in the "Sky Islands" of Coronado National Forest (NF), AZ using SAVS. Two publications resulted, a Forest Service General Technical Report and a paper in the peer-reviewed literature. In this second paper, authors evaluated 15 animal species that had been scored with SAVS, and applied the SAVS vulnerability scores to each species' respective potential habitat model (spatially-explicit) in order to visualize the spatial patterns of cross-species vulnerability across the biologically diverse Coronado NF, and to identify the considerations of spatially referencing such indices.
  http://www.fs.fed.us/rm/pubs_other/rmrs_2012_davison_j001.pdf
  http://www.fs.fed.us/rm/pubs/rmrs_gtr273.pdf

- **Vulnerability of Species to Climate Change in the Southwest: Threatened, Endangered, and At-Risk Species at the Barry M. Goldwater Range, Arizona (Bagne and Finch 2012)**
  This Forest Service conducted assessment of 15 vertebrates and 1 plant species uses SAVS to rank individual species of interest within the eastern portion of the Barry M. Goldwater Range, Arizona, according to predicted climate change responses and associated population declines balanced with responses expected to incur resilience or population increases.
  http://www.fs.fed.us/rm/pubs/rmrs_gtr284.pdf

- **An Assessment of Vulnerability of Threatened, Endangered and At-Risk Species to Climate Change at Fort Huachuca, Arizona (Bagne and Finch 2010)**
  The Forest Service conducted an assessment of 21 vertebrates and 2 plant species using SAVS to rank individual species of interest within Fort Huachuca, Arizona, according to predicted climate change responses and associated population declines balanced with responses expected to incur resilience or population increases.
  http://www.denix.osd.mil/nr/upload/09-433-Fort-Huachuca-Full-Assessment.pdf

2.1.3 Framework for categorizing the relative vulnerability of threatened & endangered species to climate change (US Environmental Protection Agency)

The EPA Framework is composed of four modules. Module 1 categorizes baseline vulnerability to extinction or major population reduction. Module 2 scores the likely vulnerability of a species to future climate change, including the species' potential physiological, behavioral, demographic,

and ecological response to climate change. Module 3 combines the results of Modules 1 and 2 into a matrix to produce an overall score of the species' vulnerability to climate change. Module 4 is a qualitative determination of uncertainty of overall vulnerability based on evaluations of uncertainty done in each of the first 3 modules.
Developer: Environmental Protection Agency (prepared by Galbraith and Price under contract)
http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203743

EPA Framework Case Studies:

- The publication describing the method, cited above, includes a case study of six vertebrate, ESA-listed taxa.

- **Mexican Spotted Owl Recovery Plan (USFWS 2012)**
  The Mexican Spotted Owl (*Strix occidentalis lucida*) Recovery Plan explored the vulnerability of Mexican spotted owls to climate change using current knowledge of Mexican spotted owl ecology and three tools designed to allow assessment of effects of climate change on species of interest, including the EPA framework.
  http://ecos.fws.gov/docs/recovery_plan/MSO_Recovery_Plan_First_Revision_Dec2012.pdf

- **Climate Change Vulnerability of Native and Alien Freshwater Fishes of California: A Systematic Assessment Approach (Moyle et al. 2013)**
  The authors developed a systematic assessment approach that incorporates expert knowledge to determine status and future vulnerability to climate change of native and alien freshwater fishes in California, USA. The method, which was modified from the framework developed by Galbraith and Price, uses expert knowledge, supported by literature reviews of status and biology of the fishes, to score ten metrics for both (1) current status of each species (baseline vulnerability to extinction) and (2) likely future impacts of climate change (vulnerability to extinction). Baseline and climate change vulnerability scores were derived for 121 native and 43 alien fish species.
  http://www.plosone.org/article/fetchObject.action?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0063883&representation=PDF

2.1.4 Standardized Index of Vulnerability and Value, SIVVA (Reece and Noss 2014)

Reece and Noss (2014) developed an integrative and flexible vulnerability assessment framework that incorporates existing assessments and is useful for illuminating the differences between systems such as the IUCN Red List, the US Endangered Species Act, and NatureServe's Conservation Status Assessment and Climate Change Vulnerability Index. The Standardized Index of Vulnerability and Value Assessment (SIVVA) includes five advancements over existing tools: (1) the ability to import criteria and data from previous assessments, (2) explicit attention to SLR, (3) a flexible system of scoring, (4) metrics for both vulnerability and conservation value, and (5) quantitative and transparent accounting of multiple sources of uncertainty.
http://www.bioone.org/doi/abs/10.3375/043.034.0105

SIVVA Case Studies:

- **Prioritizing Species by Conservation Value and Vulnerability: A New Index Applied to Species Threatened by Sea-Level Rise and Other Risks in Florida (Reece and Noss 2014)**
  Authors apply the SIVVA system to 40 species in Florida previously identified as being vulnerable to SLR by the year 2100, describe the influence of different types of uncertainty on the resulting prioritizations, and explore the power of SIVVA to evaluate alternative prioritization schemes. This type of assessment is particularly relevant in low-lying coastal regions where vulnerability to SLR is predictable, severe, and likely to interact synergistically with other threats such as coastal development.
  http://www.bioone.org/doi/abs/10.3375/043.034.0105

- **A Vulnerability Assessment of 300 Species in Florida: Threats from Sea Level Rise, Land Use, and Climate Change (Reece et al. 2013)**
  Authors applied SIVVA to assess the conservation priority of 300 species of plants and animals in Florida given projections of climate change, human land-use patterns, and sea level rise by the year 2100. They for multiple sources of uncertainty and prioritize species under five different systems of value, ranging from a primary emphasis on vulnerability to threats to an emphasis on metrics of conservation value such as phylogenetic distinctiveness. Results reveal remarkable consistency in the prioritization of species across different conservation value systems.
  http://www.plosone.org/article/fetchObject.action?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0080658&representation=PDF

- **Threatened and Endangered Subspecies with Vulnerable Ecological Traits Also Have High Susceptibility to Sea Level Rise and Habitat Fragmentation (Benscoter et al. 2013)**
  Vulnerability assessments using the SIVVA framework were conducted for 12 endangered subspecies and their closely related non-endangered subspecies (n = 23 total assessments. The SIVVA framework consists of four modules: vulnerability (sensitivity + exposure to threats), adaptive capacity (ability to adjust to threats), conservation value, and information availability. Each module contains a set of criteria (n = 30 total SIVVA criteria) that describe key threats and factors relevant to conservation planning. For example, the vulnerability module includes 12 different criteria describing potential threats to species persistence, including sea level rise, habitat fragmentation, and altered temperature and precipitation. Each taxon was assessed independently by two experts with knowledge regarding the taxon of interest. Experts were provided with detailed taxon range maps, projections (e.g., sea level rise, human population growth), and a summary of published literature for the taxon.
  http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0070647

2.1.5 Climate Change Vulnerability Assessment Framework, CCVAF (IUCN)

IUCN (Foden et al. 2008) developed a framework for identifying the species most vulnerable to extinction from a range of climate change induced stresses. The framework guides users to

independently measure three dimensions of climate change vulnerability, namely sensitivity (the lack of potential for a species to persist in situ), exposure (the extent to which each species' physical environment will change) and low adaptive capacity (a species' inability to avoid the negative impacts of climate change through dispersal and/or micro-evolutionary change). The three dimensions can then be used to allocate species to one of four classes of climate change vulnerability, each with different implications for conservation. Species are considered to be highly climate change vulnerable if they qualify as highly sensitive, highly exposed and of lowest adaptive capacity.
http://cmsdata.iucn.org/downloads/climatic_change_chapter_en_final.pdf

CCVAF Case Studies:

- **Vital but vulnerable: Climate change vulnerability and human use of wildlife in Africa's Albertine Rift (Carr et al. 2013)**
  Authors used IUCN's Climate Change Vulnerability Assessment Framework to independently assess three components of species' vulnerability, namely sensitivity (the ability to persist in situ), adaptive capacity (the ability to mitigate impacts by dispersing or undergoing micro-evolutionary change) and exposure (the degree to which the species will be subjected climatic changes). Sensitivity and adaptive capacity assessments were based on a combination of species' life history, ecological, physiological and genetic traits. Exposure was calculated by modelling the degree of changes in temperature and precipitation across species' ranges. For fishes, exposure was calculated as climatic changes across the water catchments in which species occur. By combining sensitivity, adaptive capacity and exposure, we calculated relative measures of overall climate change vulnerability for each taxonomic group. These results indicate the species likely to be at greatest risk from climate change within each group, but as they are not absolute measures, they cannot be interpreted to indicate which species are 'safe' from climate change, nor whether one taxonomic group is more climate change vulnerable than another.
  https://portals.iucn.org/library/efiles/edocs/SSC-OP-048.pdf

- **World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals (Foden et al. 2013)**
  Authors used the IUCN Framework to identify the species most vulnerable to extinction from a range of climate change induced stresses. The framework guides users to independently measure three dimensions of climate change vulnerability, namely sensitivity (the lack of potential for a species to persist in situ), exposure (the extent to which each species' physical environment will change) and low adaptive capacity (a species' inability to avoid the negative impacts of climate change through dispersal and/or micro-evolutionary change). Using this framework, we assessed the climate change vulnerability of each of the world's birds (9,856 species), amphibians (6,204 species) and warm-water reef-building corals (797 species). These taxonomic groups were selected as they are relatively well-studied and include species from terrestrial, freshwater and marine biomes. Gathering trait data involved extensive literature surveys, data compilation and expert consultation.
  http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0065427

2.1.6 Framework for Assessing Climate Change Vulnerability of California's At-risk Birds (Gardali et al. 2012)

Point Reyes Bird Observatory and Cal Fish and Game developed a modified vulnerability index, based in part on the CCVI and EPA approaches, but tailored for California bird populations (Gardali et al. 2012). They developed four sensitivity and three exposure criteria (with assessed confidence levels for each) and used these to develop a climate vulnerability index. They then developed a matrix that integrates the California Bird Species of Special Concern ranks with the climate vulnerability rankings to generate three levels of priority for conservation action. Using this index, they ranked 358 bird taxa, and classified 128 as vulnerable to climate change.
http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0029507

2.1.7 Assessing the Vulnerability of Biodiversity to Climate Change Using Landscape-scale Indicators (Klausmeyer et al. 2011)

Klausmeyer et al. (2011) present a "rapid and cost-effective method to estimate the vulnerability of biodiversity to climate change impacts across broad areas using landscape-scale indicators." This coarse-scale approach does not replace species-specific vulnerability assessments, but allows managers to focus analysis on the species likely to be most vulnerable to climate change and identify the categories of conservation strategies for implementation to reduce vulnerability. They applied this method to California, USA to map the portions of the state where biodiversity managers should focus on minimizing current threats to biodiversity, and reducing constraints to adaptation, reducing exposure to climatic changes.
http://www.esajournals.org/doi/abs/10.1890/ES11-00044.1

2.1.8 Novel predictive framework of species extinction vulnerability for coral reef fishes (Graham et al. 2011)

Graham et al. (2011) developed a predictive bivariate approach to assess species vulnerability to extinction through climate change associated coral reef disturbance. With this framework, a species' vulnerability to population declines following a climatic disturbance event (termed "climate vulnerability") is plotted against the intrinsic extinction risk of that species (termed "extinction risk"). Based on scientific theory and published empirical assessments, four variables were included in the climate vulnerability index that are known to relate to population declines following benthic disturbances; diet specialization, habitat specialization, recruitment specialization for live coral and body size.
http://onlinelibrary.wiley.com/doi/10.1111/j.1461-0248.2011.01592.x/pdf

2.2 Fine-filter Species Approaches -- Modeling

A number of modeling approaches are used to look at the vulnerability of species to future climate change, including mechanistic approaches and correlative approaches. "Mechanistic models aim to incorporate physiologically limiting mechanisms in a species' tolerance to environmental conditions. Such mechanistic models require detailed understanding of the physiological response of species to environmental factors and are therefore difficult to develop for all but the most well understood species. Correlative models aim to estimate the environmental conditions that are suitable for a species by associating known species' occurrence records with suites of environmental variables that can reasonably be expected to affect the species' physiology and probability of persistence. The central premise of this approach is that the observed distribution of a species provides useful information as to the environmental requirements of that species" (Pearson 2007). "Potential impacts of projected climate change on biodiversity are often assessed using single-species bioclimatic 'envelope' models. Such models are a special case of species distribution models in which the current geographical distribution of species is related to climatic variables so to enable projections of distributions under future climate change scenarios" (Heikinnen et al. 2006). There is a rich and growing literature on SDM and bioclimate envelope models, including assessments of the pros and cons of the approach (Araújo and Peterson 2012).

Species Modeling Case Studies:

- **20 Species in Virginia (Kane et al. 2013)**
  The goal of this effort was to conduct a spatially-explicit species vulnerability assessment using dynamically downscaled projected changes in climate to better understand how climate will likely affect species and habitats in Virginia, and to provide essential climate information for use in updating the Virginia Wildlife Action Plan. Twenty species were assessed for this project, including species of greatest conservation need (SGCN) or species associated with Virginia's Wildlife Action Plan. Authors compiled distribution data and climate tolerance data for each species. This information was coupled with the down-scaled climate change data set to build predictive distribution models, using categorical regression tree analysis. The approach for the species modeling was to develop a species distribution file and associate it with the climate change points on the landscape. The most statistically relevant variables were used in the model.
  http://www.bewildvirginia.org/climate-change/virginias-climate-vulnerability-assessment.pdf

- **Tree and bird species in the eastern United States (Iverson et al. 2011)**
  Iverson et al. (2011) took an empirical-statistical modeling approach, using randomForest, with species abundance data from national inventories combined with soil, climate, and landscape variables, to build abundance-based habitat models for 134 tree and 147 bird species. They developed a framework, ModFacs, in which they used the literature to assign default modification factor scores for species characteristics that cannot be readily assessed in such models, including 12 disturbance factors, nine biological factors, and assessment scores of novel climates, long-distance extrapolations, and output variability by climate model and emission scenario. They also used a spatially explicit cellular model, SHIFT, to calculate colonization potentials for some species, based on their abundance, historic dispersal distances, and the fragmented nature of the landscape. By combining results from the three efforts, they created projections of

potential climate change impacts over the next 100 years or so. http://www.nrs.fs.fed.us/pubs/jrnl/2011/nrs_2011_iverson_001.pdf

- **Native Plants in Hawaii (Fortini et al. 2013)**
  In this assessment, authors quantified the climate change vulnerability of more than 1,000 native Hawaiian plant species by estimating the relative ability of species to persist under projected climate change by tolerating expected changes, enduring in microrefugia within areas where compatible climate is lost, and/or migrating to new climate-compatible areas. As a first attempt to operationalize this response-based definition of species vulnerability, authors integrated SDMs into a vulnerability assessment framework using a Bayesian network (BN)-based species vulnerability model. They used the BN species vulnerability model to estimate the ability of a species to exhibit each of the responses required for it to persist under a changing climate in probabilistic terms. For each possible response, they estimated the relative probability of the species exhibiting the response based on a set of relevant landscape factors related to the amount, quality, and distribution of projected areas lost, gained, and maintained in climate-compatible areas between now and 2100. Finally, they used these relative response probabilities for each individual species to determine overall climate change vulnerability by using a response-based species vulnerability index. They applied this novel methodology to quantify the climate change vulnerability of native Hawaiian plant species to demonstrate patterns of vulnerability with respect to habitat associations, conservation status, and other characteristics. http://hilo.hawaii.edu/hcsu/documents/TR44_Fortini_plant_vulnerability_assessment.pdf

- **2,500 Species of African Vertebrates (Garcia et al. 2012)**
  Using an ensemble forecasting framework, authors examined projections of future shifts in climatic suitability, and their methodological uncertainties, for over 2500 species of mammals, birds, amphibians and snakes in sub-Saharan Africa. To summarize a priori the variability in the ensemble of 17 general circulation models, they introduced a consensus methodology that combines co-varying models. They quantify and map the relative contribution to uncertainty of seven bioclimatic envelope models, three multi-model climate projections and three emissions scenarios, and explore the resulting variability in species turnover estimates. Bioclimatic envelope models contributed most to variability, particularly in projected novel climatic conditions over Sahelian and southern Saharan Africa. To summarize agreements among projections from the bioclimatic envelope models they compare five consensus methodologies, which generally increase or retain projection accuracy and provide consistent estimates of species turnover.
  http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2011.02605.x/abstract

- **Climate-induced faunal change in the Western Hemisphere (Lawler et al. 2009)**
  Previous range-shift projections have also been limited by uncertainties in modeling approaches and overly simplistic estimates of extinction rates. Authors use a consensus-based bioclimatic modeling approach that reduces model uncertainties to assess the potential effects of 30 different future climate simulations on the ranges of 1818 bird, 723 mammal, and 413 amphibian species in the Western Hemisphere. Instead of assessing

extinction rates, their approach simply asks whether climatic conditions are predicted to shift so much that a species will not likely be found in a particular location (defined as a particular 50 x 50 km grid cell) in the future and whether new areas with suitable climatic conditions will emerge.
http://www.esajournals.org/doi/abs/10.1890/08-0823.1

- **Greater Glider (*Petauroides volans*) in Australia (Kearney et al. 2010)**
Kearney et al. (2010) applied both mechanistic (Niche Mapper) and correlative (Maxent, Bioclim) SDMs to predict current and future distributions and fertility of the greater glider, an Australian gliding possum. They found that the approaches make congruent, accurate predictions of current distribution and similar predictions about the impact of a warming scenario, thus supporting previous predictions for similar species using only correlative approaches. Authors argue that convergent lines of independent evidence provide a robust basis for predicting and managing extinction risks under climate change.
http://www.environmentportal.in/files/Correlative%20and%20mechanistic%20models%20of%20species%20distribution.pdf

- **Polar Bears in the Southern Beaufort Sea (Hunter et al. 2010) (Regehr et al. 2010) (Rode et al. 2010)**

    - Hunter et al. (2010) evaluated the impacts of climate change on polar bears in the southern Beaufort Sea of Alaska and Canada by means of a demographic analysis, combining deterministic, stochastic, environment dependent matrix population models with forecasts of future sea ice conditions from IPCC general circulation models (GCMs).
https://darchive.mblwhoilibrary.org/bitstream/handle/1912/4685/09-1641.1.pdf?sequence=1

    - Regehr et al. (2010) evaluated the effects of sea ice conditions on vital rates (survival and breeding probabilities) for polar bears in the southern Beaufort Sea. They estimated vital rates using multistate capture–recapture models that classified individuals by sex, age and reproductive category. They used multimodel inference to evaluate a range of statistical models, all of which were structurally based on the polar bear life cycle. We estimated parameters by model averaging, and developed a parametric bootstrap procedure to quantify parameter uncertainty.
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2656.2009.01603.x/abstract

    - Rode et al. (2010) tested whether patterns in body size, condition, and cub recruitment of polar bears in the southern Beaufort Sea of Alaska were related to the availability of preferred sea ice habitats and whether these measures and habitat availability exhibited trends over time, between 1982 and 2006. Specifically, they addressed the following four questions: (1) Is reproductive output, quantified as litter mass, associated with maternal condition? If so, what measures of female stature/condition (condition indices, body mass, skull size) are most closely related to reproductive output? (2) Did body mass, skull size, or

condition relate to interannual variation in available ice habitat? (3) Did body mass, skull size, or condition of polar bears exhibit a trend between 1982 and 2006? (4) Did reproductive output (litter mass and cubs per female) exhibit a trend between 1982 and 2006? Was it related to interannual variation in available ice habitat?
http://www.esajournals.org/doi/pdf/10.1890/08-1036.1

- **Pacific Walrus (MacCracken et al. 2013)**
Authors developed a Bayesian belief network model structured around the ESA 5-factor analysis during a workshop attended by walrus and ESA experts to 1) elicit expert opinion on important stressors and their effects, 2) develop the model, and 3) develop and analyze plausible future scenarios. The listing factors and associated stressors were organized as sub-models, capturing the cumulative effects of the factors through model output, which was the probability of negative, neutral, or positive effects. They found that in a time-constrained workshop, the graphical display of Bayesian belief networks allowed for rapid development, assessment, and revision of model structure and parameters. They modeled up to 3 scenarios (most likely-, worst-, and best-case) for each of 4 time periods (recent past, contemporary, mid-century, and late-century). Model output for the recent past (reference condition) was consistent with observations and provided a baseline for comparison of the outcomes of other periods and scenarios; stressor effects became increasingly negative with time.
http://onlinelibrary.wiley.com/doi/10.1002/wsb.229/pdf

- **American Pika in Western United States (Calkins et al. 2012)**
Authors modeled current and future distribution of suitable habitat for the talus-obligate l *Ochotona princeps* (American pika) across the western USA under increases in temperature associated with climate change, to: (a) compare forecasts using only climate variables vs using those plus habitat considerations; (b) identify possible patterns of range collapse; and (c) compare conservation and management implications of changes at two taxonomic resolutions, and using binned- vs binary-probability maps. They used MaxEnt to analyze relationships between occurrence records and climatic variables to develop a bioclimatic-envelope model, which was refined by masking with a deductive appropriate-habitat filter based on suitable land-cover types. They used this final species-distribution model to predict distribution of suitable habitat under range-wide temperature increases from 1 to 7°C, in 1°C increments.
http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0587.2011.07227.x/abstract;jsessionid=0A1FFF42B6698DEEC24C46D6FA75446D.d01t01?systemMessage=Wiley+Online+Library+will+be+disrupted+on+18+May+from+10%3A00-12%3A00+BST+%2805%3A00-07%3A00+EDT%29+for+essential+maintenance&userIsAuthenticated=false&deniedAccessCustomisedMessage=

- **Wolverine Circumboreal Distribution (Copeland et al. 2010)**
Authors hypothesized that the occurrence of wolverines is constrained by their obligate association with persistent spring snow cover for successful reproductive denning and by an upper limit of thermoneutrality. To investigate this hypothesis, they developed a

composite of MODIS classified satellite images representing persistent snow cover from 24 April to 15 May, which encompasses the end of the wolverine's reproductive denning period. To investigate the wolverine's spatial relationship with average maximum August temperatures, they used interpolated temperature maps. They then compared and correlated these climatic factors with spatially referenced data on wolverine den sites and telemetry locations from North America and Fennoscandia, and our contemporary understanding of the wolverine's circumboreal range.
http://www.fs.fed.us/rm/pubs_other/rmrs_2010_copeland_j001.pdf

- **Dispersal will limit ability of mammals to track climate change in the Western Hemisphere (Schloss et al. 2012)**
  Authors investigated the potential for mammals in the Western Hemisphere to keep pace with a changing climate by comparing the velocities of climate change that each of 493 mammals will likely experience with modeled dispersal velocities for these species. First, they calculated the velocity of climatic changes relevant to each species on a cell-by-cell basis across a 0.5° by 0.5° grid using bioclimatic model projections for the coming century. Next, they modeled dispersal velocities for each species as a function of body mass, diet type, the successive time between generations, and the potential variability in dispersal distances. They then determined the percentage of species in each grid cell for which the velocity of climate change will likely exceed the species' dispersal velocity, and thus, the percentage of species that will be unable to keep pace with projected climate changes. They also investigated the relative degree to which human land use may further impede movement of species by analyzing land-use patterns along simple movement routes connecting current and future suitable climates and calculated the additional distances that some species may need to travel to avoid movement through less suitable landscapes.
  http://www.pnas.org/content/early/2012/05/07/1116791109.full.pdf

- **Montane Mammals in Cascadia (Johnston et al. 2012)**
  Johnston et al. (2012) examined potential impacts of climate change over the next century on eight mammal species of conservation concern in western Washington State, under four warming scenarios. They used two species distribution models, including a logistic regression-based model and the "maximum entropy" (MaxEnt) model, to project the location and extent of the potential current and future range of each species based on a suite of environmental and geographical variables.
  http://www.esajournals.org/doi/abs/10.1890/ES12-00077.1

- **Snow Leopards in the Himalaya (Forrest et al. 2012)**
  Authors developed a hybrid approach to climate-adaptive conservation landscape planning for snow leopards in the Himalayan Mountains. First they mapped current snow leopard habitat using a mechanistic approach that incorporated field-based data, and then combined it with a climate impact model using a correlative approach. For the latter, they used statistical methods to test hypotheses about climatic drivers of treeline in the Himalaya and its potential response to climate change under three IPCC GHG emissions scenarios. Second, they assessed how change in treeline might affect the distribution of snow leopard habitat.

http://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Biol.Cons.2012_Vulnerability_of_Snow_Leopard_Habitat_to_Treeline_Shift__1_.pdf

- **Giant Panda in China (Songer et al. 2012)**
  Authors used Maxent to relate current giant panda distribution to environmental variables and to project future giant panda habitat within China.
  http://www.hindawi.com/journals/ijeco/2012/108752/

- **Koala in Australia (Adams-Hosking et al. 2011)**
  Authors aimed to predict the likely shifts in the climate envelope of the koala throughout its natural distribution under various climate change scenarios and identify potential future climate refugia. To predict possible future koala climate envelopes, they developed bioclimatic models using Maxent, based on a substantial database of locality records and several climate change scenarios.
  http://www.publish.csiro.au/?paper=WR10156

- **Tidal Marsh Birds in the San Francisco Estuary (Nur et al. 2012 and Veloz et al. 2013)**

  - Nur et al. (2012) developed population-dynamic models to assess and better understand the long-term population viability of four key, tidal marsh-dependent species, under a variety of environmental conditions, including climate change impacts, in the San Francisco Estuary. Species are: California Black Rail (*Laterallus jamaicensis coturniculus*), California Clapper Rail (*Rallus longirostris obsoletus*), Saltmarsh Common Yellowthroat (*Geothlypis trichas sinuosa*), and three tidal marsh subspecies of Song Sparrow: Alameda (*Melospiza melodia pusillula*), Samuel's (*M. m. samuelis*), and Suisun (*M. m. maxillaris*).
    http://data.prbo.org/apps/sfbslr/LCC%20PRBO%20SFBay%20TidalMarsh%20Demogr%20ClimateChange_2012.pdf

  - Veloz et al. (2013) is essentially the published version of the Nur et al. (2012) report. They used a boosted regression tree approach to project the future distribution and abundance of five marsh bird species (through 2110) in response to changes in habitat availability and suitability as a result of projected sea-level rise, salinity, and sediment availability in the Estuary. To bracket the uncertainty, they considered four future scenarios based on two sediment availability scenarios (high or low), which varied regionally, and two rates of sea-level rise (0.52 or 1.65 m/100 yr). We evaluated three approaches for using model results to inform the selection of potential restoration projects: (1) Use current conditions only to prioritize restoration. (2) Use a single future scenario (among the four referred to above) in combination with current conditions to select priority restoration projects. (3) Combine current conditions with all four future scenarios, while incorporating uncertainty among future scenarios into the selection of restoration projects.
    http://www.esajournals.org/doi/pdf/10.1890/ES12-00341.1

- **Waterbirds in the Prairie Pothole Region, U.S.A. (Steen and Powell 2012)**
  Current and future distributions of American Bittern (*Botaurus lentiginosus*), American Coot (*Fulica americana*), Black Tern (*Chlidonias niger*), Pied-billed Grebe (*Podilymbus podiceps*) and Sora (*Porzana carolina*), five waterbird species common in the Prairie Pothole Region (PPR), were predicted using species distribution models (SDMs) in combination with climate data that projected a drier future for the PPR. Regional-scale SDMs were created for the U.S. PPR using breeding bird survey occurrence records for 1971–2000 and wetland and climate parameters. For each waterbird species, current distribution and four potential future distributions were predicted: all combinations of two Global Circulation Models and two emissions scenarios.
  http://www.bioone.org/doi/abs/10.1675/063.035.0204

- **Sichuan Jay in West-central China (Lu et al. 2012)**
  Authors used MaxEnt software to construct models and make predictions for the rare Sichuan Jay (*Perisoreus internigrans*), which is known only from isolated fragments of high-elevation coniferous forest on the Qinghai–Tibet plateau of west-central China.
  http://www.jstor.org/stable/full/10.1525/cond.2012.110030

- **36 amphibian and reptile species endemic to the United States (Pearson et al. 2014)**
  Authors coupled ecological niche models (ENMs) with demographic models and expanded this approach by developing a generic life history (GLH) method. The coupled modelling approach estimates extinction risk as the probability of abundance falling to zero by the year 2100, rather than as the proportion of species committed to extinction due to contraction of bioclimate envelopes. By matching ENMs for 36 amphibian and reptile species endemic to the US with corresponding GLH models, they estimate mean extinction risk by 2100 to be 28 ± 7% under a high CO2 concentration Reference climate scenario and 23 ± 7% under a Policy climate scenario that assumes substantive intervention. In contrast, extinction risk is estimated by the same models to be <1% without climate change, showing that the methods are not biased towards predicting high risks.
  http://www.nature.com/nclimate/journal/v4/n3/full/nclimate2113.html

- **Sand Dune Lizard in Coachella Valley, California (Barrows et al. 2010)**
  Authors assess climate-change sensitivity using niche modeling that unlike bioclimatic modeling incorporates both climate variables as well as other habitat features that constrain a species' distribution. We analyzed the effects of potential increases in drought frequency for an endangered, sand dune-restricted lizard (Coachella Valley fringe-toed lizard), a species restricted to a narrowly occurring substrate and so unable to move up-slope or pole-ward to track climate shifts.
  http://www.sciencedirect.com/science/article/pii/S0006320709005217

- **Two reptiles at the Mojave-Sonoran Desert interface (Barrows 2011)**
  The author examined climate change sensitivity for desert tortoises, *Gopherus agassizii*, and common chuckwallas, *Sauromalus ater*, two large-bodied reptiles that occur across the Mojave-Sonoran Desert interface. He employed the Mahalanobis D2 statistic to

model their niche spaces and then assessed climate-change sensitivity by altering climate variables along a gradient of increasing temperature and decreasing precipitation. While shifting climate variables, author held terrain and soils variables that otherwise define these species' preferred habitat constant, providing a more realistic prediction of available niche space. Both reptiles' modeled niches responded to climate change by shifting to higher elevations and increasingly away from their Sonoran Desert distribution.
http://www.fws.gov/southwest/ES/Documents/Barrows%202011.pdf

- **Lizard Diversity in Mexico (Sinervo et al. 2010)**
  Sinervo et al. (2010) compared recent and historical surveys for 48 Mexican lizard species at 200 sites. Since 1975, 12% of local populations have gone extinct. Authors verified physiological models of extinction risk with observed local extinctions and extended projections worldwide. Since 1975, authors estimate that 4% of local populations have gone extinct worldwide, but by 2080 local extinctions are projected to reach 39% worldwide, and species extinctions may reach 20%.
  http://bio.research.ucsc.edu/~barrylab/classes/climate_change/SinervoSci2010.pdf

- **Salamander Biodiversity in Appalachia (Milanovich et al. 2010)**
  Milanovich et al. (2010) used Maxent to model the suitable climatic habitat of 41 plethodontid salamander species inhabiting the Appalachian Highlands region (33 individual species and eight species included within two species complexes). They evaluated the relative change in suitable climatic habitat for these species in the Appalachian Highlands from the current climate to the years 2020, 2050, and 2080, using two models and two emissions scenarios and using two-model thresholds levels (relative suitability thresholds for determining suitable/unsuitable range).
  http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0012189

- **Body Size Reductions in Appalachian Salamanders (Caruso et al. 2014)**
  Authors compared historic and contemporary size measurements in 15 *Plethodon* species from 102 populations (9450 individuals) in Appalachia and found that six species exhibited significant reductions in body size over 55 years. Biophysical models, accounting for actual changes in moisture and air temperature over that period, showed a 7.1–7.9% increase in metabolic expenditure at three latitudes but showed no change in annual duration of activity.
  http://onlinelibrary.wiley.com/doi/10.1111/gcb.12550/full

- **Bull Trout in the Columbia River Basin, Pacific Northwest (Wenger et al. 2013)**
  We developed a Monte Carlo approach that accounts for uncertainty within generalized linear regression models (parameter uncertainty and residual error), uncertainty among competing models (model uncertainty), and uncertainty in future climate conditions (climate uncertainty) to produce site-specific frequency distributions of occurrence probabilities across a species' range. They illustrated the method by forecasting suitable habitat for bull trout (*Salvelinus confluentus*) in the Interior Columbia River Basin, USA, under recent and projected 2040s and 2080s climate conditions.
  http://onlinelibrary.wiley.com/doi/10.1111/gcb.12294/abstract

- **Steelhead in the Pacific Northwest (Wade et al. 2013)**
  We demonstrate a spatially explicit method for assessing salmon vulnerability to projected climatic changes (scenario for the years 2030–2059), applied here to steelhead salmon across the entire Pacific Northwest (PNW). We considered steelhead exposure to increased temperatures and more extreme high and low flows during four of their primary freshwater life stages: adult migration, spawning, incubation and rearing. Steelhead sensitivity to climate change was estimated on the basis of their regulatory status and the condition of their habitat. We assessed combinations of exposure and sensitivity to suggest actions that may be most effective for reducing steelhead vulnerability to climate change.
  http://onlinelibrary.wiley.com/doi/10.1111/1365-2664.12137/abstract

- **Cutthroat Trout (*Oncorhynchus clarkii*) in the interior western USA (Wenger et al. 2011)**
  Wenger et al. (2011) assessed the effects of temperature, flow regime, biotic interactions, topographic variables and land-use variables on distribution of four trout species in the western United States, then used downscaled outputs from general circulation models coupled with a hydrologic model to forecast species suitable habitat under climate change Projections under the 2080s A1B emissions scenario project that native cutthroat trout, already excluded from much of its potential range by nonnative species, will lose a further 58% of habitat due to an increase in temperatures beyond the species' physiological optima and continued negative biotic interactions.
  http://www.pnas.org/content/early/2011/08/09/1103097108.full.pdf

- **Gila Trout (*Oncorhynchus gilae*) in New Mexico (Kennedy et al. 2009)**
  This study uses a regional climate change simulation (Leung et al., Clim Change 62:75–113, 2004) to determine changes in the climate envelope for Gila trout, which is sensitive to maximum temperature, associated with a plausible scenario for greenhouse gas increases. These regional climate changes are downscaled to derive surface temperature lapse rates using regression models.
  http://epswww.unm.edu/facstaff/gutzler/manuscripts/ClimChange_09.pdf

- **Joshua Tree (*Yucca brevifolia*) Cole et al. (2011)**
  Cole et al. (2011) combined paleoecological records, current observations and climate envelope modeling to identify future possible ranges of Joshua trees under several climate change scenarios. They developed a model of climate suitability for Joshua tree based on its 20th century range and climates, and applied it to future climates modeled through GCMs downscaled to accommodate the complex topography within Joshua tree range. All of the models projected elimination of the Joshua tree from most of the southern portion of its current range. And several models projected expansion of suitable climate space beyond the current range.
  http://www.esajournals.org/doi/abs/10.1890/09-1800.1?journalCode=ecap

- **California Mountain Plants (Dobrowski et al. 2010)**
  Authors addressed two key questions: (1) Are SDM projections transferable in time? (2) Does temporal transferability relate to species ecological traits? To address these questions they developed SDMs for 133 vascular plant species using data from the mountain ranges of California (USA) from two time periods: the 1930s and the present day. They forecast historical models over 75 years of measured climate change and assessed their projections against current distributions. Similarly, they hindcast contemporary models and compared their projections to historical data. Authors quantified transferability and related it to species ecological traits including physiognomy, endemism, dispersal capacity, fire adaptation, and commonness
  http://www.esajournals.org/doi/abs/10.1890/10-1325.1

- **California Floristic Province endemic plants (Franklin et al. 2013)**
  Authors modeled distributions for 52 plant species endemic to the California Floristic Province of different life forms and range sizes under recent and future climate across a 2000-fold range of spatial scales (0.008–16 km2). They produced unique current and future climate datasets by separately downscaling 4 km climate models to three finer resolutions based on 800, 270, and 90 m digital elevation models and deriving bioclimatic predictors from them. As climate-data resolution became coarser, SDMs predicted larger habitat area with diminishing spatial congruence between fine- and coarse-scale predictions. These trends were most pronounced at the coarsest resolutions and depended on climate scenario and species' range size. On average, SDMs projected onto 4 km climate data predicted 42% more stable habitat (the amount of spatial overlap between predicted current and future climatically suitable habitat) compared with 800 m data. They found only modest agreement between areas predicted to be stable by 90 m models generalized to 4 km grids compared with areas classified as stable based on 4 km models, suggesting that some climate refugia captured at finer scales may be missed using coarser scale data.
  http://onlinelibrary.wiley.com/doi/10.1111/gcb.12051/abstract

- **North American Trees (McKenney et al. 2011)**
  McKenney et al. (2011) reanalyzed their previous work on shifts in tree climate envelopes (CEs) using the newer-generation AOGCM projections. Based on the updated AOGCMs, by the 2071–2100 period, tree CEs shifted up to 2.4 degrees further north or 2.6 degrees further south (depending on the AOGCM) and were about 10% larger in size.
  http://climateknowledge.org/figures/Rood_Climate_Change_AOSS480_Documents/McKenney_Rood_Forest_Envelopes_GlobChanBio_2011.pdf

- **Native Plants in Australia (Summers et al. 2012)**
  Summers et al. (2012) conducted a large-scale modeling effort to assess the vulnerability of "584 native plant species under three climate change scenarios in an 11.9 million hectare fragmented agricultural region in southern Australia." The authors represented: (1) exposure as species' geographical range under each climate change scenario as quantified using species distribution models; (2) sensitivity as a function of the impact of climate change on species' geographical ranges; and (3) adaptive capacity as species' ability to migrate to new geographical ranges under each climate change scenario.

http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2012.02700.x/abstract

- **Climate Change and Vulnerability Analysis for Four Species in Three Southwestern Utah National Parks/Monuments (Shovic and Thoma 2011)**
  Shovic and Thoma (2011) conducted a modeling exercise to assess the climate vulnerability of four taxa: American pika (*Ochotona princeps*), Desert tortoise (*Xerobates* [*Gopherus*] *agassizii*), Shivwits Milk-vetch (*Astragalus ampullarioides*), and Great Basin bristlecone pine (*Pinus longaeva*). Three levels of models were developed; first to estimate the degree of climate change, then to create a local physical proxy for that change, and finally to predict the effects of modifying that proxy for each species/habitat response model.
  http://www.cfc.umt.edu/CESU/Reports/NPS/MSU/2010/10Roberts_Shovic_ZION_cc_scenario%20planning_Final.pdf

2.3 Migratory Species

- **Modeling climate change impacts on phenology and population dynamics of migratory marine species (Anderson et al. 2013)**
  Authors developed an individual-based modeling framework characterizing the effects of climate change on phenology and population dynamics. In the framework, an animal's ability to match its environmental preferences, its bioclimate envelope, to the environmental conditions by adjusting its migration timing between foraging and breeding habitats determines its condition, survival, and fecundity. Climate-induced changes in the envelope produce timing mismatches that result in a population adapting its phenology through both genetic and plastic processes.
  http://staff.washington.edu/klaidre/docs/Andersonetal2013.pdf

- **A blind spot in climate change vulnerability assessments (Small-Lorenz et al. 2013)**
  Small-Lorenz et al. (2013) "reviewed how five multi-species frameworks used to assess climate change vulnerability in North America treat migratory species, and found their approaches to be varied and incomplete." They outlined three areas for improving species-level CCVAs to "make them more robust in accounting for migratory species": (1) examine the full annual cycle; (2) consider key life-history traits; and (3) incorporate conservation status.
  http://www.parcc-web.org/parcc-project/documents/2013/02/a-blind-spot-in-climate-change-vulnerability-assessments.pdf

- **Migratory connectivity magnifies the consequences of habitat loss from sea-level rise for shorebird populations (Iwamura et al. 2013)**
  Iwamura et al (2013) developed a novel graph-theoretic approach to measure the vulnerability of a migratory network to the impact of habitat loss from SLR based on population flow through the network. They show that reductions in population flow far exceed the proportion of habitat lost for 10 long-distance migrant shorebirds using the East Asian–Australasian Flyway.
  http://rspb.royalsocietypublishing.org/content/280/1761/20130325.short

2.4 Observed Effects of Climate Change on Species

- **Do stream fish track climate change? Assessing distribution shifts in recent decades (Comte and Grenouillet 2013)**
  Based on national monitoring data, we examined the distributional changes of 32 stream fish species in France and quantified potential time lags in species responses, providing a unique opportunity to analyze range shifts over recent decades of warming in freshwater environments. A multi-facetted approach, based on several range measures along spatial gradients, allowed us to quantify range shifts of numerous species across the whole hydrographic network between an initial period (1980–1992) and a contemporary one (2003–2009), and to contrast them to the rates of isotherm shift in elevation and stream distance. Our results highlight systematic species shifts towards higher elevation and upstream, with mean shifts in range center of 13.7 m decade−1 and 0.6 km decade−1, respectively. Fish species displayed dispersal-driven expansions along the altitudinal gradient at their upper range limit (61.5 m decade−1), while substantial range contractions at the lower limit (6.3 km decade−1) were documented for most species along the upstream–downstream gradient.
  http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0587.2013.00282.x/abstract

- **Climate-induced changes in the distribution of freshwater fish: observed and predicted trends (Comte et al. 2013)**
  Authors provide a review and some meta-analyses of the literature reporting both observed and predicted climate-induced effects on the distribution of freshwater fish. After reviewing three decades of research, they summarize how methods in assessing the effects of climate change have evolved, and whether current knowledge is geographically or taxonomically biased. They conducted multispecies qualitative and quantitative analyses to find out whether the observed responses of freshwater fish to recent changes in climate are consistent with those predicted under future climate scenarios. They highlight the fact that, in recent years, freshwater fish distributions have already been affected by contemporary climate change in ways consistent with anticipated responses under future climate change scenarios: the range of most cold-water species could be reduced or shift to higher altitude or latitude, whereas that of cool- and warm-water species could expand or contract.
  http://onlinelibrary.wiley.com/doi/10.1111/fwb.12081/abstract

- **Climate change is linked to long-term decline in a stream salamander (Lowe 2011)**
  Author hypothesized that increasing air temperature and precipitation in northeastern North America caused abundance of the stream salamander *Gyrinophilus porphyriticus* in a New Hampshire population to decline between 1999 and 2010. He found a significant decline in abundance of *G. porphyriticus* adults over this 12-year period, and no trend in larval abundance. Adult abundance was negatively related to annual precipitation, which is predicted to increase further in the Northeast due to climate change. Analysis of a 6-year capture–mark–recapture data set for the same population showed no temporal variation in larval and adult detectability, validating the abundance data, and no variation in larval and adult survival. However, survival during metamorphosis from the larval to

adult stage declined dramatically. These results suggest that increasing precipitation is causing a decline in adult recruitment, which, if it persists, will lead to local extinction. http://dbs.umt.edu/research_labs/lowelab/images/stories/fruit/Lowe_2012_BioCon.pdf

- **Species of North American Turtles Over the Past 320 Ka (Rodder et al. 2013)**
  In this study authors combine modern geographic range data, phylogeny, Pleistocene paleoclimatic models, and isotopic records of changes in global mean annual temperature, to produce a temporally continuous model of geographic changes in potential habitat for 59 species of North American turtles over the past 320 Ka (three full glacial-interglacial cycles). These paleophylogeographic models indicate the areas where past climates were compatible with the modern ranges of the species and serve as hypotheses for how their geographic ranges would have changed in response to Quaternary climate cycles. They test these hypotheses against physiological, genetic, taxonomic and fossil evidence, and we then use them to measure the effects of Quaternary climate cycles on species distributions.
  http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0072855

- **Spatiotemporal Variation in Avian Migration Phenology: Citizen Science Reveals Effects of Climate Change (Hurlbert and Liang 2012)**
  Authors used a database of citizen science bird observations to explore spatiotemporal variation in mean arrival dates across an unprecedented geographic extent for 18 common species in North America over the past decade, relating arrival dates to mean minimum spring temperature. Across all species and geographic locations, species shifted arrival dates 0.8 days earlier for every °C of warming of spring temperature, but it was common for some species in some locations to shift as much as 3–6 days earlier per °C. Species that advanced arrival dates the earliest in response to warming were those that migrate more slowly, short distance migrants, and species with broader climatic niches. These three variables explained 63% of the interspecific variation in phenological response.
  http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0031662

- **Climate change has indirect effects on resource use and overlap among coexisting bird species with negative consequences for their reproductive success (Auer and Martin 2013)**
  Climate change can modify ecological interactions, but whether it can have cascading effects throughout ecological networks of multiple interacting species remains poorly studied. Climate-driven alterations in the intensity of plant–herbivore interactions may have particularly profound effects on the larger community because plants provide habitat for a wide diversity of organisms. Here we show that changes in vegetation over the last 21 years, due to climate effects on plant–herbivore interactions, have consequences for songbird nest site overlap and breeding success. Browsing-induced reductions in the availability of preferred nesting sites for two of three ground nesting songbirds led to increasing overlap in nest site characteristics among all three bird species with increasingly negative consequences for reproductive success over the long term. These results demonstrate that changes in the vegetation community from effects of climate change on plant–herbivore interactions can cause subtle shifts in ecological

interactions that have critical demographic ramifications for other species in the larger community.
http://onlinelibrary.wiley.com/doi/10.1111/gcb.12062/abstract

- **Observed impacts of climate change on terrestrial birds in Europe: an overview (Pautasso 2012)**
  Focusing on Europe, this overview summarizes recently published observed impacts of modern climate change on birds. Due to the sensitivity of birds to weather fluctuations, the high numbers of ornithologists throughout Europe and the tradition in the long-term study of bird populations, there is no doubt that climate change impacts on birds have already occurred. These impacts include changes in (i) phenology (e.g., breeding times), (ii) migration patterns (e.g., time of spring arrival from the wintering grounds), (iii) species distribution (e.g., poleward shift of range margins) and (iv) abundances (e.g., population declines of habitat-specialist birds). Although the overall evidence available is comprehensive, there is a challenge in disentangling the effects of climate change from those of other concurrent factors such as habitat loss and degradation, e.g. due to large-scale intensification of agriculture. Birds are coping with climate change by means of their phenotypic plasticity, but little evidence is available to prove that evolutionary adaptation is already taking place.
  http://www.tandfonline.com/doi/full/10.1080/11250003.2011.627381

- **Tracking of climatic niche boundaries under recent climate change (LaSorte and Jetz 2012)**
  Authors provide a continental assessment of the temporal structure of species responses to recent spatial shifts in climatic conditions. They examined geographic associations with minimum winter temperature for 59 species of winter avifauna at 476 Christmas Bird Count circles in North America from 1975 to 2009 under three sampling schemes that account for spatial and temporal sampling effects.
  http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2656.2012.01958.x/abstract

- **Body size and activity times mediate mammalian responses to climate change (McCain and King 2014)**
  To date, 73 mammal species in North America and eight additional species worldwide have been assessed for responses to climate change, including local extirpations, range contractions and shifts, decreased abundance, phenological shifts, morphological or genetic changes. Only 52% of those species have responded as expected, 7% responded opposite to expectations, and the remaining 41% have not responded. Which mammals are and are not responding to climate change is mediated predominantly by body size and activity times (phylogenetic multivariate logistic regressions, $P < 0.0001$).
  http://onlinelibrary.wiley.com/doi/10.1111/gcb.12499/abstract

- **Climate-induced changes in the small mammal communities of the Northern Great Lakes Region (Myers et al. 2009)**
  Authors used museum and other collection records to document large and extraordinarily rapid changes in the ranges and relative abundance of nine species of mammals in the northern Great Lakes region (white-footed mice, woodland deer mice, southern red-

backed voles, woodland jumping mice, eastern chipmunks, least chipmunks, southern flying squirrels, northern flying squirrels, common opossums). These species reach either the southern or the northern limit of their distributions in this region. Changes consistently reflect increases in species of primarily southern distribution (white-footed mice, eastern chipmunks, southern flying squirrels, common opossums) and declines by northern species (woodland deer mice, southern red-backed voles, woodland jumping mice, least chipmunks, northern flying squirrels). White-footed mice and southern flying squirrels have extended their ranges over 225 km since 1980, and at particularly well-studied sites in Michigan's Upper Peninsula, small mammal assemblages have shifted from numerical domination by northern species to domination by southern species.
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2009.01846.x/abstract

- **Impact of a Century of Climate Change on Small-Mammal Communities in Yosemite National Park, USA (Moritz et al. 2008)**
  Authors provide a century-scale view of small-mammal responses to global warming, without confounding effects of land-use change, by repeating Grinnell's early–20th century survey across a 3000-meter-elevation gradient that spans Yosemite National Park, California, USA. Using occupancy modeling to control for variation in detectability, they show substantial (~500 meters on average) upward changes in elevational limits for half of 28 species monitored, consistent with the observed ~3°C increase in minimum temperatures. Formerly low-elevation species expanded their ranges and high-elevation species contracted theirs, leading to changed community composition at mid- and high elevations.
  https://www.sciencemag.org/content/322/5899/261

- **Shifts in flowering phenology reshape a subalpine plant community (CaraDonna et al. 2014)**
  Using a uniquely comprehensive 39-y flowering phenology dataset from the Colorado Rocky Mountains that contains more than 2 million flower counts, we reveal a diversity of species-level phenological shifts that bring into question the accuracy of previous estimates of long-term phenological change. For 60 species, we show that first, peak, and last flowering rarely shift uniformly and instead usually shift independently of one another, resulting in a diversity of phenological changes through time. Shifts in the timing of first flowering on average overestimate the magnitude of shifts in the timing of peak flowering, fail to predict shifts in the timing of last flowering, and underrepresent the number of species changing phenology in this plant community. Ultimately, this diversity of species-level phenological shifts contributes to altered coflowering patterns within the community, a redistribution of floral abundance across the season, and an expansion of the flowering season by more than I mo during the course of our study period.
  http://www.pnas.org/content/early/2014/03/12/1323073111.abstract

- **Global Warming and Flowering Times in Thoreau's Concord: A Community Perspective (Miller-Rushing and Primack 2008)**
  In order to determine how North American species' flowering times respond to climate, we analyzed a series of previously unstudied records of the dates of first flowering for

over 500 plant taxa in Concord, Massachusetts, USA. These records began with six years of observations by the famous naturalist Henry David Thoreau from 1852 to 1858, continued with 16 years of observations by the botanist Alfred Hosmer in 1878 and 1888–1902, and concluded with our own observations in 2004, 2005, and 2006. From 1852 through 2006, Concord warmed by 2.48C due to global climate change and urbanization. Using a subset of 43 common species, we determined that plants are now flowering seven days earlier on average than they did in Thoreau's times. Plant flowering times were most correlated with mean temperatures in the one or two months just before flowering and were also correlated with January temperatures.
http://www.esajournals.org/doi/abs/10.1890/07-0068.1

- **Global imprint of climate change on marine life (Poloczanska et al. 2013)**
  Past meta-analyses of the response of marine organisms to climate change have examined a limited range of locations taxonomic groups and/or biological responses. Authors synthesized all available studies of the consistency of marine ecological observations with expectations under climate change. This yielded a meta-database of 1,735 marine biological responses for which either regional or global climate change was considered as a driver. Included were instances of marine taxa responding as expected, in a manner inconsistent with expectations, and taxa demonstrating no response. From this database, 81–83% of all observations for distribution, phenology, community composition, abundance, demography and calcification across taxa and ocean basins were consistent with the expected impacts of climate change.
  http://www.nature.com/nclimate/journal/v3/n10/full/nclimate1958.html

2.5 Other

- **Comparison of climate change vulnerability assessments for wildlife (Lankford et al. 2014)**
  Although many approaches exist for assessing sensitivity and vulnerability to climate change, little is known about the similarity of results between methods. Authors compared outputs of 3 widely available assessments for the western United States: the NatureServe Climate Change Vulnerability Index (CCVI), the U.S. Forest Service System for Assessing the Vulnerability of Species (SAVS), and the Climate Change Sensitivity Database. They performed a broad categorical comparison and examined correlations across rankings to compare assessment outputs. They found little agreement in species rankings between pairs of assessments. There is no apparent pattern within, or between, taxa or habitat associations that could explain this poor correlation. Disparities likely result from differences in question format, choice of data input, or how vulnerability or sensitivity is calculated. Consideration of vulnerability quantification is needed, particularly regarding species sensitivity and adaptive capacity, because of limited understanding of species and community responses to climate exposure. Results indicate it is extremely important to be aware of the specific goal and the quality, quantity, and variety of data used in each individual assessment in order to adequately use these assessments as tools for management planning
  http://onlinelibrary.wiley.com/doi/10.1002/wsb.399/abstract

- **Vulnerability Assessment Methodologies: An Annotated Bibliography for Climate Change and the Fisheries and Aquaculture Sector (Barsley et al. 2013)**
  This circular contains a comprehensive annotated bibliography of vulnerability methodologies specific to climate change and the fisheries and aquaculture sector. The circular was prepared between 2012 and 2013 and commissioned by FAO as a supporting background document for an international expert workshop in Namibia on climate change vulnerability methodologies, funded under the project "Fisheries management and marine conservation within a changing ecosystem context". The annotated bibliography presents a range of the most contemporary and seminal vulnerability methodologies from over the past decade, providing a reference for workshop participants and also practitioners, policy-makers, non-governmental organizations and governmental organizations conducting vulnerability assessments.
  http://www.fao.org/docrep/018/i3315e/i3315e.pdf

- **Climate Change and Biodiversity in Maine: Vulnerability of Habitats and Priority Species (Whitman et al. 2013)**
  Species vulnerability was assessed in a three-step, expert-opinion elicitation process involving more than one-hundred reviewers: (1) expert input through an online species assessment survey, (2) review and modification of online survey results by expert panels at a workshop, and (3) final expert review by key state agency biologists and others to fill in species review gaps. The vulnerability of habitats was assessed in a two-step, expert-opinion elicitation process: (1) results of the online assessment were used to assess the vulnerability of ME CWCS Key Habitats based on the vulnerability of their constituent SGCN and state-listed Threatened or Endangered plant species and (2) expert panels at a workshop assessed the vulnerability of ME CWCS Key Habitats. These results and those from a northeastern regional habitat vulnerability assessment were reviewed by the authors.
  https://www.manomet.org/sites/default/files/publications_and_tools/2013%20BwH%20Vulnerability%20Report%20CS5v7_0.pdf

3.0 Habitat Approaches

CCVAs at the habitat level can also be categorized into "coarse-filter" approaches that use indices to develop a qualitative categorization of vulnerability, and "fine-filter" approaches that use models, often spatially-explicit, to determine where and how species may be vulnerable to climate change. As with species indices, each of these approaches has strengths and limitations.

3.1 Coarse-filter Habitat Approaches – Indices

3.1.1 Climate Change and Massachusetts Fish and Wildlife: Volume 2, Habitat and Species Vulnerability (Manomet)

One of the earliest habitat-based vulnerability assessments was conducted for a 3-volume report on "Climate Change and Massachusetts Fish and Wildlife" by Manomet Center for Conservation Science and Massachusetts Division of Fisheries and Wildlife. It was intended to provide supplementary climate change related materials to the existing SWAP. The assessment was conducted using an expert panel approach and a simple "habitat vulnerability scoring system." Twenty habitat types were selected for evaluation.
Developer: Hector Galbraith of Manomet
http://www.mass.gov/dfwele/dfw/habitat/cwcs/pdf/climate_change_habitat_vulnerability.pdf

3.1.2 Northeast Association of Fish and Wildlife Agencies Regional Habitat Vulnerability Model (Manomet)

The NEAFWA model, based on an Excel spreadsheet platform, comprises four connected modules: Module 1 (Attachment 1) consists of 9 variables and scores the likely vulnerabilities of non-tidal habitats to future climate change (and the potential interaction between climate and non-climate stressors). Module 2, using 5 variables, categorizes the comparative vulnerabilities of habitats to existing, non-climate change stressors. Module 3 combines the results of Modules 1 and 2 to produce an overall evaluation and a score of the habitat's future vulnerability to climate change and to nonclimate stressors. Module 3 also groups these scores into five categories: critically vulnerable, highly vulnerable, vulnerable, less vulnerable, and least vulnerable. The primary aim of the narrative (Module 4) that accompanies each habitat

assessment is to make transparent the rationales and assumptions underlying the scores that were assigned to each variable.
Developer: Hector Galbraith of Manomet
http://static.rcngrants.org/sites/default/files/final_reports/RCN%202009-01%20Final%20Report%20-%20NEreport%202%20THE%20MODEL.pdf

NEAFWA Case Study:

- **The Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change**
  In this report the authors: summarize our current scientific understanding about how the climate in the Northeast region is projected to change over the rest of this century; how the NEAFWA Habitat Vulnerability Model was developed; how habitats were selected for analysis; and the results of applying the model to major habitat types in the northeast.
  http://static.rcngrants.org/sites/default/files/final_reports/RCN%202009-01%20Final%20Report%20-%20THE%20VULNERABILITIES%20OF%20FISH%20AND%20WILDLIFE%20HABITATS%20IN%20THE%20NORTHEAST%20TO%20CLIMATE%20CHANGE.pdf

3.1.3 Habitat Climate Change Vulnerability Index (HCCVI)(NatureServe)

The HCCVI aims to implement a series of measures addressing climate change sensitivity and ecological resilience for each community type for its distribution within a given ecoregion. Since quantitative estimates may not be feasible for all measures, both numerical index scores (normalized 0.0-1.0 scores) and qualitative expert categorizations may be used in the HCCVI. The combined relative scores for sensitivity and resilience determine the categorical estimate of climate change vulnerability by the year 2060 for a community type. Index measures are organized within categories of direct effects, indirect effects, and adaptive capacity. A series of 3-5 measures, each requiring a separate type of analysis, produces sub-scores that are then used to generate an overall score for sensitivity (from direct effects) vs. resilience (indirect effects + adaptive capacity). For the HCCVI, climate-change vulnerability is expressed in four categories: Very High, High, Moderate, and Low. Therefore, the index ratings are quite general, but this is because predictive uncertainty is often high, and the overall intent is a generalized indication of vulnerability.
Developer: NatureServe
http://www.fws.gov/refuges/whm/pdfs/NatureServe_HCCVI_Report.pdf

HCCVI Case Study:

- **Climate Change Vulnerability and Adaptation Strategies for Natural Communities: Piloting Methods in the Mojave and Sonoran Deserts (Comer et al. 2012)**
  NatureServe piloted their NCCVI on an assessment of community type in the Sonoran and Mojave deserts (Comer et al. 2012). For the HCCVI, climate-change vulnerability is expressed in four categories, including This pilot analysis resulted in six type/ecoregion combinations being categorized high for climate-change vulnerability. These included

Mojave Mid-Elevation [Joshua tree-Black brush] Desert Scrub (Mojave Desert), North American Warm Desert Riparian Woodland and Stream (Mojave and Sonoran deserts), North American Warm Desert Mesquite Bosque (Mojave and Sonoran deserts), Sonora-Mojave Creosotebush-White Bursage Desert Scrub (Sonoran Desert). All other types were categorized as moderate for climate-change vulnerability. No types from this pilot analysis were categorized as either very high or low for climate-change vulnerability.
http://www.fws.gov/refuges/whm/pdfs/NatureServe_HCCVI_Report.pdf
http://www.fws.gov/refuges/whm/pdfs/NatureServe_HCCVI_Appendix%202.pdf

3.1.4 Climate Change Vulnerability Assessment for Shorebird Habitat (CC-VASH)

The CC-VASH is an Excel-based vulnerability assessment and decision-making tool developed by the Manomet Center for Conservation Science in partnership with the United States Fish and Wildlife Service Northeast Region Division of Refuges. The CC-VASH guides participants through a series of worksheets and exercises that enable them to assess the vulnerability of coastal shorebird habitats to climate change, using three categories: (1) Effects of sea-level rise; (2) Effects of other climate-change variables, such as predicted changes in temperature and precipitation; and (3) Effects of increased frequency and intensity of storms. Once the vulnerability is measured, the assessment outlines explicit strategies and adaptation options, and evaluates each option's chances for success.
Developer: Dorie Stolley, US Fish and Wildlife Service
http://www.whsrn.org/tools/climate-change-tool

3.2 Fine-filter Habitat Approaches – Modeling

Habitat Modeling Case Studies:

- **Assessing potential climate change effects on vegetation using a linked model approach (Halofsky et al. 2013)**
  We developed a process that links the mechanistic power of dynamic global vegetation models with the detailed vegetation dynamics of state-and-transition models to project local vegetation shifts driven by projected climate change. We applied our approach to central Oregon (USA) ecosystems using three climate change scenarios to assess potential future changes in species composition and community structure.
  http://www.sciencedirect.com/science/article/pii/S0304380013003281

- **Projected vegetation changes for the American Southwest: combined dynamic modeling and bioclimatic-envelope approach (Notaro et al. 2012)**
  This study focuses on potential impacts of 21st century climate change on vegetation in the Southwest United States, based on debiased and interpolated climate projections from 17 global climate models used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Two independent methods were applied: a dynamic global vegetation model to assess changes in plant functional types and bioclimatic envelope

modeling to assess changes in individual tree and shrub species and biodiversity. The former approach investigates broad responses of plant functional types to climate change, while considering competition, disturbances, and carbon fertilization, while the latter approach focuses on the response of individual plant species, and net biodiversity, to climate change.
http://www.esajournals.org/doi/abs/10.1890/11-1269.1

- **Projected Future Climate and Vegetation Changes and Potential Biotic Effects for Fort Benning, Georgia; Fort Hood, Texas; and Fort Irwin, California (Shafer et al. 2011)**
  This report describes projected future changes in climate and vegetation for three study areas surrounding the military installations of Fort Benning, Georgia, Fort Hood, Texas, and Fort Irwin, California. We describe projected climate changes for the time period 2070–2099 (30-year mean) as compared to 1961–1990 (30-year mean) for each study area using data simulated by the coupled atmosphere-ocean general circulation models CCSM3, CGCM3.1(T47), and UKMO-HadCM3, run under the B1, A1B, and A2 future greenhouse gas emissions scenarios. We use these climate data to simulate potential changes in important components of the vegetation for each study area using LPJ, a dynamic global vegetation model, and LPJ-GUESS, a dynamic vegetation model optimized for regional studies. The simulated vegetation results are compared with observed vegetation data for the study areas. We discuss the potential effects of the simulated future climate and vegetation changes for species and habitats of management concern in each study area,
  http://pubs.usgs.gov/sir/2011/5099/report/SIR11-5099.pdf

- **Sagebrush (*Artemisia* spp.) ecosystems in the state of Nevada (Bradley 2010)**
  Bradley (2010) modeled sagebrush (*Artemisia* spp.) ecosystems in the state of Nevada, USA from climate change, land use/land cover change, and species invasion. Risk from climate change is based on an ensemble of 10 AOGCM projections applied to two bioclimatic envelope models (Mahalanobis distance and Maxent). Risk from land use is based on the distribution of roads, agriculture, and powerlines, and on the spatial relationships between land use and probability of cheatgrass *Bromus tectorum* invasion in Nevada. Risk from land cover change is based on probability and extent of pinyon-juniper (*Pinus monophylla*; *Juniperus* spp.) woodland expansion.
  http://people.umass.edu/bethanyb/Bradley,%20Ecography,%202010.pdf

- **Mapping vulnerability and conservation adaptation strategies under climate change (Watson et al. 2013)**
  Authors produce a methodology by undertaking an ecoregional assessment at the global scale that integrates an ecoregion's adaptive capacity, based on a spatial analysis of the ecoregion's natural integrity (defined as the proportion of intact natural vegetation found in each ecoregion, and thus a function of land use), with its relative exposure to future climate change, to help inform spatially explicit adaptation guidance for conservation practitioners. Ecoregions were used as the spatial unit of assessment as they are the most relevant environmental and ecologically distinct spatial unit at the global scale, and are used widely to guide global conservation investments, assessments and action. They

mapped ecoregional exposure to future climate by using an envelope-based gauge of future climate stability, defined as the similarity between present and future climate (2050s).
http://www.nature.com/nclimate/journal/v3/n11/full/nclimate2007.html

- **Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change (Gonzalez et al. 2010)**
  Gonzalez et al. (2010) examined nine combinations of three sets of potential indicators of the vulnerability of ecosystems to biome change: (1) observed changes of 20thcentury climate, (2) projected 21st-century vegetation changes using the MC1 dynamic global vegetation model under three IPCC emissions scenarios, and (3) overlap of results from (1) and (2). Estimating probability density functions for climate observations and confidence levels for vegetation projections, we classified areas into vulnerability classes based on IPCC treatment of uncertainty.
  http://site.xavier.edu/blairb/sustainable-agriculture-2/climate-change/gonzalez-2010.pdf

- **Forest restoration in a mixed-ownership landscape under climate change (Ravenscroft et al. 2010)**
  We used a spatially explicit forest ecosystem model, LANDIS-II, to simulate the interaction of climate change and forest management in northeastern Minnesota, USA. We assessed the relevance of restoration strategies and conservation targets based on the RNV in the context of future climate change. Three climate scenarios (no climate change, low emissions, and high emissions) were simulated with three forest management scenarios: no harvest, current management, and a restoration-based approach where harvest activity mimicked the frequency, severity, and size distribution of historic natural disturbance regimes
  http://www.esajournals.org/doi/abs/10.1890/08-1698.1

- **North American vegetation model for land-use planning in a changing climate: a solution to large classification problems (Rehfeldt et al. 2012)**
  Data points intensively sampling 46 North American biomes were used to predict the geographic distribution of biomes from climate variables using the Random Forests classification tree. Techniques were incorporated to accommodate a large number of classes and to predict the future occurrence of climates beyond the contemporary climatic range of the biomes. Errors of prediction from the statistical model averaged 3.7%, but for individual biomes, ranged from 0% to 21.5%. In validating the ability of the model to identify climates without analogs, 78% of 1528 locations outside North America and 81% of land area of the Caribbean Islands were predicted to have no analogs among the 46 biomes. Biome climates were projected into the future according to low and high greenhouse gas emission scenarios of three General Circulation Models for three periods, the decades surrounding 2030, 2060, and 2090.
  http://www.esajournals.org/doi/abs/10.1890/11-0495.1

3.3 Specific Habitat Types

3.3.1 Forest

Central Hardwoods Ecosystem Vulnerability Assessment and Synthesis: A Report from the Central Hardwoods Climate Change Response Framework Project (Brandt et al. 2014)
Climate trends for the next 100 years were projected by using downscaled global climate model data. Authors identified potential impacts on forests by incorporating these climate projections into three forest impact models (Tree Atlas, LINKAGES, and LANDIS PRO). Authors further assessed ecosystem vulnerability for nine natural community types in the region by using these model results along with projected changes in other factors such as wildfire, invasive species, and diseases. The basic assessment was conducted through a formal elicitation process of 20 science and management experts from across the region, who considered vulnerability in terms of potential impacts on a system and the adaptive capacity of the system. The projected changes in climate and the associated impacts and vulnerabilities will have important implications for economically important timber species, forest-dependent wildlife and plants, recreation, and long-range planning.
http://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs124.pdf

Ecosystem Vulnerability Assessment and Synthesis: A Report from the Climate Change Response Framework Project in Northern Wisconsin (Swantson et al. 2011)
This effort assessed the climate change vulnerability of northern Wisconsin forests. The report begins by describing the contemporary landscape and major existing climate trends using state climatological data, and then proceeds to discuss potential future climate trends for northern Wisconsin using downscaled data from general circulation models. Potential vulnerabilities are identified by incorporating the future climate projections into species distribution and ecosystem process models and assessing potential changes to northern Wisconsin forests.
Conducted by: US Forest Service
Citation: Swantson et al. (2011)
http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs82.pdf

Forest restoration in a mixed-ownership landscape under climate change (Ravenscroft et al. 2010)
We used a spatially explicit forest ecosystem model, LANDIS-II, to simulate the interaction of climate change and forest management in northeastern Minnesota, USA. We assessed the relevance of restoration strategies and conservation targets based on the RNV in the context of future climate change. Three climate scenarios (no climate change, low emissions, and high emissions) were simulated with three forest management scenarios: no harvest, current management, and a restoration-based approach where harvest activity mimicked the frequency, severity, and size distribution of historic natural disturbance regimes
http://www.esajournals.org/doi/abs/10.1890/08-1698.1

3.3.2 Freshwater and Riparian

Flowing Forward: Freshwater ecosystem adaptation to climate change in water resources management and biodiversity conservation (Le Quesne et al. 2010)
This review was prepared by World Wildlife Fund for the World Bank. Its purpose is to develop the guiding principles, processes, and methodologies for incorporating anthropogenic climate

change within an analytical framework for evaluating water sector projects, with a particular emphasis on impacts on ecosystems. It is a contribution toward the development of a systematic approach to climate change adaptation in the Bank's water and environment sectors. One section of the report deals with vulnerability assessment. The report recommends that attempts to assess and respond to climate change should adopt a risk-based approach rather than focus on impact assessment: "The considerable uncertainty about ecosystem impacts of climate change means that attention should be focused on using scenario analysis to identify those ecosystems that are most sensitive to and at risk from change rather than relying only on the development of deterministic predictions of impacts."
http://assets.worldwildlife.org/publications/385/files/original/Flowing_Forward_Freshwater_ecosystem_adaptation_to_climate_change_in_water_resources_management_and_biodiversity_conservation.pdf?1345749323

Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of climate change on freshwater biodiversity (Tisseuil et al. 2012)
Authors develop a novel methodology that combines statistical downscaling and fish species distribution modeling, to enhance the understanding of how global climate changes (modeled by global climate models at coarse-resolution) may affect local riverine fish diversity. The novelty of this work is the downscaling framework developed to provide suitable future projections of fish habitat descriptors, focusing particularly on the hydrology which has been rarely considered in previous studies.
http://gael.grenouillet.free.fr/grenouillet_publications_fichiers/Tisseuil_STE2012.pdf

Freshwater Case Studies:

- **Changing streamflow on Columbia basin tribal lands—climate change and salmon (Dittmer 2013)**
  Analysis of independent flow measures (Seasonal Flow Fraction, Center Timing, Spring Flow Onset, High Flow, Low Flow) using the Student t test and Mann- Kendall trend test suggests evidence for climate change trends for many of the 32 study basins. The trends exist despite interannual climate variability driven by the El Niño–Southern Oscillation and Pacific Decadal Oscillation. The average April—July flow volume declined by 16 %. The median runoff volume date has moved earlier by 5.8 days. The Spring Flow Onset date has shifted earlier by 5.7 days. The trend of the flow standard deviation (i.e., weather variability) increased 3 % to 11 %. The 100-year November floods increased 49 %. The mid-Columbia 7Q10 low flows have decreased by 5 % to 38 %. Continuation of these climatic and hydrological trends may seriously challenge the future of salmon, their critical habitats, and the tribal peoples who depend upon these resources for their traditional livelihood, subsistence, and ceremonial purposes.

- **Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes (Isaak et al. 2012)**
  We assembled 18 temperature time-series from sites on regulated and unregulated streams in the northwest U.S. to describe historical trends from 1980–2009 and assess thermal consistency between these stream categories. Statistically significant temperature trends were detected across seven sites on unregulated streams during all seasons of the

year, with a cooling trend apparent during the spring and warming trends during the summer, fall, and winter. The amount of warming more than compensated for spring cooling to cause a net temperature increase, and rates of warming were highest during the summer (raw trend = 0.17°C/decade; reconstructed trend = 0.22°C/decade). Air temperature was the dominant factor explaining long-term stream temperature trends (82–94% of trends) and inter-annual variability (48–86% of variability), except during the summer when discharge accounted for approximately half (52%) of the inter-annual variation in stream temperatures. Continuation of warming trends this century will increasingly stress important regional salmon and trout resources and hamper efforts to recover these species, so comprehensive vulnerability assessments are needed to provide strategic frameworks for prioritizing conservation efforts.
http://www.hydro.washington.edu/pub/leesy/water_temp/Isaak_etal_2012.pdf

- **Cutthroat Trout (*Oncorhynchus clarkii*) (Wenger et al. 2011)**
  Wenger et al. (2011) assessed the effects of temperature, flow regime, biotic interactions, topographic variables and land-use variables on distribution of four trout species in the western United States, then used downscaled outputs from general circulation models coupled with a hydrologic model to forecast species suitable habitat under climate change. Projections under the 2080s A1B emissions scenario project that native cutthroat trout, already excluded from much of its potential range by nonnative species, will lose a further 58% of habitat due to an increase in temperatures beyond the species' physiological optima and continued negative biotic interactions.
  http://www.pnas.org/content/early/2011/08/09/1103097108.full.pdf

- **Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes (Chessman 2013)**
  Chessman (2013) used trait analysis -- data from a large-scale monitoring program to assess how 14 dietary, life-history and physiological-tolerance traits related to changes in occurrence and abundance of 39 freshwater fish species in Australia's Murray-Darling Basin. Rankings of drought vulnerability of fish species derived from correlations between population changes and traits showed good agreement with a previous assessment of inter-specific variation in resistance to drought, and were corroborated by independent observations of drought responses for some species. Trait analysis should have wide application to identifying species at risk from climate change, provided that sufficient traits are assessed and that adequate consideration is given to variation in trait-vulnerability relationships among different groups of organisms, geographic regions and types of ecosystems.
  http://www.parcc-web.org/parcc-project/documents/2013/02/identifying-species-at-risk-from-climate-change-traits-predict-the-drought-vulnerability-of-freshwater-fishes.pdf

- **Climate Change and Cold Water Fish Habitat in the Northeast: A Vulnerability Assessment (Manomet Center for Conservation Sciences and the National Wildlife Federation 2012)**
  Manomet Center for Conservation Sciences and the National Wildlife Federation (2012) attempted to estimate the likely vulnerability of riverine habitat for cold water fish to future climate change in the northeastern US, using a framework with components of

sensitivity, adaptive capacity, exposure, and uncertainty analysis. The report begins with a description of the distribution of the habitat in the Northeast and its general and thermal ecology. Then it reviews previous attempts to model the vulnerability of this habitat and its fish in the Northeast to climate change. Following that, they describe how current exposures to climate variables are likely to change in the future, the extent to which the habitat and its fish may be resilient to and able to adapt to these climatic changes, and the resulting vulnerabilities of this habitat to climate change. Throughout these analyses they identify and discuss the major uncertainties that affect vulnerability projections.
http://static.rcngrants.org/sites/default/files/final_reports/RCN%202009-01%20Final%20Report%20-%20CLIMATE%20CHANGE%20AND%20COLD%20WATER%20FISH%20HABITAT%20IN%20THE%20NORTHEAST-%20A%20VULNERABILITY%20ASSESSMENT.pdf

- **Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Clay Belt Ecodistrict (3E-1) of Northeastern Ontario (Chu and Fischer 2012)**
  Chu and Fischer (2012) assessed the potential effects of climate change on the wetland, stream, and lake ecosystems of the Clay Belt, represented using five indicators: wetland vulnerability, a coldwater stream fish index, maximum lake surface water temperature, smallmouth bass (*Micropterus dolomieu*) thermal habitat availability, and walleye (*Sander vitreus*) productivity. Existing empirical models were used to relate the ecosystem indicators to climate. Present climate conditions were estimated using 1971 to 2000 Canadian climate averages. The Canadian Coupled Global Climate Model 3 was used to project future climate for the 2011-2040, 2041-2070, and 2071-2100 time periods for B1 and A2 emissions scenarios.
  http://www.mnr.gov.on.ca/stdprodconsume/groups/lr/@mnr/@climatechange/documents/document/stdprod_100953.pdf

- **Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America (Perry et al. 2012)**
  In this literature review, Perry et al. (2012): (1) summarize expected changes in [CO2], climate, hydrology, and water management in dryland western North America, (2) consider likely effects of those changes on riparian ecosystems, and (3) identify critical knowledge gaps.
  http://www.fort.usgs.gov/Products/Publications/23228/23228.pdf

3.3.3 Freshwater Wetlands

A Framework for assessing the vulnerability of wetlands to climate change (RAMSAR)

RAMSAR technical consultants brought together a variety of methods and approaches to develop a general framework for assessing the vulnerability of wetlands to climate change. The framework has the following elements: (1) establishing present status and recent trends (description of the wetland (biophysical and social)), the present and recent pressures that exist,

and the present condition); (2) determining the wetland's sensitivity and adaptive capacity to multiple pressures (description of the pressures on the wetland and the development of plausible future changes in order to assess the sensitivity and adaptive capacity of the wetland to multiple pressures); (3) developing responses (determining the likely impacts of these changes on the wetland and the desired outcomes for it, as well as the responses that must be developed and implemented given its sensitivity and resilience); and (4) monitoring and adaptive management (determining the necessary steps to ensure the path to the desired outcomes).
Developer: RAMSAR/Gitay (2011)
http://www.ramsar.org/pdf/lib/lib_rtr05.pdf

Freshwater Wetland Case Studies:

- **A geospatial assessment on the distribution, condition, and vulnerability of Wyoming's wetlands (Copeland et al. 2010)**
  Copeland et al. (2010) presents a landscape-scale geospatial assessment of wetlands in Wyoming. Areas containing high densities of wetlands were identified and mapped, and wetland complexes were quantified as a function of their biological diversity, protection status, susceptibility to climate change, and proximity to sources of impairment. To estimate climate vulnerability, authors followed the methods in Enquist et al. (2008) and Enquist et al. (under review) and compiled climate data of monthly temperature and precipitation, and identified wetland complexes already impacted by drying trends in a basic water balance metric called the 'water balance deficit'.
  http://www.sciencedirect.com/science/article/pii/S1470160X1000021X

- **The Vulnerability of Wetlands to Climate Change: A Hydrologic Landscape Perspective (Winter 2007)**
  Winter (2007) discussed the vulnerability of wetlands to changes in climate. He found that vulnerability depends on the position of the wetland within hydrologic landscapes. Hydrologic landscapes are defined by the flow characteristics of ground water and surface water and by the interaction of atmospheric water, surface water, and ground water for any given locality or region. Six general hydrologic landscapes are defined; mountainous, plateau and high plain, broad basins of interior drainage, riverine, flat coastal, and hummocky glacial and dune. Assessment of these landscapes indicate that the vulnerability of all wetlands to climate change fall between two extremes: those dependent primarily on precipitation for their water supply are highly vulnerable, and those dependent primarily on discharge from regional ground water flow systems are the least vulnerable, because of the great buffering capacity of large ground water flow systems to climate change.
  http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2000.tb04269.x/abstract

- **Vulnerability of Northern Prairie Wetlands to Climate Change (Johnson et al. 2005)**
  Johnson et al. (2005) explored the broad spatial and temporal patterns across the Prairie Pothole Region of the USA and Canada between climate and wetland water levels and vegetation by applying a wetland simulation model (WETSIM) to 18 stations with 95-year weather records. WETSIM is a process-oriented, deterministic model that simulates watershed and wetland surface processes, watershed groundwater, and wetland

vegetation dynamics. The model uses daily precipitation and mean daily temperature to estimate wetland water balance, wetland stage, and wetland vegetation dynamics.
http://www.bioone.org/doi/pdf/10.1641/0006-3568(2005)055%5B0863:VONPWT%5D2.0.CO%3B2

- **Prairie Wetland Complexes as Landscape Functional Units in a Changing Climate (Johnson et al. 2010)**
  Johnson et al. (2010) conducted climate warming simulations using the new model WETLANDSCAPE (WLS) project major reductions in water volume, shortening of hydroperiods, and less-dynamic vegetation for prairie wetland complexes across the Prairie Pothole Region of the USA and Canada. WETLANDSCAPE (WLS) is a climate driven, process-based, deterministic simulation model. Its predecessor, WETSIM, was the backbone of the group's previous climate-change research (e.g., Johnson et al. 2005), but it modeled only semipermanent wetlands. The development of WLS allowed for a more comprehensive analysis of the climate-change issue across the northern prairies because it simultaneously simulates wetland surface water, groundwater, and vegetation dynamics of the wetland complex, including multiple wetland basins of semipermanent, seasonal, and temporary permanence types, in addition to overflows between basins.
  http://www.fws.gov/home/feature/2010/pdf/PrairiePotholesBioScience.pdf

- **Great Lakes Coastal Wetland Communities: Vulnerabilities to Climate Change and Response to Adaptation Strategies (Mortsch et al. 2006)**
  Mortsch et al. (2006) developed vulnerability indices to assess the current sensitivity of Great Lakes coastal wetland vegetation and wetland-dependent breeding birds to hydrologic changes, and fishes to hydrologic and thermal changes. Scores for vulnerability factors were used to categorize species into low, moderate, and high risk groups.
  http://environment.uwaterloo.ca/research/aird/aird_pub/Great_Lakes_Coastal_Wetlands_Report_2006.pdf

3.3.4 Coastal Habitats

3.3.4.1 Indices

Coastal Vulnerability Index (CVI) (USGS)

The USGS CVI ranks the following in terms of their physical contribution to sea-level rise-related coastal change: geomorphology, regional coastal slope, rate of relative sea-level rise, historical shoreline change rate, mean tidal range, and mean significant wave height. The rankings for each variable are combined and an index value is calculated for 1-kilometer grid cells along the coast. The CVI highlights those regions where the physical effects of sea-level rise might be the greatest.
Developer: USGS
Gornitz et al. (1994)

CVI Case Studies:

- **Case Studies in Sea Level Rise Planning: Public Access in the NY-NJ Harbor Estuary (Great Ecology 2012)**
  A literature search for GIS models that estimate SLR using LiDAR data on the east coast of the United States was conducted. Based on this literature review, six variables (as described in Gornitz et al. 1991) were identified as the primary factors influencing SLR vulnerability: 1) geomorphology, 2) relief (percent slope), 3) the extent of flood-prone (low-lying) areas, 4) the extent of natural habitats (land use/land cover data), 5) soil drainage/hydrology, and 6) sea level change. Each of these variables contributes towards making an individual site more or less susceptible to impacts from SLR. These variables are detailed in the Coastal Vulnerability Index Variables subsections in the report.
  http://www.harborestuary.org/pdf/ClimateChange/CaseStudiesInSLRPlanning.pdf

- **Coastal Vulnerability Assessment of the Northern Gulf of Mexico to Sea-Level Rise and Coastal Change (Pendleton et al. 2010)**
  The CVI assessment presented in Pendleton et al. (2010) builds on an earlier assessment conducted for the Gulf of Mexico. Recent higher resolution shoreline change, land loss, elevation, and subsidence data provide the foundation for a better assessment for the Northern Gulf of Mexico. The areas along the Northern Gulf of Mexico that are likely to be most vulnerable to sea-level rise are parts of the Louisiana Chenier Plain, Teche-Vermillion Basin, and the Mississippi barrier islands, as well as most of the Terrebonne and Barataria Bay region and the Chandeleur Islands. These very high vulnerability areas have the highest rates of relative sea-level rise and the highest rates of shoreline change or land area loss. The information provided by coastal vulnerability assessments can be used in long-term coastal management and policy decision making.
  http://pubs.usgs.gov/of/2010/1146/pdf/ofr2010-1146.pdf

  Importance of Coastal Change Variables in Determining Vulnerability to Sea- and Lake-Level Change (Pendleton et al. 2010)
  In 2001, the U.S. Geological Survey began conducting scientific assessments of coastal vulnerability to potential future sea- and lake-level changes in 22 National Park Service sea- and lakeshore units. In this paper, Pendleton et al. (2010) analyze the results of coastal vulnerability assessments (CVIs) for 22 coastal national park units. Index-based assessments quantify the likelihood that physical changes may occur based on analysis of the following variables: tidal range, ice cover, wave height, coastal slope, historical shoreline change rate, geomorphology, and historical rate of relative sea- or lake-level change. This approach seeks to combine a coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and it provides a measure of the system's potential vulnerability to the effects of sea- or lake-level change. Assessments for 22 park units are combined to evaluate relationships among the variables used to derive the index.
  http://www.jcronline.org/doi/pdf/10.2112/08-1102.1

3.3.4.2 Modeling

Sea Level Rise Affecting Marshes Model Version 6 (SLAMM 6.0) (Warren Pinnacle)

SLAMM simulates the dominant processes in wetland conversion and shoreline modifications during long-term sea level rise (SLR). SLAMM accounts for inundation, subsidence, soil saturation, erosion, accretion, and barrier island overwash to project future wetland changes. It can be applied to a range of landscape scales (<1 km2 to 100,000 km2) at high resolution and identifies potential changes in both extent and composition of different wetland types. Feedback mechanisms between SLR and marsh accretion rates can be accounted for in SLAMM 6 predictions. However, other complex factors affecting regional marsh system response to SLR are not, such as localized geomorphology, hydrodynamic effects, higher average temperatures, and more-intense hurricanes. SLAMM 6 integrates a stochastic uncertainty analysis module to provide best/worst case scenarios, and likelihood and confidence statistics given uncertainty in future SLR, future erosion rates, and feedbacks between marsh vertical-accretion rates and SLR. Developer: Warren Pinnacle Consulting, Inc. (warrenpinnacle.com/prof/SLAMM/)
http://www.warrenpinnacle.com/prof/SLAMM/

SLAMM Case Studies:

- **Potential Impacts and Management Implications of Climate Change on Tampa Bay Estuary Critical Coastal Habitats (Sherwood and Greening 2014)**
  Authors modeled the anticipated changes to a suite of habitats within the Tampa Bay estuary using the sea level affecting marshes model under various sea level rise (SLR) scenarios. This paper discusses an update to the initial estimates of Glick and Clough (2006) using the most recent land use, elevation, and sea level rise scenarios available for the Tampa Bay region using the SLAMM v.6.0.1 (2013).
  http://download.springer.com/static/pdf/207/art%253A10.1007%252Fs00267-013-0179-5.pdf?auth66=1398610845_d60fb64a5de35cc45b3e14e2e8f80b55&ext=.pdf

- **Potential Effects of Sea-Level Rise on Coastal Wetlands in Southeastern Louisiana (Glick et al. 2013)**
  This study investigates the potential impact of current and accelerating sea-level rise rates on key coastal wetland habitats in southeastern Louisiana using the Sea Level Affecting Marshes Model (SLAMM). Model calibration was conducted using a 1956–2007 observation period and hindcasting results predicted 35% versus observed 39% total marsh loss. Multiple sea-level-rise scenarios were then simulated for the period of 2007–2100. Results indicate a range of potential wetland losses by 2100, from an additional 2,188.97 km2 (218,897 ha, 9% of the 2007 wetland area) under the lowest sea-level-rise scenario (0.34 m), to a potential loss of 5,875.27 km2 (587,527 ha, 24% of the 2007 wetland area) in the highest sea-level-rise scenario (1.9 m).
  http://www.jcronline.org/doi/abs/10.2112/SI63-0017.1

- **Modeling and Abating the Impacts of Sea Level Rise on Five Significant Estuarine Systems in the Gulf of Mexico (Geselbracht et al. 2013)**
  Authors applied SLAMM to simulate SLR impacts on coastal wetland systems at five estuaries across the U.S. Gulf of Mexico: Corpus Christi Bay in Texas; Mobile Bay in Alabama; and Pensacola Bay, Southern Big Bend and Tampa Bay in Florida. In each estuary, we modeled three SLR scenarios through the year 2100: 0.7 m, 1.0 m and 2.0 m and reported out results in 25 year increments, 2025, 2050, 2075 and 2100. Uncertainty analyses were conducted on selected input parameters to better understand their influence on modeling results. In addition to the SLR modeling, impacts of SLR on the most vulnerable species were assessed and vulnerable infrastructure, historic and cultural resources were identified.
  http://www.nature.org/media/florida/MX-95463410-2_Report.pdf

- **Assessment of Inundation Risk from Sea Level Rise and Storm Surge in Northeastern Coastal National Parks (Murdukhayeva et al. 2013)**
  To help park managers meet their goal of preserving resources, authors developed a methodology to evaluate risk of inundation from sea level rise and storm surge at sentinel sites, areas of importance for natural, cultural, and infrastructural resources. We selected the most recent, readily available, and appropriate geospatial tools, models, and data sets to conduct case studies of our coastal inundation risk assessments in two northeastern coastal national parks—Cape Cod National Seashore, MA, and Assateague Island National Seashore, MD/VA. We collected elevation data at sentinel sites using real-time kinematic global positioning system (RTK GPS) technology. We used three modeling approaches: modified bathtub modeling; the Sea Level Affecting Marshes Model (SLAMM); and the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to assess the likelihood of inundation at sentinel sites.
  http://www.bioone.org/doi/abs/10.2112/JCOASTRES-D-12-00196.1

- **Retrospective and prospective model simulations of sea level rise impacts on Gulf of Mexico coastal marshes and forests in Waccasassa Bay, Florida (Geselbracht et al. 2011)**
  Geselbracht et al. (2011) used SLAMM simulation to improve understanding of the magnitude and location of these changes for 58,000 ha of the Waccasassa Bay region of Florida's central Gulf of Mexico coast. To assess how well SLAMM portrays changes in coastal wetland systems resulting from sea level rise, the authors conducted a hindcast in which they compared model results to 30 years of field plot data. Overall, the model showed the same pattern of coastal forest loss as observed.
  http://research.fit.edu/sealevelriselibrary/documents/doc_mgr/447/Big_Bend_SLAMM_Simulations_of_SLR_%20Impacts_-_Geselbracht_et_al._2011.pdf

- **Global Sensitivity and Uncertainty Analysis of SLAMM for the Purpose of Habitat Vulnerability Assessment and Decision Making (Chu-Agor et al. 2010)**
  Recent studies used SLAMM (Sea Level Affecting Marshes Model) to simulate wetland conversion and shoreline modification for the purpose of habitat vulnerability assessment and decision making. Nonetheless, there are questions regarding the validity and suitability of the model due to the uncertainty involved in selecting many of the model's

empirical input factors. The objectives of this study were to use a state-of-the-art screening and variance-based global sensitivity and uncertainty methods to: (1) identify the important input factors that control the model's output uncertainty and (2) quantify the model's global output uncertainty and apportion it to the direct contributions and interactions of the important factors. The screening method of Morris for a qualitative ranking of the input parameters was carried out followed by the variance-based method of Sobol for quantitative sensitivity and uncertainty analyses
http://ascelibrary.org/doi/abs/10.1061/41114(371)477

- **Application of the Sea Level Rise Affecting Marsh Model (SLAMM) Using High Resolution Data At Prime Hook National Wildlife Refuge (Scarborough 2009)**
Scarborough (2009) used SLAMM 5 to assess the potential impacts of sea-level rise on Prime Hook National Wildlife Refuge, Delaware for use in the Refuge's Comprehensive Conservation Plan (CCP) development.
http://www.dnrec.delaware.gov/coastal/Documents/PHNWR%20SLAMM.pdf

- **Impacts of Sea-Level Rise on National Wildlife Refuges (Liu and Delach, no date)**
Liu and Delach (no date) used SLAMM 6.0 to model sea-level rise in 8 national wildlife refuges: Blackwater, Great White Heron, Laguna Atascosa & Lower Rio Grande Valley, Lower Suwannee, Cape Romain, St. Mark, and Savannah. The goal was to provide information relevant for deciding on land protection priorities in these coastal refuges.
http://www.defenders.org/publications/impacts-of-sea-level-rise-on-refuge-land-protection-priorities.pdf

- **Sea Level Rise Modeling for the SAMBI Designing Sustainable Landscapes Project (Rubino, no date)**
The Biodiversity and Spatial Information Center is modeling landscape scale changes to avian habitats based on various climate change scenarios within the South Atlantic Migratory Bird Initiative (SAMBI) geographic planning region. In coastal areas, the Sea Level Affecting Marshes Model (SLAMM) is being utilized to incorporate marsh migration dynamics due to longterm sea level rise.
http://www.basic.ncsu.edu/dsl/downloads/DSL-SAMBI_Sealevel_Rise_Modeling.pdf

- **The Vulnerabilities of Northeastern Fish and Wildlife Habitats to Sea Level Rise (Manomet Center for Conservation Sciences and the National Wildlife Federation 2012)**
This report reviewed SLAMM modeling conducted at 28 national wildlife refuges in the northeastern US, funded by the U.S. Fish and Wildlife Service. Both SLAMM 5 and SLAMM 6 were used.
http://static.rcngrants.org/sites/default/files/final_reports/RCN%202009-01%20Final%20Report%20-THE%20VULNERABILITIES%20OF%20NORTHEASTERN%20FISH%20AND%20WILDLIFE%20HABITATS%20TO%20SEA%20LEVEL%20RISE.pdf

Other Modeling Approaches and Tools

Tools

- **Sea Level Rise and Coastal Flooding Impacts Viewer (NOAA)**
  Being able to visualize potential impacts from sea level rise is a powerful teaching and planning tool, and the Sea Level Rise Viewer brings this capability to coastal communities. A slider bar is used to show how various levels of sea level rise will impact coastal communities. Additional coastal counties will be added in the near future. Maps are not available for Alaska due to elevation data accuracy and vertical datum transformation gaps.
  http://www.csc.noaa.gov/digitalcoast/tools/slrviewer

- **Coastal Resilience (The Nature Conservancy and partners)**
  Coastal Resilience is an approach that supports decisions to reduce the ecological and socio-economic risks of coastal hazards. The Nature Conservancy and partners are advancing this approach by creating a global network for Coastal Resilience to support adaptation planning and post-storm redevelopment decisions. The approach includes 4 critical elements: (1) **Assess Risk and Vulnerability** to coastal hazards including alternative scenarios for current and future storms and sea level rise with community input: (2) **Identify Solutions** for reducing vulnerability focusing on joint solutions across social, economic and ecological systems; (3) **Take Action** to help communities develop and implement solutions; and (4) **Measure Effectiveness** to ensure that efforts to reduce disaster risk and apply ecosystem-based adaptation are successful. Includes case studies.
  http://www.coastalresilience.org/

Other Modeling Approach Case Studies:

- **A geospatial dataset for U.S. hurricane storm surge and sea-level rise vulnerability: Development and case study applications (Maloney and Preston 2014)**
  The geographic distribution of storm surge hazard zones was delineated using archived simulations with the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model from the National Hurricane Center (NHC) of the National Oceanic and Atmospheric Association (NOAA) (NWS, 2011). The SLOSH model estimates storm surge heights associated with hurricanes by simulating the effects of storm size, forward speed, track, wind speed and atmospheric pressure on water heights in the coastal zone. In addition to the development of storm surge hazard data based upon hurricanes alone, additional data layers were developed to represent the effects of sea-level rise on future storm surge inundation. Sea-level rise projections by 2100 from four of the illustrative SRES scenarios were used: A1Fi (+0.82 m), A2 (+0.69 m), B1 (+0.50 m) and B2 (+0.58 m) as well as fifth (base case) that represented no sea-level rise. Although based upon scenarios originally published in 2001 (IPCC 2001), these sea-level rise estimates are consistent with those of the more recent AR5 report (IPCC 2013).
  http://ac.els-cdn.com/S2212096314000060/1-s2.0-S2212096314000060-main.pdf?_tid=4674f46c-cca5-11e3-ae74-00000aab0f6c&acdnat=1398449777_cc55f6f84d8a7a4c73d20b69b8be7626

- **Modeling Tidal Marsh Distribution with Sea-Level Rise: Evaluating the Role of Vegetation, Sediment, and Upland Habitat in Marsh Resiliency (Schile et al. 2014)**
  Authors examined marsh resiliency under these uncertainties using the Marsh Equilibrium Model, a mechanistic, elevation-based soil cohort model, using a rich data set of plant productivity and physical properties from sites across the estuarine salinity gradient. Four tidal marshes were chosen along this gradient: two islands and two with adjacent uplands. Varying century sea-level rise (52, 100, 165, 180 cm) and suspended sediment concentrations (100%, 50%, and 25% of current concentrations), they simulated marsh accretion across vegetated elevations for 100 years, applying the results to high spatial resolution digital elevation models to quantify potential changes in marsh distributions.

- **Evaluating Tidal Marsh Sustainability in the Face of Sea-Level Rise: A Hybrid Modeling Approach Applied to San Francisco Bay (Stralberg et al. 2011)**
  Stralberg et al. (2011) built upon established models to develop a hybrid approach that involves a mechanistic treatment of marsh accretion dynamics and incorporates spatial variation at a scale relevant for conservation and restoration decision-making. They applied this model to San Francisco Bay, using best-available elevation data and estimates of sediment supply and organic matter accumulation developed for 15 Bay subregions. Accretion models were run over 100 years for 70 combinations of starting elevation, mineral sediment, organic matter, and SLR assumptions. Results were applied spatially to evaluate eight Bay-wide climate change scenarios.
  http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0027388

- **Modeling of Coastal Inundation, Storm Surge, and Relative Sea-Level Rise at Naval Station Norfolk, Norfolk, Virginia, U.S.A. (Li et al. 2012)**
  Li et al. (2012) examined the potential risk and effects of storm-surge damage caused by the combination of hurricane-force waves, tides, and relative sea-level-rise (RSLR) scenarios at the U.S. Naval Station, Norfolk, Virginia. A hydrodynamic and sediment transport modeling system validated with measured water levels from Hurricane Isabel was used to simulate two synthesized storms representing 50-year and 100-year return-period hurricanes, a northeaster, and five future RSLR scenarios to evaluate the combined impacts of inundation on this military installation in the lower Chesapeake Bay.

- **Preparing for Tomorrow's High Tide: Sea Level Rise Vulnerability Assessment for the State of Delaware (Delaware Coastal Programs of the Department of Natural Resources and Environmental Control 2012)**
  Authors used high resolution elevation data to create a bathtub model of Delaware. The bathtub model floods all land below a certain elevation, unless there is a structure that would block tidal flow (like dikes and dams). Based upon this model, a series of maps was developed to show what the recommended sea level rise scenarios would look like on the ground at mean higher-high water. The Vulnerability Assessment was developed in five stages: (1) Identification of Resources of Concern; (2) Data Collection; (3) Exposure Assessment; (4) Impact Assessment; and (5) Risk Assessment.
  http://www.dnrec.delaware.gov/coastal/Documents/SeaLevelRise/AssesmentForWeb.pdf

- **Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States (Strauss et al. 2012)**
  Strauss et al. (2012) employed a recent high-resolution edition of the National Elevation Dataset and using VDatum, a newly available tidal model covering the contiguous US, together with data from the 2010 Census, to quantify low-lying coastal land, housing and population relative to local mean high tide levels, which range from ~0 to 3 m in elevation (North American Vertical Datum of 1988). Previous work at regional to national scales has sometimes equated elevation with the amount of sea level rise, leading to underestimated risk anywhere where the mean high tide elevation exceeds 0 m, and compromising comparisons across regions with different tidal levels.
  http://iopscience.iop.org/1748-9326/7/1/014033/article

- **Vulnerability of Shallow Tidal Water Habitats in Virginia to Climate Change (Bilkovic et al. 2009)**
  The principal objective of this study was to develop a characterization of current shallow-water habitat components in Virginia tidal waters and predict climate driven changes to these habitats. To project broad-scale climate change effects on the abundance and distribution of coastal habitats, an inundation model based on anticipated relative sea-level rise, temperature and salinity projections, and coastal development were integrated into a GIS modeling framework. Using this framework, simple models were constructed that forecast the distribution of key coastal habitat parameters within the next 50 to 100 years including: shallow-water areas, tidal wetlands, submerged aquatic vegetation and estuarine beaches.
  http://ccrm.vims.edu/research/climate_change/COASTALHABITATS_FinalReport.pdf

3.3.5 Mangroves

Climate Change Vulnerability Assessment and Adaptation Planning for Mangrove Systems (World Wildlife Fund)

This manual draws on on-the-ground experience and scientific knowledge to help conservation practitioners assess the vulnerability of mangrove ecosystems to climate change and assist them in planning adaptation activities. Eight methods are discussed in the VA, including field-based techniques to assess forest condition and health and more sophisticated approaches for understanding past and present change. Each method includes a case study from a WWF project that clearly describes how the method was carried out and how the results were analyzed. Guidance is given on how to combine the results from each method to form a composite understanding of vulnerability for a given mangrove area, and how to select and prioritize adaptation strategies for reducing that area's vulnerability to climate change.
Developer: World Wildlife Fund (Ellison 2012)
http://worldwildlife.org/publications/climate-change-vulnerability-assessment-and-adaptation-planning-for-mangrove-systems

A methodology for assessing the vulnerability of mangroves and fisherfolk to climate change (Faraco et al. 2010)

Faraco et al. (2010) propose a research methodology for assessing the vulnerability to climate change of the social-ecological system mangroves - fisherfolk, by analyzing exposure to sea-level rise, sensitivity and adaptive capacity, and the impacts of conservation policies on these elements, particularly the effects of coastal protected areas in southern Brazil. An integrated social-ecological diagnosis may lead to more flexible policies, elaborated with stakeholders' participation, more adequate to local realities and more inclusive of strategies for mitigation and adaptation to climate change.
http://www.panamjas.org/pdf_artigos/PANAMJAS_5(2)_205-223.pdf

3.3.5 Islands and Marine

***Climate change, sea-level rise, and conservation: keeping island biodiversity afloat* (Courchamp et al. 2014)**
Island conservation programs have been spectacularly successful over the past five decades, yet they generally do not account for impacts of climate change. Here, we argue that the full spectrum of climate change, especially sea-level rise and loss of suitable climatic conditions, should be rapidly integrated into island biodiversity research and management.
http://ac.els-cdn.com/S0169534714000147/1-s2.0-S0169534714000147-main.pdf?_tid=a85b7d42-bf51-11e3-b581-00000aab0f26&acdnat=1396984499_871c8b56c046080fbb6525f4561e5410

***Impact of sea level rise on the 10 insular biodiversity hotspots* (Bellard et al. 2013)**
Authors investigated four scenarios of projected sea level rise (1, 2, 3 and 6 m) on ten insular biodiversity hotspots including the Caribbean islands, the Japanese islands, the Philippines, the East Melanesian islands, Polynesia-Micronesia, Sundaland, Wallacea, New Caledonia, New Zealand and Madagascar and the Indian Ocean islands (i.e., 4447 islands). For each scenario, they assessed the number of islands that would be entirely and partially submerged by overlying precise digital elevation model and island data. They estimated the number of endemic species for each taxon (i.e. plants, birds, reptiles, mammals, amphibians and fishes) potentially affected by insular habitat submersion using the endemic–area relationship. Three hotspots displayed the most significant loss of insular habitat: the Caribbean islands, the Philippines and Sundaland, representing a potential threat for 300 endemic species.
http://max2.ese.u-psud.fr/epc/conservation/PDFs/SLRhot.pdf

***Predicting Sea-Level Rise Vulnerability of Terrestrial Habitat and Wildlife of the Northwestern Hawaiian Islands* (Reynolds et al. 2012)**
Reynolds et al. (2012) used remote sensing and geospatial techniques to estimate topography, classify vegetation, model SLR, and evaluate a range of climate change scenarios for the northwestern Hawaiian Islands (NWHI). On the basis of high-resolution airborne data collected during 2010−11 (root-mean-squared error = 0.05–0.18 m), authors estimated the maximum elevation of 20 individual islands extending from Kure Atoll to French Frigate Shoals (range: 1.8–39.7 m) and computed the mean elevation (1.7 m, standard deviation 1.1 m) across all low-

lying islands. They also analyzed general climate models to describe rainfall and temperature scenarios expected to influence adaptation of some plants and animals for this region. Outcomes for the NWHI predicted an increase in temperature of 1.8–2.6 degrees Celsius (°C) and an annual decrease in precipitation of 24.7–76.3 millimeters (mm) across the NWHI by 2100.
http://pubs.usgs.gov/of/2012/1182/of2012-1182.pdf

Vulnerability of terrestrial island vertebrates to projected sea-level rise **(Wetzel et al. 2013)**
Wetzel et al. (2013) quantified area loss for over 12,900 islands and over 3,000 terrestrial vertebrates in the Pacific and Southeast Asia under three different SLR scenarios (1 m, 3 m and 6 m). They used very fine-grained elevation information, which offered >100 times greater spatial detail than previous analyses and allowed them to evaluate thousands of hitherto not assessed small islands.
http://onlinelibrary.wiley.com/doi/10.1111/gcb.12185/abstract

Using expert judgment to estimate marine ecosystem vulnerability in the California Current **(Teck et al. 2010)**
Drawing on methods from decision science, Teck et al. (2010) offer a method for eliciting expert judgment to (1) quantitatively estimate the relative vulnerability of ecosystems to stressors, (2) help prioritize the management of stressors across multiple ecosystems, (3) evaluate how experts give weight to different criteria to characterize vulnerability of ecosystems to anthropogenic stressors, and (4) identify key knowledge gaps.
http://www.esajournals.org/doi/pdf/10.1890/09-1173.1

Global reductions in seafloor biomass in response to climate change **(Jones et al. 2013)**
Authors show that decadal-to-century scale changes in carbon export associated with climate change lead to an estimated 5.2% decrease in future (2091–2100) global open ocean benthic biomass under RCP8.5 (reduction of 5.2 Mt C) compared with contemporary conditions (2006–2015). Their projections use multi-model mean export flux estimates from eight fully coupled earth system models, which contributed to the Coupled Model Intercomparison Project Phase 5, that have been forced by high and low representative concentration pathways (RCP8.5 and 4.5, respectively). These export flux estimates are used in conjunction with published empirical relationships to predict changes in benthic biomass.
http://onlinelibrary.wiley.com/doi/10.1111/gcb.12480/abstract

4.0 Place-Based Approaches

Place-based approaches typically use a combination of methods to look at species, habitats, landscapes, water resources, cultural resources, infrastructure and other resources.

4.1 National Parks

Badlands National Park: Climate Change Vulnerability Assessment
This report assesses the vulnerability of natural, paleontological, and cultural resources in Badlands National Park, South Dakota, to climate change. It characterizes the projected regional downscaled climate changes and the best estimates of resource vulnerabilities based on available literature and professional judgment. Natural resources evaluated include plant communities and individual wildlife species (or groups of species, such as grasslands birds), as well as three ecological processes that shape the Badlands landscape (fire, grazing, and erosion). The Park's significant paleontological resources are also addressed, as are the Park's cultural resources (e.g., historic roads, archeological sites, ethnographic resources).
Citation: Amberg et al. (2012)
http://www.cfr.washington.edu/research.cesu/reports/J8W07100036_final_report.pdf

The value of a multi-faceted climate change vulnerability assessment to managing protected lands: Lessons from a case study in Point Reyes National Seashore
Based on existing climate change vulnerability assessment frameworks in the literature, the authors developed a multifaceted climate change vulnerability assessment at the biological community level comprised of: a) expert judgment, b) predictive vegetation mapping, c) predictive geophysical mapping, and d) species-specific evaluations. Authors wrote a climate change vulnerability assessment for Point Reyes National Seashore and evaluated the usefulness of each facet, alone and in concert. They found that the facets were complementary and that each one was useful to inform some management goals; they also found that expert judgment was the most widely applicable and flexible assessment method. They believe that this multifaceted framework can be employed in other protected areas to facilitate management decisions under a changing and uncertain future climate.
Citation: Hameed et al. (2013)

http://www.parcc-web.org/parcc-project/documents/2013/04/hameed-s-o-et-al-2013-the-value-of-a-multi-faceted-climate-change-vulnerability-assessment-to-managing-protected-lands-lessons-from-a-case-study-in-point-reyes-national-seashore.pdf

4.2 National Forests and/or National Parks

Climate Change and Forest Biodiversity: A Vulnerability Assessment and Action Plan for National Forests in Western Washington

The specific objectives of this assessment were to: (1) Assess the potential impacts of projected changes in climate on both forest trees and selected vulnerable habitats (alpine and subalpine habitats, dry grasslands, and wetlands); (2) Evaluate tools that have been developed to assess vulnerability and mitigate the expected stress of a warming climate; (3) Recommend actions that will improve understanding of changes taking place with forest tree species and vulnerable habitats, maintain and increase biodiversity and increase resilience, and prepare for an uncertain future; and (4) Collaborate in the implementation of these actions with the National Park Service and the Washington State Department of Natural Resources.
Citation: Aubry et al. (2011)
http://ecoshare.info/wp-content/uploads/2011/05/CCFB.pdf

Adapting to Climate Change at Olympic National Forest and Olympic National Park

A vulnerability assessment was conducted to facilitate development of adaptation strategies and actions for Olympic National Forest (ONF) and Olympic National Park (ONP). The authors first reviewed available climate model projections to determine likely levels of exposure to climate change on the Olympic Peninsula. The second step involved working with regional scientists and resource specialists to review relevant literature on the effects of climate change and on available projections to identify likely climate change sensitivities in each of four focus areas on the Olympic Peninsula (hydrology and roads, fish, vegetation, and wildlife). The final step was a review of current management activities at ONF and ONP and identification of management constraints in order to evaluate some aspects of institutional capacity to implement adaptation actions.
Citation: Halofsky et al. (2011)
http://www.fs.fed.us/pnw/pubs/pnw_gtr844.pdf

Climate Change Vulnerability and Adaptation in the North Cascades Region, Washington (DRAFT May 2013)

The North Cascadia Adaptation Partnership (NCAP) is a science-management partnership consisting of Mt. Baker-Snoqualmie National Forest (NF), Okanogan-Wenatchee NF, North Cascades National Park Complex, Mount Rainier National Park, the U.S. Forest Service Pacific Northwest Research Station, and the University of Washington Climate Impacts Group. These organizations worked with numerous stakeholders over two years to identify climate change issues relevant to resource management in the North Cascades and to find solutions that will facilitate the transition of the diverse ecosystems of this region into a warmer climate. The NCAP provided education, conducted a climate change vulnerability assessment, and developed adaptation options for federal agencies that manage 2.4 million hectares in north-central Washington.

Citation: Raymond et al. (2013)
http://northcascadia.org/pdf/DRAFT_raymond_et_al_NCAP.pdf

Ecosystem Vulnerability Assessment and Synthesis: A Report from the Climate Change Response Framework Project in Northern Wisconsin
This effort assessed the climate change vulnerability of northern Wisconsin forests. The report begins by describing the contemporary landscape and major existing climate trends using state climatological data, and then proceeds to discuss potential future climate trends for northern Wisconsin using downscaled data from general circulation models. Potential vulnerabilities are identified by incorporating the future climate projections into species distribution and ecosystem process models and assessing potential changes to northern Wisconsin forests.
Citation: Swantson et al. (2011)
http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs82.pdf

Climate Change Response Framework Vulnerability Assessments for Forest Ecosystems
Vulnerability assessments are being developed for three forest regions in the eastern US by the US Forest Service. Each vulnerability assessment is tailored to meet the needs of a particular region while maintaining a consistent approach and format across assessments. The vulnerability assessments: (1) focus on forest ecosystems within a region defined by a combination of ecoregional and political boundaries; (2) address vulnerabilities of individual tree species and forest or natural community types within each region; (3) use gridded historical and modeled climate change information as well as two different approaches to modeling impacts on tree species; and (4) rely on a panel of scientists and managers with local expertise to put scientific results in context.
http://forestadaptation.org/sites/default/files/Vulnerability%20Assessments%20Brief_Aug2012.pdf

- **Central Hardwoods Ecosystem Vulnerability Assessment and Synthesis: A Report from the Central Hardwoods Climate Change Response Framework Project**
  Climate trends for the next 100 years were projected by using downscaled global climate model data. Authors identified potential impacts on forests by incorporating these climate projections into three forest impact models (Tree Atlas, LINKAGES, and LANDIS PRO). Authors further assessed ecosystem vulnerability for nine natural community types in the region by using these model results along with projected changes in other factors such as wildfire, invasive species, and diseases. The basic assessment was conducted through a formal elicitation process of 20 science and management experts from across the region, who considered vulnerability in terms of potential impacts on a system and the adaptive capacity of the system. The projected changes in climate and the associated impacts and vulnerabilities will have important implications for economically important timber species, forest-dependent wildlife and plants, recreation, and long-range planning.
  Citation: Brandt et al. (2014)
  http://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs124.pdf

Climate Change on the Shoshone National Forest, Wyoming: A Synthesis of Past Climate, Climate Projections, and Ecosystem Implications

This report synthesizes the current understanding of the paleo- and historical climate of the Shoshone National Forest in Wyoming, US as a reference point, determine what future climates may look like, and what the effects of future climate may be on natural resources. Authors synthesize current resource conditions and the latest scientific information about how future climate change may affect natural resources on the Shoshone and GYE, and synthesize the studies related to resources and natural or human influenced processes that may be vulnerable to climate change—specifically, water, vegetation, fish and wildlife, fire or insect disturbance, biochemical cycling, economic activities, and land use.

Citation: Rice et al. (2012)

http://www.fs.fed.us/rm/pubs/rmrs_gtr264.pdf

4.3 National Wildlife Refuges

Vulnerability Assessment and Strategies for the Sheldon National Wildlife Refuge and Hart Mountain National Antelope Refuge Complex

Nature Serve conducted a vulnerability assessment of a complex of two national wildlife refuges in southeastern Oregon. The condition of priority resources on the Refuge complex was assessed using NatureServe's Vista software. Vista is a free decision-support system that helps users integrate conservation with land use and resource planning of all types. Vegetation resources were assessed using the Vegetation Dynamic Development Tool (VDDT). VDDT was developed to facilitate improved understanding of vegetation change through the use of successional pathway modeling. The processes modeled could include succession, harvest, disease, insects, and fire.

Citation: Crist et al. (2011)

http://www.fws.gov/refuges/whm/pdfs/SheldonHartNWR_RVA_Report.pdf

Following the methodology of Crist et al. (2012):

http://www.fws.gov/refuges/whm/pdfs/RefugeVulnerabilityAssessmentTechnicalGuide_FINAL.pdf

National Wildlife Refuge System-Wide Vulnerability Assessment

Magness et al. (2011) used a GIS analysis to assess the vulnerability of 501 reserve units in the National Wildlife Refuge System as a basis for a nationally coordinated response to climate change adaptation. They used measures of climate change exposure (historic rate of temperature change), sensitivity (biome edge and critical habitat for threatened and endangered species), and adaptive capacity (elevation range, latitude range, watershed road density, and watershed protection) to evaluate refuge vulnerability.

Citation: Magness et al. (2011)

http://dlc.dlib.indiana.edu/dlc/bitstream/handle/10535/8348/ES11-00200.pdf?sequence=1

4.4 Tribes

Swinomish Climate Change Initiative: Impact Assessment Technical Report
The report describes the scientific data and potential climate change scenarios, assesses possible local impacts, and identifies specific areas of potential risk and vulnerability to climate change effects on the Swinomish Indian Reservation community, lands, and resources in Washington State.
Citation: Swinomish Indian Tribal Community, Office of Planning and Community Development (2009)
http://www.swinomish-nsn.gov/climate_change/Docs/SITC_CC_ImpactAssessmentTechnicalReport_complete.pdf

Confederated Salish & Kootenai Tribes (CSKT) Climate Change Strategic Plan
This Climate Change Strategic Plan includes a section that summarizes the vulnerabilities and risks of the forestry, land, fish, wildlife, water, air, infrastructure, people, and culture sectors to the impacts of climate change. This assessment was completed by Tribal departments and local organizations using the Vulnerability Matrix, Risk Matrix, and Identifying Priority Planning Areas tool.
Citation: Durglo et al. (2013)
http://www.cskt.org/NRD/docs/CSKT%20Climate%20Change%20Adaptation%20Plan%20FINAL%2009%2010%202013.pdf

Jamestown S'Klallam Tribe Climate Vulnerability Assessment and Adaptation Plan
Jamestown S'Klallam Tribe developed the Adaptation Plan with support from a U.S. Environmental Protection Agency (EPA) Indian Environmental General Assistance Program (IGAP) grant. The project team convened a committee of fifteen tribal elders, staff members, and council members, and held a two day workshop to work with the climate committee on identifying adaptation priorities and developing adaptation strategies. Adaptation International and Washington Sea Grant provided summaries of a wide range of anticipated climate impacts and the committee then identified and prioritized key areas of concern for the Tribe. Primary outcomes from the workshop included selection of key areas of concern and detailed climate vulnerability rankings, based on potential climate exposure, sensitivity (how susceptible an area of concern is to a given climate impact), and adaptive capacity (the ability of that system to adapt to a given climate impact). The vulnerability rankings take into account community input when prioritizing areas of concern. By investigating climate impacts and identifying key areas of concern, the Jamestown S'Klallam Tribe's climate adaptation plan reflects community priorities while also acknowledging the sectors that may be most severely impacted.
Citation: Petersen and Bell (eds.) (2013)
http://www.jamestowntribe.org/programs/nrs/climchg/JSK_Climate_Change_Adaptation_Report_Final_Aug_2013s.pdf

4.5 Other

A Vulnerability-Based Strategy for Incorporating the Climate Threat in Conservation Planning: A Case Study from the British Columbia Central Interior

Authors present a framework to handle uncertainty in the incorporation of climate change in regional conservation planning. The framework uses expert opinion to: (1) formulate qualitative scenarios of climatic and ecological change based on expected as well as less probable but plausible futures not tied to specific model projections; (2) synthesize established knowledge of the climate vulnerability of species and ecosystems of concern; and (3) specify no-regrets climate adaptation strategies to reduce these vulnerabilities in conservation site selection. This framework was implemented in an ecoregional assessment of the British Columbia Central Interior selecting terrestrial and freshwater high-priority conservation sites. Including climate vulnerability based adaptation strategies in the regional site-selection process had a substantial effect on both freshwater and terrestrial assessments.
Citation: Kittel et al. (2011)
http://jem.forrex.org/index.php/jem/article/view/89

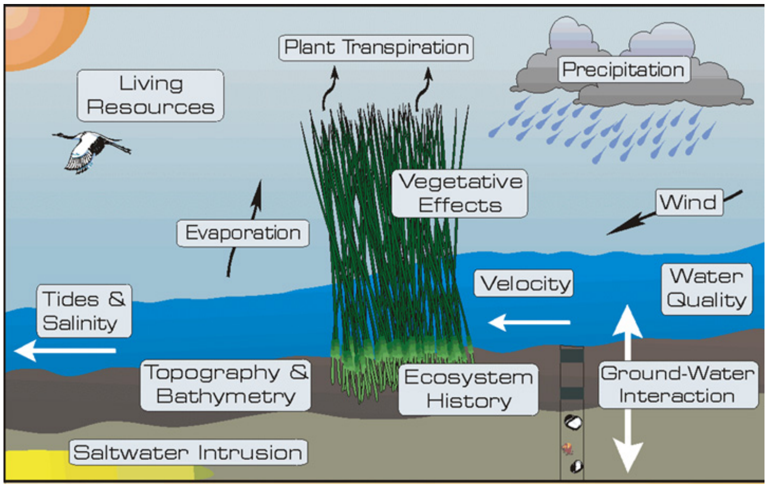
Montane Meadows in the Sierra Nevada: Changing Hydroclimatic Conditions and Concepts for Vulnerability Assessment
This technical report provides guidance for resource managers in considering conservation and restoration options for meadow ecosystems considering global atmospheric warming and resultant regional hydroclimatic alteration. This report begins by establishing a context for the nature, importance, and organization of montane meadows with a specific focus on a study region including the Sierra Nevada and portions of the southern Cascade Range. The report then proceeds with an overview of climate change and potential impact to meadows with specific discussion of general trends and projected outcomes, regional differences, and a comprehensive review of potential impacts on hydrological processes. This review is complemented by a discussion of how hydroclimatic alteration may impact meadow dependent species, and which indicator species are likely to be most beneficial for monitoring and management from a conservation standpoint.
Citation: Viers et al. (2013)
https://watershed.ucdavis.edu/files/biblio/CWSMeadowsVulnerabilityWhitePaper_2013-1-1_FinalReport.pdf

A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada
This vulnerability assessment is an initial science-based effort to identify how and why focal resources (ecosystems, species, populations, and ecosystem services) across the Sierra Nevada region are likely to be affected by future climate conditions. The overarching goal is to help resource managers and stakeholders plan their management of these focal resources in light of a changing climate. Twenty-seven focal resources including eight ecosystems, populations of fifteen species, and four ecosystem services were identified as important by the U.S. Forest Service as part of their forest plan revision process or by Sierra Nevada stakeholders and are considered in this assessment. This assessment centers on the Sierra Nevada region of California, from foothills to crests, including ten national forests and two national parks.
Citation: Kershner (2014)
http://ecoadapt.org/data/library-documents/EcoAdapt_CALCC_Sierra%20Nevada%20Vulnerability%20Assessment_26Feb2014.pdf

Review and Recommendations for Climate Change Vulnerability Assessment Approaches with Examples from the Southwest
Authors review pertinent information regarding methods and approaches used to conduct climate change vulnerability assessments to reveal assumptions and appropriate application of results. Secondly, they provide managers with an updated summary of knowledge regarding vulnerability of species and habitats to climate change in the American Southwest. Overall, vulnerability assessments provided valuable information on climate change effects and possible management actions but were far from a comprehensive picture for the future of the Southwest. Scales, targets, and assessment approaches varied widely and focused on only a subset of resources. They recommend that land managers critically examine methods when using assessment results; select scale, methods, and targets carefully when planning new assessments; and communicate assessment needs to researchers of climate change response.
Citation: Friggens et al. (2013)
http://www.fs.fed.us/rm/pubs/rmrs_gtr309.pdf

Ocean of Grass: A Conservation Assessment for the Northern Great Plains Addendum: Climate Change Impacts and Adaptation Strategies
This report provides an overview of climate change impacts to the Northern Great Plains Ecoregion, as defined in Forrest et al. (2004; Fig. 1), and suggests general adaptation techniques that will be beneficial in this region. The analysis and literature review contained within this report is meant to provide regional-scale data on the exposure of species and systems to historical and predicted future climate change, as well as provide information from the scientific literature that can serve as a qualitative vulnerability analysis for the region as a whole. The purpose of this report is to suggest priorities for conservation work in the Northern Great Plains with a focus on potential climate change impacts. This report uses the priority landscapes and species identified in Ocean of Grass as a basis for understanding climate change impacts and prioritizing adaptation actions.
Citation: Schrag (2011)
http://www.cakex.org/sites/default/files/project/documents/Ocean_Grass_ClimateChangeAddendum_2011.pdf

Gunnison Basin Climate Change Vulnerability Assessment
This report summarizes the results of a landscape-scale climate change vulnerability assessment of the Upper Gunnison Basin in Colorado to determine the relative vulnerability of 24 ecosystems using methods developed by Manomet Center for Conservation Science and 73 species of conservation concern using the CCVI of NatureServe. The report also summarizes the results of a social vulnerability and resilience assessment of ranching and recreation sectors in the Basin, which consisted of a document review and interviews with ranchers, recreation business representatives and one water expert.
Citation: Neely et al. (2011)
http://www.cnhp.colostate.edu/download/documents/2011/Gunnison-CC-Vulnerability-Assessment_and_Appendices-FULL_REPORT-Jan_9_2012.pdf



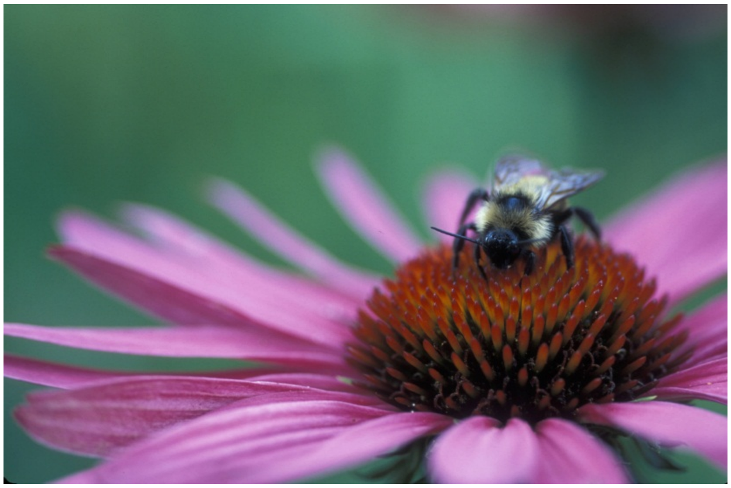
5.0 Ecosystem Processes

***Vulnerability Assessments in Support of the Climate Ready Estuaries Program: A Novel Approach Using Expert Judgment, Volume I, Results for the San Francisco Estuary Partnership* (U.S. EPA 2012a)**

The San Francisco Estuary Partnership (SFEP), the San Francisco Bay Conservation and Development Commission, and the Environmental Protection Agency (EPA) collaborated on an ecological vulnerability assessment, using an expert elicitation-type exercise to systematically elicit judgments from experts in a workshop setting regarding climate change effects on two key ecosystem processes: sediment retention in salt marshes and community interactions in mudflats. For each process, an influence diagram was developed identifying key process variables and their interrelationships (influences). Using a coding scheme, each expert characterized the type and sensitivity of each influence under both current and future climate change scenarios. The experts also discussed the relative impact of certain influences on the endpoints.
The same approach was applied to Massachusetts Bay (EPA 2012b)
http://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=241556#Download

***Potential climate change impacts on temperate forest ecosystem processes* (Peters et al. 2013)**

Large changes in atmospheric CO2, temperature, and precipitation are predicted by 2100, yet the long-term consequences for carbon (C), water, and nitrogen (N) cycling in forests are poorly understood. We applied the PnET-CN ecosystem model to compare the long-term effects of changing climate and atmospheric CO2 on productivity, evapotranspiration, runoff, and net nitrogen mineralization in current Great Lakes forest types. We used two statistically downscaled climate projections, PCM B1 (warmer and wetter) and GFDL A1FI (hotter and drier), to represent two potential future climate and atmospheric CO_2 scenarios.



6.0 Ecosystem Services

Ecosystem services and livelihoods – vulnerability and adaptation to a changing climate:
This report summarizes the results of a Vulnerability Assessment of Ecosystem Services for Climate Change Impacts and Adaptation (VACCIA) for Finland. The assessment looked at the vulnerability of several key sectors of the Finnish society/economy, including watersheds and water bodies, urban areas, coastal areas, ex situ plant conservation, forestry, fisheries, and tourism. Sector-specific approaches were used in each assessment of vulnerability. They assessed the threats and challenges posed by climate change to ecosystem services and livelihoods, and suggested methods for adapting to changing conditions.
Conducted by: Finnish Environment Institute
Citation: Bergstrom et al. (2011)
http://www.ymparisto.fi/default.asp?contentid=404218&lan=en

Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services
Authors used field and laboratory measurements, geographic information systems, and simulation modeling to investigate the potential effects of accelerated sea-level rise on tidal marsh area and delivery of ecosystem services along the Georgia coast. They specifically looked at ecosystem services related to production (macrophyte biomass) and waste treatment (nitrogen [N] accumulation in soil, potential denitrification).
Citation: Craft et al. (2009)
http://www.iu.edu/~spea/pubs/faculty/Frontiers_March_2009.pdf

The Impact of Climate Change on California's Ecosystem Services
This report projects the impact of future climate change on the natural provision of four key ecosystem services in California (carbon sequestration, forage production, water for instream flows for salmon, and snow recreation) and biodiversity, and the resulting change in market and non-market value of each service.
Citation: Shaw et al. (2009)
http://www.energy.ca.gov/2009publications/CEC-500-2009-025/CEC-500-2009-025-D.PDF

Potential Impacts of Climate Change on Biodiversity and Ecosystem Services in the San Francisco Bay Area

The objective of this paper is to summarize the current state of research on the potential impacts of anthropogenic climate change on SFBA biodiversity and ecosystem services. Studies addressing climate change include observational, experimental, and modeling approaches. Variability of natural ecosystems across spatial gradients provides important insights into how natural ecosystems respond to climate, and may respond to climate change given enough time to equilibrate. Historical data can provide evidence of response to past climate change, though these changes have rarely if ever proceeded as rapidly as those forecast in the next 100 years.
Citation: Ackerly et al. (2012)
http://www.energy.ca.gov/2012publications/CEC-500-2012-037/CEC-500-2012-037.pdf

Climate change's impact on key ecosystem services and the human well-being they support in the US

Scientists' understanding of the effects of climate change on ecosystem service provision and value is improving rapidly. Although no comprehensive national system for tracking the status or trends in US ecosystem service provision and value exists, numerous studies and databases are available from which researchers can begin to identify the ecosystem services that are sensitive to climate change (PCAST 2011). Authors use a selection of these studies and databases to identify some ecosystem services that have been and will continue to be affected by climate change and the potential impact of these service transformations on human well-being in the US. The aim of this paper is to extract highlights regarding selected ecosystem services. In particular, we focus on services that (1) are important to a broad swath of US society and to the nation's economy, (2) if altered could substantially impact the well-being of many people living in the US, and (3) are sufficiently represented in the literature so that conclusions about their sensitivity to climate change can be drawn.
Citation: Nelson et al. (2013)
http://www.esajournals.org/doi/pdf/10.1890/120312

7.0 Watershed and Water Resources

Assessing the Vulnerability of Watersheds to Climate Change: Results of National Forest Watershed Vulnerability Assessment Pilot Project
The US Forest Service recently completed a pilot project on 11 national forests around the country to assess potential hydrologic change due to ongoing and expected climate warming. A pilot assessment approach was developed and implemented. Each National Forest identified water resources important in that area, assessed climate change exposure and watershed sensitivity, and evaluated the relative vulnerabilities of watersheds to climate change. The assessments provided management recommendations to anticipate and respond to projected climate-hydrologic changes.
Citation: Furniss et al. 2013
http://www.fs.fed.us/ccrc/wva/PilotNFWatershedVulnerabilityReport.pdf

Climate Change Handbook for Regional Water Planning
This US EPA and CA Department of Water Resources document was developed by consulting firm CDM and presents an approach for assessing regional vulnerability of water resources to climate change and for measuring regional impacts. The vulnerability assessment approach includes: (1) characterizing a region; (2) identifying qualitative water-related climate change impacts; (3) identifying key indicators of potential vulnerability; and (4) prioritizing vulnerable water resources.
Citation: CDM 2012
http://www.water.ca.gov/climatechange/CCHandbook.cfm

Climate Change Vulnerability Assessments: A Review of Water Utility Practices
The EPA reviewed the approaches used by eight municipal water utilities to assess their vulnerability to climate change. The eight utilities' climate change vulnerability analyses were studied in depth to identify tools and approaches used by those water utilities in their assessments. The report synthesizes the insights from the analysis of these eight utilities in the following sections: approaches to assessing climate change vulnerability, sources of climate information, modeling changes in water resources, summary, and recommendations for further study.
Citation: U.S. EPA 2010, 2011

http://water.epa.gov/scitech/climatechange/upload/climate-change-vulnerability-assessments-sept-2010.pdf

Watershed Modeling to Assess the Sensitivity of Streamflow, Nutrient, and Sediment Loads to Potential Climate Change and Urban Development in 20 U.S. Watersheds (External Review Draft)

This report describes watershed modeling in 20 large U.S. drainage basins (6,000-27,000 mi^2) to characterize the sensitivity of U.S. streamflow, nutrient (N and P) loading, and sediment loading to a range of potential mid-21st century climate futures, to assess the potential interaction of climate change and urbanization in these basins, and to improve our understanding of methodological challenges associated with integrating existing tools (e.g., climate models, downscaling approaches, and watershed models) and datasets to address these scientific questions. Study areas were selected to represent a range of geographic, hydroclimatic, physiographic, and land use conditions together with practical considerations such as the availability of data to calibrate and validate watershed models. Climate change scenarios are based on mid-21st century climate model projections downscaled with regional climate models from the North American Regional Climate Change Assessment Program (NARCCAP) and the bias-corrected and spatially downscaled (BCSD) data set. Urban and residential development scenarios are based on EPA's national-scale Integrated Climate and Land Use Scenarios (ICLUS) project. Watershed modeling was conducted using the Hydrologic Simulation Program-FORTRAN (HSPF) and Soil and Water Assessment Tool (SWAT) watershed models.
Citation: U.S. EPA (2013)
http://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=247495#Download

Vulnerability of U.S. Water Supply to Shortage: A Technical Document Supporting the Forest Service 2010 RPA Assessment

Comparison of supply and demand within a probabilistic framework yields an estimate of the probability of shortage and thus a measure of the vulnerability of the water supply system. This comparison was performed for current conditions and for several possible future conditions reflecting alternative socio-economic scenarios and climatic projections. Examining alternative futures provides a measure of the extent to which serious future risks of water shortage must be anticipated. Water supply was quantified by first estimating freshwater input as precipitation minus evapotranspiration for each point in a grid covering the study area. These water inputs were then allocated to major river basins and made available to meet basic in-stream flow requirements, satisfy off-stream demands including those from downstream basins or those reached by trans-basin diversions, and add to reservoir storage. Off-stream demands were estimated as threshold quantities of desired water use based on extending past trends in water use under the assumption that water supply would be no more constraining to future water withdrawals than in the recent past. Modeling water supply and demand in this way does not provide a forecast of future shortage levels. Rather, it provides a projection of the degree to which water shortages would occur in the absence of adaptation measures to either increase supply or decrease demand.
Citation: Foti et al. (2012)
http://www.fs.fed.us/rm/pubs/rmrs_gtr295.pdf

Hydrologic Response and Watershed Sensitivity to Climate Warming in California's Sierra Nevada

Authors describe climate warming models for 15 west-slope Sierra Nevada watersheds in California under unimpaired conditions using WEAP21, a weekly one-dimensional rainfall-runoff model (Null et al. 2010). Incremental climate warming alternatives increase air temperature uniformly by 2°, 4°, and 6°C, but leave other climatic variables unchanged from observed values. Results are analyzed for changes in mean annual flow, peak runoff timing, and duration of low flow conditions to highlight which watersheds are most resilient to climate warming within a region, and how individual watersheds may be affected by changes to runoff quantity and timing. Results are compared with current water resources development and ecosystem services in each watershed to gain insight into how regional climate warming may affect water supply, hydropower generation, and montane ecosystems.
Citation: Null et al. (2010)
http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0009932

Stream Temperature Sensitivity to Climate Warming in California's Sierra Nevada: Impacts to Coldwater Habitat

This study assesses climate warming impacts on stream temperatures in California's west-slope Sierra Nevada watersheds, and explores stream temperature modeling at the mesoscale. We used natural flow hydrology to isolate climate induced changes from those of water operations and land use changes. A 21 year time series of weekly streamflow estimates from WEAP21, a spatially explicit rainfall-runoff model were passed to RTEMP, an equilibrium temperature model, to estimate stream temperatures. Air temperature was uniformly increased by 2°C, 4°C, and 6°C as a sensitivity analysis to bracket the range of likely outcomes for stream temperatures. Other meteorological conditions, including precipitation, were unchanged from historical values. Raising air temperature affects precipitation partitioning into snowpack, runoff, and snowmelt in WEAP21, which change runoff volume and timing as well as stream temperatures.
Citation: Null et al. (2013)
http://link.springer.com/article/10.1007%2Fs10584-012-0459-8

Managing Coastal Watersheds to Address Climate Change: Vulnerability Assessment and Adaptation Options for the Middle Patuxent Subwatershed of the Chesapeake Bay

The National Wildlife Federation worked with NOAA, a panel, and technical experts to identify climate change impacts for the Middle Patuxent subwatershed and developed options for adapting restoration and conservation practices to address those impacts. This project was designed to help NOAA consider its investments and how to protect them and ensure their effectiveness over the long-term in the face of climate change. The report focuses on describing the vulnerability of the Middle Patuxent subwatershed and a selection of 11 species, habitats, and conservation and restoration project types to climate change, as well as providing a suite of potential adaptation options to address those vulnerabilities. Water quality and sea level rise considerations were included in the analyses.
Citation: Kane (2013)
http://www.nwf.org/pdf/Climate-Smart-Conservation/Middle%20Patuxent%20Subwatershed%20Vulnerability%20Assessment%20and%20Adaptation%20Report%20August%202013.pdf

Changing streamflow on Columbia basin tribal lands—climate change and salmon
Analysis of independent flow measures (Seasonal Flow Fraction, Center Timing, Spring Flow Onset, High Flow, Low Flow) using the Student t test and Mann- Kendall trend test suggests evidence for climate change trends for many of the 32 study basins. The trends exist despite interannual climate variability driven by the El Niño–Southern Oscillation and Pacific Decadal Oscillation. The average April—July flow volume declined by 16 %. The median runoff volume date has moved earlier by 5.8 days. The Spring Flow Onset date has shifted earlier by 5.7 days. The trend of the flow standard deviation (i.e., weather variability) increased 3 % to 11 %. The 100-year November floods increased 49 %. The mid-Columbia 7Q10 low flows have decreased by 5 % to 38 %. Continuation of these climatic and hydrological trends may seriously challenge the future of salmon, their critical habitats, and the tribal peoples who depend upon these resources for their traditional livelihood, subsistence, and ceremonial purposes.
Citation: Dittmer (2013)

Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes
Authors assembled 18 temperature time-series from sites on regulated and unregulated streams in the northwest U.S. to describe historical trends from 1980–2009 and assess thermal consistency between these stream categories. Statistically significant temperature trends were detected across seven sites on unregulated streams during all seasons of the year, with a cooling trend apparent during the spring and warming trends during the summer, fall, and winter. Continuation of warming trends this century will increasingly stress important regional salmon and trout resources and hamper efforts to recover these species, so comprehensive vulnerability assessments are needed to provide strategic frameworks for prioritizing conservation efforts.
Citation: Isaak et al. (2012)
http://download.springer.com/static/pdf/278/art%253A10.1007%252Fs10584-011-0326-z.pdf?auth66=1396558489_87cf05642cf49a7d9b403db61b8ce7c9&ext=.pdf

Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy
Authors evaluated effects of climate change on the coupled human-environmental system of the McKenzie River watershed in the Oregon Cascades in order to assess its vulnerability. Published empirical and modeling results indicate that climate change will alter both the timing and quantity of stream flow, but understanding how these changes will impact different water users is essential to facilitate adaptation to changing conditions. In order to better understand the vulnerability of four water use sectors to changing stream flow, authors conducted a series of semi-structured interviews with representatives of each sector, in which they presented projected changes in stream flow and asked respondents to assess how changing water availability would impact their activities.
Citation: Farley et al. (2010)
http://www.fsl.orst.edu/wpg/pubs/inpress_Farleyetal_GloEnvCha.pdf

8.0 International

Climate Change Vulnerability Assessment for the Island of Saipan

In the summer of 2012 a climate change working group convened on the Island of Saipan to begin climate change adaptation planning in the Commonwealth of the Northern Mariana Islands (CNMI). In the year following this formation, the government agencies, non-governmental organizations, business associations and community groups that comprise the Working Group developed a collaborative structure and process to achieve a series of goals and objectives. The first objective was to identify the social, physical, and natural features in the CNMI that are most susceptible to the impacts of climate change. To achieve this objective, a community-based vulnerability assessment was conducted. The assessment focuses on projected changes to sea level and rainfall patterns in the CNMI, the exposure and sensitivity of Saipan to these changes, and the Island's capacity to respond to possible impacts. This document summarizes the process, results, and recommendations of the assessment.

Citation: Greene (2014)

http://www.climatecnmi.net/p/vulnerability-assessment.html

Dominican Republic Climate Change Vulnerability Assessment Report

The U.S. Agency for International Development (USAID)/African and Latin American Resilience to Climate Change (ARCC) Project conducted the Dominican Republic Climate Change Vulnerability Assessment (DR VA) from December 2012 to May 2013 in response to requests from the USAID/Latin America and Caribbean Bureau and USAID/Dominican Republic. The overall DR VA approach has six steps: a desk review of all relevant literature, a scoping visit, a field assessment phase, data compilation and analysis, a presentation of results, and a participatory analysis and definition of climate adaptation options. The assessment seeks to improve understanding of climate change impacts on watersheds and coastal resources — as well as the people dependent on them — in the four climate-sensitive hotspots that the assessment targets.

Citation: Caffrey et al. (2013)

http://www.usaid.gov/sites/default/files/documents/1862/Dominican%20Republic%20Climate%20Change%20Vulnerability%20Assessment%20Report.pdf

Climate Change and the Great Barrier Reef: A Vulnerability Assessment
This multi-chapter (24 chapters) vulnerability assessment of the entire Great Barrier Reef in Australia engaged expert scientists who integrated all current knowledge to assess the vulnerability of the different components of the ecosystem. The assessment of social vulnerability engaged with communities and industries that depend on the Great Barrier Reef, are regular users of the reef, or reside in the reef catchment. The chapters include an introduction, a species and species group section, a habitat section, and a conclusion.
Citation: Johnson and Marshall (2007)
http://www.gbrmpa.gov.au/resources-and-publications/publications/climate-change-and-the-great-barrier-reef-a-vulnerability-assessment

Climate Change Vulnerability Assessment of Wangchuck Centennial Park, Bhutan
This pilot study conducts a climate change vulnerability assessment in Wangchuck Centennial Park, Bhutan and focuses on three components: biodiversity, livelihood, and water. The study looks at the resource settings in and around the park, assesses the vulnerability of each resource to climate change, and recommends appropriate adaptation measures that seek to reduce these vulnerabilities.
Citation: Lhendup et al. (2011)
http://awsassets.panda.org/downloads/wcp_ccva_report.pdf

Climate Change Vulnerability Assessment of the Galápagos Islands
This vulnerability assessment represents collaboration among three organizations, with local stakeholder involvement. The process culminated in a vulnerability assessment expert workshop held in April 2009 in Puerto Ayora, Galápagos. At the workshop, local, national and international experts, scientists and decision makers reviewed the existing data, integrated data across disciplines and provided recommendations and priority actions for the next steps in ensuring Galápagos can adapt to the impacts of climate change. The objectives of the vulnerability assessment were: (1) To determine the potential impacts of climate change on the biodiversity and related human welfare of the Galápagos; (2) To provide recommendations for management that addresses these impacts; (3) To build in-country support for addressing the impacts of climate; and (4) To provide working examples of adaptation for the Eastern Pacific.
Citation: Larrea and DiCarlo (2011)
http://awsassets.panda.org/downloads/integrated_report_final.pdf

Climate Vulnerability in the Barents Sea Ecoregion: A Multi-Stressor Approach
In this report, authors examine how climate change impacts may intersect and interact with other stressors in the Barents Sea Ecoregion. They investigated the vulnerability of the Barents Sea Ecoregion to both climate change and increased transport activity, particularly in relation to oil and gas transport from Western Russia, in order to develop a preliminary framework for assessing the effects of multiple stressors. Based on a survey of existing literature, some of the key processes and species that contribute to biodiversity in the Barents Sea Ecoregion are identified and current and future threats from maritime traffic discussed. They next discuss climate change impacts and vulnerability and present some future climate scenarios based on the results for 2050 from the Bergen Climate Model. Then they assess potential interactions between the two stressors and present an example of a structural analysis of multiple stressors for the Barents Sea Ecoregion.

Citation: O'Brien et al. (2003)
http://www.cicero.uio.no/media/3024.pdf

Climate Change Vulnerability of Mountain Ecosystems in the Eastern Himalayas: Climate Change Impact and Vulnerability in the Eastern Himalayas - Synthesis Report
The International Centre for Integrated Mountain Development (ICIMOD) undertook a series of research activities together with partners in the Eastern Himalayas from 2007 to 2008 to provide a preliminary assessment of the impacts and vulnerability of this region to climate change. Activities included rapid surveys at country level, thematic workshops, interaction with stakeholders at national and regional levels, and development of technical papers by individual experts in collaboration with institutions that synthesized the available information on the region. A summary of the findings of the rapid assessment was published in 2009, and is being followed with a series of publication comprising the main vulnerability synthesis report (this publication) and technical papers on the thematic topics climate change projections, biodiversity, wetlands, water resources, hazards, and human wellbeing.
Citation: Tse-ring et al. (2010)
http://www.icimod.org/?opg=949&q=drr_document&document=1686

Climate Change Vulnerability Mapping for Southeast Asia
This paper provides information on the sub-national areas (regions/districts/provinces) most vulnerable to climate change impacts in Southeast Asia. This assessment was carried out by overlaying climate hazard maps, sensitivity maps, and adaptive capacity maps following the vulnerability assessment framework of the IPCC. The study used data on the spatial distribution of various climate-related hazards in 530 sub-national areas of Indonesia, Thailand, Vietnam, Lao PDR, Cambodia, Malaysia, and the Philippines. Based on this mapping assessment, all the regions of the Philippines; the Mekong River Delta in Vietnam; almost all the regions of Cambodia; North and East Lao PDR; the Bangkok region of Thailand; and West Sumatra, South Sumatra, West Java, and East Java of Indonesia are among the most vulnerable regions in Southeast Asia.
Citation: Yusuf and Francisco (2009)
http://www.preventionweb.net/files/7865_12324196651MappingReport1.pdf

A holistic approach to climate change vulnerability and adaptation assessment: Pilot study in Thailand
This pilot vulnerability assessment uses a new holistic approach to assess the climate change vulnerability of multiple sectors in Thailand. The approach is premised on the notion that in order to provide an accurate view of the landscape in the long term, a vulnerability and adaptation assessment must take a holistic view, including socioeconomic factors as well as interactions among sectors. The process begins with assessments of individual sectors, but in a critical second step, it assembles the results of those individual assessments to create a storyline that looks at the whole landscape and its complex systems. The assessment process can be summarized as follows: (1) Identify key sectors in the landscape; (2) Analyze key climate concerns for each sector, including both the specific projected impacts, and their potential effects; (3) Analyze key socioeconomic factors that could affect each sector, and their potential impacts; (4) Consider plausible responses each of the different sectors to the combined impacts of climate change and socioeconomic factors; (5) Assemble the results of the sector-by-sector

assessments to build one or more storylines or scenarios for the landscape as a whole, as the basis for landscape-wide adaptation planning; and (6) Looking at cross-sectoral impacts, identify adaptation pathways that minimize negative interactions.
Citation: Chinvanno (2013)
http://static.weadapt.org/knowledge-base/files/1149/5140abc4d6369full-report-krabi.pdf

Freshwater Ecosystem Vulnerability Assessment The Indrawati Sub-Basin, Nepal
This report is part of a project of WWF Nepal and the Nepalese Water and Energy Commission Secretariat. It outlines the discussions and conclusions of three workshops held in Nepal to determine the vulnerability of the Indrawati sub-basin to the impacts of climate change and development within the context of climate change vulnerability at the national level. The workshops brought together a diverse group of more than 60 participants, including Nepali national experts, local bureaucrats, and most importantly, local water users and subsistence farmers with direct knowledge of resource management issues in the basin. Using a modified version of the ecosystem-based and water resource-focused vulnerability assessment methodology (Flowing Forward) developed by the World Wildlife Fund, workshop participants evaluated the combined impacts of climate change and development in the basin on both vulnerable ecosystems and local livelihoods. With this understanding, they outlined potential remedies, from macro-level policy reforms to on-farm technical capacity building. They then connected the outcomes of this process with some additional analysis of two key economic sectors (hydropower and agriculture) that are important in the Indrawati basin. The report briefly assesses the vulnerability of these sectors to climate change and identifies some potential adaptation options.
Citation: Bartlett et al. (2011)
http://nicholasinstitute.duke.edu/sites/default/files/publications/freshwater-ecosystem-vulnerability-assessment-indrawati-sub-basin-nepal-paper.pdf

Climate Change Vulnerability Assessment for the Namakwa District Municipality
This report assesses vulnerability to climate change in the Namakwa District Municipality (NDM) of South Africa. It: (a) addresses climate change risks and impacts in the NDM; (b) profiles the structural conditions that contribute to socio-economic vulnerability in the NDM; (c) assesses institutional vulnerability and local government capacity; (d) identifies priority areas for Ecosystem-based Adaptation and conservation actions; and (e) makes recommendations for Ecosystem-based Adaptation actions. A vulnerability index complements the map, informing priority setting for resource allocation to Ecosystem-based Adaptation and for use as the metrics for measuring reduced vulnerability overtime as a result of government effort and the efforts of other stakeholders.
Citation: Bourne et al. (2012)
http://static.weadapt.org/knowledge-base/files/1230/51c4c23ad02f8final-vulnerability-assessment-full-technical-report-ndm-with-cover.pdf

A Preliminary Assessment of the Vulnerability of Australian Forests to the Impacts of Climate Change: Synthesis
This report is a synthesis of the Forest Vulnerability Assessment project undertaken by a consortium of research groups in Australia. The project was an initiative of the Natural Resource Management Ministerial Council and undertaken under the auspices of the National Climate

Change Adaptation Research Facility, Griffith University. The project was established in 2009 to: (1) review current knowledge of the likely biophysical and socio-economic consequences of climate change on Australia's forests; (2) understand the vulnerabilities of Australia's forests; (3) identify current adaptation actions; and (4) identify information gaps to improve adaptive capacity. The assessment was carried out using a basic vulnerability assessment framework which considers sensitivity, exposure and adaptive capacity to determine the vulnerability of Australia's forests to climate change. Each of these factors was considered in turn using the general scientific literature. In addition interviews with stakeholders were used to identify key issues and current actions by forest managers and policy-makers. Four reports were developed and published as result of each of those projects. This synthesis report was developed based on those reports.
Citation: Boulter (2012)
http://www.nccarf.edu.au/sites/default/files/attached_files_research_projects/Final%20FVA%20Synthesis_final.pdf

GIS assessment of coastal vulnerability to climate change and coastal adaption planning in Vietnam
This paper assesses the potential vulnerability of Vietnam's coast to climate change and discusses possible adaptation policies and plan to reduce the impacts. GIS analysis was used for the assessment of coastal vulnerability. Geo-reference Shuttle Radar Topography Mission (SRTM) data of Vietnam, which is a satellite image with ground elevation was obtained from the University of Maryland, USA. The data was rectified and opened in ERDAS Imagine (image interpretation software) Virtual GIS and then three different unsupervised flood layers were created on the image. They are: (1) One meter: (2) two meters; and (3) five meters.
Citation: Boateng (2012)

9.0 Other

***Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks* (Preston et al. 2011)**
Authors review climate change vulnerability mapping in the context of four key questions that are fundamental to assessment design. First, what are the goals of the assessment? Second, how is the assessment of vulnerability framed? Third, what are the technical methods by which an assessment is conducted? Fourth, who participates in the assessment and how will it be used to facilitate change? Each of these questions is reviewed in turn by drawing on an illustrative set of 45 vulnerability mapping studies appearing in the literature. A number of pathways for placing vulnerability mapping on a more robust footing are also identified.
http://adaptation.arizona.edu/files/public/post%20conference%20uploads/SS-Vulnerability_mapping.pdf

***Social Vulnerability and Climate Change: Synthesis of Literature* (Lynn et al. 2011)**
This synthesis of literature illustrates information about the socioeconomic, political, health, and cultural effects of climate change on socially vulnerable populations in the United States, with some additional examples in Canada. Through this synthesis, social vulnerability, equity, and climate justice are defined and described, and key issues, themes, and considerations that pertain to the effects of climate change on socially vulnerable populations are identified. The synthesis reviews what available science says about social vulnerability and climate change, and documents the emergence of issues not currently addressed in academic literature. In so doing, the synthesis identifies knowledge gaps and questions for future research.
http://www.fs.fed.us/pnw/pubs/pnw_gtr838.pdf

***Climate change vulnerability assessments as catalysts for social learning: four case studies in south-eastern Australia* (Yuen et al. 2013)**
This paper explores the value of vulnerability/risk assessments in climate change adaptation planning processes as a catalyst for learning in four case studies in Southeastern Australia. Data were collected using qualitative interviews with stakeholders involved in the assessments and analyzed using a social learning framework. This analysis revealed that detailed and tangible strategies or actions often do not emerge directly from technical assessments. However, it also revealed that the assessments became important platforms for social learning. In providing these platforms, assessments present opportunities to question initial assumptions, explore multiple

framings of an issue, generate new information, and galvanise support for collective actions. This study highlights the need for more explicit recognition and understanding of the important role social learning plays in climate change vulnerability assessments and adaptation planning more broadly.
http://link.springer.com/article/10.1007%2Fs11027-012-9376-4

Climate Change Vulnerability Assessments, Lessons Learned from Practical Experience: Practitioner's Responses to Frequently Asked Questions **(McCarthy et al. 2010)**
The Nature Conservancy's Global Climate Change Team, Southwest Climate Change Initiative and Colorado chapter organized a two-day workshop in April 2010 for internal and external climate adaptation experts engaged in assessing climate change vulnerability. Participants shared their methods, lessons learned and recommendations for climate change vulnerability assessments at regional, state and landscape scales. This document is a rapid summary of the methods and tools discussed at the workshop and is intended to provide a foundation for others embarking on development of adaptation planning and implementation.
http://conserveonline.org/workspaces/climateadaptation/documents/vulnerability-assessments/documents/climate-change-vulnerability-assessments-lessons/@@view.html

CRiSTALTool
CRiSTAL is a project planning tool that helps users design activities that support climate adaptation (i.e., adaptation to climate variability and change) at the community level. CRiSTAL stands for "Community-based Risk Screening Tool – Adaptation and Livelihoods." "Community-based" – CRiSTAL focuses on projects at the local community level. "Risk Screening" – CRiSTAL helps users to identify and prioritize climate risks that their projects might address. "Adaptation and Livelihoods" – CRiSTAL helps users to identify livelihood resources most important to climate adaptation (i.e., adaptation to climate variability and change) and uses these as a basis for designing adaptation strategies.
http://www.iisd.org/cristaltool/

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