V. Addressing Uncertainty in Vulnerability Assessments

This chapter addresses issues and approaches for dealing with uncertainty specifically within the context of conducting climate change vulnerability assessments (i.e., uncertainties related to identifying and modeling the sensitivities, levels of exposure, and adaptive capacity of the assessment targets). The following chapter (Chapter VI) discusses how to develop adaptation management and planning activities in light of those uncertainties.

To begin, we define *uncertainty* as it applies in both of these contexts. According to the IPCC (2007a), uncertainty is:

"An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) and/or by qualitative statements (e.g., reflecting the judgment of a team of experts)."

Quantification of uncertainty can allow for inclusion into a risk assessment or analysis. Risk assessment involves estimating both the probability of an event occurring, and the severity of the impacts or consequences of that event. Analyses of risk, therefore, provide an opportunity to address quantifiable uncertainties through probabilistic calculations.

Dealing with uncertainty is nothing new in natural resource management.

Not all uncertainties can be addressed in a risk assessment, as there are unknowns that in many cases cannot be quantified. While risk assessment may allow for the inclusion of some types of uncertainty, it is also important to communicate those uncertainties that cannot be handled through exact quantification.

Managers have always made decisions even though there are uncertainties that cannot be quantified, much less reduced or eliminated. Dealing with uncertainty is nothing new in natural resource management. Being transparent about the general magnitude of uncertainty and understanding the range of possibilities given the uncertainty allows managers to articulate the reasoning for making a specific decision. With regard to climate change, managers may be seeking "bet hedging" strategies that make sense under a number of plausible future scenarios or that are generally robust to uncertainty.

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With respect to vulnerability assessments, the goal should be to use the best available information on the uncertainties involved in estimating vulnerability, while recognizing that it may be necessary to reassess vulnerability and the associated uncertainties in an iterative fashion as new information becomes available. The assessment of uncertainty should identify both the best estimate of how vulnerable a system is to climate change but also the potential range of vulnerability given uncertainties.

The Language of Uncertainty

Before diving into specific methods for assessing uncertainty, it is important to acknowledge the need for "a language of uncertainty." The vulnerability assessment will synthesize scientific information from field studies, experimental studies, and modeling experiments, as well as the scientific knowledge of the experts pulling the information together. Users of the vulnerability assessment will want to know what the authors conclude about the assessment results based on the variety of different sources of information. How much confidence do the authors have in the results of the vulnerability assessment? There is a need to be consistent in describing the uncertainty so that the degree of uncertainty can be clearly communicated across vulnerability assessments (U.S. CCSP 2009c). We present several methods that can be used to describe the certainty of the assessment.

Uncertainty in the Scientific Literature

Methods to quantify uncertainty or confidence in assessments and analyses have been the subject of much study (e.g., uncertainty can arise in a variety of ways in an analysis or an assessment). Quantitative analyses of species vulnerability to climate change use mathematics or statistics to describe the relationship between climate and the species of interest. In these quantitative analyses, uncertainty can arise in the structure of the mathematics used to describe the phenomena as well as the field data used to parameterize the equations. For example, different vegetation models may describe quantitatively the growth of vegetation using different mathematical expressions, which can mean slight differences in the results under climate change. Uncertainty is also found in what is not known about the phenomena. For example, how elevated CO_2 will influence plant growth is not known precisely, and the vegetation models differ in their expression of this process.

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When the assessment is based on quantitative and qualitative analyses and a synthesis of the scientific literature by experts, then uncertainty is found in the lack of available information specific to the question of interest in addition to the uncertainty in the quantitative studies. The breadth and nature of the authors' background and experience also contributes uncertainty. For example, assessing the climate impacts on a particular bird species may be limited by what is known today about relationships between the bird's biology and climate metrics such as temperature and precipitation. However, there may also be more complex interactions with climate, such as soil moisture affecting the habitat the birds use.

Many techniques are available to quantify and communicate uncertainty in mathematical, computer, and statistical models, many of which are summarized in the U.S. Climate Change Science Program's recent publication *Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Climate Decision Making* (U.S. CCSP 2009c). Risk analysis methods, for example, can be used to assess uncertainty when the range of all possible events is known, and objective probabilities can be assigned to these events. The challenge in assessing climate change impacts is in quantifying the range of all possible events. In reviews of the attempts to quantify uncertainty in the IPCC reports, reviewers note that the process was limited by the amount of work done in the primary literature on quantifying uncertainty in the field or modeling studies. Fewer techniques are available to structure the uncertainty in assessments where information from a variety of sources is synthesized to assess the vulnerability of species or communities or ecosystems to climate change. It should also be noted that this discussion focuses only on the assessment of vulnerability. These results must be cast against the broader background on which the decision is made—and there will be uncertainty in those other factors influencing the management of the species, habitat, or ecosystem.

IPCC Approach to Uncertainty

The IPCC represents the longest focused attempt to describe uncertainty in the context of climate change and has been evolutionary in the development of the methodology used (Risbey and Kandlikar 2007). The 2007 IPCC reports were explicit about the language they used in describing uncertainty and levels of confidence in climate change. Yet, even though a common set of guidance was given to the authors, the uncertainty language in the IPCC

Quantitatively Calibrated Levels of Confidence

Terminology	Degree of Confidence in Being Correct
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

reports reflected the disciplinary nature of the subjects—for the physical sciences, the uncertainty language can build on the quantitative analyses in the sciences; for the socio-economic analyses, a more qualitative approach was taken given the nature of the primary literature being less quantitative.

Some uncertainties can be quantified using statistics and modeling approaches, while others may require more qualitative assessment.

"Where uncertainty is assessed more quantitatively using expert judgment of the correctness of underlying data, models or analyses, then the following scale of confidence levels is used to express the assessed chance of a finding being correct" (IPCC 2007a):

"Where uncertainty in specific outcomes is assessed using expert judgment and statistical analysis of a body of evidence (e.g. observations or model results), then the following likelihood ranges are used to express the assessed probability of occurrence" (IPCC 2007a):

"Where uncertainty is assessed qualitatively, it is characterized by providing a relative sense of the amount and quality of evidence (that is, information from theory, observations or models indicating whether a belief or proposition is true or valid) and the degree of agreement (that is, the level of concurrence in the literature on a particular finding). This approach is used by Working Group III through a series of self-explanatory terms such as: high agreement, much evidence; high agreement, medium evidence; medium agreement, medium evidence; etc." (IPCC 2007d).

A key observation about the language of uncertainty in the IPCC reports is that it has evolved as scientists learn how to further refine their science and the uncertainty related to their analyses (Risbey and Kandlikar 2007). One criticism of the analysis literature is the absence of a thorough assessment of the uncertainty. In some cases, exploring the uncertainty in quantitative analyses can be expensive in terms of time and effort and hence are not done as extensively as someone applying that analysis might prefer. Further, the lack of a consistent approach to describing uncertainty in the IPCC reports has been seen as inevitable given the very different nature of the science and the role of human decisions in the potential responses to climate change.

Likelihood Scale

Terminology	Likelihood of the Occurrence/Outcome
Virtually certain	>99 percent probability of occurrence
Very likely	>90 percent probability
Likely	>66 percent probability
About as likely as not	33 to 66 percent probability
Unlikely	<33 percent probability
Very unlikely	<10 percent probability
Exceptionally unlikely	<1 percent probability

Assessing and Understanding Uncertainty

Identifying Sources of Uncertainty

Uncertainty in climate change vulnerability assessments can be rooted in a number of stages in the process, including: limited/unreliable data; unidentified or unknown interactions with non-climate stressors; unidentified or unknown interactions among different elements of climate change; unidentified or unknown interspecific interactions; unidentified or unknown thresholds; ambiguously defined concepts or terminology; scientific disagreements about what is known; or uncertain projections of human behavior. Some of these uncertainties can be quantified using statistics and modeling approaches, while others may require more qualitative assessment. A combination of these different methods can be used to bound the uncertainty and understand the range of possibility for vulnerability to climate change (Refsgaard et al. 2007).

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The following are a few examples of methods available to address uncertainty in climate change vulnerability assessments:

- **Monte Carlo Simulation.** One common quantitative approach for measuring uncertainty is Monte Carlo analysis, as exemplified in the Nevada case study in Chapter VII (Case Study 1). Put simply, a Monte Carlo simulation is a computer-based statistical technique that uses random sampling to convert uncertainties in the input variables of a model (e.g., incomplete knowledge of the climate sensitivity of a particular species) into probability distributions over output variables (Park 2008; Refsgaard et al. 2007; New and Hulme 2000; U.S. EPA 1997).

- **Expert Elicitation.** The vulnerability assessment for Massachusetts fish and wildlife habitats (Case Study 4) addressed uncertainty via "expert elicitation," which is a formal, systematic process to determine subjective judgments about uncertainties from relevant experts (Refsgaard et al. 2007). Expert elicitations are often warranted in cases where there are many sources of uncertainty and where critical information may be unavailable. The results of expert elicitation are often characterized quantitatively as probabilities that represent their levels of confidence. However, it is also important to include documentation of the evidence and criteria used by the experts to support their decisions.

- **Scenario Analysis.** A relatively straightforward way to address uncertainties inherent in projecting the future is to base assessments on multiple scenarios (Walker et al. 2003). Scenario uncertainty implies that there is a range of possible outcomes, but the mechanisms leading to these outcomes are not well understood and it is, therefore, not possible to formulate the probability of any one particular outcome occurring. For example, if downscaled climate models are unable to determine whether future conditions in a particular area will be warmer and wetter or warmer and drier, assessing the vulnerability of species or systems under both possible scenarios may be warranted. Similarly, given the currently wide range of possible scenarios for eustatic sea-level rise and the numerous factors that can affect relative sea level at a local or regional level, projecting future impacts and vulnerability based on a number of scenarios and assumptions may offer the most flexibility for determining possible management strategies (see Case Study 5).

Combining Multiple Sources of Uncertainty

Understanding the degree of uncertainty in each of the components that make up a vulnerability assessment is useful in understanding the overall vulnerability of a system to climate change. However, one of the major goals of doing a vulnerability assessment should be to combine the different components of the assessment in a way that provides an understanding of the range of vulnerability given the uncertainties in each of the components. Being able to combine these multiple sources of uncertainty is really the glue that brings vulnerability assessments together into a synthetic product that can be used for decision-making and adaptation planning.

Combining the various sources of uncertainty is important because the uncertainties may interact to magnify or reduce the overall uncertainty. For example, there may be a species in the arid southwestern United States that is moisture limited, and global climate models range from projecting small increases to fairly large decreases in precipitation, with temperatures increasing 2.5 to 4.5 degrees Celsius by the 2080s. Although there is a degree of uncertainty in the different components, combining the temperature and precipitation information shows that the increase in temperature will offset any projected increase in precipitation resulting in a moderate to large decrease in water availability, and thus a consistent increase in that species' vulnerability. On the other hand, if a different species in this same area has a springtime temperature threshold that cues it to flower at a certain time, which is known within a range of approximately 4 degrees Celsius, the vulnerability of the species may range from very little and unlikely to fairly great and likely.

The key to combining multiple sources of uncertainty is to identify interactions between the different components, such as how temperature and precipitation interact to affect soil moisture and river flows. This can be done qualitatively through conceptual models, diagrams, and narratives, or more quantitatively through scientific models and computational algorithms. The method used for combining uncertainty should be chosen based on the methods used to assess uncertainty of the components (e.g., qualitative vs. quantitative), the degree of understanding about the interactions between the components and the resources available for combining the data (e.g., technological capacity and budget).