Chapter 4

Recognizing Uncertainties in Evaluating Responses

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BOXES

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Main Messages

Decisions about how to respond to external stresses are, of necessity, made under conditions of uncertainty. Incomplete information and imperfect knowledge about context and efficacy are facts of life, but well-established methods designed to help decision-makers cope with uncertainty exist. Applying them wisely can contribute directly to making decisions more effective.

Scenario analysis of the sort described in the *Scenarios* volume is one of many methods that can be employed to incorporate uncertainty into the evaluation of alternative responses to external stress. Sensitivity analysis, the construction of scenario trees, the augmentation of scenario trees with subjective probability distributions, and the estimation of response surfaces can all be applied in response evaluation. Each has its own strength, standing alone or used as part of a more integrated scenario analysis.

Cascades of uncertainty typically cloud our understanding of legal, market, institutional, and behavioral responses to change. Integrating across response strategies can mitigate and reduce elements of uncertainty, but it is unlikely that uncertainty can be eliminated in any important context. Decision-makers face pervasive uncertainty in choosing between responses. Each type of response has different sources of uncertainty. Regulatory responses have uncertain outcomes because of risk aversion in regulatory organizations, divergent stakeholder objectives, and diversity in human preferences for ecosystem services. Legal, institutional, and integrated responses exhibit uncertainty in the degree to which their implementation will be effective. All response strategies depend on stakeholders to establish their legitimacy, so governance structures introduce novel uncertainties. Combining and integrating response strategies often reduces implementation risks because integration can increase legitimacy and provide means for adaptive learning.

Uncertainty is manifest in surprise and unintended consequences. It is *well established* that our understanding of the complex systems within which response measures for ecosystem services are to be analyzed are clouded by uncertainty. As a result, responses can lead to unforeseen and often negative consequences. Ecosystems have intrinsic thresholds so that changes in their condition and feedback are often episodic and associated with changes in ecosystem function. Unintended consequences can arise even when many of the consequences of action are predictable because different decision-making bodies can cause negative spillovers into other areas even if they are successful in the pursuit of their own objectives.

Uncertainties expand when evaluations must be conducted beyond the bounds of historical experience. Projecting responses beyond the boundaries of historical experience brings the compounding effects of unknown contextual change to bear on their evaluation. Representations of uncertainty must then reflect the expanding implications of this uncertainty by conducting evaluations within hypothesized descriptions of the political, economic, social, and natural factors that will define future environments.

Uncertainty limits the ability of economic valuation methods to support collective decision-making for nontraded services, but not completely. Economic and institutional response strategies depend on decision tools that involve comparison of individual well-being across time and space. There are well-established methods for handling and quantifying uncertainties in these methods in contexts where markets exist. It is also well accepted that economic decision tools are limited in assessing responses for ecosystem services that are not traded in markets and where the values associated with them are not utilitarian in nature. The results of economic valuation techniques are not easily aggregated across scales; it follows that economic metrics cannot be applied in every circumstance where the relative merits of alternative responses are being contemplated. Other decision support techniques such as risk, multicriteria, and vulnerability analyses have also been designed explicitly to handle risk and uncertainty; they can sometimes more comfortably accommodate a diversity of decision-making contexts.

Uncertainties in the validation of vulnerability assessments arise because of scale and context specificity. Methods for determining vulnerability require quantitative and qualitative data that describe the drivers of change as well as the state of well-being for individuals and for social and ecological systems. They are important when the choice of a response tries to maximize the well-being of the most marginalized by identifying the most vulnerable people and places. There is debate as to whether vulnerability assessment methods allow for aggregation across scales because vulnerability depends on the position of the observer. It follows that uncertainties in vulnerability assessment can limit the degree to which findings from any particular context can be transported to another.

Scenarios provide one means of coping with many aspects of uncertainty, but our limited understanding of the ecological and human response process shrouds any individual scenario in its own characteristic uncertainty. Scenarios can be used to highlight the implications of alternative assumptions about critical uncertainties related to the behavior of human and ecological systems. At the same time, though, individual scenarios represent conditional projections based upon these specific assumptions. To the extent that our understanding of ecological and human systems represented in the scenarios is limited, specific scenarios are characterized by their own uncertainty. Furthermore, there is uncertainty in translating the lessons derived from scenarios developed at one scale (for instance, global) to the assessment of responses at other scales (for example, sub-national).

It is possible to integrate the political, economic, and social factors that impede or enhance the likelihood of success of any response with representations of the uncertainties that cloud our understanding of how they might work. The political, economic, and social factors identified in Chapter 3 map well into the determinants of adaptive (response) capacity, and applying a weakest link evaluation is appropriate. More specifically, the capacity to respond is fundamentally dependent on the factors that support the largest obstacle to response. Meanwhile, applying tools that explicitly recognize various sources of uncertainty can provide insight into the likelihood that the objectives of any response might actually be achieved without creating unintended consequences.

Scientific understanding of response mechanisms is frequently clouded by uncertainty, and this uncertainty affects the confidence with which descriptions of how these mechanisms can be expected to operate in a changing environment. Evaluating the relative strengths of the underlying determinants of response capacity can, however, provide a method by which this confidence can, itself, be assessed. When uncertainty can be quantified, standard thresholds can be applied to assign various degrees of confidence to specific conclusions. When only qualitative descriptors of uncertainty are available, confidence can still be conveyed in terms of the degree to which conclusions are or are not well established in theory and/or well supported by data and other evidence.

4.1 Introduction

Decision-makers face pervasive uncertainty in implementing response strategies as they try to manage ecosystem services. Uncertainty clouds their understanding of everything from how their response options might actually work to the methods that they use to assess their relative efficacy. This chapter takes this simple observation as a point of departure and tries to provide an insight into how valuation and decision-analytic frameworks can accommodate uncertainty. It also offers some guidance to those who want to assess how uncertainty combines with issues of political feasibility and governance (discussed in Chapter 3) to affect the confidence with which they can trust their conclusions about how best to respond. Both objectives recognize the fundamental truth that decision-makers have to make decisions even when uncertainty is extremely large; and both recognize that maintaining the status quo (that is, enacting no new response to one or more new sources of stress) is as much of a decision as moving robustly in many directions at the same time.

4.2 Cascading Uncertainties in Response Options and Assessment Methods

The different response strategies outlined in Chapter 2 and identified in subsequent chapters all operate in a landscape of uncertainty. Legal, economic, and institutional responses have fundamentally different types of risks and uncertainty associated with them. Uncertainty often reflects subjective views on the likelihood of various outcomes across a range of "states of nature." (See Box 4.1.) The corresponding levels of risk represent the product of these likelihoods and the consequences of their associated outcomes expressed in terms of ecosystem and/or human well-being and include the possibility of unintended consequences and other feedbacks. There are also other uncertainties associated with decision-making processes that include the possible divergence of opinion about approaches to risk across different stakeholders; these are concerns raised in Chapter 3. Taken together, all of these elements of uncertainty must be accommodated by methods and models used for the assessment of any response option including, of course, maintaining the status quo.

To illustrate the degree to which uncertainty is ubiquitous in the consideration of response strategies, Yohe and Strzepek (2004) have created a taxonomy of sources of uncertainty from a practical perspective anchored by methods and models that have been employed to describe and simulate critical connections between experience and expectation, drivers and state variables, and outcomes and consequences. To begin with, analytical methods and models are abstractions of the real world, and different approaches can produce wildly different answers to the very same questions. This simple phenomenon can be important in examining the relative merits of one particular model or another, but it introduces *model uncertainty* for analysts who are looking across model results for coherent views of the future. In addition, the ability of any particular model to offer a credible depiction of any connection is limited by the analyst's statistical ability to summarize perhaps vast but sometime paltry quantities of data that may or may not be particularly well defined. This can be called *calibration uncertainty.*

The limitations of calibrating a model are well understood by most practitioners, but they can be exacerbated when any one estimated model is used to produce *uncertain* predictions or projections of critical state variables. The difference between *prediction uncertainty* and *projection uncertainty* is, however, critical. To see the distinction, consider the simple case where a researcher has access to a set of historical data on a driving variable X and state variable Y whose causal relationship can be summarized by a linear relationship—a line whose points minimize the sum of the squared error of using the line rather than the data to represent the correlation between changes in X and resulting changes in Y. Now consider the question: what value of Y would be expected if variable X were to move along a particular trajectory over time? The best guess would be a series of points that lie along the line, but confidence about those guesses would fall as the trajectory took X farther away from the mean value of its historical range. Indeed, it would be possible to identify the boundaries of, for example, 95% confidence intervals for any possible value of X that lies within the extremes of the historical record with which the straight line was calibrated; these intervals would be credible representations of *prediction uncertainty.* If future drivers of change moved X outside the range of historical experience, then the value for Y read from the line would still be the best guess, but confidence would fall even more (the confidence intervals would expand even more) because the independent variable X would have moved beyond the realm within which the processes that sustained the relationship can be assumed to be valid. It is in this range that *projection uncertainty* presents itself.

The existence of projection uncertainty is the first recognition that underlying social and economic structures in many societies and contexts may change over time. Because these changes could occur even if the driving variable X did not exceed the boundaries of past experience, this sort of evolution of preferences and contexts is yet another way that the passage of time can undermine the credibility of using historically based modeling structures and methods as representations of future conditions. This is what might be called *contextual uncertainty,* and it can be enormous. It contains what most would understand as structural change, but it also includes value and preference uncertainties about which little is known at this point. Finally, *scale uncertainties* emerge when results for similar questions are compared across different geographic or temporal scales. The obvious point is that results generated at one scale cannot necessarily be scaled up or scaled down because emergent behaviors and baseline characteristics can vary dramatically. Box 4.2 illustrates a more subtle point: analyses conducted at different scales on the same data can produce different answers to the same question.

Turning finally to responses, it must be emphasized that the uncertainties that cloud our understanding of the connections be-

BOX 4.1

Subjective and Estimated Perceptions of Uncertainty and Risk

Computing the probabilities required to undertake a risk calculation is not always a simple matter. It may not, for example, be possible to conduct repeated trials. Nor is it always possible to produce theoretically based estimates of relative likelihood. Indeed, most interesting cases involve individuals' creating subjective views of probabilities from experience and/or careful reviews of scientific literature. Nonetheless, the output of a risk calculation will only be as good as its underlying data—estimates of outcomes in various states of nature, their consequences, and their associated likelihoods. How good are people at judging the critical outcomes and probabilities?

Slovic et al. (1979) authored an early investigation of this question that is still widely respected in the risk assessment literature. They found that experts systematically overestimate the chance of death associated with low-risk activities such as skiing and vaccination. Similarly, they underestimate the chance of death associated with high risk activities such as using handguns and smoking. Lay people showed the same systematic tendencies toward underestimation and overestimation, and their errors on the extremes of relative safety and extreme danger were actually more pronounced.

BOX 4.2

Using Indices to Track Changes in Land Use

The concept of an index is simple and intuitive, especially for a single scale and level of aggregation. The mathematics of indices can be deceptively tricky, though, when researchers analyze the behavior of the indices at various scales and sundry levels of aggregation. For example, suppose a researcher wanted to create an index to indicate land cover change over three decades in a region of Massachusetts (USA) where the conversion from natural to built land has been a source of enormous concern. The first step would be to compare maps of land cover at two points in time, but what would be the best way to perform the calculation if each pixel contains more than one land cover type? Consider a pixel that is $\frac{3}{4}$ natural and $\frac{1}{4}$ built land cover at time *1* and then transitions to $\frac{1}{4}$ natural and $\frac{3}{4}$ built at time *2.* There are at least three reasonable ways to compute the transition from natural to built for this pixel.

A common technique used by landscape scientists is to reclassify the pixel into the category that dominates. For this Boolean technique, the pixel would be classified as entirely natural in time *1* and as entirely built in time *2.* A second technique would be to assume that the proportions of natural and built land cover are distributed randomly within the pixel, so the probability that a patch of natural land within the pixel at time *1* transitions to built in time *2* is computed as $\frac{3}{4}$ times $\frac{1}{4}$, which is $\frac{3}{16}$ of the pixel. This case reflects the multiplication rule for joint probabilities. A third technique would assume that the natural and built patches within the pixel persist from time *1* to time *2.* For example, this third technique would assume that the built land at time *1* is part of the built land at time *2,* and that the natural land at time *2* was part of the natural land at time *1.* Therefore, the only change within the pixel is a transition of one half of the pixel from natural to built land cover. This technique is based on a minimum rule of agreement, which is consistent with fuzzy set theory and is becoming accepted in landscape science.

However, Pontius and Cheuk (2004) have shown that these three accepted methods to compute the transition from forest to built land cover for the given pixel could easily produce different trends for land use changes. The Boolean rule can behave chaotically at coarser resolution, the multiplication rule can detect larger transitions at coarser resolutions, but the minimum rule can be fairly stable across the same data. This is an example of how statistical results can be extremely sensitive to the selection of the units of analysis.

tween drivers and impacts are compounded by uncertainties that fog our understanding of how responses might work across a wide range of futures. The point here is simple: it is impossible to predict how any particular response might work in the future even along an assumed trajectory of how future gross impacts might evolve. Conversely, assessing the effectiveness of a response option within a single portrait of how the future might evolve (that is., conducting analysis as if the time trajectory of a gross impact on an ecosystem were known) would produce a dramatically overstated confidence in the time trajectory of net impacts.

4.3 Synthesis of Uncertainty in Identified Response Strategies

Subsequent chapters highlight a range of legal, institutional, and regulatory, behavioral, and market responses for fresh water, food, culture, and other services. The uncertainties and risks associated with these approaches are well documented. So, too, is the knowledge that uncertainty clouds our understanding of both the nature and characterization of the ecosystem services as well as the links between those services, human well-being, and the institutional context of any policy response. This section provides an overview of these uncertainties.

4.3.1 Uncertainty in Legal and Control Responses

The nature of uncertainty in legal, regulatory, and control responses to the management of ecological services is, first of all, associated with the characteristics of ecological systems and the degree to which they are amenable to human control. The risk factors associated with ecological management are typically interconnected. Holling et al. (1995) argue that ecological systems frequently have shared characteristics, perhaps most importantly the notion that changes in ecosystem function associated with human interference are not usually gradual. They are, instead, triggered by external perturbations and are therefore typically episodic. These authors also note that some of the functions that control ecosystems promote stability while others create destabilizing influences. It follows that regulating simultaneously for stability and resilience (that is, trying to achieve long-term stability while accommodating short-term variability) may be impossible. In addition, the spatial attributes of ecosystems are not uniform; they are skewed in their distribution and patchy at different scales. As a result, regulation cannot simply be aggregated across scales—what works for a single location will not *necessarily* work for a whole region. These characteristics of ecosystems often mean that management actions that are applied as blueprints across scales to maintain stability in ecosystem function can inadvertently lead to reduced resilience (Holling and Meffe 1996). Irrigation and homogenization of plant genetic stock in agriculture are good examples of the promotion of stability at the expense of resilience.

Second, there is uncertainty in outcome of control responses because regulatory environments can be quite diverse. Decisions are shaped by incentives, objectives, and attitudes toward risk, and these would be uncertain even if our understanding of natural systems were perfect. Nobody understands those systems perfectly, though, so a second layer of uncertainty must also be recognized. Taken together, these uncertainties can manifest themselves in three major ways. First, regulators are often averse to risk in their decision-making and concentrate on high-cost and extreme scenarios. Fear of making wrong decisions causes them to underemphasize the most likely outcomes or to take present day costs much more seriously than future costs. Either of these tendencies has implications for decision-making. In the literature about regulating invasive species, for example, Leung et al. (2002) argue for increased preventative action to reduce the threat to U.S. freshwater lakes. They estimate that preventing one species of invasive mussel moving into one lake would produce greater social and ecological benefit than the U.S. Fish and Wildlife Service spends on managing the invaders in all of the lakes in their jurisdiction. In this case, they argue an "ounce of prevention" is better than "a pound of cure."

Divergent utility functions and/or objectives of competing decision-makers also produce uncertainty in regulatory environments. In many cases, the need for regulation to encompass incommensurable objectives leads to what Ludwig et al. (2001) describe as "radical uncertainty"—even when consequences of action are predictable, objectives may be in conflict. Actions to reduce pollution loading in rivers in the Pacific Northwest region of the United States provide an example here—lowering levels of persistent pollutants has led to a population explosion in top predators from which disturbed river ecosystems may never recover.

Human demand for ecosystem function presents a third source of uncertainty. Human preferences for ecosystem functions change over time and space as economic and social circumstances change in unknown ways. The ultimate value to humanity of key functions may be infinite because of the interdependence of social and ecological integrity and continued existence, but some functions of nature are nonetheless more highly valued in particular societies, and these preferences change over time. Although it may be possible to observe historical changes in preferences for clean air and water, for example, Goulder and Kennedy (1997) argue that these changes provide no reliable guide either to future preference formation or to the cultural and social context within which the demand for ecosystem functions will arise. At the same time, however, even present day regulation of ecosystem functions is distorted by other interventions. Perverse subsidies for energy, water use, and agricultural commodities distort and create uncertainty in the regulation of environmental functions. Regulators act in social arenas where there may be preferences not only for the outcomes of regulation, but also for the social and political processes of decision-making. In institutional response, the legitimacy of their decision-making processes may be as important as the regulations that result.

4.3.2 Uncertainty in Institutional Responses to Ecosystem Protection

Institutional responses to threats to ecosystem services often involve a change in ownership or control of resources. In many instances, resources are privatized. In others, they are brought under government protection (or even ownership) because of perceived failures of private or collective management. Protected areas have effectively overturned previously held individual or common rights to resources, but this type of response can be limited by a number of uncertainties. There have been significant moves away from protected areas because of their perceived lack of legitimacy, particularly in the case of protected areas, which exclude previous users and even residents in these areas. As a result, the role of protected areas as a legitimate response is being reconsidered in some places, especially given the need for sustainable solutions that do not undermine social equity or impoverish and disadvantage poor rural communities in the developing world (see Brown 2002). Although they can be mitigated by clear and credible communication, the design and implementation of area protection face major uncertainties derived from three conditions: an incompatibility with the legitimacy of state appropriation; potential conflicts with other objectives of public policy and moral hazard; the lack of effective means of integrated implementation.

First, protected areas face uncertainty in conserving ecosystem services where there is a perceived lack of legitimacy of the de jure rights (rights in law). Regulations and rights to use resources may be incompatible with previous or de facto (rights in practice) management regimes. State appropriation of protected areas can therefore be a factor in the breakdown of traditional, usually communal, regimes of property rights and resource management (Bromley 1991). Indeed erosion of these systems of resource management has been shown to open the door to further environmental degradation, impoverishment, and demographic change. Moreover, expectations about what comes next after state appropriation can create additional uncertainty. For instance, the forestry sector in Nepal and the wetlands of Indonesia were once managed through local collective action institutions. State intervention led these institutions to unexpectedly allow open access because people expected further state appropriation (Bromley 1999; Adger and Luttrell 2000).

Second, uncertainty can be created by incompatibility with other policy areas. Perverse incentives in agriculture and other areas can, for example, undermine whatever responses are adopted for area protection. Sinclair et al (2002) find significant loss of bird diversity in agricultural land in the Serengeti compared to adjacent native savanna because of the reduction in insect abundance in the ground covering vegetation. Increases in agricultural land in the east African savanna habitats are not, however, being driven by agropastoral population growth, cattle numbers, or smallholder land use. Rather, the primary drivers are in the incentives to convert land by major landowners responding to agricultural policy. Homewood et al. (2001) demonstrate this result by differentiating between land cover change and its drivers in the Kenyan and Tanzanian parts of the Serengeti ecosystem.

Third, institutional responses involving changing property rights also lead to uncertainty if state resources are used to promote compliance with measures that may have been undertaken voluntarily. Agriculture and conservation policies in the United Kingdom have, for example, always been based on the primacy of private property. They are implemented through systems of incentives and compensation payments to private landowners. Areas such as Sites of Special Scientific Interest and others areas under the EU Habitats Directive are protected for a variety of functions and services. To conserve them on private land, owners are compensated for potential income rather than income actually foregone. Compensation for foregone income is estimated on the basis of prices for agricultural commodities that are inflated due to the workings of the Common Agricultural Policy in the EU member states. In other words, the perverse subsidies of the agricultural policy have further unintended consequences in making conservation payments more costly. Thus there is a significant moral hazard in such conservation responses based on the primary claims of private land (Bromley 1991).

4.3.3 Uncertainty in Institutional Responses that Engage Stakeholders

In recognition of the limitations in the traditional response options of controlling ecosystem services or changing the institutions of ownership, alternative approaches have emerged recently to integrate across response options. (See Chapter 15.) These alternative approaches often involve changing the basis of management to include wider sets of stakeholders. They aim to provide positive incentives for resource users and avoid the divergence between local and state objectives. There have been numerous attempts at sharing responsibility between regulators and resource users in fisheries, forestry, and other natural resource areas. In fisheries, for example, multistakeholder bodies like the U.S. Regional Fisheries Management Councils advise regulators on all aspects of ecosystem function and potential extraction rates (Brown et al. 2002; Berkes 2002). Alternatively, co-management institutional arrangements like the Australian Torres Strait Fisheries Management Committee involve sharing of power such that communities define their own management objectives. Either approach grants, in effect, user and ownership rights to local resource users and thereby allows them to develop sets of management rules. The hope is that these arrangements can resolve many of the resource conflicts that usually encumber the preservation of ecosystem functions (Bromley 1999).

There are uncertainties in these integrated multistakeholder responses. These include the potential for perverse incentive structures, incomplete or improper representation of stakeholders, and the inertia of governments in adopting co-management and, in effect, giving up their authority and power. Uncertainty in the sustainability of local collective action stems from the limitations of either state agency or local institutions to promote best practice. It is increasingly realized that simply allocating responsibility to local users is not necessarily a sufficient criterion for sustainability. Sustainable resource use requires a number of conditions. These include a favorable external environment such as appropriate technology and legal frameworks, a set of group and resource system characteristics such as defined boundaries and an identifiable set of stakeholders, as well as an agreed set of institutional arrangements that are easy to understand and enforce (Agrawal 2001). In the best cases, co-management overcomes the difficulties and limitations of both the government regulator and the local institution—the government agency provides the laws and the regulation of the external environment, while local institutions identify the legitimate stakeholders and enforce the rules (Berkes 2002). While effective monitoring and ex-post evaluation can help, significant risks and uncertainties involved in meeting the key criteria for sustainable management can remain.

Further uncertainty lies in the representation of stakeholders within any co-management arrangement. There are difficulties in "non-representation for contingent reasons" and "problems of the very possibility of representation" (Brown et al. 2002). Education programs can help, of course, but non-representation derives from inevitable bias in co-management in favor of the powerful and the articulate. Underlying ability and willingness and capacity to be heard and to articulate preferences are unevenly distributed across class, age, ethnicity, and gender. Other perspectives and interests, such as those of future generations and of the rights of ecosystems themselves, also suffer from the problems of the possibility of representation.

Much of the uncertainty in these response options derives from the unwillingness of regulators and government agents charged with conservation of ecosystem functions to embark on co-management and empowerment responses. Many environmental policy institutions fail to articulate a reason why all policy dialogue is presumed to be at the national level while the institutions of regional and local levels are assumed to be part of an implementation process (Bromley 1999). In many cases, national agencies are unwilling to share responsibility and power, even when they also perceive empowerment responses as means of reducing costs of enforcement and regulation. Further barriers to effective adoption of participatory and co-management arrangements in this area include a lack of legal and constitutional framework, a lack of trust in representation, and the resource cost of actually undertaking participatory management (for example, Tompkins et al. 2002). In terms of cost, despite perceptions to the contrary, co-management tends to be equally if not more resource intensive than traditional management, even when successful (Singleton 1998).

4.3.4 Comparing Effectiveness and the Case for Integration

Governance issues are the key to handling all of these uncertainties, both in reconciling values and in coping with surprises and unexpected consequences of interventions. Convergence and synergies in policy responses can be promoted through recognition of the legitimacy of processes alongside their efficiency, effectiveness, and equity. Legitimacy relates to the extent to which decisions are acceptable to participants on the basis of who makes and implements the decisions and how. Legitimacy can be gained as well as compromised through the process of making environmental decisions. There are no universal rules for procedures that guarantee the legitimacy of policy responses because cultural expectations and interpretations define what is or is not legitimate. When integration occurs, as argued in Chapter 15, the added legitimacy of horizontal and vertical response solutions increases the effectiveness of response for a number of reasons. First, including stakeholders gives greater sense of control over resources and hence reduces the overall cost of enforcement of protecting rights to the resource. Second, networks of stakeholders have value for other reasons, particularly in handling unforeseeable pressures and stresses on the ecosystems. Third, integrated responses lead to perceptions of greater value from the ecosystem services. (See Box 4.3.)

When the dynamics of ecosystem functions and the costs of amelioration are known, market-based policy responses have some advantage over regulatory or other forms of responses, primarily related to their efficiency or cost effectiveness in changing behavior among the agents causing loss of ecosystem functions. Regulation of the use of ecosystem function may inadvertently be

BOX 4.3

The Value of Stakeholder Perceptions in Decreasing Dissatisfaction with Response Impacts in Watershed Management

Stakeholder confidence in having access to benefits can determine their estimation of the value of watershed ecosystem services. This confidence can be hard to evaluate, but is necessary to increase the likelihood that the chosen response can be effective and gain stakeholder acceptance of the underlying processes. Willingness-to-pay is one method of decreasing uncertainty associated with stakeholder values. Some studies (for example, Koundouri, et al. 2003) have found a higher willingness-to-pay for responses about protection of wetlands along an international bird migration route under scenarios in which all of the relevant stakeholders participate (in this case, all countries along the migration route). Similarly, Porto et al. (1999) reported that domestic water users in Brazil (where nationwide river basin management policies had been adopted) were willing to pay more for water if the revenue from water fees were invested in the basin where the funds are generated and if users were able to participate in decisions about how the revenue was to be spent. Both of these examples speak to the sensitivity of contingent valuation results to the ownership ("property rights") assumptions of the participants.

O'Connor (2000) has argued that differences in willingness-to-pay often depend on the protection mechanism suggested, and whether it was regarded as fair and effective. This implies the need to develop effective institutional arrangements to control access, without which economic value cannot be captured. They are also a source of tremendous site-specific variation that needs to be considered to develop effective Payment Arrangements for Watershed Ecosystem Services (PWES) initiatives. Property rights, which define rights to particular streams of benefits as well as responsibilities for their provision, are critical because they determine whether those who pay the costs of management practices have access to any of the benefits, and therefore, see an incentive for conservation. Institutional arrangements also refer to relationships established among buyers, sellers, and intermediary organizations so as to reduce transaction costs. This evidence suggests that integrating stakeholder perceptions about response options can reduce uncertainty that might arise by ignoring key aspects of response options.

cost-effective when first designed, but market-based responses (of which taxes or tradable permits are the most common) generate dynamically efficient patterns of incentives on behavior over time. But these stylized arguments do not hold in the face of uncertainties described in earlier sections. Where the impacts of loss of ecosystem function are unknown, regulators and agents choosing between different market-based response options can underestimate or overestimate the necessary level of action and lead to both inefficient policy response and to the risk of nonlinear reorganization of ecosystem function (though the errors of over- or under-estimation need not be symmetric in magnitude or significance).

4.3.5 Unintended Consequences

History demonstrates the importance of attempting to evaluate, on as broad a scale as is feasible, the possible consequences of implementation of specific strategies, policies, and measures designed to protect and enhance ecosystem services. Unintended consequences associated with implementation of the original intervention can result in new significant problems that replace or compound the original issue. The capacity to respond effectively to threats to ecosystem services is dependent on the ability to foresee and anticipate surprise, as well as to deal with unexpected consequences of actions (Kates and Clark 1996). A systematic and thorough assessment of the dynamics of a particular issue (including the risks and benefits of doing nothing), the extent to which there are key uncertainties, and the magnitude of any potential adverse impacts can reduce the probability of unintended consequences (Ebi et al. 2005).

Without an assessment of the potential consequences of an intervention, beneficial steps may be inadvertently presented as cures. The determination of possible consequences of policies and measures should be across all relevant sectors and should consider current and potential future consequences. All implemented actions should include an on-going program for evaluation of both the program's effectiveness as well as any adverse consequences that could arise. Otherwise, recognition of a problem will be delayed, which can have adverse impacts on human well-being and the health of ecosystems. Two examples illustrate the importance of this issue.

In northern Ethiopia, micro-dams have been constructed to increase the availability of water for irrigation. After construction, Ghebreyesus et al. (1999) conducted a survey on the incidence of malaria (90% *Plasmodium falciparum*—the deadly strain of malaria) in at-risk communities close to dams and in control villages at similar altitudes but beyond the flight range of mosquitoes (primarily *Anopheles arabiensis*). The results showed that the micro-dams led to increased malaria transmission over a range of altitudes and seasons; the overall incidence of malaria for villages close to dams was 14.0 episodes per thousand child-months at risk, compared with 1.9 episodes in the control villages. These results could have been anticipated based on knowledge of the ecology of malaria, and appropriate measures to address the probable malaria problem could have been included in the development program. Including the health sector in the evaluation of the trade-offs of and responses to this irrigation development program could have prevented many children from suffering and dying from malaria.

A further example of unanticipated surprise is the on-going issue of the consequences of the installation of tubewells in Bangladesh and India to provide the population with access to clean drinking water. Beginning in the 1970s, tubewells were widely installed in an effort to provide a "safe" source of drinking water to populations experiencing high morbidity and mortality, especially among children, from water-related diarrheal diseases. At that time, standard water testing did not include tests for arsenic and it was not known that the groundwater accessed by these wells has naturally occurring high concentrations of arsenic. Unfortunately, it is still not a standard or routine test for rural water supplies. However, arsenic in drinking water was recognized as a problem prior to the installation of tubewells, so an evaluation program established at or soon after the installation of tubewells would have identified the problem much sooner. The U.S. Environmental Protection Agency set the current standard of 50 parts per billion in 1975, based on a Public Health Service standard originally established in 1942.

Possibly 30 million out of the 125 million inhabitants of Bangladesh drink arsenic-contaminated water (Hoque et al. 2000). Health consequences of exposure range from skin lesions to a variety of cancers. Because of the latency of arsenic-related cancers, it is expected that morbidity and mortality from historic and current exposures will continue for approximately 20 years after exposures are discontinued. Although a number of international initiatives are under way to help resolve this problem, solutions will likely take a decade or more. The installation of tubewells to reduce the burden of diarrheal diseases offers a variety of lessons for how to avoid unintended consequences of strategies, policies, and measures; more are likely to be learned as the resolution of this problem unfolds over time (Ebi et al. 2005). This situation clearly illustrates the risk of undertaking massive intervention programs without a determination of benefits and risks. Acute problems, such as access to safe drinking water, create pressure to find quick solutions. Programs should evaluate short-term responses while finding long-term solutions within the context of the underlying causes. Issues of scale and differences between absolute versus relative risks are imbedded in this lesson. A solution associated with a small risk implemented on a wide scale (such as the installation of tubewells) may have far more significant adverse health impacts than a solution with a larger risk implemented on a small scale.

A further lesson from the Bangladesh example relates to the process of implementation of interventions. Because tubewells were viewed as a technological fix, installation was implemented on a broad scale as rapidly as possible, not in an incremental or staged fashion that would incorporate regular evaluation of success (Ebi et al. 2005). Flexible and responsive approaches are needed in which new information and experience is properly evaluated and then used to appropriately modify interventions. Because arsenic contamination of drinking water is a classic second-generation problem, with the contamination discovered many years after the initial tubewells were installed, taking a staged approach to implementation could have had a much different result. The arsenic problem also reinforces the problem of reliance on a single or "silver bullet" technical solution to a problem instead of taking an integrated, multidisciplinary approach (Ebi et al. 2005).

4.4 Methods for Analyzing Uncertainty

Many techniques have been developed to include uncertainty in the evaluation of the relative efficacy of the various options that might be available to a system as it tries to respond to an external stress. Morgan and Henrion (1990) provide a concise overview of how to select a method for analyzing uncertainty. Presented here is a a quick summary of some of the more popular approaches. Since the MA has adopted a scenario-based approach, this section devotes most of its attention to scenarios, but other approaches are briefly summarized, with reference to their role in supporting scenario analysis.

4.4.1 Scenarios

The typology of uncertainties presented earlier in this chapter raises fundamental questions about our ability to foresee the impacts of particular response options, including both intended and unintended effects. This is closely related to our general uncertainty about what the future might hold. For many reasons, there has been an increasing use of scenarios to address complex issues involving socioecological systems and to explore how systems might respond to changes. The MA, for which both global and sub-global scenarios have been developed, is no exception. Thus it is important to understand how scenarios can and have been used to help us cope with the issue of uncertainty.

Berkhout and Hertin (2002, p. 39) argue that the future ''needs to be thought of as being emergent and only partially knowable.'' Our uncertainty in knowing the future in general and, more specifically, the impacts of response options stems from three distinct types of indeterminacy: ignorance, surprise, and volition (Raskin et al. 2002). *Ignorance* refers to limits of scientific knowledge on current conditions and dynamics and is thus closely related to what this chapter has called model, calibration, prediction, and projection uncertainty. It implies that even if socioecological systems were deterministic in principle, our understanding of their future would still be uncertain. This is of particular concern for systems exhibiting chaotic behavior, where even slight changes in initial conditions can lead to dramatically different outcomes. Uncertainty due to ignorance is further compounded by *surprise,* the uncertainty due to the inherent indeterminism of complex systems that can exhibit emergent phenomena and structural shifts.

Finally, *volition* refers to the uncertainty that is introduced when human actors are internal to the system under study. Berkhout et al (2002) highlight the fact that because of conscious choice, the assumption of continuity made in the natural sciences is not applicable to social systems, implying that novelty and discontinuity are normal features of these systems. This compounds the types of uncertainty noted above, but is also a key aspect of what was referred to as contextual uncertainty. Moreover, the very process of ruminating on the future can influence these choices. Through this reflexivity, people work either to create the future they desire or to avoid that which they find objectionable.

As defined by Raskin et al. (MA *Scenarios,* Chapter 2), scenarios are ''plausible, challenging, and relevant stories about how the future might unfold that can be told in both words and numbers. Scenarios are not forecasts, projections, or predictions.'' At best, scenarios might be considered conditional projections in that particular outcomes ''reflect different assumptions about how current trends will unfold, how critical uncertainties will play out, and what new factors will come into play'' (UNEP 2002; Robinson 2003). It is important to note that scenarios are not merely alternative runs of a model or a sensitivity analysis, although these can be important for looking at uncertainty within scenarios, as noted below.

If done properly, particularly when formal quantitative models are used, all of the underlying assumptions are made explicit in a scenario. Certain assumptions will take precedence, however. These represent the primary axes along which the scenarios will differ and are generally related to contextual issues. These fundamental differences provide the ''logic'' behind the individual scenarios and the scenario exercise as a whole (Schwartz 1996). The dimensions can be as simple as high versus low economic growth or high versus low population growth, but they can be much richer, reflecting amalgamations of more than one driving force, critical uncertainty, or new factor. A well-known example of this is the Special Report on Emissions Scenarios process of the IPCC, in which four scenario families were distinguished based upon two principle axes—degree of globalization versus regionalization and degree of emphasis on economic growth versus issues of environmental and equity (IPCC 2000). Less explicit framing of sets of scenarios, where multiple dimensions were considered but all combinations were not fully enumerated, can be found in the work of the Global Scenarios Group (Raskin et al 2002) and UNEP (2002). In these cases, the emphasis was on the most interesting and coherent combinations, recognizing that not all are plausible or worth exploring.

The establishment of a framework distinguishing different scenarios emphasizes the differences between scenarios and represents the principle way in which they have been used to address the issue of uncertainty. Looking deeper, though, it is clear that a scenario cannot be defined fully by one or two key assumptions. The other key driving forces and critical uncertainties must also be fleshed out. In doing so, it may be clear that other assumptions hold particular significance for the issues of concern. For example, in one of the IPCC SRES scenario families, a third axis related to energy technology was introduced in order to examine more explicitly what was considered a fundamental assumption related to the issue of greenhouse gas emissions (IPCC 2000). Furthermore, specific assumptions expressed in a scenario narrative can be consistent with a variety of quantitative representations. With respect to assumptions about particular driving forces, this relates to what was termed earlier as projection uncertainty; with respect to particular system relationships, it is more akin to model uncertainty. Finally, estimates of the results of particular assumptions, whether these are determined by qualitative reasoning or formal quantitative models, are subject to the other forms of uncertainty discussed above.

Although this has not necessarily been a key emphasis in scenario development, various strategies have been used to address this issue of within scenario uncertainty. In the IPCC SRES process, in addition to the particular case of different assumptions about energy technology in one scenario family, six modeling groups provided quantitative representations of the four primary scenarios. This resulted in the development of a total of 40 scenario realizations. Based on this, many of the key results, such as total greenhouse gas emissions and atmospheric concentrations, are presented as a range of estimates for each scenario family, rather than as a single trend line. In the case of the United Nations Environment Programme GEO3 scenarios, the original quantification of the four storylines was accomplished using a combination of modeling tools, with each tool taking responsibility for specific outcomes. Only afterwards has an analysis been undertaken to compare the results for consequences that were estimated by more than one tool (Potting and Bakkes, forthcoming). Finally, the Global Scenarios Group defines three classes of scenarios, each with two variants (Raskin et al 2002). These variants, however, differ to such a degree that they more truly reflect distinct scenarios, pointing out what can be a fuzzy boundary dividing what is called uncertainty across versus within scenarios.

The scenarios discussed above have all been undertaken at a global scale, with a limited amount of regional and local disaggregation. Within these scenarios, a wide range of variation at lower scales, in both driving forces and outcomes, is glossed over. At the same time, they are usually done over a long time period, with a large degree of smoothing of variability over shorter time periods. Finally, the elaboration of key actors is generally quite limited. As demonstrated in Strzepek et al. (2001) and Yohe et al. (2003), downscaling scenarios, both narrative and numerical, introduces additional uncertainties that must be recognized, but not necessarily probabilistically. In this situation, using a collection of scenarios to span a range of ''not-implausible'' futures can be useful in evaluating the relative robustness of alternative responses. (See Box 4.4 for a discussion of the development of the MA scenarios.)

4.4.2 Alternative Methods for Accommodating Uncertainty

A variety of other approaches can bring uncertainty to bear on response evaluations. Sensitivity analysis can, for example, be employed to compute the effects of changes in specific parameterizations and/or assumptions on important state variables and to construct measures of the relative importance of various sources of uncertainty. Sensitivity analysis can, therefore, be employed to explore the degree to which various alternatives might support scenarios that portray fundamentally different futures. Scenario trees like the SRES alternative story lines can thereby be created and differentiated not only by differences in their driving variables, but also by differences in their social, economic, political, and scientific contexts. More elaborate explorations of scenario trees sometimes attach probabilities to the various branches, but this can be dangerous; indeed, the authors of the SRES futures insist that no storyline is any more likely than another. When probability distributions for driving variables can be quantified, though, probabilistic portraits of wide ranges of possible outcomes for state variables can be produced in support of expected value

BOX 4.4

Uncertainty and Scenarios in the Millennium Ecosystem Assessment

The developers of the MA global scenarios and scenarios within the sub-global assessments have had to deal with the question of differences between and uncertainty within scenarios. These issues are discussed in much greater detail in other MA volumes, including *Scenarios* (Chapter 6), *Multiscale Assessments* (Chapter 9), and several sub-global reports. This box provides a brief summary of some of the key issues related to how uncertainty has been addressed in these exercises.

Three primary sources of information were used to help determine the primary axes along which the MA global scenarios differ: the specific needs expressed by the primary audiences for the MA; the insights drawn from interviews with leaders in nongovernmental organizations, governments, and businesses from around the globe; and explorations of ecological management dilemmas. In the end, the choice was made to focus on different possible strategies for achieving a sustainable and diverse future. One of the scenarios, called ''Order from Strength,'' represents one plausible path for global breakdown wherein no clear strategy is pursued. In ''Global Orchestration,'' by way of contrast, the focus is primarily on fair global policies. ''Adapting Mosaic'' focuses on local and regional flexibility, and ''TechnoGarden'' highlights technological innovation.

Within the sub-global assessments, a variety of uncertainties were articulated in the development of distinct scenarios, including uncertainties in both exogenous drivers and endogenous behavior. Two of the most commonly cited exogenous drivers were the nature of governance at higher scales and regional or international markets for products produced within the sub-global site. Among the most common endogenous uncertainties were the future of local institutional arrangements and the evolution of social attitudes toward the environment.

The development and presentation of the global scenarios has tried to address uncertainty in both the narrative storylines and their quantitative underpinning. There was an effort to be open and consistent in communicating issues of uncertainties in the global narratives. This was done, in part, by utilizing the scheme developed for handling uncertainty in the IPCC assessments, where particular expressions were associated with a level of, generally subjective, confidence. Also, the scenario developers explored how uncertain events could cause one scenario to branch into another.

Looking at the quantitative underpinning, as with the United Nations Environment Programme GEO3 scenarios, a number of different modeling tools were used to provide numerical estimates of key input and output indicators for the scenarios. This is somewhat different from the case for the IPCC emission scenarios, where each of the different modeling tools provided an independent and complete quantitative picture of the scenarios. In the MA, a process of harmonization was undertaken to ensure that the different tools used consistent sets of drivers. Specific tools were identified for calculating output indicators of ecosystem services and human well-being. The process included detailed assessments of the ability of different tools to forecast the indicators of interest. This usually resulted in a single tool for each indicator, but in particular cases different tools were used for different regions. Finally, the resulting estimates derived from the various tools were reviewed to assess their uncertainties and the potential influence these might have on the scenarios.

The scenarios in the sub-global assessments are much less clear about how they dealt with the question of uncertainties within individual scenarios. Most of the sub-global scenario exercises focused on the development of qualitative scenarios that rely solely on narratives, with the use of quantitative models being the exception. This limited the degree to which they were able to do the kind of sensitivity analysis seen in the global scenarios.

Finally, the issue of the development of multilevel scenarios, and the uncertainties inherent in doing so, is an issue that is more particular to the scenarios in the sub-global assessments. This development of multilevel scenarios goes beyond the incorporation of driving forces from higher scales, which has been present in all of the exercises; it also includes coping with the problem of actually linking scenarios at one scale to those at another, which has been much less common. Two approaches can be recognized here. The first is to embed the scenarios in the sub-global assessments in the MA (or other) global scenarios. This has been explored in the Portugal sub-global assessment, and may be more common in the later-starting sub-global assessments, as the MA global scenarios are now more developed. The other approach is to develop multiscale scenarios within a single sub-global assessment; this has been explored in the southern Africa sub-global assessment. The advantages and difficulties with both of these approaches, including issues of uncertainty in the linkages and feedbacks across scales, are just now being explored; the MA work is a productive first step in this process.

It must be noted, though, that the global scenarios are using elements from the sub-global narratives to add texture to their stories. Furthermore, particular issues of uncertainty related to scale arise in global scenarios in terms of modeling cross-scale effects and the presentation of quantitative results. Since the different models vary in their geographical breakdown, many of the quantitative results are presented at a highly aggregated scale. This poses a particular problem in the form of the loss of information about variability, which can undermine the confidence attributed to the conclusions drawn from the scenarios.

calculations of associated consequences and/or analyses of the robustness of various responses.

Finally, it is sometimes possible to provide estimates of response surfaces—empirically calibrated reduced-form relationships between driving variable and state variables—which can summarize the results of a large number of scenarios and/or alternative futures. These are particularly valuable when complex models are expensive (in time and money) to run; and they can also be especially useful in completing scenario interactions when the researcher is focusing attention on another part of the problem. A researcher interested in the detailed impacts of climate change on the likelihood of flooding might, for example, use a response surface representation of the energy sector and how it would respond to alternative population futures and different mitigation strategies in constructing the requisite connection between economic activity and flooding without building an elaborate energy model (Yohe and Strzepek 2004).

4.5 Decision Analytic Frameworks under Uncertainty

Every framework designed to support decisions about response options must be able to accommodate uncertainty in its application; their diversity is outlined in the MA framework volume (MA 2003, p. 196), with the advantages and disadvantages of each identified. For present purposes, it is sufficient to note that some frameworks have evolved to the point where uncertainty can be brought on board even if they were initially developed in deterministic environments. Others, though, were created with the explicit purpose of incorporating uncertainty into their structures. This section reviews how a few of the most important approaches to response decisions accomplish the proposition that uncertainty is ubiquitous.

4.5.1 Cost–Benefit Frameworks

Cast into a world of uncertainty, applications of the cost-benefit approach to selecting and designing response options require understanding of the range of possible outcomes in order to provide a full accounting of (potential) net benefits. The fundamental decision steps underpinning CBA are summarized in Hanley et al. (1997), among other places:

- derive estimates of costs and benefits,
- rank initiatives from high to low in terms of net benefits, and
- pursue as many initiatives (with positive net benefits) as possible within resource constraints.

If analysts can assess probabilities (even based on subjective judgments) across a range of outcomes that accommodate the full range of possibilities, then expected net benefits can be the basis of decision rankings. If analysts cannot assess probabilities, they can still assess robustness—the range of possible outcomes for which net benefits are positive—and perhaps identify critical thresholds for critical sources of uncertainty along which net benefits turn from positive to negative.

It is important to recognize from the outset that the cost-benefit approach to decision-making ignores the distribution of costs and benefits—an omission that can bring contextual uncertainty to the fore. Programs or projects are judged to be attractive as long as total (expected) benefits exceed total (expected) costs regardless of who bears the cost and who enjoys the benefit. Chapter 5 illustrates this point as it considers the range of costs and benefits that might be attributed to projects designed to restore or rehabilitate ecosystems. It highlights the potential need for compensating side-payments; especially if stakeholders are involved in restoration decisions, these compensation schemes add another layer of contextual uncertainty.

Choosing the correct discount rate is also an enormous issue when costs and benefits extend into the future because discounting can render long-term future effects almost irrelevant in the calculation of discounted net benefits. IPCC (1996) spent an entire chapter making a distinction between descriptive and prescriptive discounting for long time horizons—a distinction whose fundamental content is perhaps best exhibited by the Ramsey rule for inter-temporal optimization. According to this rule, intertemporal utility would be maximized if per capita consumption at the end of any year were discounted relative to consumption at the end of the previous year by the sum of a pure rate of time preference (a measure of impatience in consumption) and the product of the elasticity of the marginal utility of consumption (the rate at which utility changes as consumption grows) and the rate of growth of per capita consumption over the year in question.

Many analysts find the argument for including the second term convincing. Indeed, they commonly work with logarithmic utility functions for which the elasticity of marginal utility is equal to unity and the second term is simply the rate of growth of per capita consumption. The key to their conviction is that wealthier generations who will inhabit the future will attach smaller utility values to marginal changes in per capita consumption. Meanwhile, most attempts to measure the pure rate of time preference have focused attention on individuals' decisions over time, and those decisions do not shed much light on how society should weight the relative welfare of successive generations (Lowenstein 2002). The IPCC (1996) noted that many scholars think that the pure rate of time preference should be set at or close to zero when costs and benefits are extended well into the future. Weitzman (1998) reinforced their convictions by noting that low rates dominate expected discounted value calculations when they extend deep into the future; recently proposed hyperbolic approaches similarly guard against overly enthusiastic discounting.

Short-term calculations are less problematic. Markets are driven by private agents who discount the future at the return to private capital, that is, the opportunity cost of financial capital. If capital markets were perfect, then this discount rate would match the (short-term) pure rate of time preference. Capital markets are not perfect, of course, so the rate of return to private capital can exceed the pure rate of time preference for risky responses to market stresses (add a risk premium) or because the return to private capital is subject to (corporate) income taxation. In either case (and many others), the appropriate discount rate simply adds the effect of whatever distortion exists (such as risk or taxation) to the pure rate of time preference. Following Arrow and Lind (1970), Ogura and Yohe (1977) demonstrated that the marginal return to government investment (that is, the rate at which future costs and benefits of such an investment are discounted) could be allowed to fall below the pure rate of time preference if public investment would complement private investment and private capital markets were distorted by taxes. Their result simply recognizes that lower discount rates encourage investment (by making it more likely that discounted expected net benefits are positive) and thereby diminish the efficiency losses caused by existing economic distortions.

When the intensity of various initiatives can be modulated, the level that maximizes net benefits equates expected marginal cost with expected marginal benefit. Tol (2003) has observed, however, that marginal costs or marginal benefits may not be well defined under all plausible futures even if benefit and cost measures are, themselves, finite. In such cases, the paradigm breaks down. (See Box 4.5 for a discussion of issues of timing and uncertainty.)

Nonetheless, optimization techniques can inform not only how a policy intervention might be targeted, but also how it might be designed. Smit et al. (2000) emphasize the necessity, in the context of adaptation, of clearly understanding ''Who is responding to what?'' and ''What do they know when they have to 'pull the trigger'?'' Weitzman (1974) showed why they were right to do so. He envisioned a policy-maker who, on the basis of limited information, must choose between price- and quantity-based interventions in an effort to hold expected output at the optimal level. Economic agents could, however, respond to the price-based intervention by adjusting their outputs in response to changes in their environments that would materialize only after the policy intervention had been designed. Their outputs would vary under the price control, but they would be fixed under the quantity-based intervention. The price control would therefore increase expected private benefit to agents (otherwise, they would not adjust their outputs), but the associated variable output would also cause expected social cost to rise (if marginal social cost were rising). It turns out, therefore, that the policy design choice was critically dependent upon the relative size of these two increases.

4.5.2 Risk Assessment

The classic risk assessment approach to, for example, evaluating health or ecological risks, adopts a four-step risk paradigm:

- identify the hazard (could a particular agent or activity harm humans, animals, or plants?);
- assess the exposure-response relationship (to what degree can exposure to a hazard cause a response that could be harmful?);
- assess the level of exposure (to what degree are humans, animals, or plants exposed to the hazard); and
- characterize the associate risk (a reflection of the probability exposure times the associated consequences).

Each step involves a policy judgment; for example, the choice of one dose-response model over another is a ''science-policy'' choice (NRC 1994, 1996; Presidential Commission 1997).

The limitations of risk assessment should be recognized and understood. The underlying assumptions may, first of all, limit its applicability to complex environmental problems (Bernard and Ebi 2001). The assumption that a defined exposure to a specific agent causes a specific adverse outcome for identifiable exposed populations can, in particular, be questioned in many contexts. A health outcome may be distinctive and the association between immediate cause and its impact can be fairly clearly determined, but most outcomes associated with environmental exposures have many causal factors, which may be interrelated. These multiple, interrelated causal factors need to be addressed along with relevant feedback mechanisms in investigating complex disease/exposure associations, because they may limit the predictability of the health outcome and even the ability to estimate the degree of uncertainty in any risk estimation (Bernard and Ebi 2001).

While early risk assessments focused narrowly on determining the probability of harm, the general approach is evolving and becoming more relevant to complex environmental problems (Bernard and Ebi 2001). Recent assessments are considering social, economic, and political factors, and stakeholders are now expected to be involved throughout the risk assessment process to ensure that the characterization of risk addresses a broad range of concerns. Especially in light of increasing complexity, it is extremely difficult to make detailed and accurate assessments of risks

BOX 4.5

Cost–Benefit Analysis in the Presence of Uncertainty, Irreversibility, and Choice in Timing

Conventional theory and practice holds that a positive expected net present value (NPV) returned by a cost-benefit analysis tells the investor that it might be prudent to go ahead with an investment. In reviewing the applicability of CBA to natural systems, Aylward et al. (2001) recall a warning by Dixit and Pindyck (1994) in light of two hidden assumptions in the CBA. In the first case, the investment is reversible insofar as the investor can exit from the investment and recover the expenditure if the future (for example, future market conditions) turns out worse than expected. In the second case, the NPV rule assumes that there is no choice of timing if the investment is irreversible; that is, the investment is a "now or never" proposition. Most investment decisions do not fulfill either of these assumptions. Indeed, irreversibility and the possibility of postponing investment are very important characteristics of investments faced by firms and by society.

The value of delaying investment is equivalent to holding an "option" to invest the right, but not the obligation to invest, and thus can be called an option value. When an irreversible investment is made, the investor exercising the option effectively gives up the opportunity to wait for additional information (to reduce the uncertainty over the present worth or timing of the expenditure). This is the central point made by Dixit and Pindyck (1994): the opportunity cost of making a decision to go ahead with the investment is the loss of an option value. As a result, the NPV rule needs to be reworked so that the decision to invest is taken only when the benefits of the investment exceed the standard costs of investment *plus* the value of keeping the option alive. Dixit and Pindyck also show how the opportunity cost represented by the value of an option to invest can be very sensitive to uncertainties. Given that the growing literature on these options values shows that they can "profoundly affect" the decision to invest, they argue that these uncertainties may explain more of the variation in investment behavior than other variables such as discount rates.

The application of the theory of investment under uncertainty and irreversibility to natural systems (dams and water resources development, for example) is novel at this stage. Further investigation is needed to determine the applicability of these ideas to the project planning and evaluation process. Still, it seems likely that at least the insertion of a qualitative discussion and analysis of different alternatives in this regard may be useful at an early stage in the screening and ranking of projects. Indeed, it is possible to argue that stakeholder discussion of different scenarios for water and energy resources development should include these issues in an explicit fashion, given that they may have considerable bearing on the CBA outcomes.

In terms of specific areas for further investigation, it would be worth considering the extent to which, in practice, the passage of time is likely to reduce (or to increase) markedly the uncertainty about future values of the irreversible investments and divestitures associated with different options, particularly the environmental and social impacts. Attention should be paid to examining how the costs and benefits of investments may differ in terms of irreversibility, uncertainty, and timing. The objective here would be to see whether the different components of the alternatives under consideration are likely to have the same characteristics in this regard and thus can be bypassed, or whether important differences between alternatives are expected and should be accounted for in the decision process.

and hazards because of profound uncertainty in both the probability of an event occurring and the scale and nature of its consequences. These uncertainties may arise from a variety of factors (WHO EUR 1999), including:

- a lack of (credible) data in many situations;
- complexity in the interactions between humans and the environment, which typically means there are many possible causes for any adverse effect;
- complexity in space and time that makes it doubly difficult to establish causal connections;
- synergistic and/or cumulative effects that muddle our understanding of the combined effects of toxicants;
- the likelihood that hazards will appear from unpredicted sources; and
- diversity in the susceptibility to exposure across populations due to genetic, social, or environmental factors.

If a risk assessment fails to explicitly address these issues, it may give the illusion of an objectivity that is not justified.

4.5.3 Multicriteria Analysis

Issues derived from conflicting interests in the management of a given resource pose particular problems, especially when distributional implications are to be considered. Multicriteria analysis and its variants are often the formal framework of analysis used to decide among various response options under these circumstances. Formal MCA can trace its roots to Pareto at the end of the nineteenth century. In the 1970s, the development of multiobjective maximization methods permitted widespread application of quantitative MCA, especially in the management of water resources and (more recently given the advent of GIS) land-use planning. Multicriteria analysis depends on completing a number of concrete steps:

- identifying objectives,
- identifying options for reaching these objectives,
- identifying evaluation criteria,
- analyzing options against those criteria,
- making choices based on those analyses, and
- evaluation and feedback.

MCA's explicit recognition of a multiplicity of objectives and evaluation criteria gives it a potential advantage over economic paradigms based on cost, benefit, and efficiency in identifying sources of vulnerability to uncertainty and even to ignorance. Using the framework outlined above, it is possible to discover uncertainty in objectives, unexplored options, incomplete evaluation criteria, ignorance about system properties, and volatile rules of choice.

All of this complexity comes at a price, however. In allowing the sources of uncertainty to include ignorance and the incomplete representation of evaluation criteria and available options, practitioners of MCA usually assume, at least implicitly, that the objectives being considered, the means for reaching them, and the systems from which services are being derived are independent in time, space, and consequence from other questions and decisions regarding the interaction of natural and social systems. In making this assumption of independence, a large number of concerns about path dependency, cross-scale effects, and cumulative impacts can be missed entirely. (See Box 4.6.)

BOX 4.6

Scale Uncertainty in Multicriteria Analysis

Even if biodiversity patterns from place to place could be estimated well, uncertainty would remain in society's valuation of biodiversity relative to other needs. The application of MCA to explorations of biodiversity trade-offs is consistent with the notion that economic decision tools are limited in assessing responses for ecosystem services that are not traded in markets and where the values associated with them are not utilitarian in nature.

Faith (2002) illustrated how uncertainty might be reflected in multicriteria analyses. He considered, for example, a trade-off between devoting land to biodiversity conservation or other uses (for example, forestry production). The best outcome for a region could be found along a deterministic budget constraint by imposing a biodiversity target, but uncertainty may be addressed by sensitivity analysis. More specifically, analysis of trade-offs in Australia showed how some areas were always (or, alternatively, never) allocated to biodiversity conservation regardless of the relative weighting of various criteria within the biodiversity target.

Faith (2002) also calculated trade-offs under two scenarios for Papua New Guinea. In one case, he assumed no land-use constraints and concluded that that about 85% of the study's biodiversity target could be achievable at a very low cost. A second case represented a scenario in which areas already having some degree of high land-use intensity were assumed to be lost to biodiversity conservation. The capacity for cost-effective conservation was dramatically reduced. Indeed, the cost for the same conservation achievement level had more than doubled. Scenarios of this sort can be valuable tools with which to incorporate uncertainties into decisions about regional biodiversity trade-offs.

4.5.4 Precautionary Principle and "Safe Stopping Rules"

The precautionary principle is an approach used by policy-makers in which they consider taking action to protect a population from potential hazards with serious or irreversible threats to health or the environment before there is strong proof that harm will occur. In essence, the precautionary principle prescribes how to bring scientific uncertainty into the decision-making process by explicitly formalizing precaution and bringing it to the forefront of the deliberations (Marchant 2003). It posits that significant actions (ranging from doing nothing to banning a potentially harmful substance or activity, for instance) may be justified when the degree of possible harm is large and irreversible. Many factors influence these deliberations, including an assessment of the possible severity of the potential harm and the degree of scientific uncertainty associated with that assessment.

The application of the precautionary principle to environmental hazards and their uncertainties began with the Swedish Environmental Protection Act of 1969, with further elaboration in the German Clean Air Act of 1974 and the 1985 report on the Clean Air Act (Kheifets et al. 2001; Boehmer-Christiansen 1994; EEA 2001). Since the 1970s, the precautionary principle has been incorporated into over a dozen international environmental agreements, expressly incorporated into the legal framework of the European Union, and adopted into the domestic laws of numerous nations (Marchant 2003). This principle featured in the 1992 Rio Declaration on Environment and Development as Principle 15 (UN 1993): "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

Tamburlini and Ebi (2002) report that the European Commission's decision to ban beef from the United Kingdom represents a recent and dramatic application of the precautionary principle with a view to limiting the risk of transmission of bovine *spongiform encephalopathy.* The European Court of Justice ruled that this decision was justified by the seriousness of the risk and the urgency of the situation. The Commission did not, the Court ruled, act inappropriately in adopting a decision on a temporary basis pending improved scientific information. Its actions followed procedures approved in a communication on the precautionary principle authored by the Commission in February of 2000 (CEC 2000), which included the following guidelines for adopting measures on the basis of the precautionary principle:

- tailoring the measure to a chosen level of protection;
- applying the measure without discrimination (that is, treating comparable situations similarly);
- confirming that the measure was consistent with similar measures already taken;
- examining the potential benefits and costs of action or lack of action (including, where appropriate and feasible, an economic cost-benefit analysis);
- constructing review mechanisms by which new scientific data could be brought to bear on timely re-evaluation; and
- assigning the responsibility for producing the scientific evidence necessary for a more comprehensive risk assessment.

In this definition, the precautionary principle is "risk-oriented" in that it requires evaluations of risk that include cost and benefit considerations (Tamburlini and Ebi 2002). It is clearly intended for use in drafting provisional responses to potentially serious health threats until adequate data are available for more scientifically based responses. It also can be applied when there may be undue delay in the regulatory process.

The application of the precautionary principle does not mean that a scientific approach is not required. Nor does it mean that critical attributes of the risk can be ignored; these include irreversibility, magnitude of possible consequences, the probability of occurrence, the amount and type of uncertainty associated with the risk, societal benefits of the risk-creating activity, difficulty and costs of reducing risk, potential alternatives to the risk-creating activity, potential risk-risk trade-offs (that is, the degree to which proposed solutions create new risks), and public perceptions of the risk (Marchant 2003).

Proponents of the precautionary principle cite many examples of risks that were initially ignored or underestimated and later turned out to cause significant adverse human health impacts. There is the perception that environmental and health problems are growing more rapidly than society's ability to identify and mitigate them (Kriebel et al. 2001). In addition, increasing awareness of the potential for severe adverse effects due to global environmental change has weakened confidence in the abilities of decision-makers to identify and control risks in a timely and effective manner. Application of the precautionary principle is intended to prevent society from the costs of false negatives (that is, waiting to implement regulations when risks turned out to be real and significant); but increasing application of the precautionary principle raises the question of costs of false positives, that is, taking more regulatory action than turns out to have been required.

4.5.5 Vulnerability Analysis

Methods of vulnerability assessment have been developed over the past several decades in addressing natural hazards, food security, poverty analysis, sustainable livelihoods, and related fields. These assessments have helped to determine the baseline characteristics of those individuals, groups, or ecosystems that are sensitive to changes and shocks in the system. Vulnerability assessment can identify both general and specific vulnerabilities that enable targeted intervention and can guide future development projects. In identifying the most vulnerable systems or groups, measures to increase social resilience and ecosystem productivity can be prioritized; but the methods and tools used to undertake such assessments involve particular uncertainties. Model, calibration, and scale uncertainties are relevant to VAs. They are discussed in this chapter, MA *Current State and Trends* provides more detailed explanations of vulnerability and vulnerability assessments.

Vulnerability is a contested and ill-defined term. For example, vulnerability can be defined as the degree to which "an exposure unit is susceptible to harm due to exposure to a perturbation or stress and the ability (or lack thereof) of the exposure unit to cope, recover, or fundamentally adapt (become a new system or become extinct)" (Kasperson and Kasperson 2001, p. 21). By contrast, the climate change community uses the term in a significantly different manner. The Intergovernmental Panel on Climate Change defines vulnerability as, "The degree to which a system is susceptible to, or unable to cope with, adverse effects of *climate change,* including *climate variability* and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its *sensitivity,* and its *adaptive capacity*" (IPCC 2001a, p. 995). The implications of these varying definitions have been elaborated in attempts to provide synthesis between competing paradigms (Brooks 2003; Downing et al. 2003; Turner et al. 2003a). The competing definitions, when implemented to assess vulnerability, lead to uncertainty in exactly what is being measured and thus limit the scope of comparative studies.

Within the competing definitions, there is varying emphasis on common causal factors and outcomes. Some approaches emphasize the external conditions and impacts that lead to vulnerable states, such as the rate of climate change or the duration of a drought, for instance (IPCC 2001a). These approaches often assume that a change in the hazard would change the state of vulnerability of those impacted. An alternative approach focuses on the agents of interest and their underlying internal characteristic (Brooks 2003). This can be termed "social vulnerability." Studies in this vein explicitly consider livelihood elements (such as access to information and resources) as well as the broader socioeconomic environment (such as factors that determine the ability of the system and agents within the system) to cope with their existing situation and to respond to potential impacts (Adger 1999; Blaikie et al 1994; Turner et al. 2003b).

Calibration uncertainty is associated with diverse data used in VAs. Both quantitative and qualitative methods are used to evaluate vulnerability with their recognized limitations. Quantitative methods often entail the use of indicators. These indicators are frequently displayed in vulnerability and risk maps indicating the location of the most vulnerable areas (for example, Stephen and Downing 2001 and UNEP-GRID 2003). However, vulnerability indices should be treated with caution. Not only is the diversity and sensitivity of vulnerability hard to measure, but combining different variables of different scales and dimensions to produce one index can also mask many of the underlying processes.

Qualitative data can be equally difficult to validate. Oral histories, for example, are discussions with key local stakeholders that help to elicit information about local historical vulnerability. These histories rely on individual perceptions of the past state of the environment or society. These methods can be effective at gathering information on local vulnerabilities over past decades where there is limited data, but the nature of the information means that triangulation and validation is constrained within shared recall and memory. Other participatory methods that rely on involvement from multiple stakeholders can be subject to political motives and cultural perceptions that are often hard to tease out. It is important that these constraints are recognized and triangulation is undertaken to obtain multiple perspectives.

Scale uncertainty can occur when integrating data that assess different temporal and spatial scales and so the units of measurement are often inconsistent. For example, a village might be vulnerable to climatic variability if it does not have the means to cope with drought, but a household within the village may have planted drought-resistant maize and cope adequately with a dry season. Similarly, within that household the mother might ensure that her children eat the food first. The household may therefore appear to be resilient to drought even though many members within the household suffer. If, as a result, a family member fell ill the next year, then available labor would fall, resources would be spent on healthcare, and the household would become more vulnerable than other households in the village. Phenomena like these have different expressions at different scales that are important if vulnerability is to be captured adequately in a VA.

Although overlaying scales is difficult, VAs are beginning to move beyond static snapshots at a particular time and place to assessments that depict cumulative and long-term vulnerability at a variety of spatial scales. (See Box 4.7.) It has been recognized that vulnerability cannot be viewed as a static phenomena. Vulnerability is, rather, part of a dynamic process (Leichenko and O'Brien 2002). This recognition has implications for the level of uncertainty associated with vulnerability assessments because dynamic analyses require information about how processes and characteristics change over time.

BOX 4.7

RiskMap as a Vulnerability Analysis Tool: Different Lenses Lead to Different Outcomes

RiskMap is an interactive computer-aided tool that enables levels of vulnerability to be mapped within the dominant livelihood and household food economy zones (see Seaman 2000; Save the Children Fund 1997). It was developed in the early 1990s to predict, assess, and monitor famine. The input data to the program is qualitative and field-based.

Stephen (2003) reported that the program typically assesses the risk and dynamics of household livelihood security by describing income and reserves for three household categories (rich, modal, and poor) based on a variety of factors (including the normal pattern of employment, specific employment, livestock and other markets used, and the likely distribution of food and other goods among households). Surveys are conducted among experienced field-based and international staffs, in collaboration with local "informants," who generally live in the area and follow local market and trading patterns. Although this approach has its strengths, Stephen (2003) also noted that some users are uncertain about how the data can be validated.

The results describing who is vulnerable vary depending on the scale of analysis. In RiskMap, different indicators can be turned "on" and "off" and so determine which areas are mapped as vulnerable. This highlights the nature of vulnerability given a variety of specific definitions (see Downing et al. 2003). For example, if the indicator reflecting livestock-dependent households are used then a large area might be considered vulnerable. If access to aid is added, then a smaller area might be considered vulnerable. This highlights the importance of understanding the dynamics of vulnerability and the scope of the study, as these will determine the outcome of "vulnerable" groups.

4.5.6 Summary

Table 4.1 offers a summary of how the various decision-analytic frameworks reviewed in this section have been employed. Modeled after a similar IPCC table provided by Toth and Mwandosya (2001, Chapter 10), it shows that though all of the frameworks are able to support optimization exercises, few have much to say about equity. Cost-benefit analysis can, for example, be modified to weight the interests of some people more than others. The discount rate can be viewed, in long-term analyses, as a means of weighing the welfare of future generations; and the precautionary principal can be expressed in terms of reducing the exposure of certain populations or systems whose preferential status may be the result of equity considerations. Table 4.1 also suggests that only multicriteria analysis was designed primarily to accommodate optimization across multiple objectives with complex interactions, but MCA can also be adapted to consider equity and threshold issues at national and sub-national scales. Finally, the existence and significance of various thresholds for change can be explored by several tools, but only the precautionary principle was designed explicitly to address such issues.

All of these frameworks fall under what many view as decision analysis—a general rubric capturing a broad range of structures based on other representations of the losses or gains associated with external stress and the corresponding gains (diminished losses) or additional benefits of responding to those stresses. Several primary insights can be drawn from referring briefly to this wider perspective. One is that the expected outcome computed against any criteria across a wide range of futures is, given the enormous nonlinearities in most system responses, usually quite different from the outcome computed for the expected (best guess) future. Secondly, many decisions can be made iteratively in an adaptive management mode where new information is systematically incorporated into "mid-course" corrections through techniques that are as sophisticated as Bayesian updating of subjective probability distributions or as simple as excluding (or including) new possibilities.

In every case, the point is to make the best decision, where "best" is defined by the underlying evaluation criteria, given the available information and the information that is likely to become available as the future unfolds. In some cases, where decisions can be modified and adjusted easily, contingency-based rules designed to exploit future information can be the best choice. In others, where decisions made now involve investments with long lifetimes and/or reduce the set of feasible alternatives in the future, then the representations of uncertainty include representations of the distribution of future information. Lempert and Schlesinger (2000) offer an excellent example of how these considerations play out in the climate arena when profound uncertainties about the climate system and its interactions with the socioeconomic-political system (in the contexts of both drivers and impacts) are recognized.

4.6 Valuation Techniques under Uncertainty

Many of the decision-analytic approaches employed by analysts rely on the application of valuation techniques to market and nonmarket contexts. The idea is that relying exclusively on markets to provide estimates of value misses a wide range of other sources of human well-being that are not captured by markets per se. Bringing these sources to bear on the calculations that support various approaches to decision-making allows them to be informed by estimates that come closer to reflecting total economic value. In each case, uncertainty must be recognized and accom-

Table 4.1. Applicability of Decision Support Methods and Frameworks. Interpreting the *optimization, equity,* and *thresholds columns*: (*) designates direct applicability by design; (+) designates possible applicability with modification; and (−) designates weak but not impossible applicability with considerable effort. Interpreting the *uncertainty column*: (A) designates a method that has been modified to accommodate uncertainty and (E) designates a method that has been designed explicitly to handle uncertainty. Interpreting the *scale column*: (M) designates primary applicability at a micro scale; (N) designates applicability up to a national scale; (R) designates applicability to a regional or sector scale; (G) designates applicability up to a global scale; and (X) designates applicability at all scales. Interpreting the *domain column*: (M) designates primary application to mitigating the sources of stress; (A) designates primary application to adaptation; (B) indicates applicability to either mitigation or adaptation; (I) designates applicability to both mitigation and adaptation in an integrated way; and (X) designates applicability in all of the above.

Method	Optimization	Equity	Thresholds	Uncertainty	Scale	Domain
Cost–Benefit Analysis	+	+	−	A	X	B
Risk Assessment	+	+	*	E	X	X
Multicriteria Analysis	*	+	+	A	N and M	I
Precautionary Principle	+	+	*	E	X	X
Vulnerability Analysis	+	+	*	A	N and M	A

modated to a degree that is consistent with the needs of the decision-maker for precision. In some cases, uncertainty in the estimate of total economic value does not cloud the decision space because particular responses would be favored (or not) across the entire range (or at least most of it). In other cases, though, recognizing uncertainty in the estimates of economic value can lead to mixed and therefore contingent assessments. This section offers brief descriptions of how this is accomplished for some of the more popular methods.

4.6.1 Market-based Valuations

Techniques for estimating the values of goods and services that are derived from well-functioning markets are well established. Varian (2003) provides a concise description, and the intuitive underpinnings can be reviewed in Mansfield and Yohe (2004). Fundamentally, these techniques interpret demand curves (correlations between price and quantities willingly demanded) as marginal benefit schedules; that is, prices paid by consumers reflect the value that they place on the last unit demanded. They also interpret supply curves (correlations between price and quantities willingly supplied) as marginal cost schedules; that is, prices received by suppliers reflect the cost of producing the last unit delivered to the market. For any good, therefore, the area between these two curves from zero up to any specific quantity can be interpreted as a direct reflection of the net benefit achieved by society from the consumption of that quantity. It is the sum of ''consumer surplus'' (the amount that people would have been willing to pay for a given quantity if they had paid the marginal value of each unit rather than a single market clearing price) and ''producer surplus'' (the amount that firms receive in excess of the sum of the marginal cost of each successive unit).

Notwithstanding some technical details underlying this interpretation of net benefit (including the difference between using ordinary demand curves instead of compensated demand curves as the basis of benefit calculations), model uncertainty arises in these estimates because different market structures can produce different results. Estimates produced from a model based on the assumptions of perfect competition (for example, presuming that no actor in the market has power over the price actually charged by the market) can be dramatically different from estimates derived from a model that recognizes the game-theoretic strategic behavior of a limited number of suppliers who do have power over the price. So, too, can different assumptions about the degree to which market distortions and asymmetric information cause the specifications of the underlying determinants of demand and supply to deviate from efficiency (as opposed to adequacy and/or rights-based) norms. Even specifying the functional form of demand and supply schedules introduces model uncertainty.

Calibration uncertainty can also cloud market-based valuation estimates, since any empirical procedure will be able to explain only part of the variance in equilibrium prices and quantities even if it can handle pervasive identification problems and the aggregation of the preferences of a myriad of individual consumers and the marketing strategies of a collection of suppliers. In this case, though, paying attention to standard errors of parameter estimates and corresponding prediction errors can suggest an upper bound on uncertainty, but only given an underlying model specification. Prediction and projection uncertainty about the underlying determinants of demand and supply (prices of other goods, the distribution of income, the prices of inputs, and the pace of technological change, for example) and about how these drivers will evolve over time, can also cause trouble. Finally, contextual uncertainty can become particularly problematic. Issues about the persistence over time of existing distortions (wedges between actual marginal cost and benefit created by taxes, externalities, and other sources of omitted social cost, etc.) across an integrated economy must be raised, and valuation estimates will be critically sensitive to how these issues are resolved. Moreover, the degree to which valuation techniques and/or estimates are portable from one context to another depends on the degree to which underlying contextual structures are comparable.

4.6.2 Nonmarket Valuations

A variety of techniques have been developed to estimate the values of goods and services for which markets do not exist. Most are, nonetheless, firmly rooted in the market-based paradigm because they try to create ''pseudo-demand curves'' so that the calculus of consumer surplus just described can be applied directly. As a result, application of any of these techniques must begin by recognizing that all five sources of uncertainty can undermine confidence in the resulting value estimates—sometimes with a vengeance. In addition, each technique brings its own problems with consistency and potential bias to the table, so results in this area need careful interpretation if they are not to be misused. While directed specifically at contingent valuation techniques, this general concern was underscored by Diamond and Hausman

(1994) with the rhetorical question "Is some number better than no number?" Smith (1993) offers a solid appraisal of how to interpret nonmarket valuations of environmental goods; Section IV of Cropper and Oates (1992) similarly provides a presentation of the theoretical technicalities.

4.6.2.1 Hedonic Methods

Hedonic valuation methods are based on the notion that the value of certain properties for which there are no markets can be detected indirectly by calibrating their roles in supporting the prices of other goods and services. More specifically, this expectation holds that many of the underlying determinants of the demand for marketed goods like real estate or agricultural property might include variables that reflect things like environmental quality or climatic conditions. If the associations between the prices of marketed goods and these underlying characteristics can be quantified, then the value of these characteristics can be assessed indirectly by tracking changes in observed market prices.

Hedonic techniques have been employed in assessing the labor-market wage implications of negative characteristics of various locations (such as crime, pollution, congestion, extreme climate, and so on) as well as the benefits of positive attributes (educational opportunity, fine arts, mild climate, or sports facilities, for instance). Ridker and Henning (1967) offered a seminal analysis for sulfur particulates; Brookshire et al. (1982) and Bloomquist et al. (1988) provide more recent but well-respected estimates for nitrous oxide and particulate exposure. Mendelsohn et al. (1994) also applied hedonic techniques to assessments of the effects of long-term climate change in the context of maximally efficient adaptation by the agricultural sector across the United States. In so doing, they developed a controversial methodology that Mendelsohn and others have used in many other contexts.

The controversy over using hedonic techniques cannot be attributed entirely to the ravages of uncertainty, but prediction, projection, and contextual uncertainties certainly play a role. Application of hedonic techniques to climate change assumes, at least implicitly, that individuals at all locations have already adapted optimally to the current climatic conditions and that these adaptations can follow as long as climatic change pushes these conditions into new geographic areas. Recognition of this assumption is a source of concern when it was applied to climate change, and not simply because it contributes to model uncertainty or fails to report calibration difficulties. Results from hedonic applications to the climate arena depend critically upon apparently contradictory assumptions of how human systems will respond to change over time. More specifically, this application of hedonic techniques produces interpretable results only if the relative prices of market goods as well as the other determinants of demand do not change (a specific truncation of projection uncertainty). At the same time, however, the determinants of capacities that supported optimal (market-reflected) adaptations at the initial locations must change significantly; indeed, they must migrate completely to new locations (an equally rigid truncation of contextual uncertainty). Moreover, when the set of external stresses is expanded beyond the climate realm, second-best solutions create problems. It is impossible to understand precisely, in multi-stress contexts, what motivated the observed structure and so it is difficult to conclude with high confidence that an environmental stress was the cause.

Travel cost methods expand the hedonic approach, but their point is also to create a "pseudo demand curve"; see Brown and Mendelsohn (1984) or Kahn (1997) for a description of methodological details. In these exercises, relationships between how much individuals pay to travel to a particular location (like a lake or beach) and the number of times per year that they would be willing to make the trip are estimated. Some applications are based on the average number of trips (per capita) by residences of specific zones or regions; these require less data, but they produce only aggregate estimates. Other applications focus on individuals who actually visit, or could have visited, the study location. These provide more detailed information, but they are data intensive and subject to selection bias. Moreover, all applications must confront questions about what to include in their "willingness to pay" (for example, should they include the value of the time involved in traveling to the location, or just actual expenditures?). Once the data are collected, however, they can be used to produce "market" demand curves for specific populations for which travel costs represent the price of a nonmarket good. Environmental qualities anchor these demand curves, just as before, so changes in environmental parameters can be expected to shift demand. As in the hedonic construction, therefore, corresponding adjustments in price can be interpreted as estimates of the value of those changes.

4.6.2.2 Contingent Valuation

Contingent valuation techniques have been developed over time to produce valuations that are not tied to use values that can be observed from market interactions; but they, too, are designed to build demand curves where they do not exist. Mitchell and Carson (1989) were among the first to recognize the need to have some reflection of relative prices if natural resources were to be managed effectively. They invented CV, and thereby started the debate over whether or not survey results could be trusted. Hanemann (1994) offers a thorough description of how CV can be applied to a variety of circumstances; Portney (1994) as well as Diamond and Hausman (1994) provide coverage of the debate. For purposes of a cursory review, it is sufficient to emphasize that non-use values refer to the increases in individual utility generated by the satisfaction of knowing that something exists. The CV approach asks people to offer monetary estimates of those utility gains. A CV study must, therefore, describe the outcome to be valued, describe a (hypothetical) method of payment, and design a method of elicitation. Results across a large number of people are then summarized empirically as a demand curve and scaled-up so that it is representative of demand across a relevant population. At that point, all of the market-based valuation techniques described above can be applied directly.

The devil is in the details, of course, and so careful design is essential. Recent work suggests, for example, that practitioners do more than ask what something is worth; they create elicitation vehicles that carefully define the context of the valuation exercise and include questions whose answers allow some evaluation of internal bias; see Bateman and Willis (1995) and Bateman (2002) for examples and Arrow and Solow (1993) for some practical guidance. All these contributors to a growing literature confirm that the description of context must be constructed in a way that does not create biased reactions of respondents who might know nothing about the subject. The method of payment must be clearly understood to alleviate, at least to some degree, the concern that respondents never fully comprehend the method unless they see real money leaving their pockets.

One issue of particular importance is derived from the widely accepted result that the willingness to pay for an environmental improvement is generally smaller than the willingness to accept (compensation) to forego that improvement is perhaps the critical element of a long list of possible biases and design problems. Empirical support for this result can be found in Hammack and

Brown (1974), Rowe et al. (1980), and Knetsch and Sinden (1984). These authors derive theoretical support directly from diminishing marginal utility—a building block assumption of neoclassical economic theory. Other researchers, like Coursey et al. (1987), suggest that observed differences (for small payments in one direction or the other) are simple reflections of the fact that most people are more familiar with buying something than they are with selling it. In either case, these differences mean that the consumers of CV elicitations must do more than read the numbers; they must understand the entire elicitation process even before issues of uncertainty are raised. Moreover, prediction, projection, and contextual uncertainties can be particularly troublesome for contingent valuation, since individual responses to even a well-designed elicitation are extraordinarily context specific.

Despite all of these problems, Rothman (2000) has argued that valuation methods like contingent valuation can inform decision-makers in their consideration of various responses. The key lies in careful recognition of the level of precision required to support a particular decision. If, for example, a decision to implement a particular response were based on a cost-benefit calculation, then the issues raised here would be troublesome only if the estimates of net benefits derived from some analyses (say, from studies employing ''willingness to accept'' calculations) were positive while other estimates (for example, those derived from studies employing ''willingness to pay'' calculations) were negative.

4.6.3 Cross-cutting Issues

At least two cross-cutting concerns about all valuation techniques should be raised. First, all of the techniques noted above use the net-benefit interpretation of demand and supply structures to derive their fundamental measures of value; but this interpretation only makes sense in a utility (welfare) context when people pursue their own, well-defined best interest. As a result, every method is rooted firmly in the assumption of economic rationality (that people consume goods up to the point where the increase in their utility created by spending their last dollar on one good is the same as it would be if they spent that dollar on another good). But do people actually behave that way?

Second, each measure is also fundamentally derived from theories that describe individual decisions and produce individual demand curves for marketed goods or ''pseudo-demand'' curves for nonmarket goods. Scaling these representations of individual decisions up to structures that claim to represent collective behavior over entire markets, communities, or nations adds aggregation to the list of major sources of uncertainty; and it means that defining aggregation techniques adds another level of subjectivity to the results. Neither of these concerns is insurmountable, but both suggest that care needs to be taken in interpreting and applying valuation results in the decision-making process.

4.7 Synthesizing Political, Economic, and Social Factors in the Context of Uncertainty

The previous sections have offered reviews of valuation and decision-support tools that have been modified to accommodate uncertainty. A complete assessment of the ability to respond to external stresses cannot, however, stop with representations of the likelihood of success or the range of possible outcomes. If it is to be at all useful, processes that amplify our understanding of the cascade of uncertainty noted above need to feed into a structure where the factors that determine the feasibility of various response options (see Chapter 3) can be explored. In short, an integrated structure needs to be constructed so that synthetic analyses of response options can be conducted.

This section builds on the IPCC (2001a) notion of adaptive capacity and its determinants as identified by Yohe and Tol (2002) to suggest how this integration might be accomplished. While some have used this structure to produce mechanical indices of vulnerability based on the generic adaptive capacities of entire systems and to evaluate the feasibility that specific responses will accomplish their goal based on their specific adaptive capacities, it is perhaps best viewed as one way of organizing one's thoughts in an effort to try to understand why some responses work in some circumstances and not others.

4.7.1 Matching Political, Economic, and Social Factors to the Determinants of Responsive Capacity

Working from the IPCC (2001a) perspective that the vulnerability of any system to external stress is a function of exposure and sensitivity and that either or both of these manifestations can be influenced by its adaptive capacity, Yohe and Tol (2002) list seven determinants of (specific) adaptive capacity that are required to support any given response option:

(1) the availability of resources and their distribution across the population;
(2) the structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed;
(3) the stock of human capital including education and personal security;
(4) the stock of social capital including the definition of property rights;
(5) the system's access to risk-spreading processes;
(6) the ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers themselves; and
(7) the public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

Thinking of these determinants as the underlying components that support a system's ability to respond to a set of external stresses (that is, its *responsive capacity*) makes it clear that they simply add some detail to the critical factors for assessing responses identified in Chapter 3. Determinants 2, 6 and 7, for example, add some texture to the political factors described there. Determinants 1 and 5 reflect economic considerations, but also connect with determinants 3 and 4 to portray the significant role played by social factors.

4.7.2 A ''Weakest Link'' Approach to Evaluating Capacity

Taking the conceptual approach implied by the list of determinants to something applicable to systematic evaluation of various responses across site-specific and path-dependent contexts relies basically on the notion that a system's responsive capacity is fundamentally determined by the weakest link—the underlying determinant that provides the least support for the available responses in its ability to cope with variability and change in local environmental conditions. This hypothesis clearly requires some justification. Yohe and Tol (2002) reported some suggestive empirical results from international comparisons, but subsequent literature has been more persuasive. A growing body of literature has, for example, reached similar conclusions regarding income inequality and mortality (see, for example, Lynch et al. 2000;

Kaplan et al. 1996; Ross et al. 2000). Even more recently, McGuire (2002) looked for statistically significant explanations for variability in infant mortality across developing countries. Yohe and Ebi (2004) also noted a strong match between the prerequisites for prevention in the public health literature (where a weakest link hypothesis is well established) and the determinants of responsive capacity.

A review of economic literature also produces some supporting evidence. Rozelle and Swinnen (2004), for example, looked at transition countries across central Europe and the former Soviet Union to observe that countries which grew steadily a decade or more after their reforms have managed to (among other things) reform property rights *and* to create institutions that facilitate exchange and develop an environment within which contracts can be enforced and new firms can enter. Order and timing did not matter, but success depended on meeting all of these underlying objectives. Winters et al. (2004) similarly reviewed a long literature to conclude that the ability of trade liberalization to reduce poverty depends on the existence and stability of markets, the ability of actors to handle changes in risk, access to technology and resources, competent and honest government, *and* policies that promote conflict resolution and promote human capital accumulation.

4.8 The Challenge of Uncertainty: Creating, Communicating, and Reading Confidence Statements

Effective response options are the products of a process whose success is critically dependent upon an understanding of the key issue or problem of concern, the design of appropriate actions to address this issue, the effective implementation of the selected actions, and the honest monitoring and evaluation of outcomes to ensure that the actions achieve their goals without unintended consequences.

This chapter focused on the uncertainty inherent in implementation of responses, on the uncertainty inherent in our understanding of how ecosystems work, and on the interaction of these uncertainties with the tools that analysts employ to evaluate and choose between these response options. It began with a brief taxonomy of the sources of uncertainty, then looked back to Chapter 3 to see how the various critical factors of feasibility could be viewed as an anthropogenic source of uncertainty. From case to case, application of any of the decision-analytic frameworks and the evaluation methods reviewed earlier in this chapter will confront many if not all of these sources. Still, experience suggests that some sources of uncertainty can be expected to be more important for one framework than another. The example drawn from the climate change literature above was presented only to suggest how considerations of systems uncertainty might be integrated with the underlying factors that enable or constrain specific response options. As such, it is best viewed as a representation of the thought processes that MA authors conducted as they evaluated the confidence with which they could offer their conclusions.

The success or failure of present or past approaches to solving an issue is a function of the compatibility of the solution methods (including demand for services) and ecosystem dynamics. In a setting where demand is low relative to available system services (even at times of extreme natural stress), there will be ''successful'' management—but not necessarily because of a good management scheme. When the ecosystem is at the brink of state-change, even the wisest decision-making paradigms may be insufficient to prevent the inevitable. One challenge is recognizing the limits of our understanding of the processes underlying ecosystem dynamics and resilience. Another challenge is ensuring that management strategies for maximizing service extraction are not at the cost of system simplification and loss of effective resilience.

The most obvious opportunity is to learn from the mistakes and successes of the past. Each can be considered an experiment in how to frame and solve an ecosystem service management challenge. Systematic analyses of implemented response options are required to capitalize on this body of information and thereby to learn which factors enhanced the probability of success and which led to failures. Such learning holds the promise of teaching us how resources can be managed when baseline conditions are relatively stable and extra-scalar effects are relatively small before confronting the complication of significant shifts in baselines and simultaneous multiple stresses on ecosystems.

There are many possible response options to address a particular problem. Whether or not they can be effectively implemented depends on factors such as political feasibility; technological, economic, and social issues; and the capacity for governance. A better understanding of the process of the design and implementation of successful response options in the context of these factors is needed, including how barriers to implementation were overcome. Lessons learned could then be applied to other situations to reduce the negative consequences and take advantage of the opportunities that arise in the context of ecosystem management.

Processes and institutions need to be established to facilitate a learning-by-doing approach that includes monitoring of implemented response options and systematic evaluation of their results. These evaluations can be employed to investigate why some response options were effective while others were not. This is only possible if the original design included the establishment of necessary measures to collect the information required for a post hoc examination. It follows that the design of a response option should include actions to determine the effectiveness of the option in addressing the issue of concern and, accordingly, plans for collecting the required data—a process designed to keep track of the progress of implementation of a response option and its various components in relation to the goals established. It also follows that improved understanding of what works where will improve only if integrating analyses take careful account of spatial and temporal diversity.

Assessments of the sort presented in this volume are, of course, fundamentally the products of monitoring and evaluation exercises—nominally of our ability to manage ecosystem responses, but actually of our ability to understand exactly what is going on. This assessment is perhaps the most comprehensive and visible exercise of this sort, but its success is not guaranteed. The assessors who contributed to this work will only advance our long-term understanding of how ecosystem services support human well-being even as humans exert enormous stress on their potential longevity in an uncertain world if they are honest in identifying what is well established (*high certainty* conclusions), what is established but supported by incomplete analysis (*medium certainty*), what is subject to competing explanations (*low certainty*), what is entirely speculative (*very low certainty*), and what is entirely beyond the scope of our understanding (*severe gaps in knowledge*).

It is in the subsequent exploration of why the quality of our knowledge is so inconsistent that the thought-process described earlier in this chapter might be most valuable. Chapter 15, for example, will offer the conclusion that ''integrated responses are gaining in importance in both developing and developed countries, albeit with mixed results.'' Since this point is based on fewer than 20 studies, though, it can be advanced as ''established but incomplete'' according to the guidelines for conveying confidence. Nevertheless, a systematic evaluation of these studies using a common thought template, can perhaps provide some insight into why the results of integrated responses have been so mixed—working in some site-specific and path-dependent contexts but not in others.

The burden for communicating these findings does not lie exclusively with the authors. Readers must also be honest in their assimilation of the assessment. They cannot, for example, seize on the negative studies of integrated responses and ignore the positive studies to support a general opposition to their implementation. Nor can they focus exclusively on the positive studies to advocate integrated responses ubiquitously. They must, instead, comprehend the implications of the full range of uncertainty described by the assessors of the full set of studies (as limited and as contradictory as they might be) and they must accept the various degrees of confidence reported by the authors as they make up their own minds. (See Box 4.8 for a discussion of one approach to determining how to deal with uncertain estimates.)

BOX 4.8

Defining Hotspots in an Uncertain World

''Biodiversity conservation'' has uncertainty at its foundations—uncertainty not only about the identity and location of the many species (or other elements) that make up global biodiversity (*scale uncertainty*), but also about their values to humanity (*model and contextual uncertainty*). Sometimes estimates of possible future values simply are equated with our measures of variation (*calibration uncertainty*). But even here, surrogates or proxy information (for example, indicator species) are required because all components of biodiversity cannot be assessed in all places with any certainty. Response strategies (see Chapter 5) use surrogate information in ways that sometimes introduce new uncertainties about their adequacy (*prediction and projection uncertainty*).

For example, the advocacy of 25 global hotspots is one high-profile biodiversity response strategy; it highlights the inevitable uncertainties about surrogates. Myers (2003), in his recent review of this approach, notes differences of opinion about whether the identification of hotspots based on major taxa can be representative of patterns that would be found for other components of biodiversity. (See Chapter 4.) Myers addresses the concern that surrogacy is not ''proven'' but only ''assumed'' in this way: ''. . . when will our research be able to 'prove' much about the 9.7 million invertebrates out of a putative planetary total of 10 million species, given that only around 1 million of them have been identified thus far?'' An assessment of this literature might therefore suggest that the identification of ''hotspots'' is ''established but incomplete.''

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