Annu. Rev. Environ. Resour. 2006. 31:365–94
doi: 10.1146/annurev.energy.30.050504.144352

First published online as a Review in Advance on July 18, 2006

ASSESSING THE VULNERABILITY OF SOCIAL-ENVIRONMENTAL SYSTEMS

Hallie Eakin[1] and Amy Lynd Luers[2]
[1]*Department of Geography, University of California, Santa Barbara, California, 93106-4060; email: eakin@geog.ucsb.edu*
[2]*Global Environmental Program, Union of Concerned Scientists, Berkeley, California 94704-1567; email: aluers@ucsusa.org*

Key Words adaptation, equity, global environmental change, resilience

■ **Abstract** In this review, we highlight new insights into the conceptualization of the vulnerability of social-environmental systems and identify critical points of convergence of what otherwise might be characterized as disparate fields of research. We argue that a diversity of approaches to studying vulnerability is necessary in order to address the full complexity of the concept and that the approaches are in large part complementary. An emerging consensus on the issues of critical importance to vulnerability reduction—including concerns of equity and social justice—and growing synergy among conceptual frameworks promise even greater relevancy and utility for decision makers in the near future. We synthesize the current literature with an outline of core assessment components and key questions to guide the trajectory of future research.

CONTENTS

INTRODUCTION

In its most basic sense, vulnerability conveys the idea of susceptibility to damage or harm (1), but much debate remains around how to characterize vulnerability in theory and practice (2–6). In this review, we highlight new insights into the conceptualization of vulnerability—particularly from the ecological sciences—and identify critical points of convergence of what otherwise might be characterized as disparate fields of research. Although there continues to be some confusion in the use of vulnerability terminology and concepts, we argue that the diverse approaches to studying vulnerability can essentially be viewed as complementary and even necessary to address the full complexity of the concept and its relation to social-environmental systems. An emerging consensus on the issues of critical importance to vulnerability reduction, including concerns of equity and social justice, and growing synergy among conceptual frameworks suggest that in the near future vulnerability research may achieve far greater relevancy and utility for decision makers.

We focus on recent research and assessments of vulnerability associated with human-environment interactions. The research we review encompasses proposals for new theoretical approaches and conceptual frameworks, academic explorations of the causes and consequences of harm and loss for particular peoples and places, and applied projects designed to identify populations and peoples at risk and offer viable solutions for their vulnerabilities. Although vulnerability assessments are not necessarily local in nature, they do address specific characteristics—socioeconomic, biophysical, cultural, historical, political—of defined regions and places (7, 8). Given that climate change has served as both a theoretical and empirical focus in recent vulnerability literature, we incorporate much of this literature here in addition to other perspectives from the literatures of economic development, disaster policy, and natural resource management. Much of this literature recognizes that although important headway has been made in linking vulnerability research to policy and practice, stronger ties are needed (2, 9).

Vulnerability has frequently been characterized as a function of both a system's exposure and sensitivity to stress and its capacity to absorb or cope with the effects of these stressors (10); however, neither these attributes nor the relationships between them are well defined. Clarifying the meaning and use of the concept of vulnerability has thus become a central focus of recent cross-disciplinary efforts in vulnerability analysis.[1]

The debate over vulnerability definitions and vulnerability assessment practice has emerged from three broad intellectual lineages: (*a*) studies that draw heavily from risk/hazard or biophysical approaches, (*b*) the application of political-ecological and/or political-economic frameworks, and (*c*) recent research on vulnerability inspired by the concept of resilience in ecology. Each of these three general lineages (summarized in Table 1) has led to different methodological choices and units of analysis—and thus has resulted in different normative conclusions about the best ways to address the study of vulnerability.

In the following section, we describe broadly these three conceptual lineages of vulnerability research. In practice, however, hybrid approaches are increasingly producing both new insights into the causes and consequences of vulnerability and innovation in vulnerability metrics. This hybridization also contributes to some of the present confusion over the meaning of vulnerability while simultaneously generating productive and rich debates over what type of research framework will facilitate the integration of disparate ideas and bridge distinct worldviews. In the section Recent Vulnerability Research and Practice, we review some of the vulnerability assessments that have been produced since the mid-1990s to illustrate the evolution and hybridization of research in recent years as well as to highlight core concepts and new approaches that are emerging in practice of vulnerability research. In the section Current Challenges in Vulnerability Analysis, we return to the conceptual literature to highlight four issues that now appear central to the future trajectory of vulnerability research. In the section Integrating Approaches, we present two recent frameworks for vulnerability assessment and present our own synthesis of the literature. We conclude by stressing that vulnerability is fundamentally a relative concept concerned with issues of social justice, equity, and opportunity.

TRACING THE LINEAGES OF CURRENT VULNERABILITY RESEARCH

Although the field of vulnerability assessment is considered by some to be fragmented (11), there is a considerable amount of research that builds on theoretical insights from multiple disciplines in which researchers have drawn from a variety of methods and tools to investigate the question at hand. The literature does, however, illustrate distinct points of view that can be traced to how vulnerability has evolved within particular research paradigms. These lineages have led to

[1]See, for example, the results of two workshops on vulnerability, that of Kasperson & Kasperson (2) and that organized by the International Human Dimensions Program in 2005, the results of which are published in volume 16 of *Global Environmental Change.*

TABLE 1 A comparison of three conceptual lineages of contemporary vulnerability research

Point of comparison	Risk/hazard	Political economy/political ecology	Ecological resilience
Focal questions	What are the hazards? What are the impacts? Where and when?	How are people and places affected differently? What explains differential capacities to cope and adapt? What are the causes and consequences of differential susceptibility?	Why and how do systems change? What is the capacity to respond to change? What are the underlying processes that control the ability to cope or adapt?
Key attributes	Exposure (physical threat, external to system), sensitivity	Capacity, sensitivity, exposure	Thresholds of change, reorganization Capacity (to learn and adapt)
Exposure unit	Places, sectors, activities, landscapes, regions	Individuals, households, social groups, communities, livelihoods	Ecosystems, coupled human-environmental systems
Decision scale of assessment audience	Regional, global	Local, regional, global	Landscapes, ecoregions, multiple scales
Selected definitions	"...the likelihood that an individual or group will be exposed to and adversely affected by a hazard. It is the interaction of the hazards place with the social profile of communities" (7, p. 532) "...the idea of potential for *negative consequences* which are difficult to ameliorate through adaptive measures given the *range of possible climate changes* that might reasonably occur" (10a, p. 774)	"The characteristics of a person or persons in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard" (20, p. 9) "Vulnerability comes at the confluence of underdevelopment, social and economic marginality, and the inability to garner sufficient resources to maintain the natural-resource base and to cope with the climatological and ecological instabilities of semi-arid zones." (23, p. 28)	Vulnerability defined as the opposite of resilience, where resilience is "the capacity of a system to undergo disturbance and maintain its functions and controls" (10b, 45, p. 767) "Resilience has the following characteristics: a) the amount of change a system can undergo; b) the degree to which the system is capable of self-organization; c) the degree to which the system can build the capacity to learn and adapt" (45, p. 767)

differences in the purpose of vulnerability assessment; the concepts central to vulnerability analysis, the primary subject of concern; and the spatial, temporal, and decision scales of vulnerability analysis (Table 1). These distinct perspectives on the problem of vulnerability can either represent opportunities for synthetic and collaborative research or can constrain the science from reaching ultimate goals of fundamental understanding and social utility.

Risk-Hazard

Risk-hazard approaches to understanding vulnerability have evolved from the vast natural hazards literature in geography and the theoretical contributions of White (12), Burton et al. (13), and others on hazard characterization, risk thresholds, human behavior, and adjustment to environmental risk. This research lineage has been particularly well represented in the work of the Intergovernmental Panel on Climate Change and in research on consequences of climate change. Using the biophysical threat as the point of departure, risk-hazard researchers have essentially set out to describe on a very broad scale (*a*) to what we are vulnerable, (*b*) what consequences might be expected, and (*c*) where and when those impacts may occur.

Risk-hazard approaches tend to consider negative outcomes as functions of both biophysical risk factors (for example, in the climate change literature, a change in temperature, precipitation or the frequency of extreme events) and the "potential for loss" of a specific exposed population (7, 14). When this potential for loss is realized in negative outcomes, such outcomes serve as a rough equivalent to vulnerability, allowing the *ex post* identification of the existence of vulnerability in a specific system.

The type of research promoted through the U.S. Country Studies Program on climate change in the early 1990s (15, 16), for example, could be considered as offering first approximations of a system's sensitivity to risk (17), and some quantification of the possible economic and social losses that could be expected with global warming. In practice, however, the results of these efforts to quantify damage have often been used as rough proxies for vulnerability, leading to the conflation of causal processes and conditions with outcomes (1, 4, 14). For example, Iglesias et al. (18) evaluated the vulnerability of crop production in Asia to climate change by comparing the results of a series of studies that quantified the potential impacts in terms of percent change in land suitability, crop yields, and/or farmer incomes using dynamic crop growth models coupled with climate change scenarios. Although they mention in their review some of the geographic characteristics that affect the sensitivity of production to climate change in some regions (e.g., soil quality or propensity to waterlogging), the determinant of vulnerability in this research is the projected impact—in terms of loss in yield, income, or land area—moderated by the adaptive potential of the crop production region. In these and other similar studies, vulnerability is often implicitly or explicitly equated with an outcome of a relatively linear analysis that begins with characterizing a stressor and then moves to determining impacts and potential adjustments (4).

In the late 1990s, attention to the social drivers and institutional conditions that define differential sensitivity and capacities to environmental stress increased and an effort was made to distinguish impact-oriented research from vulnerability assessments (4, 19). This move has helped clarify that impact and vulnerability assessments are essentially complementary tasks in global change research; both are critical for understanding the challenges global change presents for human-environment systems.

Political Economy/Political Ecology

Political-economy and, more recently, political-ecology approaches to vulnerability have in some sense evolved from and often in response to risk-hazard assessments of climate impacts and disasters (20). Hewitt's (21) highly influential critique of an overly technocratic emphasis in traditional natural hazards research (*Interpretations of Calamity*) inspired a subsequent generation of political-economy research on vulnerability and disasters. Developing from roots in structuralist and neo-Marxist thought (22), today's vulnerability research in a political-economy or political-ecology framework is characterized by analyses of social and economic processes, with interacting scales of causation and of social difference: Why are particular populations vulnerable? How are they vulnerable? And, importantly, who precisely is vulnerable (23)?

Political-economy perspectives on vulnerability emphasize the sociopolitical, cultural, and economic factors that together explain differential exposure to hazards, differential impacts, and, most importantly, differential capacities to recuperate from past impacts and/or to cope and adapt to future threats. Sen's (24) concepts of entitlements and capabilities (central concerns of food security, livelihood security, and contemporary development theory) have served as the cornerstones to much of this work and have provided a theoretical bridge to research on poverty alleviation and food security (3, 4, 25). In a seminal article in 1993, Bohle et al. (25) argued that vulnerability could be conceived as a "space" delimited by political economy, entitlements, and empowerment. Their emphasis on historical processes and the dynamic nature of vulnerability inspired others to broaden the scope of vulnerability analysis to examine the context of human-environment relations. Liverman (26), for example, illustrated that differential outcomes in crop yields during drought periods in Mexico were strongly associated with differential land tenure and historical biases in farmers' access to productive resources and could not be explained simply through precipitation patterns.

In this literature, vulnerability is not an outcome but rather a state or condition of being—and a very dynamic one at that (27, 28)—moderated by existing inequities in resource distribution and access, the control individuals can exert over choices and opportunities, and historical patterns of social domination and marginalization. To some extent, these perspectives on risk and vulnerability have been synthesized in the "Pressure and Release" model of Blaike et al. (20). This model emphasizes the underlying causes of disaster and the social production of risk and has been widely used in emergency management (20).

Political-ecology research explores vulnerability with respect to broad processes of institutional and environmental change. It shares the emphasis of political-economy perspectives on the importance of scale, politics, and economic and social processes in explanations of human-environmental interactions and outcomes. Whereas political-economic analyses of vulnerability tend to downplay the explanatory power of physical processes, political ecologists argue for a more balanced consideration of both biophysical and social dynamics, with explicit attention to the representation of those dynamics in policy and decision making (1, 29).

Both perspectives focus on the political dimensions of vulnerability, highlighting social inequities and points of conflict within societies. Their assessments thus tend to be more sensitive to issues of power than traditional risk-hazard approaches (1). This research also tends to focus on specific places within a broader context of historical, political, and biophysical conditions of hazards and risks. Although these contributions are substantial, the challenge of developing theory and generalizable lessons from political-economy/ecology research remains (9). One could also argue that in the absence of a clearly defined vulnerability outcome, some research conducted within this framework has produced generic descriptions of inequities in resource distribution and opportunity without demonstrating ties to differential susceptibility to harm.

Ecological Resilience

The concept of ecological resilience is a relatively new addition to the discourse on vulnerability. It has contributed to a productive exchange of ideas about assessing and understanding vulnerability not only in relation to global environmental change, but also more broadly in relation to a variety of stresses and shocks acting on and within coupled human-environment systems. In this paradigm vulnerability is seen as a dynamic property of a system in which humans are constantly interacting with the biophysical environment.

As defined by Holling in a seminal paper in 1973, ecological resilience refers to the "ability to absorb change and disturbance and still maintain the same relationships" that control a system's behavior (30, p. 14). This core idea has been further characterized to include the capacity to reorganize while undergoing change so as to preserve structure and function (31). Holling contrasted this definition with the more common definition that he classified as *engineering resilience* or the ability of a system to return to a predisturbed state after a temporary disturbance (32).

Contrary to the earlier view that natural systems exist at or near a single equilibrium, ecologists now recognize that ecosystems often exhibit non- (33) and multi-equilibrium dynamics (34–36) and are continually affected by stochastic forces of nature (hurricanes, droughts). These dynamic processes are apparent in rangeland ecosystems, for example, where movement among stable states such as annual grass, perennial grass, and woody shrub populations is driven by such natural disturbances as climate variability, fire, and herbivory (37–39).

Ecological resilience focuses researchers and resource managers on understanding processes of change, on identifying thresholds, and on the underlying factors that allow natural systems to absorb disturbance. In contrast to the anthropocentric focus of political-ecology approaches, resilience approaches have tended to give predominant weight to the implications of social and environmental change across the broader geographic space, reducing human activity to just one of the driving forces and humans themselves as only one of the affected species. Chapin et al. (40), for example, explore the resilience of the Arctic region as a coupled human-environment system, arguing for resource management strategies that enhance the resilience of the broader northern landscape rather than specific properties or resources within that landscape. The ultimate goal is to sustain "those fundamental features of northern systems that are most important to society," including industrial resources, biological processes, and the knowledge and needs of human populations (40, p. 344).

Timmerman (41) was among the first to bring resilience theory to the social sciences, arguing that the vulnerability of a society to hazards is a product of rigidity resulting from the evolution of science, technology, and social organization. In this light, resilience researchers have recommended adopting "adaptive comanagement" strategies for human-managed resource systems to enhance their resilience to surprise and shocks (34). These community-based resource systems are intended to enable dynamic learning and to enhance the flow of different sources and types of knowledge across scales of governance (42–44), although questions have been raised over how well these concepts translate in practice to analyzing the vulnerability of social systems more broadly. In part, these concerns relate to operationalizing the concept of resilience for the analysis of complex social systems (45) and the utility of resilience on a practical level in preventing and reducing social sensitivity to disasters (6). Some have also argued that social resilience is essentially an attribute of communities and regions, not of individuals or households (46), challenging the use of resilience in assessments at the household scale.

RECENT VULNERABILITY RESEARCH AND PRACTICE

In the following discussion of the recent empirical literature, we illustrate that, although many methods and approaches are used in vulnerability assessments, they can be seen as complementary: each focuses on a particular aspect of the vulnerability puzzle. We hope that viewing the literature in this way will lead to more collaboration and integration across research frameworks and disciplinary divides. Our perspective is synthesized in the table in the section Integrating Approaches.

Identifying Thresholds of Harm

Over the past decade, concepts from both the ecological-resilience and political-economy literatures have been incorporated into impact assessments in recognition of the multiple causes and consequences of social and environmental change, thus speaking directly to the central concerns of vulnerability research. The identification of critical thresholds of significant damage has become part of the shared agenda of these expanded impact assessments, reflecting a broader effort to articulate concretely what is meant by harm (47–50). Ecological resilience analyses often explicitly define thresholds between multiple states of ecological systems. For example, in their study of eutrophication of freshwater lakes, Carpenter et al. (50a) and others define the resilience of a lake in terms of its susceptibility to crossing a threshold from a clear-water system to a turbid-water state.

In relation to managed ecosystems, Jones (47) has argued for the importance of calculating the probability that a specific combination of climate factors will lead to a significant response from the system under study. *Significant responses* equate to impact thresholds that define shifts in states (as in ecosystem functioning) or in levels of performance (as in economic production) and can change over time, reflecting the evolution of the system and its environment. Identification of such thresholds can provide stakeholders with a reference point from which to measure future vulnerability, allowing them to assess the degree of risk that they need to avoid through adaptation.

In the context of climate change research, the use of coupled and nested process models have allowed for increasingly sophisticated simulations of future impacts and system responses and thus the identification of ecological thresholds of significant change. Christensen et al. (51) used the SAVANNA grassland model to simulate the interacting effects of livestock grazing and climatic change on grassland productivity in Mongolia and to identify the thresholds of shifts in ecosystem states under various levels of livestock management and intensities of resource use. This research goes beyond a simple formula of dose response in order to account for multiple drivers and stimuli operating at different scales on the system of concern and to determine the feedback loops among these drivers. This study, together with others, also suggests the types of dangerous scenarios in which impacts may be sudden and irreversible (40, 52, 53). Internationally, scientists are increasingly focused on defining dangerous thresholds of climatic change in order to set appropriate emissions reduction targets (54). However, defining what constitutes "dangerous" is not a simple matter as it is not ultimately a science question but rather a value judgement.

Identifying such thresholds for social systems is complicated by the relative and subjective nature of risk and its variance in meaning among human populations (50, 55). Analyses of economic viability are one way to explore the concept of thresholds in socioeconomic systems. For example, Antle et al. (56) explore the economic returns to farming as thresholds to evaluate the vulnerability of northern Great Plains farm systems. Using coupled-process models, they evaluate changes in the net economic returns to farmers' annual production cycles as climate changes, with and without adaptation. Drawing from actual databases of land-use history, soils, and climate, they argue that their model reflects the existing heterogeneity of farm systems in the region and thus better captures the complex response patterns that may be expected under climate change. The challenge is finding appropriate measures of thresholds for systems that may not respond directly to market signals or for which persistence is determined more by institutional factors than by environmental or economic criteria alone.

Identifying Causal Processes and Explaining Attributes of Vulnerable Systems

A mixture of qualitative and quantitative methods has been employed to explain the complexity of social and institutional drivers of vulnerability and to determine which combinations of attributes best characterize the vulnerability of specific populations in particular places. Because authors tend to start with the assumption that social/institutional factors are primary drivers of vulnerability, a full characterization of the probability and nature of the types of outcomes expected for a population is often not considered essential (4). The contribution of political-ecology, livelihood, and resilience research has been particularly helpful in this line of investigation. Sustainable livelihood analysis, for example, emerged in economic development research as a means of reducing chronic poverty through documenting the dynamics of environmental and social relations at the household level (57). It has proven to be a useful tool in environmental change research by facilitating the differentiation of vulnerable populations according to their assets and entitlements, the identification of assets critical for coping with and adaptating to risk, and the linking of livelihood strategies to the opportunities and constraints of the broader institutional and biophysical environment (4). Theoretical research in this vein has highlighted broad and dynamic processes of economic and social change—both historical and ongoing—as sources of uncertainty, inequity, and risk (28, 58–59). Much of the case study literature adopts inductive and often participatory methods (60–62).

Given that the units of analysis are typically individuals or population groups (e.g., households or communities), the scope of analysis in these studies is not bound by sector or resource but rather reflects the fluid and diversified nature of human activity and social relations in particular places. Pelling (62), for example, interprets the contemporary vulnerability of urban populations in Guyana to floods through an analysis of the economic swings and political-power struggles that structured coastal development over several centuries. His survey and interview data reveal that the control of political elites over community organization inhibited the development of the forms of social capital necessary to reduce households' sensitivity to floods (63). He concludes that flood vulnerability is as much "outcomes of political discourse" as the consequence of environmental change and posits that vulnerability will be reduced only through improving the process of decision making over resource use and allocation (62, p. 258).

Other recent work focuses on adaptive capacity as a concept to explain observed differences in vulnerability. Vásquez-Léon et al. (61) illustrate how resource policy, ethnicity, and class have defined farmers' differential capacities to buffer their livelihoods from stress on both sides of the U.S.-Mexico border. Similarly, through comparative case studies, Eakin (60, 64) shows how new uncertainties in resource access, induced by neoliberal policy reforms, have altered farmers' choice sets, in some cases narrowing their flexibility to address climate risk. Assessing the vulnerability of Vietnamese coastal communities, Adger (27) uses poverty and the dependence of livelihoods on climate-sensitive economic activities as a proxy for household sensitivity to climatic stress. He describes how Vietnam's liberalization program (*Doi Moi*) has both eroded collective coastal protection schemes and increased incomes and resilience for some population groups. Together these case studies call into question common assumptions about the relationship among indicators such as wealth, diversity, participation, equality, and local vulnerability, and this research highlights the critical role played by institutional change, policy, and social capital in individual and group vulnerability. Importantly, these studies also make headway into understanding the meaning of harm or damage in emic terms, rather than in terms defined a priori by the researcher.

Linking Attributes to Outcomes

A third body of literature has been dedicated to the development of vulnerability metrics. The focus of this research has been on the articulation of a quantitative function that can be used in a variety of settings to reliably link system attributes (principally biophysical and economic) to vulnerability outcomes (e.g., yield decline, loss in land value or economic returns, or a decline in resource quality) (65–67). The need to use available datasets in this work makes it difficult to capture more subtle and complex dimensions of vulnerability, such as the internal and even physiological characteristics of sensitivity and loss that are so critical for coping and survival (55, 68). For global change research, there is a need for metrics that are indicative of future states. For example, researchers interested in adaptive capacity as a primary attribute of vulnerability propose that indicators such as youth education levels and investment in health are indicative of potential future capacities and states of being (68a). These indicators do not, however, adequately address the need for measures that reflect the dynamic nature of vulnerability in both its manifestation and its causes (68b, 68c).

Yet, one of the advantages of developing a specific metric is the potential, at least in theory, to test relationships *ex post* using numerical analyses or empirical data to estimate a system's resilience or vulnerability to specific threats (30, 69, 70). For example, one of the important contributions of the study on the vulnerability of lakes to eutrophication by Carpenter et al (50a) was the development of a set of empirical and theoretical models to link slowly changing variables such as soil nutrient levels (identified as key processes driving vulnerability) to the outcome of lake eutrophication (50a).

Luers et al. (65) and Luers (48) propose a generic metric of vulnerability based on established functional relationships between biophysical stressors (e.g., climate variability and change) and measures of vulnerability outcomes (e.g., specific damages in agricultural yield and income). They conceptualize vulnerability in terms of the system's state relative to a threshold beyond which the system is assumed to be damaged, the system's sensitivity, and the frequency distribution of the stressor (exposure). Using remotely sensed data and a geographic information system (GIS), they apply their model to the vulnerability of wheat yields to temperature change and price fluctuations in Mexico's Yaqui Valley. They use their metric of vulnerability to link farmers' management practices and soil characteristics to vulnerability levels observed in the wheat yields (65).

Mapping Vulnerability

Following from research on vulnerability metrics and indicators, mapping the distribution of vulnerability—either in terms of attributes of sensitivity, exposure or capacity, or in terms of outcomes and impacts—has become a central tool for communicating the results of vulnerability research to other academics, researchers, policy makers, and the community at large. Maps of exposure to environmental and technological risk have long been used in disaster management, and now the development of spatially referenced indicators such as the Social Vulnerability Index in the United States (71) has enabled disaster mapping to become increasingly sophisticated in the spatial representation of other aspects of vulnerability. Many vulnerability assessments today, including several of the studies described above, are making extensive use of GIS and remotely sensed environmental data to ground theoretical analyses of vulnerability in spatially specific evaluations of risk (65, 66, 72, 73). For example, Peterson (70) uses a probabilistic model to estimate the relative resilience or vulnerability of a landscape to a shift in vegetation. In this study, *resilience* is defined as the probability that a given ecological state will persist. Peterson used a simulation model of northern Florida forest dynamics to map the vulnerability of landscape vegetation shifts from pryogenic longleaf pine (*Pinus palustris*) savanna to mesic oak (*Quercus* spp.) forest—a dynamic largely regulated by wildfires.

Other studies have focused on mapping the theoretical determinants of vulnerability in an effort to illustrate spatially the distribution of differential capacities and sensitivities. In this type of work, the selection and definition of the spatial scale of analysis is a crucial issue, as the weight and relevance of particular indicators change with scale and degree of data aggregation (74). O'Brien et al. (72), for example, use a GIS to explore the exposure of Indian farm populations to both global economic change and climate change. Through the creation of adaptive-capacity and sensitivity indices using existing socioeconomic and biophysical databases in combination with a downscaled general circulation model, the authors superimpose maps of vulnerability to globalization over those showing vulnerability to climate change to illustrate the double exposure of populations to these stresses (75). To interpret the spatial relationships they observe, they employ case studies using surveys and interviews to explain the interaction of globalization and climate on the livelihoods of particular local populations. The challenge remains, however, for this and most mapping exercises to account for the dynamic nature of vulnerability and to represent spatially some indicators (e.g., social capital, institutional relations) that may well be the determinant of vulnerability in particular places. O'Brien et al. also point out that maps can imply abrupt rather than more realistic "fuzzy" boundaries of vulnerability across space and can mask the diversity of vulnerability states at different scales of analysis.

Ranking and Comparing Vulnerability

Over the past decade, several projects have compared and even ranked vulnerability across regions, countries, and populations, with the objective of aiding governmental bodies and other organizations in the allocation of resources for vulnerability reduction. This exercise has been particularly important in climate change research. On the basis of primarily national-level data (76–78), these attempt to monitor either the coincidence of hypothesized drivers of vulnerability (as measured by incidences of disaster, mortality, or morbidity) to climate-related stressors (73, 78) or the susceptibility of a population to such impacts (e.g., incidences of disaster, mortality, or morbidity) to climate-related stressors. Ranking and comparing vulnerability across countries, however, is challenged by everything from the quality of the available data, to the selection and creation of indicators, to the assumptions used in weighting of variables and the mathematics of aggregation. There are also problems in the interpretation of indices and the need for constant updating of the resulting vulnerability scores in order to reflect the dynamic nature of the subject. In the context of climate change, for example, can one compare the vulnerability of Haiti, an island state, to Burundi, a land-locked country? Can impacts of environmental change on the well-being of a farmer in Germany and another in Nicaragua be measured with the same variables?

Among researchers attempting such comparisons, Moss et al. (78) combined proxies for national sensitivity and adaptive capacity derived from international environmental and human development databases to create an index showing national vulnerability to climate change. Their ranking of countries proved to be sensitive to the selection the specific proxy variables, the baseline values of these proxies, as well as to whether vulnerability was indexed to the United States or a world-average value. They were concerned that the high degree of subnational variability in some proxies was lost in the creation of national-level indicators, thus masking potentially important subnational vulnerability processes (78, p. 26).

Critically, the significance—the importance weights—of particular indicators can vary significantly from place to place, depending on cultural characteristics, domestic policy, or other issues difficult to perceive in aggregated data. Brooks and coworkers (77) create a climate change vulnerability index in which the significance of indicators is tested through a process of statistical correlation with a risk outcome (mortality to climate hazards as quantified in a global database). They compare two methods of weighting the indicators in the creation of their vulnerability index: first, a process in which all indicators are weighted equally and, second, a process that derives indicator weights from consultation with experts. Although their ranking exercise does not produce surprising results in terms of the rank location of particular countries (here, national income appears determinant), it does provide interesting results regarding the importance of particular complex social variables—governance and institutional structures, for example—in overall vulnerability scores.

Participation and Policy Linkages

Increasingly the participation of existing or potentially vulnerable populations in the evaluation of their vulnerability is recognized as essential if assessments are to be useful for policy makers (82). Disaster management experts have agued that enabling communities to define their own susceptibility to loss and then empowering them to address that susceptibility is critical for disaster reduction (83, 84). Merely labeling a population vulnerable, for example, may be one further step in a long history of marginalization and disempowerment for some social groups (83).

Achieving effective participation in assessments is fraught with difficulties—not least because vulnerable populations may be institutionally and economically invisible and disenfranchised. Despite the challenges, some vulnerability assessments have aimed to be explicitly stakeholder driven. The Climate Assessment for the Southwest United States, for example, used workshops, interviews, and surveys with local experts, decision makers, and different economic groups (e.g., ranchers, water users and managers, forest fire managers) to establish a scientific agenda to evaluate vulnerability to climate variability and change that corresponded to the information needs of stakeholders (85). By establishing a clearing house, the project has formalized communication channels, tailoring scientific output to meet local decision-making needs. The researchers acknowledge the difficulty of integrating disciplinary perspectives within the research team as well as between the scientists and the various types of decision makers in the region. However, they also argue their approach is essential to ensure that its outputs are applied to reduce regional vulnerability to climatic extremes (86).

Other assessments have used expert knowledge and stakeholder input to help address the inherent uncertainties in anticipating future socioeconomic change and vulnerability. Lorenzoni et al. (87) in collaboration with local experts and sector representatives developed downscaled climate change impact scenarios for East Anglia, United Kingdom, in order to better understand the interaction of both climate and social stresses in decision making. Their "coevolutionary approach" uses qualitative, plausible social scenarios in combination with the outputs of climatic change models in a participative process with stakeholders to outline the important feedbacks and possible synergies among climatic stressors, nonclimatic stressors, and socioeconomic change. On the basis of this participatory process, they qualitatively mapped the pathways of current decisions and actions into the future to create grounded scenarios of future vulnerability (88).

CURRENT CHALLENGES IN VULNERNABILITY ANALYSIS

Collectively, the literature reviewed in the previous section has pointed to a series of challenges—logistical, theoretical, and conceptual—facing the development of vulnerability research. We have selected a few of these for explicit consideration in future vulnerability assessments.

- Addressing multiple, interacting stressors
- Capturing socioeconomic and biophysical uncertainty
- Accounting for cross-scalar influences and outcomes
- Emphasizing equity and social justice

Addressing Multiple and Interacting Stressors

How to identify and evaluate the diversity of stressors most relevant to a vulnerability assessment remains a central question of what Cutter has called "vulnerability science" (8) and has been featured in many of the recent vulnerability assessments mentioned above. The rapid and devastating spread of infectious diseases such as HIV, Ebola, or SARS; the occurrence of war and civil strife; and the disturbing increases in economic marginalization and social inequality accompanying globalization are now all being tied to environmental factors and the production and reduction of climate vulnerability in local places (55, 68b, 89). Several international research and policy initiatives have been launched to formally address these linkages under the rubric of "human-environment security" (see, for example, the World Conservation Union's Human Security/Environment program, the Global Environmental Change and Human Security Project, and the Environmental Security program of the International Institute of Sustainable Development).

Although the links among these disparate processes make intuitive sense, demonstrating them empirically and determining the relative importance of different causal processes on vulnerability are quite difficult. There are still large uncertainties, for example, in connecting social conflict with climate (90) and disease outbreaks with climate (91). O'Brien et al.'s model of double exposure as applied to India (72) (described above) is attractive in that it captures visually the idea of overlapping stressors on a population, yet the nature of the interaction, the relative importance of distinct stressors for particular systems at any given time, and the possible nonlinear responses of a system to multiple stressors remain elusive.

The long-range temporal perspective and interdisciplinary methods of some of the recent work on resilience have offered some insights into these complex interactions and their implications for present-day human activities, ecosystem dynamics, and environmental quality. Analyses of sustainable livelihoods have also offered more refined understandings of what types of diverse stressors matter to particular populations and how these stressors combine to affect response strategies (e.g., 60, 92). Ultimately, although it is increasingly accepted that "single-stressor–single-outcome" approaches (e.g., the impact of doubled CO_2 on crop yield) fail to capture the reality of vulnerability for most systems, much more research is needed on how to best elucidate the implications of global environmental change for particular systems in multistressor contexts.

Capturing Socioeconomic and Biophysical Uncertainty

Vulnerability assessment not only involves multivariate analysis but also demands a consideration of the high degree of uncertainty and surprise in both human and biophysical systems (8). Although, as Berkhout argues, "the future has to be seen as mutable, and to some extent at least, created out of purposive decisions and actions in the present" (93, p. 166), many vulnerability assessments demand assertions about future states. Furthermore, if the system in question does not effectively recognize signals of change, there is a greater possibility of maladaptations and ineffective responses to stress as those changes unfold (94).

The approach of adaptive management, as discussed in much of the resilience literature, may provide some lessons for making policy and institutions more flexible in the face of uncertainty (95, 96). These lessons may eventually lead to the identification of specific indicators of the future capacity of particular systems to confront stress. Patt et al. (97) point out that time is the critical variable: Current methods for projecting and validating evaluations of future capacities, sensitivities, and responses on the basis of present patterns of resource distribution are unlikely to be sufficiently reliable to aid decision makers.

Vulnerable systems and populations are also themselves sources of environmental change at different scales, adding to uncertainty in assessments (1). The successful responses of some exposure units to present-day environmental stress may enhance the sensitivities of systems at broader scales or may result in critical feedback loops that increase their future vulnerability. Mapping such "nested and networked" vulnerabilities may provide valuable insights into the coproduction of vulnerability and opportunity across the globe as adaptation processes occur simultaneously (98).

Exercises in future visioning (99) and recent experiments with the use of multiagent-based modeling in exploring land-use change (100) and seasonal climate-forecasting use (101, 102) have attempted to capture some of this complexity. Agent-based methods attempt to use decision rules to capture the interaction of actors in specific environments over time. These methods essentially enable the inherent uncertainty in human-environment interaction to become part of the evolution of the system, potentially allowing researchers and stakeholders to perceive unexpected or emergent outcomes. These and other dynamic decision models hold some promise as tools for illustrating how individual actions can contribute to cumulative change at broader scales and for discussing the desirability of these scenarios of change with stakeholders. More work is required in this area, however, particularly considering the new international interest in building adaptive capacity as part of policy to reduce vulnerability in particular geographic contexts (82).

Cross-Scalar Influences and Outcomes

One of the outstanding conclusions emerging from the recent history of vulnerability analysis is the scale-dependent nature of vulnerability. Wilbanks & Kates (103) outline six arguments for the importance of scale in global change research, and they illustrate how climate change affects different scale domains (e.g., global, regional, large areas, and local) differentially according to whether one is addressing issues of response, impacts, or the direct or proximate causes of climate change. Tools for addressing the problem of scale such as downscaling, nested economic models, and geographic information systems have often been limited by data constraints, modeling capabilities, and the lack of appropriate integrating frameworks (104).

Scale is not only a concern of the unit of analysis in research but also an issue of compatibility with decision making. Cash & Moser (105) argue that scientific assessments often are implemented at geographic scales that are incongruous with the scale at which management occurs. Clark et al. (106) propose selecting the scales at which vulnerability assessments should take place according to the scales at which social-environmental interactions are particularly intense or problematic and at which such interactions are managed. This proposal reflects a pragmatic approach to vulnerability research in which the needs of stakeholders and decision makers are explicit in the assessment design, and scale concerns are driven by these interests. Increasingly, however, there may be a need to question the utility of defining and analyzing vulnerability in terms of bounded economic sectors, regions, or population groups that inevitably define the geographic scale and scope of vulnerability assessments. In fact, vulnerability may be manifest precisely in the complex process of interactions within and between sectors, spatial and temporal scales, and human-environmental systems (106).

Equity and Justice

There is now widespread recognition that the challenges of managing global environmental and social change are embedded in questions of equity, justice, and ethics (107–110). Regardless of the approach employed, research addressing vulnerability is undeniably grounded in human values attached to particular systems, populations, and places. Action is taken to enhance the resilience of the Mongolian steppes, Amazon watershed, or coastal populations in Vietnam because these systems are demonstrated to be of value ecologically, economically, and socially. The concept of vulnerability also gives rise to issues of social responsibility, in terms of both the obligations of those who inflict harm on others (111) and also in terms of the implied responsibility of governments toward populations particularly susceptible to loss within their jurisdiction. Although rarely made explicit, such issues of values underlie any assessment of vulnerability, raising questions about whose values drive policy decisions and what the consequences of policy action will be for particular peoples and places. However, as Brown (112) argues in his discussion of greenhouse gas mitigation policy, the essential ethical content of global change research is often lost in debates dominated by questions of economic and scientific fact and certainty.

O'Brien (113) proposes that by framing climate change research in terms of equity, the links between vulnerability, development processes, and human security outcomes become more tangible, and policy responses will be more likely to address directly the fundamental issues of concern in vulnerability research. Sarewitz et al. debate this problem, noting that addressing risk—a concept to which cost-benefit analyses and discount rates can be applied—is often far more politically palatable then dealing with vulnerability: "risk turns more heads and grabs more headlines than vulnerability" (114, p. 809). They reject a limited focus on risk, however, arguing that "in a human rights context, issues of cost/benefit and debates over uncertainty not only lose their centrality but are rendered inappropriate" (114, p. 810).

In short, it is clear that the social context of vulnerability—particularly the institutional and political-economic dimensions of the problem—is not simply the domain in which environmental change and/or extreme events occur but rather is an integral part of vulnerability. Vulnerability demands assessments in which values are made explicit, entitlements are reviewed and questioned, and new mechanisms for addressing existing inequities are implemented. Improving vulnerability assessments in this way may well mean incorporating a greater diversity of academic perspectives, including the humanities, while also developing new tools for effective incorporation of nonacademic voices in vulnerability research.

INTEGRATING APPROACHES

The lack of a comprehensive, widely applicable theory or framework to guide both analyses and programmatic efforts for vulnerability reduction has become the bane of vulnerability research. Various models have been proposed over the past few decades, addressing to different degrees the issues raised in the previous section (see, for example 7, 20, 25). Below, we provide two recent proposals for integrated vulnerability analysis selected not because of their widespread usage or demonstrated success in addressing the challenges described above but rather because they represent contrasting approaches to improving the relevance of vulnerability analysis in decision making.

Research and Assessment Systems for Sustainability Science Program

One recent attempt to address all of these concerns is the vulnerability framework (SUST Framework) of the Research and Assessment Systems for Sustainability Science Program. This framework endeavors to integrate elements from risk/hazard approaches, entitlement analyses, and ecological theory into a single, multiscalar model of vulnerability (5). The unit of analysis or exposure in this framework is the coupled human-environment system rather than a particular sector, ecosystem, population, or economic activity. The model presents vulnerability as a product of the simultaneous interaction of multiple biophysical and human processes, stresses, and shocks acting on the coupled system, which may respond nonlinearly and dynamically with multiple feedbacks across scales. Although both qualitative and quantitative data are used in the illustrative assessments explored for this model (e.g., satellite data, soil quality data, climate data, demographic and economic data, as well as data collected in interviews, surveys, and focus groups), the integration of the data and the overall system's analysis is largely qualitative (115). The final outcome of the analysis is not necessarily the identification of present or future impacts on the system, or the identification of particularly vulnerable populations, but rather the illumination of the processes and interactions that are generating vulnerable conditions.

One of the primary aims of the SUST framework is to guide decision makers and practitioners through the key processes and feedbacks that create vulnerable conditions. However, in practice this goal is challenged by the complexity of the framework (115). Large interdisciplinary teams and significant financial resources may also be required in order to capture the full dynamics, as described in the framework, of any particular system selected for study, making the application of the framework difficult in resource-scarce regions. As others have illustrated, the challenge of undertaking place-based research while incorporating local to global interactions of both social and environmental processes, although increasingly viewed as essential in vulnerability research, is methodologically difficult (74).

The United Nations Development Programme Adaptation Policy Framework

The persistent lack of one unifying framework and theory of vulnerability has led some to argue for a more pragmatic approach, one that embraces the inevitable diversity of vulnerability applications and thus the need for flexibility in indicators, methodology, and frameworks (116). This pragmatic approach to vulnerability assessments is epitomized in the United Nations Development Programme's Adaptation Policy Framework (APF), which is intended to be used by stakeholders and researchers in developing countries to facilitate the process of adaptation to climate change (82).

The premise of the APF is that improving adaptive capacity is essential for mitigating vulnerability: Lack of capacity is, essentially, equivalent to vulnerability. Toward this goal, the APF outlines four general approaches: a climate hazards approach, a vulnerability-based approach, a policy-analysis approach, and an adaptive capacity approach (82). Instead of advocating the adoption of one conceptual framework, the APF argues for the selection of indicators, methods, and a unifying framework that best fits the scale and scope of the unit(s) of analysis, the available data, available resources, and goals of policy in the region in which the vulnerability analysis will be applied. The particular approach used would depend on the stage of the analysis—whether the research team is characterizing present vulnerabilities, identifying future climate risks, evaluating adaptive capacities, or elaborating possible adaptation options—as well as the needs and resources available to the research team. In addressing vulnerability, the approach draws heavily from food security, sustainable livelihood, and poverty assessments, so it reflects an anthropocentric conception of vulnerability in which the people, their activities, their institutions, and the resource systems on which they depend are the center of analysis.

Arguing that vulnerability is fundamentally a relative phenomenon and not something that can be directly observed and measured, the APF's technical paper on vulnerability assessment proposes the adoption of a common mathematical nomenclature for vulnerability (116). This mathematical nomenclature posits vulnerability in relational terms—in terms of the threat in question (e.g., climate change, hurricanes, and earthquakes) and of the sector, population, and impact or consequence of interest:

$$(T)\, V_{s,g}^{c},$$

where T is the threat, e.g., drought, climate change; s is the sector, e.g., health; g is the group, e.g., rural landless; and c is the consequence, e.g., loss of life.

The use of this nomenclature is expected to help stakeholders pinpoint precisely the type of vulnerability they are evaluating in ways that are most compatible with existing public policy. Various quantitative and qualitative methods are proposed for assessing the population's sensitivity and for identifying the dynamic drivers of vulnerability at different spatial and temporal scales. The resulting output of the vulnerability assessment is the identification of presently vulnerable groups/sectors/systems/regions and the development pathways that lead to different scenarios of potential future vulnerability. The purpose of such an analysis is to help policy makers in defining where programmatic efforts to reduce vulnerability and facilitate adaptation should be made and in identifying what types of development paths might lead to greater vulnerability in the future.

A Road Map for Future Assessments

Conceivably the theoretical ambitions of the SUST framework and the pragmatism of the APF might work together, despite their distinct points of departure. What is required is a road map for assessment that facilitates the explicit consideration of ethics, scale, uncertainty, and multivariate and dynamic interactions without prescribing methods or a particular world view. The existing literature, reviewed in the previous sections, provides the outline for the road map, suggesting some central components of assessment and key questions that are critical for integrated perspectives on vulnerability. The APF, for example, emphasizes the need to define the system of analysis and exposure unit in relation to the needs of decision makers and in relation to specific negative outcomes that are to be avoided. In contrast, the SUST framework places more emphasis on exploring the interactions between the drivers acting on and within the system that lead to more (or less) sustainable outcomes. A combination of the two implies explicit attention to both the social values and desires that define the scope of analysis and units of exposure as well as a rigorous exploration of the dynamic, relational, and interactive aspects of vulnerability in coupled human-environment systems.

With the intention of providing synthesis across lineages and disciplines while also a way forward, we have identified a series of central components for vulnerability assessment and key research questions associated with each component (Table 2). Although several of the components we list are familiar, i.e., defining exposure units, sensitivities, capacities, and outcomes, we propose others that are perhaps less familiar but also, perhaps, more critical. These include making explicit the values that that define the system and units of analysis in any assessment and, given those values, characterizing what is damage, loss, or harm to the system of concern. There is also a need for more attention to defining the complex interactions among drivers of change and among these drivers and the unit(s) of exposure. Central to this process is the characterization of thresholds that delineate harm. These thresholds will inevitably reflect values that may change or vary between populations and systems. Conceptual or quantitative models are needed to link units of exposure, specific stressors, and potential negative outcomes. Whereas in many outcome-oriented assessments vulnerability is evaluated in relation to a relatively narrow range of scenarios of harm, here we propose that assessments consider multiple scenarios of change to the system, each dependent on the cross-scalar and dynamic interactions of the drivers and units of exposure in the system in question. Stakeholders and policy makers can then identify scenarios to be avoided and work to reinforce the institutions that are most likely to lead to the preferred state(s) of the system.

CONCLUSION

The surge in interest in vulnerability in the 1990s has been driven in large part by the global environmental change community where there was a marked shift in focus from the diagnosis of impacts to an evaluation of the processes, conditions, and characteristics of systems that exacerbate sensitivity and inhibit adaptive response. This shift in focus can also be viewed as a convergence of three paradigms of vulnerability assessment, bringing together insights from diverse disciplines on global environmental change, natural disasters, and human-environmental interaction. Consequently, vulnerability research now exhibits increasing complexity and methodological diversity, as researchers explore and, in some cases, attempt to clarify the many uncertainties in the concept's meaning and measurement.

The apparent lack of consistency in the use and meaning of the variety of concepts employed in vulnerability research contributes to impeding communication across disciplines and to inhibiting the full incorporation of relevant lessons from research on, for example, poverty, environmental quality, food security, resource management, or public administration and institutional development. Clarity in

TABLE 2 Core components of vulnerability assessment[a]

Assessment components	Key questions	Component featured in existing vulnerability approaches?[b]
Definition of the human-environment system	What is the scope of assessment?	R
Definition of the desired state(s) of system	Why do we care? What future is valued highly in this system? Whose values are important and why?	None adequately
Definition of the exposure unit(s)	Who or what is (potentially) vulnerable?	R, H, P
Identification of attributes of concern and definition of damage	What is dangerous or undesirable for the unit(s) of analysis? What is dangerous for the system of study? What is the relationship between harm and the unit of study, and harm and the human-environment system?	R, H, P
Identification of proximate and underlying drivers of system Delineation of interactions among drivers Delineation of interactions between drivers and unit(s) of analysis	What social and biophysical factors are driving change in the system? What are the immediate threats and how are they evolving? Where are the greatest uncertainties about the system's change? What are the underlying causes of differential susceptibility?	R, H*, P
Evaluation of differential capacities and sensitivities (considering fast and slow variables)	Who or what has least capacity to respond and why? What explains differential capacities to cope and adapt? Why and how do systems change?	R*, P

Identification of thresholds of change	How can a shift in the state of the system be observed? What indicators will signal that a threshold has been passed? How does the identified threshold relate to the desired state of the system or welfare of the unit(s) of exposure	R, H, P*
Model relationship between stressors, attributes, and outcomes	How does the system respond to stress?	R, H, P
Characterization of plausible outcomes of change; evaluation of relation of plausible outcomes to desired outcomes	What range of changes can be expected? What outcomes are least tolerable? Who loses, who gains?	R, H*, P*
Characterization of actions to avoid undesired states	What actions can be taken now to increase future flexibility? What capacities are needed to enable desired response to change? What policies are needed to support these capacities?	R*

[a]This table highlights what we consider to be the core components of vulnerability assessment and their associated questions. The last column of this table shows where research in each of the three lineages has focused traditionally.

[b]Abbreviations: R, resilience; H, risk/hazard; P, political ecology/economy; *, to limited extent or not with the intention suggested in this table

the identification of the unit and scale of analysis, intended audience, purpose of assessment, and aspect of vulnerability being addressed is helpful (e.g., Is the study defining underlying vulnerability drivers? immediate causes of negative outcomes? differential capacities to cope and adapt? differential sensitivities to impacts?). Such clarity inhibits overly ambitious research claims and facilitates meta-analyses and cross-case study comparisons. In part because of the lack of such clarity, the past decade has not produced any consensus on the best practice for vulnerability research.

That said, incremental progress has been made. In distinguishing vulnerability assessments from climate impact assessments, it is now recognized that vulnerability involves far more than its manifestation in loss and harm. The growing contribution of research from political ecology and ecological resilience has illuminated the importance of capacity, organization, and learning as well as cross-scalar linkages in both the production and reduction of vulnerability. It is also clear that, in part, the substantial differences in approach and method in vulnerability research can be attributed to the central questions of interest, the intended research audience, and the disciplinary composition and history of the research team. A significant challenge for the future is to develop research models that unite these disparate contributions coherently to support more effective policy and decision making in the area of vulnerability reduction. We hope that the simple road map we have provided here will be a first step in this direction.

Although the precise meaning of vulnerability and thus its identification and measurement remains a subject of debate, there appears to be some consensus about what vulnerability assessments should aim to do. Vulnerability is a relative concept: its cultural, political-economic, and physical geography is essential to its evaluation. Vulnerability assessments thus appear most successful—or perhaps most relevant—when they are conducted for defined human-environment systems, particular places, and with particular stakeholders in mind. Assessment of vulnerability is thus unlikely to be boiled down to a single recipe. The most constructive contributions from these assessments are likely to come from the recognition that the research process itself involves integration of paradigms and worldviews that are not easily reconcilable, and in that process, a considerable amount of humility is needed.

This humility is central to the inescapable ethical ambition of vulnerability research. Vulnerability is inherently about ethics and equity. The questions that vulnerability analyses raise about resource access, risk exposure, and opportunity to live safely and securely are also political. As we consider future scenarios, vulnerability research demands attention to the difficult questions of how and why populations are able to manage risk differently, and what the implications of decisions today will be for the vulnerability of ourselves and others tomorrow. For this reason, the institutional context of vulnerability is increasingly impossible to ignore, requiring new analytical methods and approaches and both critical and practical research stances to bridge the science/policy divide and facilitate the translation of theory into decision making and practice.

ACKNOWLEDGMENTS

The authors greatly appreciate the comments and suggestions of N. Adger, K. O'Brien, and D. Liverman on earlier drafts of this chapter, the editorial assistance of S. and J. Eakin, and the suggestions provided by the editorial committee on behalf of anonymous reviewers.

The *Annual Review of Environment and Resources* is online at http://environ.annualreviews.org

LITERATURE CITED

1. Liverman DM. 2001. Vulnerability to global environmental change. See Ref. 99, pp. 201–16
2. Kasperson JX, Kasperson RE. 2001. Workshop summary. *Int. Workshop Vulnerability Glob. Environ. Change*, Stockholm: Stockh. Environ. Instit.
3. Alwang J, Siegel P, Jorgensen SL. 2001. *Vulnerability: a view from different disciplines*. Soc. Prot. Discuss. Pap. Ser.115, Soc. Prot. Unit, World Bank, Washington, DC. 42 pp.
4. Kelly PM, Adger WN. 2000. Theory and practice in assessing vulnerability to climate change and facilitating adaptation. *Clim. Change* 47:325–52
5. Turner II BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, et al. 2003. A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. USA* 100:8074–79
6. Klein RJT, Nicholls RJ, Thomalla F. 2003. Resilience to natural hazards: How useful is this concept? *Environ. Hazards* 5:35–45
7. Cutter SL. 1996. Vulnerability to environmental hazards. *Prog. Hum. Geogr.* 20:529–39
8. Cutter SL. 2003. The vulnerability of science and the science of vulnerability. *Ann. Assoc. Am. Geogr.* 93:1–12
9. Vogel C. 1998. Vulnerability and global environmental change. *LUCC Newsl.* 3 http://www.geo.ucl.ac.be/LUCC/lucc.html
10. IPCC Working Group II, ed. 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge, UK: Cambridge Univ. Press http://www.grida.no/climate/ipcc_tar/wg2/index.htm

10a. Reilly JM, Schilmmelpfenning D. 1999. Agricultural impact assessment, vulnerability and the scope for adaptation. *Clim. Change* 43:745–88

10b. Gunderson LH, Holling CS. 2001. *Panarchy: Understanding Transformation in Human and Natural Systems*. Washington, DC: Island

11. Janssen MA, Schoon ML, Ke W, Börner K. 2006. Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. *Glob. Environ. Change* 16:240–52
12. White G. 1973. Natural hazards research. In *Directions in Geography*, ed. RJ Chorley, pp. 193–216. London: Methuen
13. Burton I, White G, Kates R. 1978. *Environment as Hazard*. New York: Oxford Univ. Press
14. Brooks N. 2003. *Vulnerability, risk and adaptation: a conceptual framework*. Work. Pap. 38 Tyndall Cent. Glob. Environ. Change, Univ. East Anglia, Norwich, UK. http://www.tyndall.ac.uk/publications/working_papers/working_papers.shtml
15. US Ctry. Stud. Program. 1994. *Guidance for Vulnerability and Adaptation Assessment*. Argonne, IL: Argonne Natl. Lab.

16. Smith J, Huq S, Lenhart S, Mata LJ, Nemesová I, Toure S, ed. 1996. *Vulnerability and Adaptation to Climate Change: Interim Results from the U.S. Country Studies Program*. Dordrecht, Neth.: Kluwer Acad. 366 pp.
17. Easterling W. 1996. Adapting North American agriculture to climate change in review. *Agric. For. Meteorol.* 80:1–53
18. Iglesias A, Erda L, Rosenzweig C. 1996. Climate change in Asia: a review of the vulnerability and adaptation of crop production. *Water Air Soil Pollut.* 92:13–27
19. Burton I, Huq S, Lim B, Pilifosova O, Schipper EL. 2002. From impacts assessment to adaptation priorities: the shaping of adaptation policy. *Clim. Policy* 2:145–59
20. Blaikie P, Cannon T, Davis I, Wisner B. 1994. *At Risk: Natural Hazards, People's Vulnerability and Disasters*. London: Routledge. 1st ed.
21. Hewitt K, ed. 1983. *Interpretations of Calamity*. Boston, MA: Allen & Unwin
22. Liverman D. 1994. Vulnerability to global environmental change. In *Environmental Risks and Hazards*, ed. SL Cutter, pp. 326–42. Englewood Cliffs, NJ: Prentice Hall
23. Ribot JC, Najam A, Watson G. 1996. Climate variation, vulnerability and sustainable development in the semiarid tropics. In *Climate Variability, Climate Change and Social Vulnerability in the Semi-arid Tropics*, ed. JC Ribot, AR Magalhaes, SS Panagides, pp. 13–51. Cambridge, UK: Univ. Cambridge Press
24. Sen A. 1990. Food, economics and entitlements. In *The Political Economy of Hunger*, ed. J Dreze, A Sen, pp. 50–67. Oxford, UK: Clarendon
25. Bohle HG, Downing TE, Watts MJ. 1994. Climate-change and social vulnerability—toward a sociology and geography of food insecurity. *Glob. Environ. Change* 4:37–48
26. Liverman D. 1990. Drought impacts in Mexico: climate, agriculture, technology and land tenure in Sonora and Puebla. *Ann. Assoc. Am. Geogr.* 80:49–72
27. Adger NW. 1999. Social vulnerability to climate change and extremes in coastal Vietnam. *World Dev.* 27:249–69
28. O'Brien K, Leichenko R. 2001. The dynamics of vulnerability to global change. *IHDP Update* 2: article 4. http://www.ihdp.uni-bonn.de/html/publications/update/update01_02/IHDPUpdate01_02_obrien.html
29. Adger WN, Benjaminsen TA, Brown K, Svarstad H. 2001. Advancing a political ecology of global environmental discourses. *Dev. Change* 32:681–715
30. Holling CS. 1973. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* 4:1–23
31. Walker B, Holling CS, Carpenter SR, Kinzig A. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecol. Soc.* 9:5. http://www.ecologyandsociety.org/vol19/iss2/art5
32. Holling CS. 1996. Engineering resilience versus ecological resilience. In *Engineering Within Ecological Constraints*, ed. P Schulze, pp. 31–44. Washington, DC: Natl. Acad. Sci.
33. Sullivan S. 1996. Towards a nonequilibrium ecology: perspectives from an arid land. *J. Biogeogr.* 23:1–5
34. Folke C, Carpenter SR, Elmqvist T, Gunderson LH, Holling CS, Walker BH. 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* 31:437–40
35. Sutherland J. 1974. Multiple stable points in natural communities. *Am. Nat.* 108:859–73
36. Ludwig D, Walker BH, Holling CS. 1997. Sustainability, stability, and resilience. *Conserv. Ecol.* 1:7. http://www.ecologyandsociety.org/vol1/iss1/art7
37. Noy-Meir I. 1975. Stability of grazing systems: an application of predator-prey graphs. *J. Ecol.* 63:459–81

38. Westoby M, Walker BH, Noy-Meir I. 1989. Opportunistic management for rangelands not at equilibrium. *J. Range Manag.* 42:266–74
39. Scholes RJ, Archer S. 1997. Interactions between woody plants and grasses in savanas. *Annu. Rev. Ecol. Syst.* 28:517–44
40. Chapin FSI, Peterson G, Berkes F, Callaghan TV, Angelstam P, et al. 2004. Resilience and vulnerability of northern regions to social and environmental change. *Ambio* 33:344–49
41. Timmerman P. 1981. Vulnerability, resilience and the collapse of society. *Rep. 1*, Inst. Environ. Stud., Toronto, Can.
42. Olsson P, Folke C. 2003. Adaptive comanagement for building resilience in social-ecological systems. *Environ. Manag.* 34:75–90
43. Newman L, Dale A. 2005. Network structure, diversity, and proactive resilience building: a response to Tompkins and Adger. *Ecol. Soc.* 10. http://www.ecologyandsociety.org/vol10/iss1/resp2/
44. Berkes F, Colding J, Folke C. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecol. Appl.* 10:1251–62
45. Carpenter SR, Walker BH, Anderies JM, Abel N. 2001. From metaphor to measurement: Resilience of what to what? *Ecosystems* 4:765–81
46. Adger WN. 2000. Social and ecological resilience: Are they related? *Prog. Hum. Geogr.* 24:347–64
47. Jones RN. 2001. An environmental risk assessment/management framework for climate change impact assessments. *Nat. Hazards* 23:197–230
48. Luers AL. 2005. The surface of vulnerability: an analytical framework for examining environmental change. *Glob. Environ. Change* 15:214–23
49. Mastrandrea MD, Schneider SH. 2004. Probabilistic integrated assessment of "dangerous" climate change. *Science* 304:571–75
50. Dessai S, Adger WN, Hulme M, Turnpenny J, Köhler J, Warren R. 2004. Defining and experiencing dangerous climate change. *Clim. Change* 64:11–25
50a. Carpenter SR, Ludwig D, Brock WA. 1999. Management of eutrophication for lakes subject to potentially irreversible damage. *Ecol. Appl.* 9:751–71
51. Christensen L, Coughenour MB, Ellis JE, Chen ZZ. 2004. Vulnerability of the Asian typical steppe to grazing and climate change. *Clim. Change* 63:351–56
52. Oyama MD, Nobre CA. 2003. A new climate-vegetation equilibrium state for tropical South America. *Geophys. Res. Lett.* 30:2199–202
53. Laurance WF, Williamson BG. 2001. Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. *Conserv. Biol.* 15:1529–35
54. Schellnhuber JH, ed. 2006. *Avoiding Dangerous Climate Change*. Cambridge, UK: Cambridge Univ. Press.
55. Bohle HG. 2001. Vulnerability and criticality. *IHDP Update* 2: article 1. http://www.ihdp.uni-bonn.de/html/publications/update/IHDPUpdate01_03.html
56. Antle JM, Capalbo SM, Elliot ET, Paustian KH. 2004. Adaptation, spatial heterogeneity and the vulnerability of agricultural systems to climate change and CO_2 fertilization: an integrated assessment approach. *Clim. Change* 64:289–315
57. Scoones I. 1998. Sustainable rural livelihoods: a framework for analysis. *IDS Work. Pap. 72*, Inst. Dev. Stud., Sussex, UK
58. Handmer JW, Dovers S, Downing TE. 1999. Societal vulnerability to climate change and variability. *Mitig. Adapt. Strateg. Glob. Change* 4:267–81
59. Forbes BC, Fresco N, Shvidencko A, Danell K, Chapin FSI. 2004. Geographic variations in anthropogenic drivers that influence the vulnerability and resilience of social-ecological systems. *Ambio* 33:377–82
60. Eakin H. 2005. Institutional change, climate risk, and rural vulnerability:

cases from central Mexico. *World Dev.* 33:1923–38

61. Vásquez-Léon M, West CT, Finan TJ. 2003. A comparative assessment of climate vulnerability: agriculture and ranching on both sides of the US-Mexico border. *Glob. Environ. Change* 13:159–73
62. Pelling M. 1999. The political ecology of flood hazard in urban Guyana. *Geoforum* 30:249–61
63. Pelling M. 1998. Participation, social capital and vulnerability to urban flooding in Guyana. *J. Int. Dev.* 10:469–86
64. Eakin H. 2003. The social vulnerability of irrigated vegetable farming households in Central Puebla. *J. Environ. Dev.* 12:414–29
65. Luers AL, Lobell DB, Sklar LS, Addams CL, Matson PA. 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. *Glob. Environ. Change* 13:255–67
66. Metzger MJ, Leemans R, Schroter D. 2005. A multidisciplinary multi-scale framework for assessing vulnerabilities to global change. *Int. J. Appl. Earth Obs. Geoinf.* 7:253–67
67. Polsky C. 2004. Putting space and time in Ricardian climate change impact studies: agriculture in the U.S. Great Plains, 1969–1992. *Ann. Assoc. Am. Geogr.* 94:549–64
68. Adger WN. 2006. Vulnerability. *Glob. Environ. Change* 16:268–81

68a. Adger WN, Brooks N, Bentham G, Agnew M, Eriksen S. 2004. New indicators of vulnerability and adaptive capacity. *Rep. 7*, Tyndall Cent. Clim. Change Res., Norwich, UK. http://www.tyndall.ac.uk/publications/pub_list_2004.shtml

68b. Vogel C, O'Brien KL. 2004. Vulnerability and global environmental change: rhetoric and reality. *AVISO* 13:1–8

68c. Leichenko R, O'Brien K. 2002. The dynamics of rural vulnerability to global change: the case of southern Africa. *Mitig. Adapt. Strateg. Glob. Change* 7:1–18

69. Carpenter SR, Brock WA, Hanson PC. 1999. Ecological and social dynamics in simple models of ecosystem management. *Conserv. Ecol.* 3:4. http://www.ecologyandsociety.org/vol3/iss2/art4/
70. Peterson GD. 2002. Estimating resilience across landscapes. *Conserv. Ecol.* 6. http://www.ecologyandsociety.org/vol6/iss1/art17/
71. Cutter S, Boruff B, Shirley WL. 2003. Social vulnerability to environmental hazards. *Soc. Sci. Q.* 84:242–61
72. O'Brien K, Leichenko R, Kelkar U, Venema H, Aandahl G, et al. 2004. Mapping vulnerability to multiple stressors: climate change and globalization in India. *Glob. Environ. Change* 14:303–13
73. Cutter SL, Mitchell JT, Scott MS. 2000. Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina. *Ann. Assoc. Am. Geogr.* 90:713–37
74. O'Brien K, Sygna L, Haugen JE. 2004. Vulnerable or resilient? A multi-scale assessment of climate impacts and vulnerability in Norway. *Clim. Change* 64:193–225
75. O'Brien KL, Leichenko RM. 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. *Glob. Environ. Change* 10:221–32
76. Pelling M, Uitto JI. 2001. Small island developing states: natural disaster vulnerability and global change. *Environ. Hazards* 3:49–62
77. Brooks N, Adger WN, Kelly PM. 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Glob. Environ. Change* 15:151–63
78. Moss RH, Brenkert AL, Malone EL. 2001. Vulnerability to climate change: a quantitative approach. *Rep. PNNl-SA-33642*, US Dept. Energy/Battelle, Oak Ridge, TN
79. Deleted in proof
80. Deleted in proof

81. Deleted in proof
82. UN Dev. Programme. 2004. *User's Guidebook for the Adaptation Policy Framework*. New York: UNDP
83. Ellemore H. 2005. Reconsidering emergency management and indigenous communities in Australia. *Environ. Hazards* 6:1–7
84. Wisner B, Blaikie P, Cannon T, Davis I. 2004. *At Risk: Natural Hazards, People's Vulnerability and Disasters*. London/New York: Routledge. 2nd ed.
85. Bales RC, Liverman DM, Morehouse BJ. 2004. Integrated assessment as a step towards reducing climate vulnerability in the southwestern United States. *Bull. Am. Meteorol. Soc*. 11:1727–34
86. Lemos MC, Morehouse BJ. 2005. The co-production of science and policy in integrated climate assessments. *Glob. Environ. Change* 15:57–68
87. Lorenzoni I, Jordan A, Hulme M, Turner RK, O'Riordan T. 2000. A coevolutionary approach to climate change impact assessment: Part I. Integrating socio-economic and climate change scenarios. *Glob. Environ. Change* 10:57–68
88. Lorenzoni I, Jordan A, O'Riordan T, Turner RK, Hulme M. 2000. A coevolutionary approach to climate change impact assessment: Part II. A scenario-based case study in East Anglia (UK). *Glob. Environ. Change* 10:145–55
89. Barnett J, Adger WN. 2005. *Security and climate change: towards an improved understanding*. Presented at Hum. Secur. Clim. Change, Asker, Nor.
90. Matthew RA, Gaulin T, McDonald. 2003. The elusive quest: linking environmental change and conflict. *Can. J. Polit. Sci.* 36:857–78
91. Patz JA, Campbell-Lendrum D, Holloway Foley JA. 2005. Impact of regional climate change on human health. *Nature* 436:310–17
92. Mortimore M, Adams WM. 1999. *Working the Sahel: Environment and Society in Northern Nigeria*. London: Routledge
93. Berkhout F, Hertin J. 2000. Socio-economic scenarios for climate impact assessment. *Glob. Environ. Change* 10:165–68
94. Schneider SH, Easterling WE, Mearns LO. 2000. Adaptation: sensitivity to natural variability, agent assumptions and dynamic spatial scale of climate change scenarios on economic assessments: an example from US agriculture. *Clim. Change* 60:131–48
95. Tomkins E, Adger WN. 2004. Does adaptive management of natural resources enhance resilience to climate change? *Ecol. Soc.* 9:10. http://www.ecologyandsociety.org/vol9/iss2/art10
96. Tompkins E, Adger WN. 2005. Defining response capacity to enhance climate change policy. *Environ. Sci. Policy* 8:562–71
97. Patt A, Klein RJT, de la Vega-Leinert A. 2005. Taking the uncertainty in climate-change vulnerability assessment seriously. *Comptes Rendus Geosci.* 337:411–24
98. Adger WN, Eakin H, Winkels A.2006. Nested and networked vulnerabilities in south east asia. In *Global Environmental Change and the South-East Asian Region: An Assessment of the State of the Science*, ed. L Lebel. Washington, DC: Island In press
99. Kasperson JX, Kasperson RE, ed. 2001. *Global Environmental Risk*. Tokyo/New York/Paris: UN Univ.
100. Parker DC, Manson SM, Janssen MA, Hoffmann MJ, Deadman P. 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. *Ann. Assoc. Am. Geogr.* 93:314–37
101. Ziervogel G, Bithell M, Washington R, Downing T. 2005. Agent-based social simulation: a method for assessing the impact of seasonal climate forecast applications among smallholder farmers. *Agric. Syst.* 83:1–26
102. Downing TE, Moss S, Pahl-Wostl C. 2001. Understanding climate policy

using participatory agent-based social simulation. *Lect. Notes Artif. Intell.* 1979:198–213

103. Wilbanks TJ, Kates RW. 1999. Global change in local places: how scale matters. *Clim. Change* 43:601–28
104. Timmerman P, Munn RE. 1997. The tiger in the dining room: designing and evaluating integrated assessments of atmospheric change. *Environ. Monit. Assess.* 46:45–58
105. Cash D, Moser SC. 2000. Linking global and local scales: designing dynamic assessment and management processes. *Glob. Environ. Change* 10:109–20
106. Clark W, Jaeger J, Corell RW, Kasperson RE, McCarthy JJ, et al. 2000. *Assessing vulnerability to global environmental risks*. Discuss. Pap. 2000–12, Environ. Nat. Resour. Program, Belfer Cent. Sci. Int. Aff., Kennedy School Gov., Harvard Univ., Cambridge, MA. http://ksgnotes1.harvard.edu/BCSIA/sust.nsf/pubs/pub1
107. Adger WN, Paavola J, Huq S, Mace MJ. 2006. *Fairness in Adaptation to Climate Change*. Cambridge: MIT Press
108. O'Brien KL, Leichenko RM. 2003. Winners and losers in the context of global change. *Ann. Assoc. Am. Geogr.* 93:89–103
109. Thomas DSG, Twyman C. 2005. Equity and justice in climate change adaptation among natural-resource-dependent societies. *Glob. Environ. Change* 15:115–24
110. Ikeme J. 2003. Equity, environmental justice and sustainability: incomplete approaches in climate change politics. *Glob. Environ. Change* 13:195–206
111. Dow K, Kasperson RE, Bohn M. 2006. Exploring the social justice implications of adaptation and vulnerability. See Ref. 107, pp. 77–96
112. Brown D. 2003. The importance of expressly examining global warming policy issues through an ethnical prism. *Glob. Environ. Change* 13:229–34
113. O'Brien K. 2006. Are we missing the point? Global environmental change as an issue of human security. *Glob. Environ. Change* 16:1–3
114. Sarewitz D, Pielke JR, Keykhah M. 2003. Vulnerability and risk: some thoughts from a political and policy perspective. *Risk Anal.* 23:805–11
115. Turner II BL, Matson PA, McCarthy JJ, Corell RW, Christensen L, et al. 2003. Illustrating the coupled human-environment system for vulnerability analysis: three case studies. *Proc. Natl. Acad. Sci. USA* 100:8080–85
116. Downing TE, Patwardhan A, Klein RJT, Mukhala E, Stephen L, et al. 2004. *Vulnerability assessment for climate adaptation*. Adaptation Policy Framework, Tech. Pap. 3, ed. B Lim. New York: UN Dev. Programme

Annual Review of Environment and Resources
Volume 31, 2006

Contents

Errata

An online log of corrections to *Annual Review of Environment and Resources* chapters (if any, 1997 to the present) may be found at http://environ.annualreviews.org