A framework for vulnerability analysis in sustainability science

B. L. Turner II[a,b,c], Roger E. Kasperson[b,d], Pamela A. Matson[e], James J. McCarthy[f], Robert W. Corell[g], Lindsey Christensen[e], Noelle Eckley[g,h], Jeanne X. Kasperson[b,d], Amy Luers[e], Marybeth L. Martello[g], Colin Polsky[a,b,g], Alexander Pulsipher[a,b], and Andrew Schiller[b]

[a]Graduate School of Geography and [b]George Perkins Marsh Institute, Clark University, Worcester, MA 01602; [d]Stockholm Environment Institute, S-130 14 Stockholm, Sweden; [e]Center for Environmental Science and Policy, Institute for International Studies, Stanford University, Stanford, CA 94305-6055; and [f]Department of Organismic and Evolutionary Biology, [g]Kennedy School of Government, and [h]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138

Communicated by Susan Hanson, Clark University, Worcester, MA, March 7, 2003 (received for review February 25, 2003)

Global environmental change and sustainability science increasingly recognize the need to address the consequences of changes taking place in the structure and function of the biosphere. These changes raise questions such as: Who and what are vulnerable to the multiple environmental changes underway, and where? Research demonstrates that vulnerability is registered not by exposure to hazards (perturbations and stresses) alone but also resides in the sensitivity and resilience of the system experiencing such hazards. This recognition requires revisions and enlargements in the basic design of vulnerability assessments, including the capacity to treat coupled human–environment systems and those linkages within and without the systems that affect their vulnerability. A vulnerability framework for the assessment of coupled human–environment systems is presented.

Research on global environmental change has significantly improved our understanding of the structure and function of the biosphere and the human impress on both (1). The emergence of "sustainability science" (2–4) builds toward an understanding of the human–environment condition with the dual objectives of meeting the needs of society while sustaining the life support systems of the planet. These objectives, in turn, require improved dialogue between science and decision making (5–8). The vulnerability of coupled human–environment systems is one of the central elements of this dialogue and sustainability research (6, 9–11). It directs attention to such questions as: Who and what are vulnerable to the multiple environmental and human changes underway, and where? How are these changes and their consequences attenuated or amplified by different human and environmental conditions? What can be done to reduce vulnerability to change? How may more resilient and adaptive communities and societies be built?

Answers to these and related questions require conceptual frameworks that account for the vulnerability of coupled human–environment systems with diverse and complex linkages. Various expert communities have made considerable progress in pointing the way toward the design of these frameworks (10, 11). These advances are briefly reviewed here and, drawing on them, we present a conceptual framework of vulnerability developed by the Research and Assessment Systems for Sustainability Program (http://sust.harvard.edu) that produced the set of works in this Special Feature of PNAS. The framework aims to make vulnerability analysis consistent with the concerns of sustainability and global environmental change science. The case study by Turner *et al.* (12) in this issue of PNAS illustrates how the framework informs vulnerability assessments.

The Emergence of Vulnerability Analysis

Approaches to and Composition of Vulnerability. Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor.[i] This definition and the concept it addresses are not new (13); they have emerged from sustained research and practice on risks and hazards, climate impacts, and resilience (14). A central lesson of this work recognizes that a focus limited to perturbations and stressors is insufficient for understanding the impacts on and responses of the affected system or its components (15–17). This lesson is underscored in two archetypal reduced-form models that have informed vulnerability analysis: the risk-hazard (RH) and pressure-and-release (PAR) models.

Foundational RH models (Fig. 1) sought to understand the impact of a hazard as a function of exposure to the hazard event and the dose–response (sensitivity) of the entity exposed (18, 19). Past quantitative applications of this model in environmental and climate impact assessment generally emphasized exposure and sensitivity to perturbations and stressors (20, 21) and worked from the hazard to the impacts. In some cases, vulnerability was explicitly addressed in the text, if not formally incorporated into the models used (19, 22). Various lines of investigation reveal the inadequacies of this RH model framework. For example, it does not treat: (*i*) the ways in which the systems in question amplify or attenuate the impacts of the hazard (23–26); (*ii*) the distinctions among exposed subsystems and components that lead to significant variations in the consequences of the hazards (27–31); and (*iii*) the role of political economy, especially social structures and institutions, in shaping differential exposure and consequences (32–39).

This recognition led to the PAR model (Fig. 2), in which risk is explicitly defined as a function of the perturbation, stressor, or stress and the vulnerability of the exposed unit (32). It directs attention to the conditions that make exposure unsafe, leading to vulnerability and to the causes creating these conditions. Used primarily to address social groups facing disaster events, the application of the model emphasizes distinctions in vulnerability by different exposure units (e.g., class, ethnicity). Although explicitly highlighting vulnerability, the PAR model seems insufficiently comprehensive for the broader concerns of sustainability science. Primarily, it does not address the coupled human–environment system in the sense of considering the vulnerability of biophysical subsystems (16); it provides little detail on the structure of the hazard's causal sequence, including the nested scales of interactions; and it tends to underemphasize

---

Abbreviations: RH, risk hazards; PAR, pressure and release.

[c]To whom correspondence should be addressed. E-mail: bturner@clarku.edu.

[i]Hazards are defined as threats to a system, comprised of perturbations and stress (and stressors), and the consequences they produce. A perturbation is a major spike in pressure (e.g., a tidal wave or hurricane) beyond the normal range of variability in which the system operates. Perturbations commonly originate beyond the system or location in question. Stress is a continuous or slowly increasing pressure (e.g., soil degradation), commonly within the range of normal variability. Stress often originates and stressors (the source of stress) often reside within the system. Risk is the probability and magnitude of consequences after a hazard (perturbation or stress).

www.pnas.org/cgi/doi/10.1073/pnas.1231335100

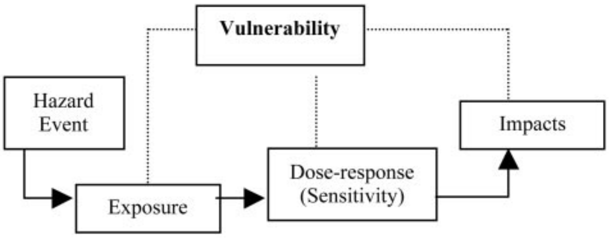

Fig. 1. RH framework (common to risk application). Chain sequence begins with hazard; concept of vulnerability commonly implicit as noted by dotted lines.

feedback beyond the system of analysis that integrative RH models include (19).

Anticipated by or explicitly embedded within the RH and PAR models, the development of vulnerability analysis draws on three major concepts: entitlement, coping through diversity, and resilience (16). Different systems maintain different sensitivities to perturbations and stressors, and this characteristic for individuals and groups (human) is strongly linked to entitlements: legal and customary rights to exercise command over food and other necessities of life (40). For example, modern famines follow not from insufficient food stocks but from the inability of social units to command food access through legal and customary means (41). These entitlements are determined by the units' endowments, especially what they have to sell, their ability to sell, and the price received; the cost of food relative to endowments; and access to markets and resources (40). Entitlement helps to explain why certain social units are differentially at risk (32).

Social units also have different coping capacities, which enable them to respond to the registered harm as well as to avert the potential harm of a hazard. In one sense, entitlement and endowment link to these capacities, and either concept can be expanded to include a large array of social institutions, such as societal "safety nets," that empower coping capacity (42). Yet entitlement and endowment are commonly reduced to questions of poverty, masking recognition that social units are not passive, and even the most economically marginal of them use a range of strategies to increase their defense mechanisms against hazards (43). Diversification is an overarching strategy aimed at reducing risks and increasing options in the face of hazards used worldwide and across economic classes and political economies, in some cases at the cost of reduced material well being (29, 32, 34, 37, 38, 44, 45). Such strategies notwithstanding, much of entitlement, endowment, and coping capacity rests within social, economic, institutional, and political structures (44–46), and therefore vulnerability analysis must account for them.

The third concept, resilience, enters vulnerability analysis from ecology, where it has evolved in meaning through extended debate and application. The concept has been used to characterize a system's ability to bounce back to a reference state after a disturbance (47, 48) and the capacity of a system to maintain certain structures and functions despite disturbance (49, 50). Recognizing that ecosystems often exhibit non- and multiequilibria dynamics, current resilience theories envision ecosystems as constantly changing (49, 51–53). As a result, the resilience of the system is often evaluated in terms of the amount of change a given system can undergo (e.g., how much disturbance or stress it can handle) and still remain within the set of natural or desirable states (i.e., remain within the same "configuration" of states, rather than maintain a single state). Resilience and related concepts influence a variety of interdisciplinary research focused on coupled human–environment systems (53–56), especially through the key component of "adaptive capacity," the flexibility of ecosystems, and the ability of social systems to learn in response to disturbances (57). Because different systems differ in their resilience characteristics, the explicit incorporation of differential resilience has become a critical element of analysis in human–environment systems.

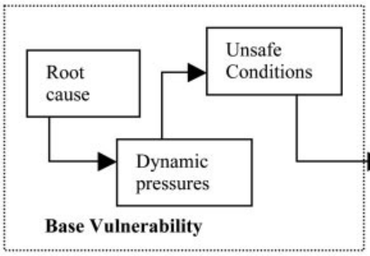

Fig. 2. PAR framework (common to risk research) with emphasis placed on "social" conditions of exposure; concept of vulnerability usually explicit.

Essential Elements for Expanded Vulnerability Analysis. The sustainability theme enlarges and redirects the focus of vulnerability analysis in several ways (10, 27, 28, 58–60). Primarily, it directs attention to coupled human–environment systems, the vulnerability and sustainability of which are predicated on synergy between the human and biophysical subsystems as they are affected by processes operating at different spatiotemporal (as well as functional) scales. We identify the following elements for inclusion in any vulnerability analysis, particularly those aimed at advancing sustainability:

(*i*) Multiple interacting perturbations and stressors/stresses and the sequencing of them;

(*ii*) Exposure beyond the presence of a perturbation and stressor/stress, including the manner in which the coupled system experiences hazards;

(*iii*) Sensitivity of the coupled system to the exposure;

(*iv*) The system's capacities to cope or respond (resilience), including the consequences and attendant risks of slow (or poor) recovery;

(*v*) The system's restructuring after the responses taken (i.e., adjustments or adaptations); and

(*vi*) Nested scales and scalar dynamics of hazards, coupled systems, and their responses.

In addition to these general elements, we suggest that approaches to and emphases within the vulnerability analysis are most useful to decision making (12, 60–62) when they:

(*i*) Complement the traditional perturbation/stressor-to-consequence approach by considering the outcomes to be avoided and working backwards toward the perturbation or stressor, thus elevating the need for stakeholder input;

(*ii*) Profile differential vulnerability, because subsystems and components of the coupled system are rarely equally vulnerable, no matter how the system may be bounded;

(*iii*) Are cognizant of the stochastic and nonlinear elements operating on and within the coupled system, giving rise to unexpected or surprise outcomes;

(*iv*) Give attention to the role of institutions operating as stressors or as a structure affecting system sensitivity and resilience;

(*v*) Identify suspect causal structures that affect vulnerability and test the cause-and-effect links through which they operate;

(*vi*) Develop appropriate metrics and measures for assessments, models, and tests; and

(*vii*) Develop institutional structures for linking vulnerability analyses to decision making, focusing on the salience, credibility, and legitimacy of information produced.

Vulnerability analysis may be undertaken at any spatial or

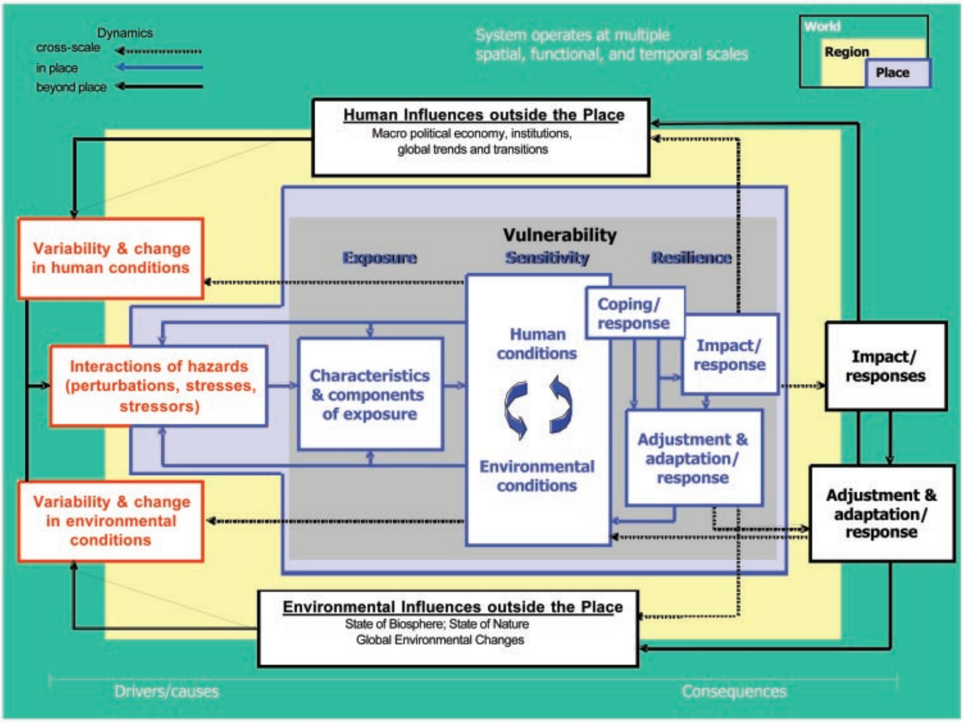

Fig. 3. Vulnerability framework. Components of vulnerability identified and linked to factors beyond the system of study and operating at various scales.

temporal scale suitable for the problem in question. The strong variation in vulnerability by location, even to hazards created by global-scale processes and phenomena, however, elevates the role of ''place-based'' analysis (6, 28, 63–66). The term ''place-based'' implies a spatially continuous distinctive ''ensemble'' of human and biophysical conditions or coupled human–environment systems (6, 67).[j] The growing role of multiple stakeholders in defining vulnerability problems, typical with local or localized concerns, lends increasing attention to this level of analysis while simultaneously linking to other places and scales of analysis (53, 64, 68).

Place-based approaches do not preclude the ability to develop general characterizations of the vulnerability of coupled systems (69). On the contrary, the use of place-based approaches makes obvious the need to find methods to operationalize vulnerability analysis that are useful for the specificity of place and for building general concepts from them. Some methodological approaches relevant for this search include semiquantitative typologies, such as ''degradation syndromes'' (70), complex indicator approaches (71–74), integrated modeling and simulation techniques (75), and statistical downscaling (75–77). The development of basic measures and metrics necessary for research and assessment is a subject of active research.

A particular strength of place-based analysis is its potential for increased public involvement and collaborative assessment, as advocated in the analytic–deliberative paradigm of risk analysis set forth by the National Research Council in its *Understanding Risk: Informing Decisions in a Democratic Society* (78) and in the U.S. National Assessment of *The Potential Consequences of Climate Variability and Change* (68). Creating effective strategies for reconciling and integrating lay and expert knowledge will prove challenging, but some promising models exist in various works (75, 79–81) that must also consider normative issues (71).

A Framework Revealed: Complexity Simplified and Illustrated

Comprehensive vulnerability analysis ideally considers the totality of the system. This ideal, however, is unrealistic. Real-world data and other constraints invariably necessitate a ''reduced'' vulnerability assessment. Nevertheless, analysts must remain aware that vulnerability rests in a multifaceted coupled system with connections operating at different spatiotemporal scales and commonly involving stochastic and nonlinear processes. Failure to consider this larger context could lead to the identification of ''response opportunities,'' which, if implemented, lead to significant unintended consequences or ''surprise'' (78, 82–84).[k]

The vulnerability framework presented here is guided by the need to provide a template suitable for ''reduced-form'' analysis yet inclusive of the larger systemic character of the problem. The framework is not explanatory but provides the broad classes of components and linkages that comprise a coupled system's vulnerability to hazards. The basic architecture (Fig. 3) consists of: (*i*) linkages to the broader human and biophysical (environmental) conditions and processes operating on the coupled system in question; (*ii*) perturbations and stressors/stress that emerge from these conditions and processes; and (*iii*) the coupled human–environment system of concern in which vulnerability resides, including exposure and responses (i.e., coping, impacts, adjustments, and adapta-

---

[j] Narrowly defined, place means location. Place does not imply specific spatial parameters. It is a relational term, connoting the existence of larger spatial scales in which the coupled human–environment system and its location are embedded. Much of the global change and geographic literature uses at least three terms that imply descending order of spatial scale: global, regional, and local or place.

[k] Surprise, strictly interpreted, cannot be anticipated. Much of what passes for surprise events, however, has been anticipated by someone, as in the case of chlorofluorocarbon–ozone linkages previous to the surprise discovery of the ''ozone hole.'' Perhaps the more appropriate issue is that of ''imaginable surprise'': when the ''event, process, or outcome departs from the expectations of the observing community or those affected by the event or process'' (ref. 84, p. 172). Reducing vulnerability analysis to make it tractable runs the danger of reducing expectations; thus, the need to remain aware of the larger vulnerability system in which the reduced analysis is undertaken.

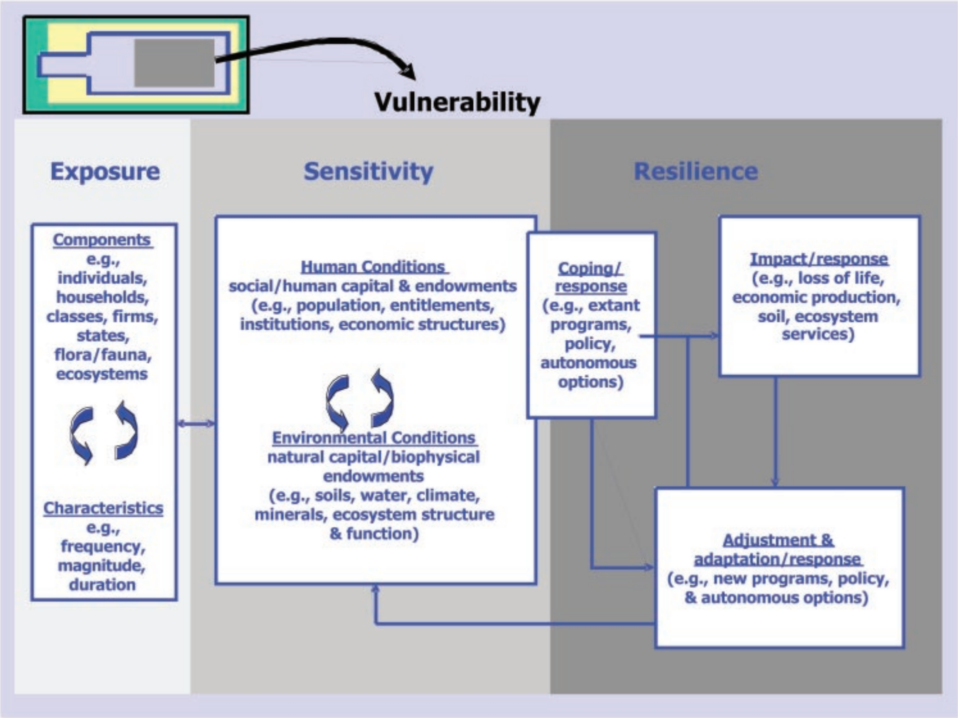

Fig. 4. Details of the exposure, sensitivity, and resilience components of the vulnerability framework. Figure at the top left refers to the full framework illustrated in Fig. 3.

tions). These elements are interactive and scale dependent, such that analysis is affected by the way in which the coupled system is conceptualized and bounded for study.

The full framework is illustrated in Fig. 3 by way of spatial scale, linking place (blue) to region (yellow) to globe (green), and various parts are elaborated in Fig. 4. The coupled human–environment system, whatever its spatial dimensions, constitutes the place of analysis. The hazards acting on the system arise from influences outside and inside the system and place but, given their complexity and possible nonlinearity, their precise character is commonly specific to the place-based system. For these reasons, the hazards themselves are located both within and beyond the place of assessment. These hazards hold the potential to affect the coupled system, including the ways in which the system experiences perturbations and stressors.

The human–environment conditions of the system determine its sensitivity to any set of exposures. These conditions include both social and biophysical capital that influences the existing coping mechanisms, which take effect as the impacts of the exposure are experienced, as well as those coping mechanisms adjusted or created because of the experience. For the human subsystem, these mechanisms may be individual or autonomous action and/or policy-directed changes. Importantly, the social and biophysical responses or coping mechanisms influence and feed back to affect each other, so that a response in the human subsystem could make the biophysical subsystem more or less able to cope, and vise versa. In some cases, coping mechanisms *per se* give way to adaptation, significant system-wide changes in the human–environment conditions. The responses, whether autonomous action or planned, public or private, individual or institutional, tactical or strategic, short- or long-term, anticipatory or reactive in kind, and their outcomes collectively determine the resilience of the coupled system and may transcend the system or location of analysis, affecting other scalar dimensions of the problem with potential feedback of the coupled system in question.

The framework illustrates the complexity and interactions involved in vulnerability analysis, drawing attention to the array of factors and linkages that potentially affect the vulnerability of the coupled human–environment system in a place. Its systemic qualities are open to left–right (hazards–consequences) or right–left (consequences–hazards) application, depending on the interest and aims of the user. As illustrated in the case studies of Turner *et al.* (12), however, different vulnerabilities in the system may be revealed by the direction of the analysis taken.

Vulnerability Analysis for Sustainability

An emerging consensus holds that vulnerability rests largely within the condition and dynamics of the coupled human–environment system exposed to hazards, and vulnerability analysis must be comprehensive, treating not only the system in question but also its many and varied linkages. Our review of the literature and experience in developing a vulnerability framework (12) suggest that the usefulness of vulnerability analysis increases when it:

(*i*) Directs attention to vulnerability anchored in the condition of the coupled human–environment system;

(*ii*) Identifies some of the complexity, interconnectedness, and iterative nature of the components giving rise to and comprising vulnerability;

(*iii*) Illuminates the nested scales of the vulnerability problem but provides an understanding of the vulnerability of a particular place;

(*iv*) Draws attention to the potential dynamics within the coupled system that give rise to new hazards;

(*v*) Facilitates the identification of critical interactions in the human–environment system that suggest response opportunities for decision makers;

(*vi*) Is open to the use of both quantitative and qualitative data and novel methods to derive and analyze information; and

(*vii*) Assists in the development of metrics, measures, and models for implementation.

Various initiatives identify the need for robust vulnerability analysis and, increasingly, sustainability and global change science is asked to improve the linkages between the science problem and decision-making needs (68, 83, 85). Although surely not complete, this vulnerability framework and the literature and case studies on which the framework draws, including the accompanying papers in this issue, suggest the following lessons, which have direct applicability for vulnerability assessments for decision making.[1]

(*i*) Human and biophysical vulnerability are linked and should be treated accordingly.

(*ii*) Beware of one-dimensional vulnerability analyses and be cognizant of varied components and scalar linkages in the coupled system, which increase the range of expected outcomes.

(*iii*) Do not assume that broadly similar coupled systems have the same vulnerabilities; complex dynamics may cause consequences to vary by system or locale.

(*iv*) Do not assume that all parts of the coupled system have the same vulnerability; subsystems and components, especially social units, may experience exposure differently, register different impacts, and maintain different response option.

(*v*) Although comprehensive vulnerability analysis and place-based variations in the coupled systems and processes affecting them favor multiple approaches, vulnerability assessments should follow a common general methodological framework.

(*vi*) Critical response opportunities are contingent on the coupled system or place in question; thus, general guidelines for response options should be malleable.

(*vii*) Conscious efforts must be made to create institutional structures that link vulnerability analyses to decision making.

Vulnerability analysis linked to sustainability requires maturation to better serve various environmental initiatives calling for increasing attention to the "so-what" questions: the International Geosphere–Biosphere Programme, International Human Dimensions of Global Environmental Change Programme, Millennium Ecosystem Assessment, and Diversitas, to name a few. This requirement builds from a rich tradition of past work toward comprehensive approaches that couple human and biophysical subsystems and detail their condition, function, and linkages to improve understanding of vulnerability and future projections thereof.

We are grateful for insights provided by Thomas Wilbanks, and we thank Rebecca Palmer for assistance. This work was supported in part by a grant from the National Science Foundation (BCS-0004236), with contributions from the National Oceanic and Atmospheric Administration's Office of Global Programs for the Research and Assessment Systems for Sustainability Program (http://sust.harvard.edu). It builds on collaborations sponsored by the Stockholm Environment Institute with Clark University, the Consortium for Social Science Associations, the International Human Dimensions Program, and the Land-Use/Cover Change Focus 1 Office at Indiana University.

---

[1] These points were developed, in part, through case studies presented by Turner *et al.* (12), which deal with the southern Yucatán, the Yaqui Valley, and the Arctic.

1. Steffen, W., Jäger, J., Carson, D. & Bradshaw, C. (2002) *Challenges of a Changing Earth* (Springer, Heidelberg).
2. Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellenhuber, H. J., Bolin, B., Dickson, N. M., *et al.* (2001) *Science* **292,** 641–642.
3. Kates, R. W., Clark, W. C., Correll, R., Hall, M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnbuber, H. J., Bolin, B., Dickson, N. M., *et al.* (2000) *Sustainability Discussion Paper 2000-33* (Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard Univ., Cambridge, MA).
4. Raven, P. H. (2002) *Science* **297,** 954–958.
5. Lee, K. N. (1993) *Compass and Gyroscope* (Island, Washington, DC).
6. National Research Council (1999) *Our Common Journey* (Natl. Acad. Press, Washington, DC).
7. Raskin, P., Chadwick, M., Jackson, T. & Leach, G. (1996) *The Sustainability Transition* (Stockholm Environment Institute, Stockholm).
8. Waggoner, P. E. & Ausubel, J. H. (2002) *Proc. Natl. Acad. Sci. USA* **99,** 7860–7865.
9. Burby, R. J. (1998) *Cooperating with Nature* (Joseph Henry, Washington, DC).
10. Kasperson, J. X. & Kasperson, R. E. (2001) *SEI Risk and Vulnerability Programme Report 2001-01* (Stockholm Environment Institute, Stockholm).
11. International Federation of Red Cross and Red Crescent (1999) *Vulnerability and Capacity Assessment* (Intergovernmental Panel on Climate Change, Geneva).
12. Turner, B. L., II, Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Hovelsrud-Broda, G. K., Kasperson, J. X., Kasperson, R. E., Luers, A., *et al.* (2003) *Proc. Natl. Acad. Sci. USA* **100,** 8080–8085.
13. White, G. F. (1974) *Natural Hazards* (Oxford, New York).
14. Cutter, S. (2001) *American Hazardscapes* (Joseph Henry, Washington, DC).
15. Mileti, D. S. (1999) *Disasters by Design* (Joseph Henry, Washington, DC).
16. Kasperson, J. X., Kasperson, R. E., Turner, B. L., II, Schiller, A. & Hsieh., W.-H. (2003) *The Human Dimensions of Global Environmental Change*, eds. Diekmann, A., Dietz, T., Jaeger, C. & Rosa, E. S. (MIT Press, Cambridge, MA).
17. White, G. F. & Haas, J. E. (1975) *Assessment of Research on Natural Hazards* (MIT Press, Cambridge, MA).
18. Burton, I., Kates, R. W. & White, G. F. (1978) *The Environment as Hazard* (Oxford Univ. Press, Oxford).
19. Kates, R. W. (1985) *Climate Impact Assessment*, eds. Kates, R. W., Ausubel, J. H. & Berberian, M. (Wiley, New York).
20. Warrick, R. (1980) in *Climatic Constraints and Human Activities* (Pergamon, Oxford), pp. 93–123.
21. Riebsame, W. E. (1991) *Gr. Plains Res.* **1,** 133–151.
22. Scientific Committee on Problems of the Environment (1978) *Report on the Workshop on Climate/Society Interface* (SCOPE, Paris).
23. Kasperson, R. E., Renn, O., Slovic, P., Brown, H., Emel, J., Goble, R., Kasperson, J. X. & Ratick, S. (1988) *Risk Anal.* **8,** 177–187.
24. Martine, G. & Guzman, J. M. (2002) *Environ. Change Sec. Proj. Rep.* **8,** 45–56.
25. Mitchell, J., Devine, N. & Jagger, K. (1989) *Geogr. Rev.* **79,** 391–409.
26. Palm, R. (1990) *Natural Hazards* (Johns Hopkins Univ. Press, Baltimore).
27. Cutter, S. (1996) *Prog. Hum. Geogr.* **20,** 529–539.
28. Cutter, S., Mitchell, J. T. & Scott, M. S. (2000) *Ann. Assoc. Am. Geogr.* **90,** 713–737.
29. Bohle, H.-G. (2001) *International Human Dimensions Programme (IHDP) Update* **2,** 1, 3–5.
30. Downing, T. E. (1991) *Glob. Environ. Change* **1,** 365–380.
31. Hewitt, K. (1983) *Interpretations of Calamity from the Viewpoint of Human Ecology* (Allen & Unwin, Boston).
32. Blaikie, P., Cannon, T., Davies, I. & Wisner, B. (1994) *At Risk* (Routledge, London).
33. Hewitt, K. (1997) *Regions of Risk* (Longman, Essex, U.K.).
34. Quarantelli, E. L. (1998) *What Is a Disaster?* (Routledge, London).
35. Comfort, L., Wisner, B., Cutter, S., Pulwarty, R., Hewitt, K., Oliver-Smith, A., Wirner, J., Fordham, M., Peacock, W. & Krimgold, F. (1999) *Environ. Hazards* **1,** 39–44.
36. Pulwarty, R. S. & Riebsame, W. E. (1997) in *Hurricanes*, eds. Diaz, H. F. & Pulwarty, R. S. (Springer, Berlin), pp. 185–214.
37. Ribot, J. C. (1995) *GeoJournal* **35,** 119–122.
38. Watts, M. J. & Bohle, H.-G. (1993) *Prog. Hum. Geogr.* **17,** 43–67.
39. Wisner, B. (1993) *GeoJournal* **30,** 127–140.
40. Sen, A. (1981) *Poverty and Famines* (Oxford Univ. Press, Oxford).
41. Drèze, J. & Sen, A. K. (1989) *Hunger and Public Action* (Clarendon, Oxford).
42. Leach, M., Mearns, R. & Scoones, I. (1999) *World Dev.* **27,** 225–247.
43. Chambers, R. (1989) *Inst. Dev. Stud. Bull.* **20,** 1–7.
44. Kasperson, J. X., Kasperson, R. E. & Turner, B. L., II (1995) *Regions at Risk* (United Nations University, Tokyo).
45. Blaikie, P. & Brookfield, H. C. (1987) *Land Degradation and Society* (Methuen, London).
46. Bohle, H.-G., Downing, T. E. & Watts, M. J. (1994) *Glob. Environ. Change* **4,** 37–48.
47. DeAngeles, D. L. (1980) *Ecology* **61,** 764–771.
48. Pimm, S. L. (1984) *Nature* **307,** 321–326.
49. Holling, C. S. (1973) *Annu. Rev. Ecol. Syst.* **4,** 1–24.
50. Harwell, M. A., Cropper, W. P. & Ragsdale, H. (1977) *Ecology* **58,** 660–666.
51. Stone, L., Gabric, A. & Berman, T. (1996) *Am. Nat.* **148,** 892–903.
52. Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C., Walker, B., Bengtsson, J., Berkes, F., Colding, J., Danell, K., *et al.* (2002) *Scientific Background Paper Prepared for the Environmental Advisory Council to the Swedish Government* (International Council for Science Series for Sustainable Development), No. 3, www.resalliance.org/ev.php?URL_ID1498&URL_DO=DO_TOPIC&URL_Section=201&reload=105281034.

53. Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Petersen, G. D. & Pritchard, R. (2002) *Conservation Ecology* **6,** www.bdt.fat.org.br/cons_ecol.
54. Carpenter, S., Walker, B., Anderies, J. M. & Abel, N. (2001) *Ecosystems* **4,** 765–781.
55. Berkes, F. & Folk, C. (1998) *Linking Social and Ecological Systems* (Cambridge Univ. Press, Cambridge, U.K.).
56. Petersen, G. (2000) *Ecol. Econ.* **35,** 323–336.
57. Gunderson, L. & Holling, C. S. (2002) *Panarchy* (Island, Washington, DC).
58. Dow, K. & Downing, T. E. (1995) *Hum. Dim. Q.* **1,** 3–5.
59. Kelly, P. M. & Adger, W. N. (2000) *Clim. Change* **47,** 335–352.
60. McLaughlin, P. & Dietz, T. (2003) *The Human Dimensions of Global Environmental Change*, eds. Diekmann, A., Dietz, T., Jaeger, C. & Rosa, E. S. (MIT Press, Cambridge, MA), in press.
61. Polsky, C., Schröter, D., Patt, A., Corell, R. W., Eckley, N., Gaffin, S., Long, L., Neff, R., Pulsipher, A., Selin, H., *et al*. (2003) *Assessing Vulnerabilities to the Effects of Global Change* (Belfer Center for Sci. and Int. Affairs, Harvard Univ., Cambridge, MA).
62. Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J. & Mitchell, R. B. (2003) *Proc. Natl. Acad. Sci. USA* **100,** 8086–8091.
63. Wilbanks, T. J. & Kates, R. W. (1999) *Clim. Change* **43,** 601–628.
64. McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. & White, K. S. (2001) *Climate Change 2001* (Cambridge Univ. Press, Cambridge, U.K.).
65. Watson, R. T., Zinyowera, M. C. & Moss, R. H. (1997) *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific–Technical Analysis* (Cambridge Univ. Press, Cambridge, U.K.).
66. Holling, C. S. (1997) *Conserv. Ecol.* **1,** 3 (www.consecol.org/vol1/iss2/art3).
67. National Research Council. (2002) *Community and Quality of Life* (Natl. Acad. Press, Washington, DC).
68. National Assessment Synthesis Team. (2001) *Climate Change Impacts on the United States* (Cambridge Univ. Press, Cambridge, U.K.).
69. Schellnhuber, H. J., Black, A., Cassel-Gintz, M., Kropp, J., Lammel, G., Lass, W., Lienenkamp, R., Loose, C., Lüdeke, M. K. B., Moldenhauer, O., *et al*. (1997) *GAIA* **6,** 19–34.
70. Petschel-Held, G., Block, A., Cassel-Gintz, M., Kropp, J., Lüdeke, M. K. B., Moldenhauer, O., Reusswig, F. & Schellnhuber, H.-J. (1999) *Environ. Mod. Assess.* **4,** 295–314.
71. Adger, N., Kelly, M. & Bentham, G. (2000) *New Indicators of Vulnerability and Adaptive Capacity* (Tyndall Centre for Climate Change Research, Norwich, CT).
72. Downing, T. E., Butterfield, R., Cohen, S., Huq, S., Moss, R., Rahman, A., Sokaona, Y. & Stephen, L. (2001*) Climate Change Vulnerability* (Oxford Environmental Change Institute, Oxford).
73. Pratt, C., Koshy, R., Kaly, U., Pal, R. & Sale-Mario, E. (2001) *Progress Report: Environmental Vulnerability Index Project* (South Pacific Applied Geoscience Commission, (www.sopac.org.fj/projects/evi/files/Evi%20Progress%20Report%202001.pdf)), Report 405.
74. World Economic Forum (2002) *2002 Environmental Sustainability Index* (Global Leaders of Tomorrow Environment Task Force, Geneva).
75. Rotmans, J. & van Asselt, M. (2001) *Scaling Issues in Integrated Assessment* (Kluwer, Masstricht, The Netherlands).
76. Benestad, R. (2001) *Int. J. Climatol.* **21,** 1645–1668.
77. Hanssen-Bauer, I.& Førland, E. J. (2000) *Int. J. Climatol.* **20,** 1693–1708.
78. Stern, P. & Fineberg, H. V. (1996) *Understanding Risk* (Natl. Acad. Press, Washington, DC).
79. Gregory, R. (2000) *Environment* **42,** 35–44.
80. Renn, O., Webler, T. & Wiedemann, P. (1995) *Fairness and Competence in Citizen Participation* (Kluwer, Dordrecht, The Netherlands).
81. Dryzek, J. S. (1990) *Discursive Democracy* (Cambridge Univ. Press, Cambridge, U.K.).
82. Kates, R. W. & Clark, W. C. (1996) *Environment* **38,** 6–11, 28–34.
83. National Research Council (2002) *Abrupt Climate Change* (Natl. Acad. Press, Washington, DC).
84. Schneider, S., Turner, B. L., II, & Garriga-Morehouse, H. (1998) *J. Risk Res.* **1,** 165–185.
85. National Research Council (2002) *Assessment of Proposed Partnerships to Implement a National Landslide Hazards Mitigation Strategy. Interim Report* (Natl. Acad. Press, Washington, DC).