



Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science?

B.L. Turner II^{a,b,*}

^a School of Geographical Sciences and Urban Planning, PO Box 875302, Tempe, AZ 85287-5302, United States

^b School of Sustainability, Arizona State University, PO Box 875302, Tempe, AZ 85287-5302, United States

ARTICLE INFO

Article history:

Received 8 May 2010

Received in revised form 5 July 2010

Accepted 8 July 2010

Keywords:

Vulnerability

Resilience

Sustainability

Coupled human–environment system

Environmental services

Tradeoffs

ABSTRACT

Vulnerability and resilience constitute different but overlapping research themes embraced by sustainability science. As practiced within this science, the two research themes appear to coalesce around one of the foundational pivots of sustainability, the coupled human–environment system. They differ in regard to their attention to two other pivots, environmental services and the tradeoffs of these services with human outcomes. In this essay I briefly review the emergence of sustainability science and the three foundational pivots relevant to vulnerability and resilience. I outline the distinctions and similarities between the two research themes foremost as practiced within sustainability science and especially in regard to the attention given to the three pivots. I conclude with the observation that improvement in the capacity of vulnerability and resilience research to inform sustainability science may hinge on their linkages in addressing tradeoffs.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Sustainability science has emerged as the intellectual umbrella for addressing human–environment problems and practice arising from those research communities closely aligned with global climate and environment change. These communities, and thus sustainability science, maintain substantial interests in questions of vulnerability and resilience, registered by Working Group II of the Intergovernmental Panel on Climate Change (IPCC) which includes vulnerability (Parry et al., 2007) and the newly minted International Council of Science's Programme on Ecosystem Change and Society (PECS, www.icsu.org/1_icsuinscience/ENVI-PECS_1.html) which builds on the Millennium Ecosystem Assessment through the resilience lens (Carpenter et al., 2009). Vulnerability and resilience constitute different but overlapping research themes, the shared understanding of which holds the potential to inform sustainability science inasmuch as either is consistent with the thematic foundations of this science. This possibility is explored here in three parts: (i) a brief review the origins of sustainability science and the identification of three

foundational pivots—coupled human–environment systems, environmental services, and tradeoffs; (ii) discussion of the distinctions and complementarities between vulnerability and resilience research, especially those parts consistent with normal science, and the linkages each has with the three pivots; and (iii) comments on future integration between vulnerability and resilience research, concluding that attention to tradeoffs may hold the key improved intellectual integration of the two.

2. Sustainability science and three pivots

The emergence of the interdisciplinary science of sustainability was anticipated in the late 1980s with the release of *Sustainable Development of the Biosphere* (Clark and Munn, 1986) by the International Institute of Applied Systems Analysis, and *Our Common Future* (WCED, 1987), the well-known Brundtland Report. Its formal development followed several collaborative pathways over the past quarter-century, each associated with the expansion of research on global climate change to global environmental change (the Earth system) and, ultimately, its human dimensions. These pathways were galvanized by the International Council of Science (ICSU, 2002) subsequent to the “World Congress on Challenges of a Changing Earth 2001” in Amsterdam, sponsored by various global change science programs associated with the Council. The base themes and agendas of sustainability science emerged from various national and related committees, interdisciplinary workshops (e.g., Schellnhuber

* Correspondence address: School of Geographical Sciences and Urban Planning, PO Box 875302, Tempe, AZ 85287-5302, United States. Tel.: +1 480 965 1535; fax: +1 480 965 8313.

E-mail address: Billie.l.turner@asu.edu.

et al., 2004), reports (e.g., Kasemir et al., 2003), and commentaries in major outlets (e.g., Lubchenco, 1998; Raven, 2002) responding to the Council and human impacts on the Earth system. The 1999 release of *Our Common Journey* by the National Academy of Sciences (U.S.; NRC, 1999) and follow-up publications in *Science* (Kates et al., 2001) and the *Proceedings of the National Academy of Sciences* (PNAS; Clark and Dickson, 2003) staked out the integrative character of the subfield. By the middle of this past decade, the research on sustainability science was sufficiently robust that the PNAS created a new section for it (Clark, 2007), while internationally such journals as *Sustainability Science*, *Sustainability Science and Engineering*, *Journal of Sustainability Science and Management*, *Sustainability: Science, Practice, and Policy*, and *Current Opinion in Environmental Sustainability* emerged to handle the large growth in the array of this research. International programs, such as the Earth System Science Partnership (ESSP, www.essp.org), attempt to keep various formal research initiatives on track toward the types in integration needed to address the questions of sustainability science.

Sustainability science addresses the provisioning of humankind relative to functioning of the Earth system, assessed at different levels down to ecosystems. This focus crosscuts all definitions of sustainability science no matter the other attributes that are variously appended to it, such as the co-production of research problems between science and society or the usefulness of research products for decision-making (e.g., Clark, 2007; Kates et al., 2001; Lubchenco, 1998; Raven, 2002). In principle, co-production and usefulness are applied to a full range of stakeholders (e.g., Reynolds et al., 2007), although it is recognized that the move from theory to practice engages different constituencies that are differentially empowered in the decision-making process.¹ However derived, a sustainable human–environment system is envisioned as provisioning humankind (in amount and distribution; Dasgupta, 2001; Kates and Dasgupta, 2007) without threatening nature’s support system (Kates et al., 2001). Viewed thusly, the human and environmental subsystems are intimately linked, and the environment constitutes the subsystem providing services required for the maintenance of humankind, regardless of our awareness of, or the lack economic value placed on, them. These subsystem linkages and environmental services constitute two of the foundational pivots of the science in question.

The coupled human–environment systems or CHES (Turner et al., 2003a,b; also coupled human and natural systems or CHANS [Liu et al., 2007a,b] and social-ecological systems or SES [Berkes et al., 2003]) recognizes the synergy or interdependency of the human and environmental subsystems in determining the condition, function, and response (e.g., to a disturbance, perturbation, or hazard) of either subsystem or that of the system as whole. In vulnerability parlance, for example, the sensitivity of CHES to a disturbance is predicated on that synergy (Turner et al., 2003a,b). Contrary to the implications of some critiques (e.g., Banerjee, 2003; Head, 2007), sustainability science is fully cognizant that treating two interacting subsystems constitutes a social construct. It treats human–environment dynamics this way for the analytical convenience of capturing the different kinds of the processes at work in each subsystem, and out of concern that emphasis on one “interacting” system fosters the danger of reducing the understanding of social dynamics to environmental ones, or vice versa.

¹ The various concepts, approaches, programs, and related politics that ultimately begot sustainability science as well as the formal research programs feeding into it have been critiqued throughout its development, perhaps with more attention to its climate change dimensions (e.g., Bäckstrand, 2003; Banerjee, 2003; Cohen et al., 1998; Demeritt, 2001; Demeritt, 2006; Lélé, 1991; Meppem and Bourke, 1999; Ravetz, 2006) and with surprisingly little response from those being critiqued (but see Schneider, 2001).

Environmental or ecosystem services (also natural capital) are the direct benefits (e.g., resources) and life supporting processes emanating from the environment (Daily, 1997; Daily et al., 2000; Jansson et al., 1994). At the global scale, these services are the product of the Earth system, and at local to regional scales, ecosystems. The Millennium Ecosystem Assessment (MEA, 2005) identifies four categories of services: provisioning (e.g., food, water), regulating (e.g., climate and flood regulation), cultural (e.g., recreation, spiritual places), and supporting (e.g., nutrient cycling, soil formation). What to value is not the question; in principle, all services are in play, and as noted above, the range of views about them should be inclusive. Discussion is on-going among research communities, however, concerning the logic of including the supporting category as a service. Beyond this typological issue lies a more fundamental problem. Some regulating and most supporting services (or the environmental function implied in the last term) have long been taken for granted and are not explicitly valued in most economic and socio-political systems (Daily et al., 2000). How to place economic value on the full array of environmental services (e.g., Ando et al., 1998; Carbone and Smith, 2010) and the discount rate for their loss constitute a major, even divisive, analytical issue. Exemplary are attempts to place value on the Earth system (e.g., Constanza et al., 1997) and the loss of its services with climate change (Stern, 2007) versus the various criticisms of them by resource and environmental economists (e.g., Bockstael et al., 2000; Dasgupta, 2007; Nordhaus, 2007). Perhaps the telling point for this discussion is that the need to place value on these services is linked to assessments of human outcomes, economic or otherwise.

Sustainability science examines the relationships between environmental services and human outcomes, in part to uncover those qualities that make CHES less vulnerable or more resilient to the multitude of forces (i.e., disturbances, stressors, perturbations) acting upon them. The overwhelming majority of contemporary CHES involve societal efforts to expand the limits and reduce the vagaries of nature in attempts to improve provisioning and regulating services and thus the material well-being of people: for example, irrigating crops and applying synthetic fertilizer for increasing food production, burning savanna grasses for new livestock fodder, or impounding water to provision cities, power electricity, provide recreation facilities, and control flooding. Such efforts invariably focus on a few environmental services and human outcomes (e.g., water control-flood protection or food production-security), although the consequences of the activities involved play out through the entire system (e.g., food production-security on albedo and evapotranspiration and climate on water and energy needs). Attempts to improve some services invariably reduce others, while increased material well-being is historically associated with environmental drawdown and the costs of maintaining or substituting for losses in services (MEA, 2005). This realization leads to a third foundational pivot, tradeoffs.

Owing to human activity, CHES axiomatically involve tradeoffs – improvements, maintenance, and losses – among environmental services and between those services and human outcomes. Tradeoffs may be addressed in two ways: by their economic value (Bockstael et al., 2000; Smith, 1996) or by comparison of their physical measure (e.g., amount or change in amount of stratospheric ozone, soil moisture, pollinators, amount of crops produced, number of air conditioned houses, number of households below the poverty line). Economic tradeoff constitutes the more elegant assessment consistent with the use of economic concepts and theory. This approach fails to treat all environmental services, however, especially supporting ones (above), because these services currently have no market value and thus no shadow prices. Comparison of physical measures is less elegant, in principle can treat all environmental services, but has yet to be employed sufficiently to demonstrate its usefulness (but see Bennett et al., 2009; Raudsepp-Hearne et al.,

2010; Swallow et al., 2009). Such issues notwithstanding, tradeoff assessment provides a way to link changes in the human and environmental subsystem. It facilitates insights about such critical issues as, for example, how much of a reduction in environmental services is associated with various standards of material consumption, or the tipping points at which these services are lost (e.g., Lenton et al., 2008). Of course, such standardized measures facilitate tests of concepts, theses, and theories in order to complement better the understanding gained from qualitative assessments of CHES dynamics. Importantly, they provide a powerful means through which to assess the vulnerability and resilience of CHES (see Adger, 2006 on the need for such assessments).

3. Vulnerability and resilience in sustainability science

If vulnerability and resilience research had not existed previous to the rise of sustainability science, some version of them would likely have emerged, given the explicit goal of societal outreach or “usefulness” of sustainability research (e.g., Lubchenco, 1998; Kates et al., 2001). Sustainability addresses threats to provisioning society and to maintaining life support systems, and decision makers want to know these threats and their implications, including the capacity (or adaptive capacity) of the system, foremost the human subsystem, to withstand and adjust to them.

Recent reviews of vulnerability and resilience and their linkages to climate and global environmental change and sustainability preclude the need to reiterate the history of these themes here (Adger, 2006; Cutter, 2003; Berkes et al., 2003; Kasperson et al., 2005; Turner et al., 2003a). Telling for sustainability science are the research orientations, both conceptual and in practice, underway in the vulnerability and resilience research. To what degree are they consistent with the analytical needs of sustainability science? Does vulnerability and resilience research appear to be coalescing intellectually and in practice, or will it remain separate but complementary? The answers reside partly in the degree to which vulnerability and resilience pay attention to the three foundational pivots of sustainability science identified above: CHES, environmental services, and services-human outcome tradeoffs.

4. Vulnerability

The concept of vulnerability developed largely in those social sciences addressing environmental risks and hazards (Kasperson et al., 2005; Blaikie et al., 1994). For our purposes it refers to the degree to which a CHES or some part of it is likely to experience harm due to exposure to a hazard(s) (Turner et al., 2003a). Research emphasis has been placed on the vulnerability of cohorts of individuals and communities to environmental perturbations, historically labeled as “natural hazards” (Cutter, 2003; Cutter et al., 2003). Parts of the vulnerability research community are strongly aligned with or speak directly to the sustainability, climate change, and global environment change sciences (Adger, 2006; Eakin and Luers, 2006; Füssel and Klein, 2006; Handmer et al., 1999; Polsky et al., 2007; Turner et al., 2003a,b). This orientation to vulnerability recognizes the synergy within the CHES affecting the sensitivity and coping capacities of either subsystem and thus the vulnerability of the CHES at large. The number of case studies that actually treat the synergy of two subsystems or that consider environmental services equitably with human outcomes are few, however (e.g., Luers, 2005; Turner et al., 2003b). To my knowledge, vulnerability research to date has not undertaken explicit assessments of the tradeoffs within and among both the human and environmental subsystems (see Turner, 2009, for a crude attempt). Attention tends to focus on one or a small set of human outcomes (e.g., poverty, hunger, or housing) in which the environmental subsystem serves as the backdrop in response to a hazard such as climate

change or sea level rise. In contrast, minimal, if any attention is given to the tradeoffs among environmental services (e.g., aquifer recharge, water quality, phenology, or flood control) responding to the hazards or the mitigating and adaptation strategies employed toward them. Interestingly, minimal attention is given as well to larger sets of tradeoffs among human outcomes (e.g., health, housing, income, equity, property losses). Consistent with its origins and the influence of social and critical theory, vulnerability research tends to emphasize the threats to and sensitivity and adaptive capacity of some element of society, although the hazard in question may be climate change or combined socio-political and environmental factors (e.g., Kelly and Adger, 2000; O'Brien and Leichenko, 2000; O'Brien et al., 2004; Wisner et al., 2005).

It is safe to say that vulnerability research at large (see Janssen et al., 2006, for its research clusters) has not embraced the three pivots of sustainability science noted here (i.e., CHES, environmental services, tradeoffs), and thus offers less insights about the vulnerability of the environmental subsystem or CHES dynamics than sustainability science seeks. Vulnerability research has provided important insights about the dynamics of the human subsystem, especially the role of economic globalization and entitlements as they affect human outcomes (Adger, 2003; O'Brien and Leichenko, 2000; Young et al., 2005). The practical lessons drawn beyond the spatio-temporal complexity of outcomes are few, however, and tend to emerge from selective narratives filtered through different theoretical lens (e.g., Turner et al., 2003b; Wisner et al., 2005) rather than applied to quantitative tests (but see Cutter et al., 2003; Luers, 2005). Common lessons point to the economically marginal and politically un-empowered as the most vulnerable cohorts to hazards because of their (often presumed) lower coping capacities, although various studies document that these cohorts also tend to be the most exposed (e.g., least desirable living locations) and sensitive (e.g., lack air-conditioning in heat waves) to the hazard. Studies tend to be case specific because the complexity of CHES, even focusing on the human subsystem alone, leads similar processes to variable outcomes (Cutter et al., 2000; Kates and Dasgupta, 2007). Places or locations may experience differential vulnerability to the same hazard owing to the geographical clustering of more vulnerable cohorts and the biophysical qualities of the location of the clusters (Cutter et al., 2000; O'Brien and Leichenko, 2000). Nevertheless, common characteristics that increase human vulnerability to a hazard across locations in the United States statistically relate to income, gender, race and ethnicity, and age, among others (Cutter et al., 2003).

Adger (2006) recognizes the need for the vulnerability communities to treat the full dimensions of CHES. To do this, he notes three challenges: measuring vulnerability, treating perceptions of risk, and addressing governance. If these same communities are to meet the challenges of sustainability science, however, they must embrace more fully its foundational pivots, or at least focus on the human subsystem in ways that couple with the environmental one, including the linkages between environmental services and human outcomes. In this regard, I remain skeptical of the usefulness of a vulnerability measure or metric per se given the need to address both the relative (proportional) and absolute outcomes to hazards (but see Adger, 2006). CHES's complexity and place-based variance in outcomes suggest that a large number of comparable case studies will be required before aggregate measures may be realized or general lessons emerge. Attention to tradeoffs offers a more tractable solution, I suggest. Tradeoffs, either physical or economic in kind, among various sets of environmental services (e.g., provisioning and regulating) and human outcomes (e.g., health, household income) can be compared across all coupled systems, providing a viable means of assessment for the system as a whole or its parts (e.g., Nelson et al., 2009; Raudsepp-Hearne et al., 2010).

5. Resilience

In contrast to vulnerability, resilience emerged from the ecological sciences to address persistence and change in ecosystems (Carpenter et al., 2001; Gunderson, 2000). It subsequently expanded to address CHES (or SES in resilience parlance; Berkes et al., 2003; Walker et al., 2006), and ultimately penetrated the natural hazards communities of the social sciences (Nelson et al., 2007; Berkes, 2007; Renaud et al., 2010; Zhuo et al., 2010). Resilience applied to CHES has at least three meanings involving: (i) response to disturbance; (ii) capacity to self-organize; and (iii) capacity to learn and adapt (Folke et al. (2002a,b)).² While each has implications for this discussion, the first is the most directly applicable: “the amount of disturbance a system can absorb and still remain within the same state or domain of attraction” (Folke et al., 2002a, p. 5).

Resilience research seeks general principles about CHES from which lessons for practice may be drawn (see the special feature on Exploring Resilience in Social-Ecological Systems of *Ecology and Society* 2006). These principles emerge from a general systems theoretic that, at least for the moment, should be viewed as sets of hypotheses about or a framework for addressing CHES (Anderies et al., 2006a). Importantly, most of the hypotheses and core attributes of the framework are derived from examinations of the ecological subsystem and laid over the human subsystem and the CHES at large (e.g., Adger et al., 2005; Alberti and Marzluff, 2004; Anderies et al., 2006a,b; Folke et al., 2005; Hudson, 2010; Simme and Martin, 2010; Walker et al., 2002a, b). This tactic raises at least one concern that has not been adequately addressed in the literature: the applicability of ecosystem-derived dynamics to explain the human subsystem composed of complex social structures and reflexive agents (Adger, 2000; Redman and Kinzig, 2003). Of more immediate concerns for sustainability science, however, are three other issues: the high level of abstraction inherent in the meta-theory character of general systems applied to resilience (e.g., adaptive cycles, creative destruction) relative to the theories of the mid-range that have served the social sciences well (Kates, 1988)³; the applicability of the lessons drawn for the management of CHES (e.g., enlarge diversity for improved sustainability, despite the long history of the opposite trajectory in plant foods as our species rose to ecological dominance); and the insufficiently untested hypotheses about CHES dynamics, which tend to be supported largely through narratives, the repeated interpretations of which appear to imply quasi-proof (e.g., macro-scale process, such as climate change, tend to act slowly and thus constitute critical controls, despite the presence in the human subsystem of fast-acting macro-scale processes, such as globalization [Young et al., 2005]).

These concerns are recognized by proponents of resilience (Carpenter et al., 2009; Levin et al., 1998), but perhaps not by the practitioner communities to which the lessons are directed. Recent stocktakings of resilience research highlight these lessons (Anderies et al., 2006a; Cumming et al., 2006; Berkes, 2007; Walker et al., 2002a,b). For example, treat multiple configurations of CHES at multiple scales owing to the complexities and scalar mismatches

in the dynamics of the two subsystems as well as the scale dependent nature of ecological process (McGill, 2010); understand that CHES tend to be co-adapting; search for a few “slow” controlling variables that require focused management; maintain diversity in order to increase options; be open to many stakeholder mental models of and ways of knowing CHES; and use adaptive governance and promote self-organization capacity. Some of these lessons are consistent with current social science thought. The last two involving variance in stakeholders and governance, for example, are the product of cooperation with social scientists as they can only be drawn from explicit attention to the human subsystem.

Regardless of the concerns noted above, resilience tracks well with the foundations of sustainability science. It is consistently applied to the CHES in which, in principle, both subsystems are treated equally. The structure and function of ecosystems are explicitly linked to the services delivered to society. And, tradeoffs among these services take center stage in much of the research portfolio, including their scalar dynamics (e.g., Kremen et al., 2000; Maass et al., 2005; Nelson et al., 2009; Polasky et al., 2008). Less attention, however, has been given to the tradeoffs between environmental services and human outcomes in the more expansive meaning of the last term (but see Ando et al., 1998; Kinzig et al., 2006). While some environmental services equate directly to a human outcomes (e.g., crop production as a provisioning service), others are more difficult to equate (e.g., nutrient cycling as a regulating service). Links to human outcomes tend to be the proximate or most immediate to services (e.g., total food and water availability). The “deeper” or distal level outcomes (e.g., food security, property value, entitlements, gender equity), those which garner attention from the social sciences, are less well addressed because they may involve multiple sets of services not yet fully addressed or, perhaps, because these outcomes link to services in indirect ways. Institutions and governance research constitutes an exception, however. The resilience community at large applies this research as lessons relevant to policy about ecosystem health (e.g., Ostrom et al., 2007), but institution and governance research also strikes to one of core dynamics of the human subsystem (e.g., Janssen et al., 2010; Young, 1999). A “full” CHES treatment must enlarge the kind of attention given to governance in order to address the tradeoffs between the many kinds of environmental services and various conditions of society (e.g., economic livelihoods, human health, life-way satisfaction). Why? Because decision-making, both at the individual and societal levels historically targets these conditions relative to those of the environment per se, at least until the drawdown in the environment affects the capacity and costs of maintaining expected living standards (e.g., Anderies et al., 2006a; Walker et al., 2002a,b). It must be recognized that resilience researchers are beginning to address the concerns noted here, especially in regard to a more complete array of services relative to societal decision-making (Nelson et al., 2009; Reynolds et al., 2007).

6. Vulnerability and resilience in the future of sustainability science

At their most fundamental level, vulnerability and resilience applied to CHES constitute different but complementary framings. The former seeks to identify the weakest parts (those most affected negatively) of coupled systems to disturbances, and the latter, the systemic characteristics that make systems more robust to disturbances. Interestingly, at least one CHES vulnerability research cluster employs the term resilience to the coping capacity component of its framework (Turner et al., 2003a), whereas resilience views vulnerability as an antonym for its label (Folke et al., 2002a). Such differences notwithstanding, much vulnerabil-

² Folke and associates (2002b) is the journal publication, reduced in size, of a lengthy report prepared by the Swedish government for 2002 World Summit on Sustainable Development (also Folke et al., 2002a). Both sources emanate from the Resilience Alliance (www.resalliance.org), but the latter should be consulted for the more throughout treatment of resilience and sustainability science.

³ Theory of the mid-range, akin to Merton's (1968) middle range theory, refers to general explanation of specific phenomenon and processes, or their sets, for example induced intensification (of agriculture) or forest transition. Such theory is not intended to be applicable beyond the specific phenomenon or process in question. In contrast, what I term meta-theory constitutes a broader form of explanation that covers large, and often diverse sets of phenomena and processes, be it general systems, complex systems, or Marxian inspired.

ity and all resilience research seeks to understand CHES dynamics useful for sustainability science. In this regard, resilience has been framed in a more consistent way with the three pivots of that science as identified here – CHES, environmental services, and tradeoffs – and appears to be addressing the human outcome component of tradeoffs, although the commitment to outcomes beyond those most proximate to environmental services is not yet clear. Vulnerability – its base identity perhaps more obvious to decision makers – has only recently begun to entertain environmental services and tradeoffs.

Those vulnerability communities not aligned with sustainability science are much less likely to emphasize the three pivots in question for a variety of reasons, ranging from their base social science interests in which environmental services are treated largely as resources (thus a focus on provisioning services with less attention to human-use feedbacks on them), to their favored explanatory perspectives which are incommensurate with science-based approach of sustainability science. These differences do not mean that the various research orientations will not inform one another (e.g., Turner and Robbins, 2008), particularly if practitioners recognize that each explanatory approach carries impediments for reconciling human–environment interactions (McLaughlin and Dietz, 2007). Importantly, all vulnerability and resilience communities increasingly display interest in such themes as nested hierarchies, co-adaptation, multiple equilibria, networks of actors, and hybrid (science-local) knowledge as they affect their research problems and real-world applications. This shared thematic interest behooves the communities to remain in conceptual contact. Indeed, Adger (2006) concludes that a merger of vulnerability and resilience is underway, at least in regard to increasingly shared thematic interests.

Within sustainability science and assisted by researchers working at the interface of research-application and open to multiple explanatory perspectives, efforts have begun that point to improved integration of vulnerability and resilience research. The Drylands Development Paradigm (DDP) is exemplary. A product of resilience and vulnerability practitioners, including a few individuals aligned with social-critical perspectives (Reynolds et al., 2007), DDP is a CHES approach applied to arid land management emphasizing the need to account for slowly evolving conditions, nonlinear processes, cross-scale interactions, and local knowledge. Such approaches have already been applied by integrated research-application teams in Australia (e.g., Stafford-Smith et al., 2007). Maintaining and improving such cooperation will be determined, in part, by the activities of formal research programs designed to tackle CHES sustainability, such as emerging PECS effort.

Beyond such programs, vulnerability and resilience aligned with sustainability science increasingly share appreciation for the complexity of CHES dynamics and its role in shaping place-based outcomes. This and the shared thematic interests noted above point to the potential for improved integration between the two communities. Sustained conceptual integration, however – that required to reach the merge Neil Adger foresees – will require vulnerability researchers to expand attention to environmental services, and resilience researchers to do the same regarding human outcomes beyond the proximate kind. In this way the two research communities will confront similar tradeoff interactions. This third foundational pivot, tradeoffs, may hold the key for intellectual fusion.

Acknowledgments

I thank Ann Kinzig and Karina Benessaiah for their comments as I developed my thoughts, and the reviewers of this paper who provided helpful ideas for improvements for the presentation of them.

References

- Adger, W.N., 2000. Social and ecological resilience: are they related. *Prog. Hum. Geogr.* 24, 347–364.
- Adger, W.N., 2003. Social capital, collective action, and adaptation to climate change. *Econ. Geogr.* 79, 387–404.
- Adger, W.N., 2006. Vulnerability. *Global Environ. Change* 16, 268–281.
- Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R., Rockstrom, J., 2005. Social-ecological resilience to coastal disasters. *Science* 309, 1036–1039.
- Alberti, M., Marzluff, J.M., 2004. Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. *Urban Ecosyst.* 241–265.
- Anderies, J.M., Walker, B.H., Kinzig, A.P., 2006a. Fifteen weddings and a funeral: case studies and resilience-based management. *Ecol. Soc.* 11, 21.
- Anderies, J.M., Ryan, P., Walker, B.H., 2006b. Loss of resilience, crisis, and institutional change: lessons from an intensive agricultural system in Southeastern Australia. *Ecosystems* 9, 865–878.
- Ando, A., Camm, J., Polsaky, S., Solow, A., 1998. Species distributions, land values and efficient conservation. *Science* 279, 2126–2128.
- Bäckstrand, K., 2003. Civic science for sustainability: reframing the role of experts, policy-makers and citizens in environmental governance. *Global Environ. Polit.* 3, 24–41.
- Banerjee, S.B., 2003. Who sustains whose development? sustainable development the reinvention of nature. *Organ Stud.* 24, 143–180.
- Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* 12, 1394–1404.
- Berkes, F., 2007. Understanding uncertainty and reducing vulnerability: lessons from resilience thinking. *Nat. Hazards* 41, 285–295.
- Berkes, F., Colding, J., Folke, C. (Eds.), 2003. Navigating social-ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge.
- Blaikie, P., Cannon, T., Davies, I., Wisner, B., 1994. *At Risk: Natural Hazards, People's Vulnerability and Disaster*. Routledge, London.
- Bockstael, N.E., Freeman III, A.M., Kopp, R.J., Portney, P.R., Smith, V.K., 2000. On measuring economic values for nature. *Environ. Sci. Technol.* 34, 1384–1389.
- Carbone, J.C., Smith, V.K., 2010. Valuing ecosystem services in general equilibrium. NBER Working Paper Series #15844. National Bureau of Economic Research, Cambridge, MA.
- Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., Dietz, T., Duralappah, A.K., Oteng-Yeboah, A., Perelral, H.M., Perrings, C., Reid, W.V., Satukhan, R., Whyte, A., 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *Proc. Natl. Acad. Sci. U.S.A.* 106, 1305–1312.
- Carpenter, S.R., Walker, B., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what? *Ecosystems* 4, 765–781.
- Clark, W.C., 2007. Sustainability science: a room of its own. *Proc. Natl. Acad. Sci. U.S.A.* 104, 1737–1738.
- Clark, W.C., Dickson, N., 2003. Sustainability science: the emerging research program. *Proc. Natl. Acad. Sci. U.S.A.* 100, 8059–8061.
- Clark, W.C., Munn, R.E. (Eds.), 1986. *Sustainable Development of the Biosphere*. Cambridge University Press, Cambridge.
- Cohen, S., Demeritt, D., Robinson, J., Rothman, D., 1998. Climate change and sustainable development: towards dialogue. *Global Environ. Change* 8, 341–371.
- Constanza, R., D'Arge, R., de Groot, R., Farber, S., Grasson, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.
- Cutter, S.L., 2003. The vulnerability of science and the science of vulnerability. *Ann. Assoc. Am. Geogr.* 93, 1–12.
- Cutter, S.L., Boruff, B.J., Shirley, W.L., 2003. Social vulnerability to environmental hazards. *Soc. Sci. Q.* 84, 242–261.
- Cutter, S.L., Mitchell, J.T., Scott, M.S., 2000. Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina. *Ann. Assoc. Am. Geogr.* 90, 713–737.
- Cumming, G.S., Cumming, D.H.M., Redman, C.L., 2006. Scale mismatches in social-ecological systems: causes, consequences, and solution. *Ecol. Soc.* 11, 14.
- Daily, G.C., 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington, DC.
- Daily, G.C., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Hansson, A.-M., Jansson, B.-O., Kautsky, N., Levin, S., Lubchenco, J., Mäler, K.-G., Simpson, D., Starrett, D., Tilman, D., Walker, B., 2000. The value of nature and the nature of value. *Science* 289, 395–396.
- Dasgupta, P., 2001. *Human Well-Being and the Natural Environment*. Oxford University Press, Oxford.
- Dasgupta, P., 2007. The Stern review's economics of climate change. *Nat. Inst. Econ. Rev.* 199, 4–7.
- Demeritt, D., 2001. The construction of global warming and the politics of science. *Ann. Assoc. Am. Geogr.* 91, 307–337.
- Demeritt, D., 2006. Science studies, climate change and the prospect for constructivist critique. *Econ. Soc.* 35, 453–479.
- Eakin, H., Luers, A., 2006. Assessing the vulnerability of social-environmental systems. *Ann. Rev. Environ. Res.* 31, 365–394.
- Folke, C., Carpenter, R., Elmqvist, T., Gunderson, L., Holling, C.S., Walker, B., Bengtsson, J., Berkes, F., Colding, H., Danell, K., Falkenmark, M., Gordon, L., Kasperson, K., Kautsky, N., Kinzig, A., Levin, S., Mäler, K.-G., Morberg, F., Olsson, L., Ostrom, E., Reid, W., Rockström, J., Savenije, H., Svedin, U., 2002a. Resilience and

- sustainable development: building adaptive capacity in a world of transformations. Report of the Environmental Advisory Council to the Swedish Government. Edita Norstedts Tryckeri AB, Stockholm.
- Folke, C., Carpenter, S., Elmqvist, T., Norberg, L., Holling, C.S., Walker, B., 2002b. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* 31, 437–440.
- Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. *Ann. Rev. Environ. Res.* 30, 441–473.
- Füssel, H.-M., Klein, R.J.T., 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change* 75, 301–329.
- Gunderson, L.H., 2000. Ecological resilience: in theory and application. *Ann. Rev. Ecol. Syst.* 31, 425–439.
- Handmer, J.W., Dovers, S., Downing, T.E., 1999. Societal vulnerability to climate change and variability. *Mitig. Adapt. Strat. Global Change* 4, 267–281.
- Head, L., 2007. Cultural ecology: the problematic human and the terms of engagement. *Prog. Hum. Geogr.* 31, 837–846.
- Hudson, R., 2010. Resilience regions in an uncertain world: wishful thinking or a practical reality? *Cambridge J. Reg. Econ. Soc.* 3, 11–25.
- ICSU (International Council of Science), 2002. Word Summit on Sustainable Development Reports. (www.icsu.org/2_resourcecentre/Resource).
- Jansson, A.-M., Hammer, M., Folke, C., Costanza, R. (Eds.), 1994. Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Island Press, Washington, DC.
- Janssen, M.A., Holahan, R., Lee, A., Ostrom, E., 2010. Lab experiments for the study of social-ecological systems. *Science* 328, 613–617.
- Janssen, M.A., Schoon, M.L., Ke, W., Börner, K., 2006. Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. *Global Environ. Change* 16, 240–252.
- Kasemir, B., Jäger, J., Jaeger, C.C., Gardner, M.T. (Eds.), 2003. Public Participation in Sustainability Science: A Handbook. Cambridge University Press, Cambridge.
- Kasperson, J.X., Kasperson, R.E., Turner II, B.L., Schiller, A., Hsieh, W.-H., 2005. Vulnerability of global environmental change. In: Kasperson, J.X., Kasperson, R.E. (Eds.), *Social Contours of Risk*. Earthscan, London, pp. 245–285.
- Kates, R., 1988. Theories of nature, society, and technology. In: Baark, E., Svedin, U. (Eds.), *Man, Nature, and Technology: Essays on the Role of Ideological Perception*. Macmillan Press, Houndmills, pp. 7–36.
- Kates, R.W., Clark, W.C., Corell, R., Hall, J., Jaeger, C., Lowe, I., McCarthy, J., Schellenhuber, H.-J., Bolin, B., Dickson, N., Faucheux, S., Gallopin, G., Grübler, A., Huntley, B., Jäger, J., Jodha, N., Kasperson, R., Mabogunje, A., Matson, P., Mooney, H., Moore III, B., O'Riordan, T., Svedin, U., 2001. Sustainability science. *Science* 292, 641–642.
- Kates, R.W., Dasgupta, P., 2007. African poverty: a grand challenge for sustainability science. *Proc. Natl. Acad. Sci. U.S.A.* 104, 16747–16750.
- Kelly, P.M., Adger, W.N., 2000. Theory and practice in assessing vulnerability to climate change and facilitating adaptation. *Climatic Change* 47, 325–352.
- Kinzig, A.P., Ryan, P., Etienne, M., Elmqvist, T., Allison, H., Walker, B.K., 2006. Resilience and regime shifts: assessing cascading effects. *Ecol. Soc.* 11.
- Kremen, C., Niles, J.O., Balton, M.G., Daily, G.C., Ehrlich, P.R., Fay, J.P., Grewal, D., Guillery, R.P., 2000. Economic incentives for rain forest conservation across species. *Science* 288, 1828–1831.
- Lélé, S.M., 1991. Sustainable development: a critical review. *World Dev.* 19, 607–621.
- Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Thamstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate. *Proc. Natl. Acad. Sci. U.S.A.* 105, 1785–1793.
- Levin, S., Barrett, S., Aniyar, S., Baumol, W., Bilss, C., Bolin, B., Dasgupta, P., Ehrlich, P., Folke, C., Gren, I.-M., Holling, C.S., Jansson, A., Jansson, B.-O., Mäler, K.-G., Martin, S., Perrings, C., Sheshinski, E., 1998. Resilience Dev. Econ. 3, 221–262.
- Liu, J., Dietz, T., Carpenter, S.R., Folke, C., Alberti, M., Redman, C., Schneider, S.H., Ostrom, E., Pell, A., Lubchenco, J., Taylor, W.W., Ouyamng, Z., Deadman, P., Kratz, T., Provencher, W., 2007a. Coupled human and natural systems. *Ambio* 36, 639–649.
- Liu, J., Dietz, T., Carpenter, S., Alberti, M., Moran, E., Pell, A., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyamng, Z., Provencher, W., Redman, C., Schneider, S., Taylor, W., 2007b. Complexity of coupled human and natural systems. *Science* 317, 1513–1516.
- Lubchenco, L., 1998. Entering the century of the environment: a new social contract for science. *Science* 279, 491–497.
- Luers, A., 2005. The surface of vulnerability: an analytical framework for examining environmental change. *Global Environ. Change* 15, 214–223.
- Maass, J., Balvanera, P., Castillo, A., Daily, G.C., Mooney, H.A., Ehrlich, P., Quesada, M., Miranda, A., Jaramillo, V.J., García-Oliva, F., Martínez-Yrizar, A., Cotler, H., López-Blanco, J., Pérez-Jiménez, A., Búrquez, A., Tinoco, C., Ceballos, G., Barraza, L., Ayala, R., Sarukhán, J., 2005. Ecosystem services of tropical dry forests: insights from long-term ecological and social research on the Pacific Coast of Mexico. *Ecol. Soc.* 10, 17.
- McGill, B.J., 2010. Matters of scale. *Science* 328, 575–576.
- McLaughlin, P., Dietz, T., 2007. Structure, agency and environment: toward an integrated perspective on vulnerability. *Global Environ. Change* 18, 99–111.
- MEA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
- Meppem, T., Bourke, S., 1999. Different ways of knowing: a communicative turn toward sustainability. *Ecol. Econ.* 30, 389–404.
- Merton, R.K., 1968. *Social Theory and Social Structure*. Free Press, New York.
- National Research Council, 1999. *Our Common Journey: A Transition Toward Sustainability*. National Academy of Sciences Press, Washington, DC.
- Nelson, D.R., Adger, W.N., Brown, K., 2007. Adaptation to environmental change: contributions of a resilience framework. *Ann. Rev. Environ. Resour.* 32, 395–419.
- Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D.R., Chan, K.M.A., Dailey, G.C., Goldstein, J., Kareiva, P.M., Lonsdorf, E., Naidoo, R., Ricketts, T.H., Shaw, M.R., 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production and tradeoffs at landscape scales. *Front. Ecol. Environ.* 7, 4–11.
- Nordhaus, W., 2007. Critical assumptions in the Stern review on climate change. *Science* 317, 201–202.
- O'Brien, K.L., Leichenko, R.M., 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. *Global Environ. Change* 10, 221–232.
- O'Brien, K.L., Leichenko, R., Kelkar, U., Veneman, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., West, J., 2004. Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environ. Change* 14, pp. 303–313.
- Ostrom, E., Janssen, M.A., Anderies, J.M., 2007. Going beyond panaceas. *Proc. Natl. Acad. Sci. U.S.A.* pp. 104–15176–15178.
- Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), 2007. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., Haight, R., Kagan, J., Starfield, A., Tobalske, C., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. *Biol. Conserv.* 141, 1505–1524.
- Polsky, C., Neff, R., Yarnal, B., 2007. Building comparable global change vulnerability assessments: the vulnerability scoping diagram. *Global Environ. Change* 17, 472–485.
- Ravetz, J.R., 2006. Post-normal science and the complexity of transitions towards sustainability. *Ecol. Complex.* 3, 275–284.
- Raven, P., 2002. Science, sustainability, and the human prospect. *Science* 297, 954–958.
- Raudsepp-Hearne, C., Petersen, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc. Natl. Acad. Sci. U.S.A.* 107, 5242–5247.
- Redman, C.L., Kinzig, A.P., 2003. Resilience of past landscapes: theory, society, and the Longue Durée. *Conserv. Ecol.* 7, 14.
- Renaud, F.G., Birkman, J., Damm, M., Gallopin, G.C., 2010. Understanding multiple thresholds of coupled social-ecological systems exposed to natural hazards as external shocks. *Nat. Hazards*, doi:10.1007/s11069-010-9505-x.
- Reynolds, J.F., Stafford Smith, M., Lambin, E.F., Turner II, B.L., Mortimore, M., Batterbury, S.P., Downing, T.E.T., Mestres, F., Ayarza, M., Walker, B., 2007. Global desertification: building a science for dryland development. *Science* 316, 847–851.
- Schellnhuber, H.J., Crutzen, P.J., Clark, W.C., Claussen, M., Held, H. (Eds.), 2004. *Earth System Analysis for Sustainability*. Massachusetts Institute of Technology and Freie Universität Berlin, Cambridge, MA.
- Schneider, S.H., 2001. A constructive deconstruction of deconstructionists: a response to Demeritt. *Ann. Assoc. Am. Geogr.* 91, 338–344.
- Simme, J., Martin, R., 2010. The economic resilience of regions: towards and evolutionary approach. *Cambridge J. Reg. Econ. Soc.* 3, 11–25.
- Smith, V.K., 1996. *Estimating Economic Values for Nature: Methods for Non-market Valuation*. Edward Elgar, Brookfield, VT.
- Swallow, B.M., Sang, J.K., Nyabenge, M., Bundotich, D.K., Duraipapp, A.K., Yatich, T.B., 2009. Tradeoffs, synergies and traps among ecosystem services in the Lake Victoria basin of East Africa. *Environ. Sci. Policy* 12, 504–519.
- Stafford-Smith, D.M., McKeon, G.M., Watson, I.W., Henry, B.K., Stone, G.S., Hall, W.B., Howden, S.M., 2007. Learning from episodes of degradation and recovery in variable Australian rangelands. *Proc. Natl. Acad. Sci. U.S.A.* 104, 20690–20695.
- Stern, N., 2007. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge.
- Turner II, B.L., 2009. Sustainability and forest transitions in the Southern Yucatán: the land architecture approach. *Land Use Policy* 27, 170–180.
- Turner II, B.L., Kasperson, R.E., Matson, P., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003a. Framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. U.S.A.* 100, 8074–8079.
- Turner II, B.L., Matson, P., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Hovelsrud-Broda, G., Kasperson, J.X., Kasperson, R.E., Luers, A., Martello, M.L., Mathiesen, C.S., Polsky, C., Pulsipher, A., Schiller, A., Tyler, N., 2003b. Illustrating the coupled human-environment system for vulnerability analysis: three case studies. *Proc. Natl. Acad. Sci. U.S.A.* 100, 8080–8085.
- Turner II, B.L., Robbins, P., 2008. Land change science and political ecology: similarities, differences, and implications for sustainability science. *Ann. Rev. Environ. Res.* 33, 6.1–6.22.
- Walker, B.H., Anderies, J.M., Kinzig, A.P., Ryan, P., 2006. Exploring resilience in social-ecological systems through comparative studies and theory development: introduction to the special issue. *Soc. Ecol.* 11, 12.
- Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G.S., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., 2002a. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Soc. Ecol.* 6, 14.

- Walker, B., Carpenter, S., Anderies, J., Abel, J., Cumming, G.S., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., Pritchard, R., 2002b. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conserv. Ecol.* 6, 14.
- Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2005. *At Risk: Natural Hazards, People's Vulnerability and Disasters*, 2nd ed. Routledge, London.
- WCED (World Commission on Environment and Development), 1987. *Our Common Future*. Oxford University Press, Oxford.
- Young, O.R. (Ed.), 1999. *The Effectiveness of International Environmental Regimes: Causal Connections and Behavioral Mechanisms*. Massachusetts Institute of Technology, Cambridge, MA.
- Young, O.R., Berkes, F., Gallopín, G.C., Janssen, M.A., Ostrom, E., van der Leeuw, S., 2005. The globalization of socio-ecological systems: an agenda for scientific research. *Global Environ. Change* 16, 304–316.
- Zhuo, H., Wang, J., Wan, J., Jia, H., 2010. Resilience to natural hazards: a geographic perspective. *Nat. Hazards* 53, 21–41.