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Editorial

The fragility of robust social-ecological systems

Human societies have a long history coping with uncertainty and change. A considerable body of recent work from the global environmental change research community attempts to understand whether and how societies will be able to continue to cope in the face of global change. Will they be able to respond to the shear pace at which social and natural systems are currently changing? If faced with one of either natural or social change, perhaps they can. However, in the face of "double exposure", the simultaneous impacts of global environmental change and globalization (O'Brien and Leichenko, 2000) that households, villages, and regions will face, they may be stretched beyond their capacity to cope on their own. Again, dealing with double exposure on its own may be possible through the concerted effort of governing bodies at multiple levels, but the pace of change may limit the effectiveness of the response. There is the additional issue that the context in which they operate is structurally changing. Both globalization and global environmental change are generating a highly connected global-scale system in which decisions at small scales are influenced by and will influence processes at the global scale in unpredictable and novel ways (Adger et al., 2009).

Some recent work has provided examples of the impact of this highly connected system. Eakin et al. (2009) report on how political changes and land reform in Vietnam enabled smallholder coffee producers to take advantage of opportunities in open markets. This induced a tenfold increase in coffee production in Vietnam from 1990 to 2000 and increased livelihood security for Vietnamese farmers. However, this contributed to a restructuring of global coffee markets and exerted significant downward pressure on prices. Not only did this hurt coffee growers a world away in Mexico, Vietnamese farmers also suffered when the coffee market collapsed in 2003. This is an instance in which globalization enabled a local action to propagate to the global scale as well as *feed back* to the local system with negative consequences in both cases. Silva et al. (2010) provide a more complex example involving both the highly connected global system and the issue of double exposure. In a study of Mozambique's Limpopo River Basin, the authors note that smallholder farmers find it difficult to transition to commercial farming, in part because farming techniques that are well adapted to managing local environmental variability – such as seeding many small plots – are not well suited to the economies of scale needed for commercial agriculture. Changes in national policy – driven in part by globalization – have caused households to change farming practices to take advantage of market opportunities. In so doing, farmers not only abandon practices that enhanced their robustness to local environmental variability they may also become more vulnerable to global commodity price fluctuations. As a result, they become more vulnerable to environmental and socio-economic variability.

These examples illustrate general features of economic systems with specialization. Actors in the system are subject to aggregate features of the system in which they interact often referred to as "market pressure", e.g. prices, aggregate demand, etc. In any such system, institutional structure and organization distributes risks and returns. In general, there will be winners and losers for any change in institutional structure and organization. In the cases above, globalization induced such changes with regard to risk management and with it, a reallocation of burden of loss and risk locally (O'Brien and Leichenko, 2003). From this perspective, globalization may simply amplify variation simply by *scaling up* the market system both spatially and temporally. The Limpopo example, however, raises deeper questions. Given that the farmers, over a long period, had developed practices and institutions that were well-adapted to local environmental variation, i.e. were locally robust. Why were some so willing to abandon them? Were they not aware of the performance-robustness trade-off they were making? Did they believe the system they were opting into would deliver both higher income and higher robustness? These are mainly empirical questions. A more theoretical question, motivated by the search for mechanisms to enhance the robustness and resilience of the global SES, is whether and how robustness of local SESs can be at once maintained and leveraged to help cope with climate change.

In the remainder of this editorial, we reflect on how ideas based on robustness and complex adaptive systems may help address these questions. In contrast to vulnerability studies that tend to focus on spatially and temporally explicit details at the individual or household level, our approach seeks to understand system-level dynamics and properties such as fragility and robustness. Resilience studies also tend to focus on system-level properties rather than households (Eakin and Luers, 2006) but are less focused on inherent trade-offs associated with different institutional design choices (Janssen and Anderies, 2007) than the multi-method, robustness-based approach we discuss here. Specifically, our work, informed by data from many case studies that is used to build formal models to link characteristics of individual households, governance structures, biophysical context, and social context to system dynamics (Anderies et al., 2004; Janssen et al., 2007) represents an attempt to connect these different traditions (see also Gallopin, 2006; Turner II, 2010).

The basic premise for a robustness approach is the fact that human actions taken in response to environmental conditions constitute *feedbacks* and feedback systems are known to exhibit

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inherent robustness-fragility trade-offs (Csete and Doyle, 2002). For example, this suggests that the feedbacks associated with farming practices in the Limpopo River basin that enhance robustness to a particular class of local environmental variation likely make the system vulnerable to variation outside this set. Further, while robustness is easily observable (households can assess that their livelihoods are less sensitive – i.e. more robust – to environmental variation), its associated fragilities are often *hidden* in that they cannot be detected until they are revealed by a system failure. We argue that these basic properties of feedback systems have important implications for global environmental change research:

- Even those SESs that exemplify local robustness are characterized by hidden fragilities that may be exposed by globalization and global environmental change. Thus, preserving local robustness is an insufficient response to global change.
- Given that local restructuring of (across time, space, or actor groups) of SESs will occur, inherent robustness-fragility trade-offs imply that local systems will almost certainly be trading one set of vulnerabilities for another. Economic policy must, therefore, be designed to navigate an ongoing sequence of vulnerabilities. At the same time, it must address the potential that because of globalization, problems associated with local restructuring may be propagated to the global system. Finally, it must do so at a time when global environmental change will lead to a more intense exposure of new endogenous hidden fragilities associated with structural change.
- Finally, we must recognize that many important features of global change will emerge from dynamics at the household scale. As such, we emphasize importance of studying how household decision responses to new opportunities and shocks resulting from globalization lead to endogenous restructuring of SESs at multiple scales.

We develop these points further based on our study of fragilities in exemplars of robust irrigation SESs.

From a practical perspective, small-scale irrigation systems are of critical importance. Nearly 90% of farms worldwide are less than 2 hectares and support the majority of world's poorest people (McIntyre et al., 2009). A large proportion of these rely on irrigation which consumes an estimated 70% of global developed water supplies (Barker and Molle, 2004) and produces 40% of global agricultural commodities from 17% of global cropped area (Wallingford, 1997). If fragilities in these systems are exposed by processes associated with globalization and global environmental change, the results could be catastrophic for billions of people.

As a result of their success in addressing the challenges of governing shared resources, many small-scale irrigation systems have become iconic exemplars of long-lasting SESs that have been able to persist and adapt to perturbations (Ostrom, 1990). As we have discussed, this past success involved becoming well tuned to particular disturbance regime which, in turn can (and in some cases *necessarily* do – see, for example Csete and Doyle, 2002) entrain hidden, systemic fragilities that can be exposed when conditions change. Climate change is exposing farming systems to disturbances at a pace not previously experienced in human history (Thornton et al., 2009), fundamentally changing when, and how much water is available. For example, in Pakistan, there is already a 10–15% decrease in precipitation in arid areas of and the predicted rainfall particularly during the summer monsoon is expected to increase (IPCC, 2007). This means that at the beginning of the growing season when farmers most need it there will be less water availability, and when they need it least, there may be flash floods that destroy irrigation headworks. In this sense, the disturbance regime to which these systems have become adapted will fundamentally change.

Experience suggests that helping these systems better cope with change is difficult. Numerous efforts by central governments to improve the performance of small scale agricultural systems (by providing infrastructure, e.g. canals, headgate systems) have largely failed (Ostrom, 2002; Ascher and Healy, 1990; Jayawardene, 1986; Levine, 1980; Shah, 2008). These failures are due, in part, to systemic fragilities. For example, central governments often do not account for subtle interdependencies between farmers, shared infrastructure, and biophysical factors and cannot effectively utilize local information critical to system performance. These subtle interdependencies are examples of fragilities that result from or past adaptation to local conditions (i.e. like key links in networks that once altered prevent the network from functioning). As a result, some government agencies have shifted to a decentralized approach (Ostrom, 2001; Bardhan, 2002) putting resources (but often only on paper) in the hands of local farmers (Johannes, 1998). This too, has met with problems due to local social interdependencies such as local elites co-opting resources. Thus, government intervention in irrigation systems has been, in part, a story of agencies discovering hidden fragilities in SESs. And this history covers a time interval in which globalization was not as strong a driver as it is now or will likely to be in the future.

Part of the success of these exemplar systems is related to key system characteristics; modularity, redundancy and diversity that have been stressed as critical to generate robustness (Csete and Doyle, 2002; Janssen and Osnas, 2005). Small-scale farmer managed irrigation systems are often broken down into interacting modules for irrigation system maintenance and water distribution. When weakly connected to the global system, they are themselves individual, modular, manageable units. They effectively exploit a diversity of land types and crops. And irrigation infrastructure is simple, and can be adapted to local conditions – i.e. temporary canals dug to bypass damage, etc. providing redundancy in the sense the system can be run multiple ways under multiple rule sets. Globalization, on the other hand, leads to a more interconnected network with increased homogeneity (reduced diversity) of crop varieties, cultural practices and economic institutions. Furthermore, increasingly intense economic competition leads to an increased focus on the efficiency of economic agents to survive leading to increased dependence of farmers on cash crops exposing them to volatile price fluctuations in the global market (Eakin, 2003) (less modularity). Alternative opportunities of income lead to outmigration and lack of labor in irrigation communities (less modularity). As globalization is transforming the structure of the global social-ecological system and makes it less robust, global environmental change leads to a more intense exposure of new endogenous fragilities (D'Odorico et al., 2010). The impacts of invasive species, climate change, and land use change are more profound with reduced modularity, redundancy and diversity.

Globalization and global environmental change lead to a fundamental dilemma concerning how to govern social-ecological systems. On the one hand, from case study analysis we know that small scale communities can self-govern very effectively due, in part, to the use of local knowledge, the development of trust relationships and the ability to adapt to local circumstances. On the other hand, in a globalizing world, we are experiencing increased volatility in social, political and economic conditions such as in commodity prices, increased inequality, increased mobility, integration with product markets, and new, unfamiliar contracts. Are the lessons we can learn from small-scale irrigation SESs about reconciling these conflicting local and global processes? Can we identify general features of these systems that scale up or across systems. Do they illustrate fragilities that tend to emerge as conditions change?

Reflecting on key properties of robustness vis-à-vis small-scale SESs can provide some ideas. An important element is the trade-off

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between local self-sufficiency and adaptive capacity (modularity and local diversity), connections to the global system (redundancy and global diversity), and the hidden fragilities inherent in complex systems. For instance, labor alternatives reduce the labor available for maintenance of local infrastructure (e.g. Lam, 1996) reducing the modularity of local systems. Likewise, clearly defined boundary rules that are critical for maintaining modularity are being challenged by 'roving bandits'. Increased mobility enables 'roving bandits' to invade successfully managed social-ecological systems, extract resources, and contribute nothing to local resource management infrastructure (Berkes et al., 2006; Pérez et al., in press). New product markets reduce redundancy by locking farmers into a single set of input providers through debt obligations they incur to purchase fertilizers, seeds, and pesticides leading to a vicious cycle of poverty and debt (sometimes with catastrophic consequences including suicide). The spread of contracting around the world leads to alternative mechanisms for risk sharing that may generate new fragilities (Aggarwal, 2007). Studies have shown that people are willing to accept some level of income diversity (inequality) as long as it is 'fair' given biophysical and social constraints (Janssen et al., 2011). However, globalization may remove or change the contexts in which income inequality was perceived as fair leading to a reduction of investment in collective action (e.g. labor in irrigation system maintenance).

To understand how to cope with global environmental change we need to take into account the how the perverse incentives of globalization affect modularity, redundancy, and diversity in both the social and biophysical domains. Polycentricity will play an important role to maintain institutional diversity at multiple levels and scales, provide room for experimentation and facilitate the diffusion of knowledge (Ostrom, 2010). These observations suggest that as we move forward, policy makers should take the recent plea of Ostrom et al. (2007) to avoid panaceas very seriously. The idea of policy panaceas flies in the face of the subtle biophysical and social contextual details that are often critical to the successful operation of local SESs.

To conclude we will suggest one possible emphasis for future research activities. We argue that it is important to study the ways social-ecological systems restructure due to globalization and global-environmental change, especially those changes that amplify system's fragilities. To do this we need to systematically study case studies, not to find correlations, but understand causations and mechanisms. Moreover, we need to use controlled experimentation to test hypotheses on how social-ecological systems restructure and explore the consequences with formal models (Poteete et al., 2010). An improved understanding of the processes in which fragilities of social-ecological systems are exposed due to globalization and global environmental change will enable us to better cope with the inevitable uncertainties and surprises.

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References

Adger, W., Eakin, H., Winkels, A., 2009. Nested and teleconnected vulnerabilities to environmental change. Frontiers in Ecology and the Environment 7 (3), 150–157.
Aggarwal, R., 2007. Role of risk sharing and transaction costs in contract choice: theory and evidence from groundwater contracts. Journal of Economic Behavior & Organization 63 (3), 475–496.
Anderies, J., Janssen, M., Ostrom, E., 2004. A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecology and Society 9 (1), 18.
Ascher, W., Healy, R., 1990. Natural Resource Policymaking in Developing Countries: Environment, Economic Growth, and Income Distribution. Duke University Press Books.
Bardhan, P., 2002. Decentralization of governance and development. The Journal of Economic Perspectives 16 (4), 185–205.
Barker, R., Molle, F., 2004. Evolution of irrigation in south and southeast Asia. Technical report, IWMI. Comprehensive Assessment Research, No: 5.
Berkes, F., Hughes, T., Steneck, R., Wilson, J., Bellwood, D., Crona, B., Folke, C., Gunderson, L., Leslie, H., Norberg, J., et al., 2006. Globalization, roving bandits, and marine resources. Science 311 (5767), 1557.
Csete, M.E., Doyle, J.C., 2002. Reverse engineering of biological complexity. Science 295, 1664L 1669.
D'Odorico, P., Laio, F., Ridolfi, L., 2010. Does globalization of water reduce social resilience to drought? Geophysical Research Letters 27 (L13403), 5.
Eakin, H., 2003. The social vulnerability of irrigated vegetable farming households in central puebla. Journal of Environment and Development 12 (4), 414–429.
Eakin, H., Luers, A., 2006. Assessing the vulnerability of social-environmental systems. Annual Reviews of Environmental Resources 31, 365L 394.
Eakin, H., Winkels, A., Sendzimir, J., 2009. Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. Environmental Science & Policy 12 (4), 398–412.
Gallopin, G., 2006. Linkages between vulnerability, resilience and adaptive capacity. Global Environmental Change 16 (3), 293–303.
IPCC (Intergovernmental Panel on Climate Change) (2007). Climate change: impacts, adaptation and vulnerability, contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change. Technical report, Intergovernmental Panel on Climate Change.
Janssen, M., Anderies, J., 2007. Robustness trade-offs in social-ecological systems. International Journal of the Commons 1 (1), 43–66.
Janssen, M., Anderies, J., Cardenas, J., 2011. Head-enders as stationary bandits in asymmetric commons: comparing irrigation experiments in the laboratory and the field. Ecological Economics 70 (9), 1590–1598.
Janssen, M., Anderies, J., Ostrom, E., 2007. Robustness of social-ecological systems to spatial and temporal variability. Society & Natural Resources 20 (4), 307–322.
Janssen, M., Osnas, E., 2005. Adaptive capacity of social-ecological systems: lessons from immune systems. EcoHealth 2 (2), 93–101.
Jayawardene, J., 1986. The Training of Mahaweli Turnout Group Leaders in Participatory Management in Sri Lanka's Irrigation Schemes. International Irrigation Management Institute, Sri Lanka.
Johannes, R., 1998. The case for data-less marine resource management: examples from tropical nearshore finfisheries. Trends in Ecology & Evolution 13 (6), 243–246.
Lam, W., 1996. Improving the performance of small-scale irrigation systems: the effects of technological investments and governance structure on irrigation performance in Nepal. World development 24 (8), 1301–1315.
Levine, G., 1980. The relationship of design, operation, and management. In: Walter Coward, E.J. (Ed.), Irrigation and Agriculture Development in Asia: Perspectives from the Social Sciences. Cornell University Press, Ithaca, NY.
McIntyre, B.D., Herren, H.R., Wakhungu, J., Watson, R.T. (Eds.), 2009. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): Global Report. IAASTD.
O'Brien, K., Leichenko, R., 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. Global Environmental Change, Part A: Human and Policy Dimensions 10 (3), 221–232.
O'Brien, K., Leichenko, R., 2003. Winners and losers in the context of global change. Annals of the Association of American Geographers 93 (1), 89–103.
Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press.
Ostrom, E., 2001. Decentralization and development: the new panacea. Challenges to Democracy: Ideas, Involvement and Institutions 237–256.
Ostrom, E., 2002. The Challenge of Underperformance in Improving Irrigation Governance and Management in Nepal. ICS Press, Oakland, CA.
Ostrom, E., 2010. A multi-scale approach to coping with climate change and other collective action problems. Journal: Solutions 1, 27–36.
Ostrom, E., Janssen, M.A., Anderies, J.M., 2007. Going beyond panaceas. Proceedings of the National Academy of Sciences of the United States of America.
Pérez, I., Janssen, M.A., Tenza, A., Giménez, A., Pedreño, A., Giménez, M., in press. Resource intruders and robustness of social-ecological systems: an irrigation system of southeast Spain, a case study. International Journal of the Commons.
Poteete, A.M., Janssen, M.A., Ostrom, E., 2010. Working Together: Collective Action, the Commons and Multiple Methods in Practice. Princeton University Press.
Shah, T., 2008. Taming the anarchy: groundwater governance in south asia. Resources for the Future.
Silva, J., Eriksen, S., Ombe, Z., 2010. Double exposure in mozambique's limpopo river basin. Geographical Journal 176 (1), 6–24.
Thornton, P., Jones, P., Alagarswamy, A., Andresen, J., 2009. Spatial variation of crop yield responses to climate change in east Africa. Global Environmental Change 19, 54–65.
Turner II, B., 2010. Vulnerability and resilience: coalescing or paralleling approaches for sustainability science? Global Environmental Change 20, 570–576.
Wallingford, H.R., 1997. Priorities for Irrigated Agriculture. Occasional Paper No. 1. Department of International Development, UK.

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