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Response Diversity and Resilience in Social-Ecological Systems

Paul Leslie¹ and J. Terrence McCabe²

¹Department of Anthropology, Curriculum for the Environment and Ecology, and Carolina Population Center, University of North Carolina, Chapel Hill, NC, USA

²Department of Anthropology and Institute of Behavioral Science, University of Colorado, Boulder, CO, USA

Abstract

Recent work in ecology suggests that the diversity of responses to environmental change among species contributing to the same ecosystem function can strongly influence ecosystem resilience. To render this important realization more useful for understanding coupled human-natural systems, we broaden the concept of *response diversity* to include heterogeneity in human decisions and action. Simply put, not all actors respond the same way to challenges, opportunities, and risks. The range, prevalence, and spatial and temporal distributions of different responses may be crucial to the resilience or the transformation of a social-ecological system, and thus have a bearing on human vulnerability and well-being in the face of environmental, socioeconomic, and political change. Response diversity can be seen at multiple scales (e.g., household, village, region) and response diversity at one scale may act synergistically with or contrary to the effects of diversity at another scale.

Although considerable research on the sources of response diversity has been done, our argument is that the consequences of response diversity warrant closer attention. We illustrate this argument with examples drawn from our studies of two East African pastoral populations and discuss the relationship of response diversity to characteristics of social-ecological systems that can promote or diminish resilience.

Keywords

human ecology; social-ecological systems; resilience; pastoralists; Africa

Introduction

We start with an observation that is unsurprising, perhaps painfully obvious, but with implications that bear further investigation. The observation is that not everyone responds to changing circumstances in the same way. Our claim about the implications of this is that variation in behavior, and more specifically variation in responses to changing circumstances, is itself important; the existence of variation, how it is distributed or patterned, may have enormous implications for the functioning and resilience of a social-

ecological system (SES). This variation must be considered in addition to behavior reflected in central tendencies or prevalence.

We do not imply that social scientists or ecologists have ignored variation. Quite to the contrary, scientists regularly document and use variation to ascertain relationships, including causal relationships. Indeed, this is the basis for much statistical analysis. Typically, however, the focus of such analysis is on the *causes* of variation: Why do some people get sick but others do not? Why do some forest patches resist infestations while others succumb? Why do some communities welcome outsiders more than do others? We argue for paying attention to the *consequences* of variation as well, because such variation may be crucial to the functioning and adaptive capacity of a system. We suggest that the resilience of a SES may in some cases depend on variation -- the diversity of responses within components of that system -- as much or more than on the typical or mean responses.

Our intent in this paper is to argue for the relevance of within-population response diversity for the functioning, resilience, and change of social-ecological systems. To that end, we

- describe the concept of response diversity as it has been used and our extension of it, and its relationship to resilience and associated ecological concepts;
- present two examples drawn from our studies of East African SESs, chosen to illustrate the range of ways in which response diversity can be integral to the dynamics of the SESs and can be crucial to their persistence and/or transformation;
- explore the implications of response diversity for resilience and adaptive capacity in those two cases and more generally, with an eye toward how response diversity is relevant to attempts to operationalize or assess resilience through accessible indicators.

Response diversity and resilience

“Resilience” has been used in several different ways, including as an evocative metaphor in discourse on sustainability and as a quantity that is potentially measurable in a specific SES (Carpenter et al. 2001). Holling (1973) defined ecosystem resilience as the amount of disturbance a system can absorb and yet remain within the same state or domain of attraction -- that is, retain the same controls and relationships among elements of the system.

Application of the resilience concept to human systems is more recent and definitions are evolving. Adger (2000) treated social resilience as the ability of human communities to withstand shocks to their social structure arising from environmental variability and economic or political upheaval. In the context of SESs, resilience is taken to mean more than simply the persistence of ecological relationships or of social structure and identity, but also the adaptive capacity to respond to the opportunities and constraints that are presented by perturbations (Folke 2006). Recent definitions thus add a more explicit concern with flexibility and adaptive capacity. Walker and Salt (2006), for example, define resilience as the capacity of a system to absorb disturbance and re-organize while undergoing change in a manner that allows for the persistence of system function, structure, and feedbacks. This definition fits our usage here.

Within a given ecosystem, several different species may perform a particular function – for example, pollination, nitrogen fixation, seed dispersal, short-grass grazing, or degradation of woody biomass. This is referred to as *functional redundancy* (sometimes also called *ecological redundancy*). Functionally redundant species may contribute to the same process within an ecosystem but respond differently to changing circumstances. In standard ecological usage, *response diversity* (RD) refers to the range of reactions to environmental change among species that contribute to the same ecosystem function (Elmqvist et al. 2003). For example, in the face of global warming or a long term drought, do all species in a given region that eat a certain sort of vegetation shift their range and go locally extinct? If so, there will be very different consequences for the ecosystem than if some of those species are more tolerant of change. Elmqvist et al. (2003) provide an impressive range of examples of response diversity within functional groups in the face of disturbance, across temporal and spatial scales, including: seed dispersal by fruit-eating species (e.g., diversity among flying foxes in response to cyclones); plants in rangelands (diversity among grass species in grazing tolerance); freshwater consumers of organic waste (diversity in sensitivity to acidification and organic pollution); and coral reef grazers (consequences of depleted diversity among algae grazers). They argue that RD is important for ecosystem renewal and reorganization following environmental perturbation or change – that is, RD can have an important influence on resilience.

Functional diversity is related to but distinct from functional redundancy. Functional diversity arises when different species that perform a similar function exploit different aspects of a habitat. For example, different grass species all tap water in soil but do so at different depths. These species thus all contribute to evapotranspiration (an important part of the water cycle) but their contributions to evapotranspiration will be more or less sensitive to changes in rainfall or groundwater levels. Walker, Kinzig, and Langridge (1999) demonstrate how functional diversity among grass species promotes resilience of rangelands in the face of changes in climate and grazing pressure; Carpenter et al. (2001) point to this as a specific example of how biodiversity enhances adaptive capacity. The relationship between biodiversity and ecosystem function is complex (Naeem et al. 2009; Griffin et al. 2009), but functional redundancy and functional diversity are both generally seen as promoting resilience. The relevance of RD to functional redundancy is explicitly recognized, as in Elmqvist et al.'s examples cited above -- RD among the entities that constitute the functionally redundant group means that a given ecosystem function is more likely to be maintained in the face of shocks to the system. But RD has not generally been seen as linked to the effect of functional diversity. Our discussion below will suggest that RD can in fact produce functional diversity, and may thereby be important to resilience through a previously unappreciated pathway.

In all of the examples mentioned above, RD refers to differences among species; discussion of the phenomenon is couched in terms of the species, or local population of the species, responding as a whole. Although the possible importance of other units is at least implicitly recognized by some, when ecologists talk about RD or functional diversity, they tend to focus on differences among species. Humans are a single species, but one characterized by enormous behavioral flexibility. We thus expand the concept of response diversity to include

heterogeneity in human decisions and action that affect one or more of the same SES functions; we wish to call attention to the importance of such within-population diversity.

Case studies of resilience or change in SESs tend to examine human behavior in terms of general trends or modal behavior for the population, community, or some segment of the population (e.g., commercial fishermen). They tend not to focus explicitly on variation within those entities in how people respond to challenges or changing situations. An exception to this generalization is discussion of innovators. But even this is typically done from the perspective of evaluating the consequences of the alternative behavior, with the implicit assumption that the innovation may replace former practices, or a focus on what will happen if that replacement occurs. Thus, in such examples the analysis of the system may acknowledge diversity in behavior, but the diversity is seen as transitory and the consequences of the existence of the diversity itself are not considered. What happens if actors do change their behavior over time in response to changing conditions, but not all individual actors do so in quite the same way? What might be the consequences of such diversity for SES resilience?

Definition and boundaries of social-ecological systems

The above discussion is couched in terms of ecosystems or social-ecological systems (SESs); it would be well to consider more explicitly the definition and difficulties of this concept. It is common to define a SES in terms of its components – species, geo-physical characteristics of the landscape, social actors, institutions -- and the relationships among those components. The choice of components is invariably shaped by the problem at hand. If we are interested in the behavior of a system – its stability, persistence, resilience, and possible transformations, it becomes necessary to consider aspects of the SES that affect the continuity of key components and relationships over time. Indeed, a central concern (perhaps *the* central concern) in the study of complex adaptive systems is how to analyze and understand, within a single coherent framework, both change and stability or persistence of those systems, including the ostensibly contradictory possibility of persistence through change (Martin and Sunley 2010). Two aspects of SESs that Cumming et al. (2005) identify as essential for understanding the dynamics of those systems are *innovation* and *system memory*. As we shall see, innovation and memory are not only conceptually important but also become practically useful in attempts to evaluate SES resilience.

The many definitions of SESs in the literature (e.g., Berkes et al. 2003, Glaser et al. 2008, and many papers published by the Resilience Alliance) generally entail setting spatial and/or functional boundaries for a SES. This challenge parallels that facing earlier ecosystem studies, especially those that incorporated human populations in the ecosystem being studied. The boundary problem was an important part of the critique of the ecosystem concept in anthropology and other social sciences (e.g., Moran 1990). In the two cases detailed below, the boundary definitions were shaped by the specific foci of the research projects. These definitions are set out within the project descriptions.

Assessing resilience

Over the past decade, much has been written about what contributes to resilience and adaptive capacity (Gunderson and Holling 2002; Walker and Salt 2006; Janssen and Ostrom 2006; Folke 2006; Adger 2006), but empirical analysis of resilience remains much rarer than conceptual exploration of the concept. This is so in part because resilience is difficult to measure, long periods of observation may be required, and because it may be problematic to make generalizations about causal relationships within complex systems in the context of historical contingency and path dependency. Indeed, resilience is more properly seen as an emergent property of a complex system than as a directly measurable characteristic (Robinson and Berkes 2010). Consequently, it has been suggested (see for example Bennett, Cumming, and Peterson 2005; Cumming et al. 2005) that surrogates – attributes of SESs that have been identified as enhancing resilience and adaptive capacity and that are more readily assessed – be utilized in place of attempts to directly measure resilience.

The notion of system identity is useful for structuring the search for and consideration of surrogates. A system's identity is seen not only in terms of the crucial components of a system and the relationships among these, but also institutions and processes that affect the continuity of those components and relationships over time (Cumming et al. 2005). As noted above, two general categories of variables that affect continuity are system memory and innovation. System memory refers to the ability to store and retrieve knowledge, which can create flexibility in problem solving and can enhance resilience (Berkes, Colding, and Folke 2003; Berkes and Seixas 2005). Faced with disturbance of the SES, be it environmental fluctuation or shifting political-economic circumstances, knowledge of how similar conditions were dealt with in the past, and the outcomes of such actions, can be enormously useful. Experience and memory can thus promote resilience. Note that memory is broader than individual recollection -- it may be collective, residing in cultural practices or institutions. That institutions and social networks as well as elders or other local experts serve as repositories of knowledge and experience is well recognized (Folke, Colding, and Berkes 2003). Innovation, more broadly including experimentation and learning, in some ways complements system memory. Carpenter et al. (2001) argue that the adaptive capacity of an SES is related to mechanisms that generate novelty and learning. Innovations are perhaps most often seen as helping to facilitate or even drive the transformation of a SES, but they may also serve to maintain system identity by promoting new ways of retaining old relationships and system components. We will return to consideration of surrogate indicators of resilience following our description of two case studies.

Two examples

We illustrate our arguments about the importance of response diversity with two concrete examples. Both derive from our long term studies of East African pastoral populations – the Ngisonyoka Turkana of northwest Kenya and Kisongo Maasai of northern Tanzania -- and the SESs of which they are a part. Both studies focus on understanding how people cope with risk and uncertainty, but differences between the two cases point to the range of ways in which RD may be important to understanding the dynamics of SESs. The Turkana example focuses on longstanding, “traditional” behavior; the Maasai example entails

response to a relatively new and rapidly changing set of challenges. In the Turkana case, RD is seen as integral to ongoing processes by which the SES functions; in the Maasai case, the importance of RD is seen in direct impact on land use/land cover with likely consequences for biodiversity and livelihood security. In each case, understanding the nature and consequences of RD is important to understanding the SES -- how it is maintained and how it may change.

Though contexts vary, nomadic and semi-nomadic pastoralists typically face social, political, economic, and ecological environments characterized by strong, often unpredictable fluctuations. How pastoralists cope with environmental fluctuations and changing circumstances, especially when they are unpredictable, is crucial for understanding not only persistence of the human populations in these habitats, but also for understanding human action within the social-ecological systems, with implications for both human well being and biodiversity.

Turkana: response diversity and persistence

Turkana District lies in the Great Rift Valley in northwest Kenya, bordered by Sudan on the north, Uganda on the west, and Lake Turkana to the east. The Ngisonyoka, who inhabit an area of roughly 10,000 sq km in the southern part of this district, are one of 19 territorial sections (*ngitela*) of Turkana. They are nomadic herders in one of the more arid habitats occupied by pastoral populations. The Turkana SES was the focus of the South Turkana Ecosystem Project (STEP), a long term, multidisciplinary study during the 1980s and 1990s that involved anthropologists, ecologists, and a variety of other scientists. The STEP scientists recognized the difficulty of setting boundaries to the ecosystem being studied and decided the aims of the project would be best served by using the sectional boundaries as recognized by the Turkana themselves to define the ecosystem. Results of this project, along with detailed description and discussion of the Turkana SES, can be found in Little and Leslie (1999) and McCabe (2004).

The Ngisonyoka are almost wholly dependent on livestock for their livelihood, so the propagation and maintenance of herds is the key to persistence of the Ngisonyoka population and society. In ecological terms, the Turkana SES is a nonequilibrium system (Ellis and Swift 1988), which means that important drivers of system dynamics are not themselves influenced by cybernetic relationships (primarily negative feedback) with other elements of the system. The most salient driver of the SES is rainfall. The timing, amount, and local distribution of rainfall are highly variable and unpredictable. Poor rainy seasons are common, and multi-year droughts can be expected at least once or twice a decade. The difficulties presented by climatic fluctuations are compounded by fluctuations in the biotic and sociopolitical environments, most importantly livestock disease epidemics and intertribal livestock raiding.

Mobility and herd diversity—The means by which Turkana have managed to cope with the fluctuations and unpredictability and to persist in this challenging environment was a central concern of STEP. Perhaps the single most obvious strategy, one that is common to most dryland pastoralists, is mobility – livestock are moved in response to the temporal and

spatial variability of rainfall and consequent forage. Indeed, Turkana are among the most mobile of pastoralists, moving frequently in response to changing conditions.

Another, perhaps less obvious, key is the Ngisonyoka practice of keeping a variety of livestock species, including cattle, camels, and goats, plus smaller numbers of fat-tailed sheep and donkeys (the latter primarily for transport). Although multi-species herding is common among pastoralists, this is a wider range of livestock than is typically found in pastoral groups. Dependence on multiple species requires more labor and complicates herding strategies, as the species have different needs in terms of forage and water, but there are a number of advantages. For example, cattle and camels tap different energy pathways that differ in timing and flux (Coughenour et al. 1985): cattle can take advantage of energy available in the rapid flush of grasses during rainy periods and propagate these large but ephemeral pulses to people through increased milk production, while camels browse in trees and tap vegetation characterized by less dramatic peaks but longer duration. The livestock species constitute a functional group of domestic herbivores that convert vegetation to human food. More generally, then, the primary benefit to keeping multiple species is that it allows Turkana to take advantage of RD of livestock to environmental fluctuations. If productivity of goats is compromised by, say, an epidemic of caprine pleuropneumonia, the cattle continue to produce; if drought conditions suppress cattle fecundity and milk production, camels may continue to yield milk; if a family's camels are stolen in a raid, their cattle, which are generally herded in a different area because of different nutritional needs, may remain safe. The same strategy of utilizing RD to mitigate effects of unpredictable disturbance is seen in diverse smallholder systems -- e.g., Polynesian polyculture (Colding, Elmqvist, and Olsson 2003). The importance of herd diversity to livelihood security is well recognized (e.g., Dahl and Hjort 1976; Mace and Houston 1989), but discussions of this strategy have not generally recognized the role and significance of behavioral diversity among households with respect to the resilience of the SESs of which they are a part.

Above we noted the often cited importance of mobility to the pastoral strategy. Now consider the importance of the variation among families in their herd movements. Turkana do not migrate like wildebeest -- great herds moving in the same cycle in more or less the same directions at the same time. Although it is certainly possible to make useful and statistically valid generalizations about Ngisonyoka migration patterns, there is much individual variation. Not all herders move to the same place or even the same sort of place; indeed, in some cases, one herder might move his family or herds to a place recently abandoned by another herder, an apparent confirmation of the dictum that "one man's trash is another's treasure." For example, three of the four families followed during a detailed study of herd movements carried out from 1980-82 (see McCabe 2004) moved to areas of higher primary productivity as the dry season advanced and vegetation dried up (as is expected in general for Ngisonyoka). But one did just the opposite, moving to areas of lower productivity as conditions worsened. That herder was able to do this because his herding strategy emphasized camels, which could exploit the browsing available along dry watercourses in places where grazing livestock would have little suitable food. This pattern kept his herds out of competition with those of other herders; it also reduced the likelihood of loss due to raiding at a time when others were at increased risk (the areas of higher productivity tend to be closer to their major enemies).

The preceding example points to two sources of heterogeneity in movement.

1. Structural differences. RD is encouraged, even demanded, by differences in herd composition and labor availability, in the context of differing livestock species' requirements. To some extent a herder's livestock "portfolio" changes due to environmental stochasticity; but different herders tend to emphasize different species. This specialization is not generally to the exclusion of other species, but rather a matter of degree, reflecting personal preferences based on experience and knowledge and on contingencies such as inheritance and herd loss.
2. Differences in perceptions of risk and opportunity. One herder may choose to minimize exposure to predators (hyenas, lions) or to raiding from neighboring groups, even if the safer areas are much poorer in suitable grazing/browsing. Another herder may risk loss of animals (and family members) to raiding in order to take advantage of resources in dry season refuges closer to enemies, rather than lose large numbers of animals to starvation or drought. Thus, some herdowners tend to follow what can be characterized as an aggressive movement strategy while others follow a more cautious strategy (McCabe 2004). Bollig (2006) also discusses risk-prone and risk-averse mobility patterns in response to drought and epidemics among Pokot (neighbors of Ngisonyoka). Differences in perceptions of risk and opportunity, and in ultimate herding strategies, arise in part from different personal experience, contingency, and differential tolerance of hazards such as drought, disease, and raiding. Turkana herders do not jointly decide on overall movements or distribution of herd composition to arrive at an optimum mix for the population as a whole. Individual herders are aware of what many others are doing, but their decisions are their own – the RD is produced at the individual level.

These are some of the sources of diversity in herd composition and movements. There are certainly others and together these are a necessary part of a full understanding of the Turkana SES. However, our primary concern here is with the *consequences* of this diversity.

RD and the efficacy of social networks—Despite the mobility, multi-species holdings, and sophisticated herding strategies practiced by Ngisonyoka, major losses of livestock are common. Families can expect to lose large portions of their herds to drought, disease, and/or raiding, and to experience such losses repeatedly (see McCabe 2004; Leslie and Dyson-Hudson 1999). In the face of such events, a key to success, or at least survival, is social networks (kin and exchange partners), which are crucial both for immediate support in the aftermath of disasters and for subsequent restocking. Examination of this phenomenon leads to an appreciation of the importance of *intra-species* RD to the persistence of families and ultimately to the resilience of the Turkana SES.

Social networks with mutual obligations for exchange or redistribution of livestock (and, to a lesser extent, redistribution of dependents) (Leslie and Dyson-Hudson 1999; Johnson 1999) are indispensable for restocking following disaster and for other purposes such as assembling bridewealth (which is unusually high among Turkana). But the efficacy of this mechanism depends on RD that serves to spread risk – including the diversity seen in herd movement and herd composition noted above. A consequence of a mix of strategies among

members of a network is a hedging of ecological bets: if people move to different places with different characteristics, it is less likely that all in a herdowner's social network, all of his exchange partners, will have devastating losses at the same time. Potential aid is thus more assured. Although there is a moral obligation to help a close relative or exchange partner if at all possible, restocking transactions depend on "donors" having sufficient numbers of the needed species (McCabe 1990).

For example, two brothers-in-law, Angor and Lori (names altered), emphasized different livestock species and practiced divergent movement patterns. Angor specialized in goats, which can reproduce quickly and can shift forage types as conditions require, and kept fewer cattle and camels, while Lori emphasized cattle production. In one particularly severe drought Lori was forced to take his animals to locations where grass was available but that area was also close to the border with the Pokot, traditional enemies of the Ngisonyoka. In one large Pokot raid Lori lost almost all his livestock. Although Angor's cattle moved to a similar location and were also raided, Angor survived this stressful period because of his large herds of goats, which were kept elsewhere. As a key member of Lori's network, Angor took care of Lori and his family over a two year period and also helped him restock. Without Angor's help, restocking would not have been possible and Lori and his family would in all likelihood have had to try to survive outside of the pastoral system.

In contrast, Apu took over as principal herdowner when his brother Loper died suddenly. Loper had been quite successful, with a growing family and large livestock holdings. For a variety of reasons, Apu did not maintain the extensive network that Loper had cultivated. Loss of all of the family's camels and most of the small stock in a large raid, followed by loss of cattle to drought and disease in the following years, left the family in dire straits. Lack of a viable network precluded restocking, and family members dispersed. The ultimate failure and dissolution of the family was the product of several factors, including repeated losses to raiding and disease and questionable management decisions, but the lack of a sufficient exchange network was an important part of the constellation of conditions leading to the failure. These cases are described in greater detail by McCabe (2004). The point here is not just that Lori's network existed while Loper's dissipated, but that the diversity of strategies in the Angor-Lori case enabled the recovery.

Livestock exchange networks include many kin (agnatic and affinal) but also many nonrelatives, and Turkana take care to cultivate relationships with others who live at some distance, who utilize different areas for wet or dry season pasture, and whose fortunes are less likely to be closely correlated with their own (Gulliver 1951; McCabe 2004). The benefits of having widely dispersed exchange partners are recognized by the neighboring Pokot as well (Bollig 2006).

Note that we have described the Turkana SES as we saw it in the 1980s-90s and based on reports by others (including Turkana informants) about earlier times. There have been some important changes in Turkana during the past decade, but most of the key characteristics of the SES that we observed and described persist, and in any event our observations about RD are not rendered less valid by the fact that they pertain most directly to a system in the past. Our claim, then, is that in Turkana the persistence of the human population, and therefore

the resilience and persistence of the SES, depends to some degree on response diversity among individuals or domestic units.

Simanjiro: response diversity, land use, and biodiversity

In contrast to Turkana, where tourism is minimal and government involvement almost grudging, Maasailand is of enormous importance from the standpoint of both economics and conservation. Northern Tanzania is the country's most prominent draw for tourism and a region of intense interest and involvement of national and international wildlife conservation organizations. As is the case elsewhere in Africa, parks and protected areas in northern Tanzania have stimulated significant social, economic, and environmental change. This includes the adoption of alternative forms of land use that can either strengthen or compromise SES resilience, promoting sustainability or leading to a major transformation and reorganization of the social, demographic and ecological systems outside of and including parks (Child 2004; Norton-Griffiths 1996; Wittemyer et al. 2008; Joppa, Loarie, and Pimm 2009).

As part of a broad, interdisciplinary study of the consequences of parks, we have been studying the SES in the vicinity of Tarangire National Park (TNP) in northern Tanzania, with a specific focus on changes in land use and livelihood strategies in several communities in Simanjiro District. The communities in Simanjiro District are composed predominantly of Kisongo Maasai people, traditionally semi-nomadic herders who, like Maasai elsewhere, increasingly are diversifying their livelihoods through adoption of agriculture and labor migration (McCabe, Leslie, and DeLuca 2010). We treat the boundaries of the SES as being defined by the rangelands of northern Tanzania and southern Kenya occupied by the Maasai people. People and livestock migrate within this SES and system wide institutions govern access to resources. As with the Turkana study, the spatial extent of the Simanjiro SES is defined largely in terms of the local Maasai's perceptions and activities – primarily the areas utilized by those people for their herding, but recognizing that important influences, including wildlife, other Maasai and ethnic groups, government and non-government institutions, originate from beyond those boundaries and must be considered in order to understand what goes on within the Simanjiro/Tarangire SES.

Cultivation in Simanjiro is notably different from that in other pastoral areas of Tanzania. Large plots are plowed by tractor or less frequently by oxen, and some villages have allowed outsiders to lease large areas for commercial cultivation. All of this represents a transition from traditional forms of common property to various forms of privatized or semi-privatized land holdings. The rapid expansion of cultivation has been of great concern to conservationists (Foley 2004; Msoffe et al. 2011), as the result may be to turn TNP into an island park, cutting off access of migrating wildlife to the Simanjiro plains.

Causes of the changing livelihoods and land use are complex (McCabe, Leslie, and DeLuca 2010). Population pressure -- increasing human population without commensurate increase in livestock populations -- is an important factor (McCabe 2003), but fear of (further) alienation of land or restricted access to resources due to conservation policy (expansion of parks, establishment of Wildlife Management Areas or other forms of protected areas) is also influential. The latter concern is fully understandable given past evictions of Maasai

from Serengeti (1959), Ngorongoro Crater (1974), Mkomazi (1980s) and, especially close to home, from Tarangire NP itself (1970). Just last year saw the appropriation of village lands in the Mkungunero Game Reserve adjacent to the southern boundary of TNP. Villages in Simanjiro began allocating land to individual household heads approximately 20 years ago, in some cases as an attempt to bolster legal claim to village lands and avert further losses.

In addition to the possible alienation of resources by conservation measures, proximity to the parks entails other risks – especially crop damage by wildlife migrating beyond the park boundaries (which are quite arbitrary from the perspective of the wildlife) (Baird, Leslie, and McCabe 2009). These contribute to the calculus of livelihood strategies and alternatives as well.

The Simanjiro study communities vary with regard to proximity to TNP, but all lie within the “zone of influence” of the park. Two of the four villages discussed here (Loiborsoit and Emboreet) border on TNP and two (Sukuro and Terrat) are separated from the park by one village. Villages are spatially large, resembling a county in some parts of the United States, so village-level decisions about land use can have a significant impact on the regional SES. Not all villages are responding to changing circumstances or risks in the same way. They differ in the prevalence of new forms of livelihood and in community efforts to manage land tenure and access to common resources (especially pasture). Livelihood diversification has been recognized as a means of risk management (e.g., Little et al. 2001) and indeed is related to resilience, but we are not concerned here with livelihood diversification per se. Rather, we point to *diversity in the diversification*.

Cultivation in Simanjiro can have substantial benefits but may also entail significant costs and risks. Benefits include both increased food security and the possibility of selling harvested crops (especially beans, which bring a good price) to purchase livestock and veterinary medicine and to pay for hired labor or household expenses. However, because precipitation in Simanjiro is limited and highly variable both spatially and temporally, cultivation is inherently risky. In some years rain falls in a relatively stable pattern once the rainy season begins (February to April); in some years heavy rains in February falter and may or may not return intermittently four or five weeks later; in other years the rains begin late and only last for a few weeks. Complete or partial crop failure, as happened in 2009 and appears to be happening again in 2011, either due to lack of rain at the right time (sometimes too much rain) or to wildlife predation is common. In some years cultivation is productive for most people and their livestock thrive; in some years crops fail but livestock do well; and in other years livestock die and crops fail. When crops fail, not only do the nutritional and economic benefits not materialize, the costs of the seed and of hiring a tractor are not recouped.

Individuals respond to these opportunities and challenges in very different ways. Some households plant large fields while others engage in limited cultivation. In years when cultivation results in a surplus some individuals invest in livestock and veterinary medicine while others use the surplus funds to expand cultivation.

Table 1 gives aggregate statistics for the amount of land allocated to a sample of households in each village, the area these households devoted to cultivation of each of the principal crops, and their livestock holdings (expressed in TLUs, Total Livestock Units), in 2010.

Table 1 reveals considerable variation both within and among villages with regard to engagement with animal husbandry. In 2010 there was more than a 5-fold difference among villages in mean or median household livestock holdings (measured in TLUs). There is substantial variation among households in number of acres cultivated, with the standard deviation exceeding the mean overall. The differences among the villages with regard to the acreage cultivated by each household is not statistically significant, but there is notable variation among villages in the emphasis on beans (likelihood ratio test, $p < 0.001$). Sukuro cultivators invested predominantly in maize. Terrat households had the second lowest number of total acres in cultivation but the highest investment in beans as a proportion of land cultivated. Emphasis on beans represents a risk-prone strategy -- beans are more profitable than maize when there is a good crop but are more likely to fail.

The villages differ markedly in the amount of land allocated to each household, with the median allocation in Emboreet being more than three times that in Terrat, but those larger allocations do not translate into more cultivation. Terrat had the highest ratio of cultivated to allocated land in 2010 (the ratio of median acres cultivated to median allocation = 0.47; the ratio for the other villages ranges between 0.09 and 0.17). But the amount of land households cultivate in Terrat is not especially high, falling within the range of the other villages. The high cultivation to allocation ratio is thus due to smaller allocations. This reflects diversity at the village level -- diversity that has implications for potential future expansion of agriculture and for the landscape.

Additional insight into the diversity of household livelihood portfolios can be gained by examining the joint distribution of households according to both TLU and acres cultivated (AC) (see Figure 1). A strong positive correlation between TLU and AC might indicate that TLU and AC rise together as a function of wealth and variation in each is associated with overall wealth rather than different livelihood strategies. The correlation between TLU and AC for all villages together is indeed positive but not especially strong ($r = 0.23$, $p = 0.026$); within villages, the correlation is strong and statistically significant only in Emboreet ($r = 0.63$, $p = 0.004$). These data do provide evidence for different mixes of livelihoods. In Sukuro and Loiborsoit, for example, some households have well above the mean TLU but below mean AC, and vice versa. These two villages exhibit a greater range of TLU associated with a given level of AC than is seen in the other two villages.

Just why different households take different strategies (here, especially, different emphasis on beans) – how it relates to their past experience, the nature and extent of their network, etc., needs further investigation. Influences may be generally similar to those described for Turkana, but the influence of village or higher level context (see below) may be additionally important. Whatever the determinants of these differences, it seems reasonable to expect that the diversity of strategies seen at the household level will affect the long-term viability of households and thus play a role in the resilience of the SES.

Overall, these data suggest that there is variation among households and among villages in mixes of livelihood strategies. The causes of this diversity must be taken up in another paper; our concern here is with the consequences of the diversity. In the context of the fluctuating climatic conditions in Simanjiro, the variation described above acts in much the same way as diversity in herd composition and mobility patterns act for the Turkana (described in the preceding section). Exchange networks are robust among the Maasai as they are among the Turkana, and extend across villages. If crops fail for a household in a particular year, other households in the exchange network may have been successful; in a year when crops fail but livestock thrive, households with large livestock holdings help those who have few livestock and have suffered crop failure. Just how the developing diversity in livelihood strategies affects the efficacy of exchange networks and, indeed, how it affects the formation of the networks, remains to be seen. We have begun a more detailed study of these networks (Baird 2012) but at this point cannot demonstrate the importance of this diversity as clearly as can be done for the Turkana case.

The consequences of variability at the village level may be even more salient for the landscape and for resilience than is variability at the household level. Each village has areas of extensive plains utilized by wildlife that migrate from TNP in the wet season, and each also has areas designated for cultivation and areas designated for livestock grazing. However, land cover and land use plans differ among the villages and they differ markedly in their policies for the size of individual allotments and the degree of large scale cultivation. The village of Loiborsoit has set aside large tracts of land for livestock grazing, formally maintaining that common pool resource. Terrat designated a large tract for wildlife conservation (especially to accommodate the wildebeest migration and calving) in 2008 and was joined in this endeavor by Sukuro in 2010; these villages are receiving funds from Tanzania National Parks (TANAPA) and conservation NGOs to keep the area free from settlement (Nelson et al. 2010). Instead of resisting the push from conservation, these two villages are embracing it. People are still herding their livestock as if the uncultivated land were all commons, but a major grazing area has been designated for future allocation to individuals. The stage is thus set for rapid fragmentation of grazing areas if cultivation increases. Developments in Sukuro and Terrat stand in stark contrast to village level decisions made in Loiborsoit and especially in Emboreet, where village leaders have continued to promote cultivation in the plains and have no intention of setting aside land for conservation. Sukuro's set-aside of a grazing area for future allocation to individuals further differentiates their land use trajectory from those of the other villages. Which of these diverse strategies will most benefit local people is not clear at this time. It is clear, however, that villages are responding differently to the challenges of living in proximity to the park and to potential benefits and costs of cultivating in the plains.

There are other differences among the villages that relate directly to land use and land cover. For example, Loiborsoit did not resist WaArusha cultivators (a neighboring population) from coming in and establishing farms; Terrat evicted them. Terrat did not resist a recent directive from the Regional Commissioner banning cultivation on the Simanjiro Plains; Emboreet has been most averse to setting aside land for conservation and is strongly resisting directives to curb cultivation on the plains. If they accede to such curtailment

people would likely move closer to the park, which would entail its own set of consequences such as deforestation.

In all of these villages in the vicinity of TNP, the overwhelming perception is that there is a significant risk of loss of land tenure due to park expansion or government-imposed changes in conservation and land use policies (Baird et al. 2009). Despite this shared perceptions, the villages are responding differently to the threat of further alienation of land. Some village-level conservation policy is leading to conversion of commons to private holdings allocated to individuals; in other villages it is leading to formal establishment of commons areas and/or special use areas. There is thus substantial RD at the village level.

The existence of RD at both the village and individual household levels introduces the possibility of cross-scale effects – that is, the effects of RD at one level might act synergistically with or counter to those at the other level. An example of this is seen in “preemptive cultivation”.

Conservation organizations (both Tanzania National Parks [TANAPA] and wildlife oriented NGOs) have sponsored numerous workshops and tours for village leaders to demonstrate the economic value of wildlife in an attempt to influence village level decisions favorable to conservation. Individual herder/farmers know this and are also aware that funds are generated through conservation related activities, but may not see themselves as benefitting. They also hear some village leaders advocating the expansion of conservation measures in their community. The common perception is that the leaders are “selling” the land to conservation interests for their own benefit – not that of the community. This increases the sense of insecurity at the individual level, and a response to this on the part of some households is to secure as much land as they can and intensify land use before their leaders “sell” it to conservation. In some cases this has entailed cultivation in the midst of wildlife migration corridors even when that is not the best agricultural land (Cooke 2007; Sachedina and Trench 2009). Thus, the government/NGO effort to influence land use decisions at the village level may have been successful in promoting conservation, but has stimulated insecurity at the individual level, prompting individual responses within villages that may be inimical to conservation.

As we mentioned in the introduction, we are considering the rangelands in northern Tanzania and southern Kenya occupied by the Maasai to be the larger SES within which Simanjoro is embedded. People and livestock migrate within this SES and system-wide institutions govern access to resources. We see this as important to the discussion of response diversity at a level higher than households and villages. Although the rangelands and people are similar, Kenya and Tanzania have had divergent political histories. While Kenya first divided the rangelands into group ranches which are now being rapidly privatized, Tanzania maintained large areas for common grazing. This has important implications for response diversity. In Kenya there has been a much more rapid adoption of newer, more productive breeds of cattle; and in some cases cattle that are more resistant to disease. These breeds have begun to be adopted by the Maasai in Tanzania. The privatization of rangelands in Kenya has fragmented the landscape making the free movement of livestock in times of stress more difficult than in Tanzania. The maintenance

of common grazing areas in Tanzania allowed Kenya Maasai to migrate with their animals during the severe drought of 2009 and again in 2011. This process would have been much more difficult had the Tanzania rangelands been fragmented like the Kenyan rangelands. In addition, this demonstrated that the institutions that facilitate access to resources have been maintained throughout Maasai-land. This might be considered an instance of RD promoting one correlate of resilience -- system memory --- for the larger SES, embodied in a cultural institution that would likely have disappeared had the Kenyan model been followed in Tanzania.

The potential importance of response diversity in Simanjiro—The Maasai responses to the changing conditions described above – changes in livelihoods, government policy, and village land allocation – have been developing only over the past 10-20 years, but with increasing rapidity in a shifting political-economic context. As described above, RD at the village and individual levels is already becoming evident. The near- and longer-term social, ecological, and political-economic consequences of this diversity are not yet clear and the whole situation is in flux. Because we see new elements in the SES, and new relationships among elements, this appears to be a period of reorganization in the adaptive cycle of a complex system (cf. Gunderson and Holling 2002; Walker and Salt 2006). But there is good reason to expect that the multi-level RD reflected in changing land use/land cover in Simanjiro will have consequences for biodiversity and the evolving SES more broadly. The diversity of uses (variety of crops, set-asides for pasture or for wildlife) itself can affect both biodiversity and the viability of traditional and new livelihood pursuits. This can be illustrated by taking a more abstract approach.

Consider a hypothetical landscape experiencing introduction of a new land use and consequent change in land cover. There is a potentially huge difference between a case where all units or agents (say, households or villages) do the same thing to the same degree and a case where those same units respond differently – e.g., all landowners devoting 20% of their land to fruit trees vs. 20% of landowners devoting all of their land to orchard while 80% devote none. The pattern of diversity makes a difference.

Figure 2 depicts two alternative distributions of the same amount of “transformed” land – strongly clustered vs. highly dispersed -- and illustrates why such differences might be important. Holding the proportion of the area transformed constant, as the dispersion of patches increases the mean area of patches decreases and the total edge (perimeter) of patches, increases.

The clustering of disturbance affects landscape characteristics and has implications for biodiversity. Species richness can be influenced by the spatial pattern of land transformation, particularly fragmentation and habitat loss (DeFries et al. 2005; Fahrig 2003). Conversely, clustering of transformed patches may achieve the minimum size of habitat needed by a new or recolonizing species to maintain itself, and the edges of patches may represent transition zones or ecotones, which are often associated with higher biodiversity. The distribution of transformed land affects the “permeability” of the landscape – whether migration corridors remain intact or whether sufficient stepping stones of suitable habitat are maintained– and thereby the isolation of local populations. Thus, the balance

between local extinction and recolonization, and opportunities for colonization by new or invasive species, are functions of the pattern of transformation (Sinclair 1998; Hansen and Rotella 2002). The spatial distribution of disturbance may affect not only wildlife but domestic species as well, through adequacy of and access to common pasture or other resources, and thus affect social institutions and the SES as a whole.

This is a very simple illustration (just one new type of land use), but it hints at how use diversity and the clustering and prevalence of various uses may interact. Consider a more general situation, with a hypothetical landscape characterized in terms of three landscape-level variables: *saturation* (the proportion of landscape cultivated), *clustering* (the degree to which, say, agricultural plots are clustered or dispersed), and *use diversity* (the diversity of agricultural fields or alternative uses). All of these variables can affect biodiversity and may interact in various ways in their effects on biodiversity. Figure 3 illustrates our expectation that as the saturation of agricultural land use in a previously non-agricultural area increases, biodiversity at first increases and then declines. The increase results mainly from creation of a mosaic of habitats and ecotones. As the landscape becomes increasingly saturated with land devoted to agriculture, we expect biodiversity to decline because of reduced environmental heterogeneity. However, we expect that the relationship between saturation and biodiversity is also affected by the diversity of land use, as indicated by the three curves for different levels of use diversity. Greater use diversity may imply greater habitat diversity. Thus, our expectation is that higher use diversity can to some extent compensate for higher saturation of land use.

However, the effect of clustering depends on the level of “intensity” or prevalence of change (saturation). Figure 4 depicts our expectation that in a landscape that is highly saturated with agriculture (or other specific use), the degree of clustering of farms (or of any land use) will not have a strong effect on biodiversity because there will be little difference between maximum clustering and a random or a uniform distribution of land uses. At lower saturation, clustering may be quite important as it fragments habitats and generates microenvironments of sufficient size to affect the distribution and populations of various species.

Empirical evidence for the importance of saturation and clustering to the tradeoffs between food security and biodiversity and conservation is accumulating. For example, Phalan et al. (2011) find that optimal solutions to the ongoing arguments over alternative approaches to reconciling needs for increasing food production and for preserving biodiversity – simultaneously using an area for agricultural production (though at lower intensity) and for conservation (“land sharing”) vs. devoting some land to more intensive production while setting other land aside for conservation (“land sparing”) – depend not only on the species of interest but also on the patterns of alternative land use/land cover within a landscape mosaic.

This discussion illustrates how the variation in land use (and thus RD) is itself important. The diversity of uses -- variety of crops, set-asides for pasture or for wildlife as described for Simanjiro, etc. -- is likely to affect biodiversity. The biodiversity will in turn have implications for the success or viability of various land uses – e.g., by influencing crop damage and predation, by stimulating changes in opportunities for tourism, hunting, and/or

restrictive conservation policies. Policies or practices that vary among villages are now producing variation in the distribution of land uses within and among villages (e.g., pasture commons in Loiborsoit; a wildlife area in Terrat).

Thus, it is reasonable to expect RD to affect resilience, but the relationship between spatial heterogeneity and system stability is complex and the specific consequences will not always be obvious. Even restricting attention to just rangelands, spatial heterogeneity can be destabilizing in some systems but enhance stability and resilience in others (see Janssen et al. 2002), and the relationship may depend on temporal variation in rainfall and on grain of the landscape (Boone 2007). Whatever the relationship in a given case, it is clear that the degree and pattern of spatial heterogeneity can be important, and that multi-level RD can influence that pattern. It can do so directly, as saturation and clustering of various land uses are potentially influenced by decisions at the individual or household level, village level, and higher levels. There may also be less obvious, more indirect consequences of RD -- for example, through influences on family formation. Landscape change may be more sensitive to the number and composition of households than to population size *per se*, and more sensitive when households are distributed widely than when they are clustered (Rindfuss et al. 2007).

Far more than biodiversity is at stake. The consequences of not setting aside common use areas for grazing could be momentous, resulting in significant transformation of the SES. Pastoral systems function as extensive systems; allocation of land to individuals, which is happening in different ways in different Simanjiro villages, fragments the landscape and could easily compromise the viability of the pastoral system. Conversion of commons to private holdings might lead to increased risk of poverty and/or greater inequality in wealth, even if allocations are equitable, by encouraging breakdown of traditional redistribution mechanisms. On the other hand, under some circumstances inequality may be beneficial to successful management of remaining commons. Those with greater interest and power might coerce others into maintaining commons (Ruttan and Borgerhoff Mulder 1999). However, in cases where inequality of wealth means that some individuals benefit more from maintenance of the commons than do others, those individuals may gain from seeing to it that the good is provided or maintained even if they have to bear the cost themselves (the “Olsen effect” – cf. Bardhan and Dayton-Johnson 2002).

Discussion

Although a number of authors have discussed the resilience of pastoralist social-ecological systems (e.g., Niamir-Fuller 1998, Homewood and Rogers 1991, Robinson and Berkes 2010), none to our knowledge have explored the role of response diversity in those systems. Further, Robinson and Berkes (2010) noted recently that there have been few attempts to operationalize measures or surrogates of resilience in pastoralist SESs, and they go on to do so for a pastoralist system in northern Kenya, paying close attention to the social elements of the system. Our paper here contributes to filling the gap that they note, but our aim is more general and our argument about the relevance of RD to resilience pertains to other SESs as well as to pastoralist/rangeland systems.

Response diversity and indirect indicators of resilience in the two case studies

Our description of response to environmental change and uncertainty on the part of Ngisonyoka Turkana and Kisongo Maasai, be it climatic fluctuations or new political-economic developments or long term trends, point to a variety of ways in which RD may be related to the functioning and resilience of those SESs. In Turkana, we argue, the system “works” (or at least persists) in part because of RD -- persistence of the human population and their nomadic pastoral livelihood depends on the diversity of responses to repeated environmental challenges (climatic, biotic, sociopolitical). Resilience and persistence of the SES is to some extent a consequence of response diversity. The most obviously crucial diversity is seen in herd composition and herd movement. As explained in the Introduction, two categories of variables that affect the continuity and thus the identity of a SES are system memory and experimentation or innovation. Although Turkana is by no means a timeless, unchanging place, the responses we describe are largely responses to well known risks and circumstances, and reflect longstanding practices – born of experience and memory rather than experimentation (but see below for an exception to this).

In contrast, the responses in Simanjiro to the developments associated with Tarangire National Park and conservation policy are just now taking shape, and the options, risks, and opportunities are not nearly so well known to the people who must cope with the changes. Already it is clear that there is RD at both the village and household levels (further diversity is also seen among sub-villages – administrative subdivisions of villages – but is not discussed here). The institutional context is in flux, but the developing patterns of land use and livelihood strategies stand to be extremely important for the Tarangire-Maasai Steppe SES, which embraces the park with its highly valued biodiversity and the study villages but extends much further. Resilience of the current SES, or the character of its transformation to an alternative state, will to some extent be shaped by RD.

The Simanjiro case also points up the possibility that RD may be observed at different levels, and that what goes on at different levels may interact in ways that are important for the dynamics of change in the SES. From the perspective of conservation interests, decisions concerning land use taken by some Simanjiro households are in conflict with actions taken at the village level. Antagonistic effects across levels might be expected when the benefits accruing to decision-makers at the different levels depend on opposing or incompatible outcomes. Cross-scale interactions are likely to be common in complex systems, but it is difficult to generalize at this point about how RD may influence such interactions.

In these two cases we find ample evidence of RD to environmental change and challenges, including well known environmental fluctuations and newer constraints and opportunities, and see reason to believe that RD is relevant to the resilience of both of these SESs. As noted earlier, measuring resilience is problematic, so demonstration that phenomena, including those that we describe here as instances of RD, affect resilience can be difficult. Carpenter et al. (2001) point out that in order to evaluate the resilience of a system, it is necessary to specify “resilience of what, to what?” – that is, what state within the system is of interest and what perturbations are most important. Only then can appropriate surrogates for resilience be chosen. Table 2 sets out an attempt at specifying these considerations for the Turkana and Simanjiro SESs. Perturbations include events or conditions that have

occurred in the past and may be expected (by researchers and/or local people) to recur. There certainly may be other system states and perturbations of interest, and consequently other resilience surrogates; those listed simply reflect concerns that have been central to our research. Our aim here is not to evaluate the resilience of either system; rather it is to point out that RD is relevant to appropriate resilience surrogates and may be an integral aspect of them. We do so while keeping an eye on how specific surrogates included in Table 2 fall within the categories of factors that influence system identity – especially memory and innovation.

Turkana—Our long term research with nomadic Turkana makes clear the ubiquity of episodic herd loss and the importance of social and exchange networks both for coping with such loss and for family building. We argued (above) that diversity of management strategies of families (with regard to species mix and movement) contributes to the ability of the Ngisonyoka to cope with environmental perturbations, and that RD reflected in differences of management strategies within exchange networks further enhances the viability and utility of these networks. These arguments need not be reiterated here. However, our description and discussion was based on Ngisonyoka families that were still in the nomadic sector. Additional evidence for the importance of the networks is seen by looking beyond these families. Studies of settled Turkana living in several of the small towns along the Kerio and Turkwel rivers in South Turkana show that the principal reason for settlement is loss of livestock (from drought, disease, and raiding) coupled with inability to restock (Campbell et al. 1999; Brainard 1991; McCabe 1990), an inability tied to an inadequate social network. The contrast between northern and southern Turkana during an especially severe drought in 1979-81 is also instructive. A breakdown of traditional drought-coping institutions and practices in northern Turkana, arising from the extended drought and exacerbated by intensified intertribal raiding, resulted in mass movement to famine relief camps. Extended residence in relief camps weakened the traditional exchange networks and the ability to restock (McCabe 1990). South Turkana (including Ngisonyoka) also suffered from the same drought but there were no famine relief camps and traditional institutions remained intact. The resilience of the Ngisonyoka relative to their neighbors in this case is attributable in part to the greater herd diversity (the north has extensive grasslands and, with less area favorable for camels, is more heavily dependent on cattle) and to the ability to maintain networks for mutual aid. Diversity of location, herd movement strategies, and herd composition of members of an exchange network increases the likelihood of being able to negotiate livelihood-saving exchanges or loans of livestock, and temporary relocation of dependents. Comparison of nomadic and formerly nomadic Turkana is most directly relevant to viability of the family or network, not the resilience of the SES as a whole. Indeed, some “failure” and movement out of the pastoral sector (and subsequent opportunities for restocking and reentry to the pastoral sector) are an integral part of the SES. Nevertheless, since persistence and viability of domestic units and their herds is central to the SES, one would expect that a marked decline in the extent and diversity of exchange networks would signal compromised resilience of the SES. Maintenance of that institution signals maintenance of system identity and resilience.

Turkana have engaged the risk of livestock raiding for a long time. However, during the years following our active fieldwork in Turkana, this old threat escalated rapidly in intensity and severity as automatic weapons became more readily available in northern Kenya. In response, a new form of social organization called an *arum-rum* emerged. In this arrangement, many households came together each night within a set of fortified fences that were actively guarded throughout the night. The *arum-rum* had a leader and all participating households moved across the landscape together, which meant that large numbers of livestock were competing for forage in a limited area. Thus, in a tradeoff for security some Turkana herd-owners were sacrificing better access to forage for their livestock and had to move more often. Others chose not to join an *arum-rum* and continued to herd as they had been. The *arum-rum* system is clearly a case of innovation and reflects RD to the intensifying risk of raiding.

Simanjiro—The Simanjiro case is complex and, as mentioned previously, is changing rapidly. Some resilience surrogates suggest that the Simanjiro SES is under considerable stress and that the resilience of the system is being eroded. Others suggest that the SES is quite resilient and can be expected to persist into the future.

Biodiversity is an important determinant of system identity in many cases because of the ecological links among species and the ecosystem services these species collectively provide. But it is especially important in Simanjiro because of the additional, enormous importance of wildlife diversity for tourism and the national economy and as a salient influence on land use policy. There is a general consensus that biological diversity tends to enhance resilience of ecosystems when it entails redundancy within functional groups (e.g., herbivores, pollinators) and results in the presence of species with overlapping functional diversity (Walker, Kinzig, and Langridge 1999; see especially Maestre et al. 2012 on ecosystem function in drylands). As noted at the outset of this paper, RD within functional groups (inter-species RD) is likely to contribute to resilience (Elmqvist et al. 2003). In some contexts it makes sense to consider diversity of livestock and crop species along with that of wildlife, and indeed alteration of traditional patterns of livestock husbandry can be detrimental to wildlife (e.g., Gregory et al. 2010). The description of Simanjiro in the preceding section indicated some of the ways in which RD within or among human communities might affect biodiversity, directly and indirectly, and thereby influence resilience. Patterns of species loss can be crucial; any influence of RD on fragmentation, minimal habitat, and other landscape characteristics can be important for local extinction or replacement of species, and the impact of invasive species. Disturbing reports of precipitous declines in wildlife numbers both within and outside of Tarangire National Park (Foley 2004) indicate compromised resilience of the Simanjiro SES. It is too early to tell how the changing land use and land cover patterns in Simanjiro (including the new set-asides for wildlife in some villages) will affect biodiversity and just how the environmental, ecological, and economic tradeoffs will affect the SES, but it seems clear that RD will play a role in these processes.

Another resilience surrogate listed in Table 2, the distribution of costs and benefits accruing from conservation and tourism, also suggests that the current SES is at risk. Although villages are benefiting from funds generated by wildlife based tourism or directly from

TANAPA, most of these funds are being captured by village elites (Sachedina 2010), so the pressure to extend agriculture has not been reduced as much as might be expected with more equitable distribution of benefits.

Nearly all Maasai in Simanjiro who are part of our ongoing research are engaged in both raising livestock and cultivation, but the options for mixed livelihood strategies are to some extent moderated by government land use policies and the Maasai's reaction to these, as well as by individual household resources. Preliminary analysis of recent survey results shows marked differences in herd size at the household level and also at the village level, and also much variation in the amount of cultivation (see Table 1). Although almost all fields are plowed by either tractors or oxen, the size of fields varies greatly. This is true for individuals, sub-villages and villages. Land use policies vary by village and sub-village. This is seen in the degree to which village land is allocated to individuals and in the amount of common grazing lands and land set aside for conservation. Land allocations vary from a few acres to thousands of acres. There is also variation in the willingness of villages to lease land to outsiders, and in the extent to which village lands include some large commercial farms.

Accessibility of resources, another surrogate indicator included in the table, has changed markedly in recent decades. The most obvious change has been loss of the right to enter TNP and use water and other resources within the park, including Silalo Swamp, long a crucial drought refuge. The partial ban on cultivation in the Simanjiro Plains represents another sort of restriction on resource utilization. These restrictions clearly compromise the ability of families to cope with environmental and political-economic perturbations, though they may have beneficial effects on biodiversity. On the other hand we witnessed the influx of many livestock and herders from northern Tanzania and southern Kenya migrating into Simanjiro in response the recent drought. While this may seem to make the SES more vulnerable by depleting local resources, it indicates that Simanjiro remains part of a much larger system whose long-term survival depends on access to distant resources in times of stress. The fact that this traditional Maasai institution remains viable despite the privatization and fragmentation of lands is a strong indication of a resilient SES, and a demonstration of the importance of system memory embedded in traditions. This is an interesting example of a latent or "cryptic" resilience-enhancing mechanism – we could not tell whether or not it was still there until it was called for. The recent drought shows that it is, but continued privatization could jeopardize its efficacy.

The practice of granting access to water and pasture to hard-pressed Maasai from other sections is a specific example of system memory. More generally, RD may serve to maintain awareness of and experience with a range of alternatives for coping with perturbations, making it more likely that other actors can effectively adopt a given response in the future if need be or if preferable. This represents both memory and learning. Shifts of livelihoods or other changes may entail loss of relevant knowledge and experience, or a shift in what knowledge is relevant. For example, herders who have recently adopted farming may have limited access to advice on crop mixes, when to plant, or what to do about outbreaks of pests. This may not only render pursuit of new livelihoods less efficient, it may also compromise the adaptive capacity of the actors and the resilience of the SES. The loss of

memory or change in the relevance of stored knowledge links this system attribute with another that is also related to resilience – experimentation or innovation.

In general, RD can represent a source of experiments or tests of novelty, and can facilitate learning. Each variant in a new context may serve as an experiment that can be evaluated and emulated or avoided by others (households, village leaders, or other decision-makers). More experimentation (greater RD) may be expected when experience with a particular challenge is limited. Maasai and Turkana herders have faced the problem of livestock disease for a long time and generally know what can be done for prevention or treatment (although there may be important differences arising from institutional sources, such as availability of veterinary services). In contrast, the Kisongo Maasai response to conservation-related challenges (especially potential alienation of land) is quite variable -- the Simanjiro villages are clearly engaging in experiments in land allocation, taking diverse approaches to achieving goals common to all four villages: securing land tenure and access to resources. Further experimentation is seen at the household level, with different mixes of crops, including sunflower and sesame along with the more usual maize and beans, and investment in different breeds of cattle and in use of veterinary drugs. The Kisongo here are facing a relatively new problem and the best strategies or all possible strategies are not known.

In both the Simanjiro and Turkana examples, the pattern of response and the variation should evolve with time and experimentation, creating experience and learning. RD is clearly part of such experimentation, and the examples and discussion presented here suggest that in general RD will enhance resilience. However, the possibility that RD could in some circumstances compromise resilience should not be dismissed. For example, continued conversion of rangeland into cultivated land could negatively impact grazing of both wildlife and livestock. Maximizing RD could result in patterns of fragmentation, as illustrated in Figure 2, which could reduce access to grazing for both wildlife and livestock, and induce significant changes in biodiversity. In some cases, greater uniformity in response might keep out “invasive” influences (e.g., invasive species, commercial farming or mining interests). More generally, not all innovations or experiments work out -- they may entail costs to individuals, families, networks, biodiversity, or the SES as a whole.

Conclusions

The primary purpose of this paper is to draw attention to the relevance of response diversity (RD) for the functioning of social-ecological systems, with a particular focus on the consequences of RD for resilience. Our argument is not that RD always creates change, nor that RD is always adaptive. RD may promote and shape change but it can also be essential to maintaining stability and enabling persistence of elements within the SES (as seen clearly in the Turkana case). RD may be crucial to understanding both change and stasis, and is thus central to understanding the functioning of SESs in general. More specifically, the diversity of responses of people within a SES to environmental fluctuations, shocks, and uncertainty is important to:

- the efficacy of the response

- the persistence of the population
- human impact on the environment
- the process of experimentation and learning
- maintenance of system memory
- SES resilience

This diversity occurs at multiple levels, which may interact with one another. The ways in which RD at different scales relates to system dynamics within and across scales, as reflected in heuristics such as the adaptive cycle or panarchy (see Walker et al. 2006, Gunderson and Holling 2002), bears further investigation.

A secondary purpose of this paper is to contribute to answering the need to operationalize “resilience”. To that end, we identified variables that can serve as surrogate indicators for the resilience of certain central system states of both the Turkana and Simanjiro SESs. We did not set out to fully evaluate the resilience of these SESs, -- doing so would require additional field work and another full length paper. Our discussion of the demonstrated and likely effects of these surrogates clearly shows the relevance of RD to evaluation of the resilience of these SESs in the face of salient perturbations (e.g., herd loss from drought, disease, and raiding; conservation-driven shifts in access to resources and land tenure). The central importance of RD in these cases suggests that attempts to operationalize resilience in other contexts should consider the potential, even likely, relevance of RD to appropriate surrogates in those SESs.

Numerous authors have noted that human homogenization of landscapes has decimated entire functional groups of species, rendering ecosystems more susceptible to disturbance and consequent regime shifts (Elmqvist et al. 2003; Folke, Colding, and Berkes 2003; Gunderson and Pritchard 2002; Scheffer et al. 2001). RD within and among human communities introduces the possibility of “heterogenization” of the landscape in some cases, which could in turn either increase or decrease species diversity at given scales, with concomitant implications for resilience.

As noted in the introduction, both functional diversity and functional redundancy (ecological redundancy) are related to resilience, but RD has not generally been seen as linked to the effect of functional diversity. The examples we have presented here show that intra-species and intra-population RD can *produce* functional diversity as well as mediate the consequences of functional redundancy for resilience. Functional diversity can be seen among the multiple livestock species kept by Turkana and in the new livelihood options in Simanjiro; both are in part products of RD. Such functional diversity should help ensure maintenance of elements of the SES in the face of perturbations. Thus, multi-level RD is related to the roles of both functional redundancy and functional diversity in system resilience and adaptive capacity.

Finally, understanding the role of RD is important not only for understanding what affects resilience (positively or negatively), but also for how resilience and related properties of systems evolve -- or perhaps more properly how the processes, structures, and interactions

that confer resilience evolve. Further, the need for exploring and understanding the causes and consequences of RD does not ride on the fate of resilience theory, which is a work in progress. Whether resilience theory thrives, is altered radically, or dissipates in favor of other approaches, understanding SESs will entail understanding the role of RD in those systems. The bottom line is that response diversity is an integral part of the dynamics of social ecological systems and should be so considered.

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Figure 1.
TLUs by Total Acreage Cultivated for Households in Four Simanjiro Villages

Figure 2.
Alternative spatial distributions of a given total amount of disturbed or transformed land.

Figure 3.
Expected influence of intensity of land use on biodiversity, for different levels of use diversity.

Figure 4.

Expected influence of spatial clustering of land use types on biodiversity, for different levels of land use saturation

Table 1

Land allocation, acreage cultivated, and livestock holdings by households in Simanjoro villages, 2010.

Village		Acres allocated	Total acres cultivated ¹	Acres in maize	Acres in beans	TLU ²
Emboreet	mean	45.4	7.0	5.7	1.3	22.6
	median	50	4.5	4	0	15.5
	sd	14.4	7.0	5.0	3.6	25.6
	n	30	30	30	30	30
Loiborsoit	mean	42.2	11.8	8.9	2.9	53.5
	median	40	6.5	6	1	26.3
	sd	26.6	17.8	12.3	5.7	64.5
	n	30	30	30	30	30
Sukuro	mean	29.6	9.3	8.7	0.6	128.0
	median	30	8	8	0	80.4
	sd	10.6	4.9	4.2	1.5	157.8
	n	25	25	25	25	27
Terrat	mean	20.1	8.6	4.9	3.7	32.1
	median	15	7	5	3	24.9
	sd	17.7	7.4	3.7	4.2	43.4
	n	29	29	29	29	29
All villages	mean	34.6	9.2	7.0	2.2	57.5
	median	30	6	5	0	27.7
	sd	21.0	10.8	7.4	4.2	94.6
	n	114	114	114	114	116

¹ One-way ANOVA, $F=0.74$, $p=0.53$

² One-way ANOVA, $F=4.91$, $p=0.003$.

Table 2

Surrogate indicators of resilience for Turkana and Simanjiro SESs.

	Turkana	Simanjiro
System state (resilience of what)	<ul style="list-style-type: none"> adequate livestock/human ratios 	<ul style="list-style-type: none"> secure livelihoods for local population biodiversity (wildlife) maintenance
Perturbations (resilience to what)	<ul style="list-style-type: none"> herd loss from drought, disease, raiding 	<ul style="list-style-type: none"> herd loss from drought, livestock disease conservation policy (park expansion, land use restrictions) immigration land use/land cover change
Resilience indicators (surrogates)	<ul style="list-style-type: none"> extent of exchange networks; diversity of management strategies (species mix, movement) of families diversity of management strategies within exchange networks expansion of family networks to settlements & towns innovative defensive formations 	<ul style="list-style-type: none"> diversity of livelihood options open to families; accessibility of resources (water, pasture/browse) to livestock and wildlife distribution of authority/power regarding land use (property rights) among interest groups distribution of costs & benefits of conservation & tourism Maintenance of institutions that facilitate restocking by redistribution of livestock, and mobility and resource access across sectional boundaries