Spatial Resilience in Social-Ecological Systems: Household-level Distribution of Risk Exposure and Coping Strategies in Eastern Province (Zambia)

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Abstract

Spatial relationships and spatial interactions affect the resilience in social-ecological systems in complex ways. This report reviews relevant literature to demonstrate the utility of a spatial perspective for the analysis of resilience in social-ecological systems, and provides selective examples from preliminary analysis of the extensive household survey in the Eastern Province (Zambia). We employ the term "spatial resilience" to characterize how spatial arrangement, spatial interactions and spatial context relate to the resilience of smallholders to climate variability. We also present a basic framework for transitioning this preliminary work to a more comprehensive analysis of the Eastern and Southern Province study areas.

1. Introduction

Rural livelihoods in many parts of the world are dramatically affected by climate variability and its corresponding impact on water availability and provision of ecosystem services. This is particularly the case in the semi-arid tropics (SAT), which contain 22% of the world's population and high concentrations of chronic poverty and inadequate food consumption (Falkenmark and Rockstrom 2008). Much of the vulnerability of smallholders within the SAT is driven by surface hydrological dynamics; both directly through rainfall variability and indirectly through additional human- or climate-induced land and water degradation. This tight coupling between social-ecological and hydrological systems in the semi-arid tropics make them an ideal setting to conduct fully integrated research between social and physical sciences.

Vulnerability to variations in precipitation is controlled by how meteorological drought propagates into agricultural and ecological drought in SAT landscapes. For example, recent work has shown that in many cases agricultural drought can be quite substantial (i.e. complete crop failure) even when meteorological drought (i.e. rainfall deficit) is mild. Mwale (2003) found that over a period of 22 years the frequency of meteorological drought across 8 agricultural zones in Malawi (defined as annual rainfall equal or less than 1/2 of potential evapotranspiration) was only 1%, but that the probability of low yields was greater than 44%, even in years when rainfall was 80% of potential evapotranspiration. Therefore, the frequency and severity of a "drought year" depends heavily on both social and agricultural factors, which are themselves strongly coupled to spatial expressions of hydrological dynamics, landcover patterns, and local coping behaviors.

When crop yields decline or fail due to insufficient or in some cases excessive precipitation, households adopt various coping strategies to survive, many of which have an explicitly spatial dimension. In a preliminary analysis of a household survey of smallholders conducted in rural Zambia, Lekprichakul (2009) documented various coping strategies employed by households as responses to climate variability and affect on resource availability. These strategies can be categorized as those which are external to the household and those internal to the household. *External coping strategies* are strongly related to the spatial arrangement of environmental resources (land holdings, water) and spatial interactions between households. For example, a household whose upland crops fail during a drought may become a source of labor for other households if they have lowland crops that did not fail. Alternatively, *internal coping mechanisms* include options that do not rely on external forces, such as reducing food consumption or diversifying crops. The decision and option to choose different coping mechanisms depends on a complex set of social and ecological conditions such as the spatial distribution of land holdings, social norms within a community, the spatial distribution of land cover and the availability of food aid.

Here we discuss a basic structure to address the spatial dimensions of coping strategies, and how the choice of external vs. internal coping strategies may be related to the spatial arrangement of households and resources. We present selected examples from the 2007 Resilience Project household survey and close with a description of proposed next steps for analysis.

2. Background

Resilience in social-ecological systems has received a considerable amount of attention in the last 7-10 years (Walker et al. 2002, Walker et al. 2006, Janssen et al. 2007, Anderies, Janssen and Ostrom 2004, Adger et al. 2005), a focus that has developed from earlier work in ecology (Holling 1973) and the hazards and vulnerability assessment literature (Blaikie 1994, Cutter 1996, Dow and Downing 1995, Liverman 1990). Innovative tools such as vulnerability scoping diagrams (Polsky, Neff and Yarnal 2007) and the resilience workbooks for both scientists and practitioners (Resilience Alliance 2007) have offered insight into how to assess vulnerability and resilience which are somewhat elusive concepts that lack consensus definitions (Cutter 1996, Walker et al. 2002). Particular contributions have been made in exploring the social dimensions of vulnerability, including behavioral responses and efforts to identify coupled linkages between social and biophysical dimensions of social-ecological systems (Folke 2006a). New frameworks are also emerging to identify how to decompose complex systems for vulnerability assessments (Turner et al. 2003) and the institutional dynamics that operate in those systems (Ostrom 2007).

Much of this work emphasizing resilience in social-ecological systems has made elegant conceptual arguments and the empirical work to articulate the dynamics in SESs is to some degree catching up with the conceptual foundation. Of course some early literature presented powerful case studies elucidating notions of both vulnerability and resilience, even if those terms were not leveraged at the time of that work. For example, Denevan (1992) demonstrated how smallholders in terraced agricultural system in the Peruvian Andes distributed land holdings in different agro-ecological zones to ensure sufficient crop yields across elevational gradients even in exceptionally cold or dry years.

Resilience research has often emphasized the importance of space and especially cross-scale interactions (Folke 2006b, Walker et al. 2002). And scale-mismatches have been highlighted as a challenge in reconciling management objectives with ecological processes (Borgström et al. 2006, Cumming, Cumming and Redman 2006). This has been demonstrated in watershed level integrated assessment methods and how the scale of climate change analysis must be reconciled with analytical units at the river-basin scale (Yarnal 1998). But while cross-scale interactions are often mentioned as important factors in an analysis of resilience, this work often stops short of a spatial analysis of coupled social-ecological dynamics at the local level. There are exceptions. Carpenter and Cottingham (1997) conducted a novel analysis of landowners around lake systems and the influence of land use on water quality. Ostrom and Nagendra (2006) examined forest condition in protected areas in the context of institutional dynamics through the use of spatially explicit remote sensing analysis. And there are many studies examining spatial characteristics in landscape ecology such as the size of forest fragments in Madagascar and influence on ecological thresholds (Bodin et al. 2006). These are simply examples from the rich literature examining coupled social-ecological systems, but in general there is an opportunity for more specific spatial dynamics (relationships and interactions) to be incorporated into the specific study of resilience because there are relatively few spatially explicit analyses of resilience that have data parity in both the social and biophysical domains.

A spatial analytical perspective to resilience is beginning to emerge. Studies of coral reef systems have demonstrated how reservoirs of biological diversity can buttress regional level resilience of marine populations (Janssen et al. 2006, Nyström and Folke 2001). Spatial interactions between vegetation patches have been found to affect local level dynamics of water flow in arid ecosystems providing insight into the resilience of grassland systems (van de Koppel and Rietkerk 2004). Spatial complexity has been used to elucidate the dynamics between policy and system resilience with regards to fish stocks and lake systems in Wisconsin (Carpenter and Brock 2004). And the concept of spatial arrangement in self-organizing systems has also been explored with specific examples from wetland areas in the US Gulf Coast Plains (Phillips 1999).

Drought prone systems such as the semi-arid tropics provide a powerful location to explore the spatial dynamics of coupled social ecological systems. These systems exhibit strong thresholds when smallholders rely on subsistence crops or market oriented crops that are vulnerable to shortages of available water (Enfors and Gordon 2007). What is of particular importance is an articulation of how resilience is being characterized in a social-ecological system where even small disturbances may cause severe consequences (Adger 2006, Carpenter et al. 2001). For the work proposed here we consider coupled social-ecological dynamics to determine what conditions, particularly the spatial conditions, contribute to the resilience of smallholders in a SAT system. Specifically, we seek to address when smallholders expend their portfolio of coping options to deal with food and income shortages thus moving into a condition of food deficit. We by no means are decoupling social and biophysical dynamics, but we are particularly focused on the spatial dynamics of coping strategies by smallholders in the context of these coupled systems.

These are systems where even small disturbances may cause severe consequences for human livelihoods (Adger 2006). The heterogeneity of water availability can result in substantial differences in vegetation productivity within local areas leading to complex dynamics at the community level. In these contexts community dynamics can play a powerful role in how natural resources are managed (Agrawal and Gibson 1999). Such an arrangement suggests the opportunity for the interplay between household level decision-making and community level institutions to be explored in resource limiting environments (Adger 2000, Agrawal and Gibson 1999, Tobin 1999).

The frequent occurrence of agricultural and ecological droughts even under conditions of adequate rainfall is a common occurrence in semi-arid agro-ecosystems across sub-Saharan African (Rockstrom and Falkenmark 2000). One reason for this apparent de-coupling between climate and vegetation productivity in agricultural settings is the fact that crops in typical smallholder farms use only 20-30% of available soil moisture, with much of the rest being lost to soil evaporation (Rockstrom, Barron and Fox 2003). In general, past approaches to understanding agro-ecosystem vulnerability to rainfall variability have focused on rainfall totals and crop water deficits defined at seasonal scales. However, many semi-arid agro-ecosystems experience only a few dozen rainfall days, and in some cases up to 80% of the seasonal rainfall totals arrive in 1 or 2 storms. Therefore, the characteristics of storm arrivals and storm depths, and the responses of crops to individual rainfall events (and subsequent soil moisture dry down) is crucial to assessing the overall productivity of semi-arid agro-ecosystems. In addition to being subject to enormous variability in spatio-temporal rainfall patterns, SAT agro-ecosystems also present an additional challenge in defining relationships between soil moisture dynamics and instantaneous rates of crop/plant production: the difficulty in obtaining accurate estimates of plant water use in areas where bare soil evaporation contributes greatly to total evapotranspiration. Therefore, predicting the response of SAT ecosystems to intra- and inter-annual variations in rainfall is greatly complicated by the fact that vegetation structural pattern and fractional cover strongly impact surface evaporation and transpiration partitioning. For example, trees and crops strongly modify both the light and moisture environment underneath their canopies, with significant consequences on grass production and efficiency as well as soil evaporation rates (Caylor et al. 2004). Because of differences in ET partitioning it is likely that a dispersed-tree savanna of similar biomass and leaf area will have a different response to climate forcing than a clumped-tree or leopard-spot savanna with respect to productivity, vegetation water use, and atmospheric coupling. These same issues arise in SAT agricultural landscapes, where E/T partitioning can be critical to success or failure of wet season crops.

The above discussion highlights two issues that are central to progress in assessing the resilience and productivity of dryland agro-ecosystems: (1) the development of coupled hydrological/ecological modeling approaches that emphasize a more temporally resolved and dynamic perspective of crop-soil-water interactions, and (2) a more refined characterization of dryland water balance in agro-ecosystems, particularly partitioning total evapotranspiration between plant water use (transpiration) and soil evaporation. Because of the pronounced physiological and ecological divergence between trees, grasses, and crops, mixed-use tropical water-limited agro-ecosystems are particularly appropriate for coupled ecological and hydrological analyses that seek to relate stochastic rainfall and subsequent soil moisture dynamics to both plant water use (D'Odorico and Porporato 2006, Rodriguez-Iturbe et al. 1999) and vegetation productivity (Scanlon et al. 2007). However, these approaches have primarily focused on natural savanna and woodland landscapes and have only rarely been applied in agricultural contexts (see (Sambatti and Caylor 2007) as one exception). In contrast to the availability of general theories and frameworks for coupling plants and soil moisture in heterogeneous, stochastic dryland ecosystems, there is a general lack of landscape-scale measurements of evapotranspiration partitioning in any dryland landscapes, and in particular dryland agriculture. The availability of more refined and direct observations of E/T partitioning and crop performance will allow us to make more substantial and transformative contributions to the social-ecological resilience of semi-arid tropical dryland communities.

3. Framework for Analysis of Spatial Resilience in Social-Ecological Systems

For this work, we employ the term “spatial resilience” to refer to the influence that the spatial arrangement of resources and the spatial interactions in a coupled social-ecological system have on the resilience of that system. We acknowledge this is not the first use of this term. Spatial resilience has been used to explain how spatial interactions in coral reef systems maintain healthy ecosystems over time and across spatial scales (Nyström and Folke 2001). Spatial interactions and resilience have also been used to explore vegetation dynamics in arid ecosystems (Scanlon and Sahu 2008, van de Koppel and Rietkerk 2004), but this is work that has not incorporated social dynamics. Much of the earlier literature on the resilience of social-ecological systems emphasizes the role of spatial dynamics (Walker et al. 2002). But this work is mostly conceptual (Janssen et al. 2007), or does not incorporate explicit spatial analysis of empirical data of both social and ecological dynamics (Carpenter and Brock 2004, Nyström and Folke 2001).

Here we propose an examination of resilience in the context of the spatial distribution of social and ecological resources and the spatial interactions across social and biophysical domains. In Figure 1 we present a conceptual diagram outlining how the different domains can interact through spatial expressions of resource distributions. We emphasize the internal vs. external coping mechanisms because of the role that spatial relationships play in the option and choice of external coping mechanisms. In the following section we describe spatial characteristics that govern these spatial dimensions of resilience and selective examples as a foundation for future analysis.

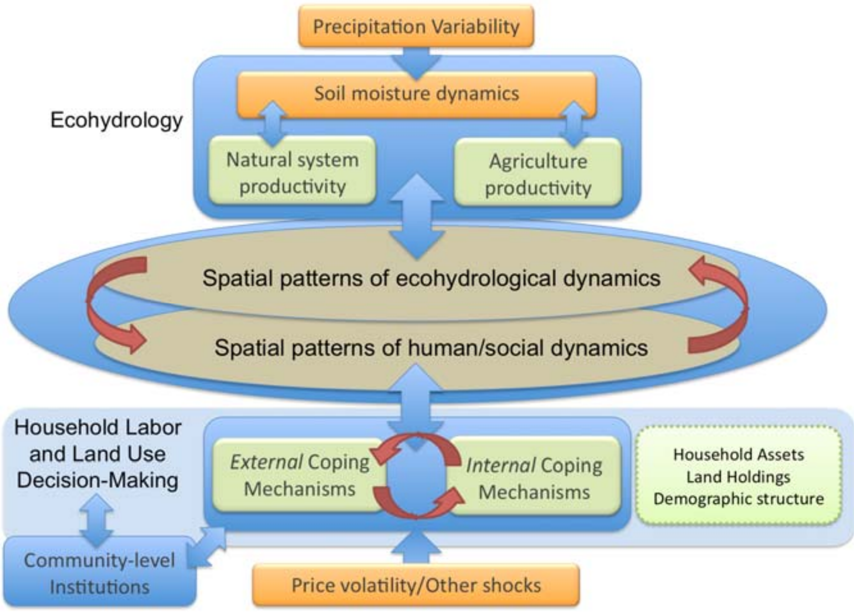

Figure 1. Spatial Resilience in Coupled Social-Ecological Systems of SAT

3.1 Spatial context and social-ecological systems

In this section we describe some spatial domains that relate to the dynamics of social-ecological systems and present preliminary descriptive results from the 2007 Resilience Project extensive survey data conducted in the Southern and Eastern Provinces. One of the most fundamental spatial issues mentioned in the SES literature is the role that spatial scale plays in both social and ecological processes (Cumming et al. 2006, Peterson, Allen and Holling 1998, Walker et al. 2002, Walsh et al. 1999). First, from a measurement perspective, the relationship between social and biophysical processes has widely been acknowledge to have scale dependent properties (Walsh et al. 1999). Likewise, simulation models also exhibit scale dependence as a function of the operational resolution and cross-scale dynamics (Evans and Kelley 2004). Lastly, institutional literature has noted the role that institutions at multiple levels (e.g. federal, state, community) play in the management of resources expressed through the concept of polycentricity (Davoudi 2003, Evans, York and Ostrom 2008). Thus, the spatial resilience of social-ecological systems in part is affected by the cross-scale dynamics affecting that system.

From a more spatial analytic perspective, concepts of pattern and process from landscape ecology have long been shown to affect the dynamics of natural systems and coupled natural-human systems (Forman 1995). Spatial metrics including measures of spatial pattern, spatial arrangement and spatial composition can be used as indicators of system function. For example, we can expect that a community that is 90% forested will have a different degree of reliance on forest resources than a community that is 5% forested (e.g. spatial composition). In addition, the spatial *distribution* of resources can be important. Assuming a community has 20% forest cover, the ecological characteristics of that forest will differ depending on whether that forest cover is spread across dozens of < 1 ha patches, or in a single 40 ha patch. Lastly, the spatial arrangement of resources can be critical to the accessibility of resources. A household whose fields are within 100 m of a water source will have different capacity to irrigate fields than a household whose fields are 1 km from a water source. And as a final example, local level topographic heterogeneity is strongly associated with crop diversification as smallholders seek to develop a portfolio of crop types in areas of varying soil moisture to mitigate against extremes in seasonal precipitation.

3.2 Preliminary examples from 2007 extensive household survey

These are merely simple examples to emphasize the role that spatial context can play in social ecological systems. To measure the influence of these spatial dynamics requires a research design that includes the collection of spatially explicit data. The 2007 Resilience Project extensive household survey data collected the spatial coordinate of household locations. Several coding errors and inconsistencies were found in the data and these were corrected during the summer of 2008. Household locations were then plotted for the Eastern Province observations for exploratory spatial data analysis of exposure to shocks and coping strategies. Data collection for the 2007 survey was focused on the 2005/2006 cropping season, and respondents were asked what disturbances/shocks they experienced in the preceding 6 years, and what coping strategies they employed in the 2005/2006 cropping season. The spatial distribution of surveyed households was organized by clusters of 15-20 households within individual Standard Enumeration Areas (SEA). The survey consisted of 1008 completed surveys, 552 from the Eastern Province SEAs and 456 from the Southern Province SEAs. Each SEA may contain up to several hundred households so the degree to which the surveyed households adequately represent individual SEAs varies across locations. The spatial data consist of the location of the household residence as it was prohibitive to collect field boundaries or locations for such a large number of observations. Still, it is possible to conduct a preliminary spatial exploration of the household data based on key variables to identify general trends and relationships in the data.

The following preliminary results will focus on the Eastern Province observations which were clustered in a subset of 5 districts and 21 SEAs, primarily in the south-central region of the province. Figure 3 shows the spatial distribution of households that reported they were affected by flooding in the preceding 6 cropping seasons. Households in the southern portion of the sampled area reported less exposure to flooding than households in the northern portion of the sampled area. This may be a product of the general regional trend in precipitation, or it could be a function of local level heterogeneity of soil moisture and topography. Future spatial analysis of digital elevation data will be used to explore this further. Figure 4 presents the corresponding reported exposure to drought. Clearly, more households reported they were affected by drought than flooding. Also, households reporting they were affected by drought are more widely distributed and less clustered than the households reporting exposure to flooding. The spatial heterogeneity of exposure to drought suggests several possibilities for subsequent analysis with respect to resilience. In local areas where a greater proportion of households report exposure to drought, vulnerable households have fewer coping options if other proximal households were similarly affected. In contrast, in areas where only a small number of households exhibit exposure then there may be more coping options such as providing labor for other households.

Spatial cluster analysis may misrepresent these relationships in areas of high population density because the sampled households may not be representative of local populations. However, a next step for analysis is a qualified preliminary analysis of the heterogeneity of exposure.

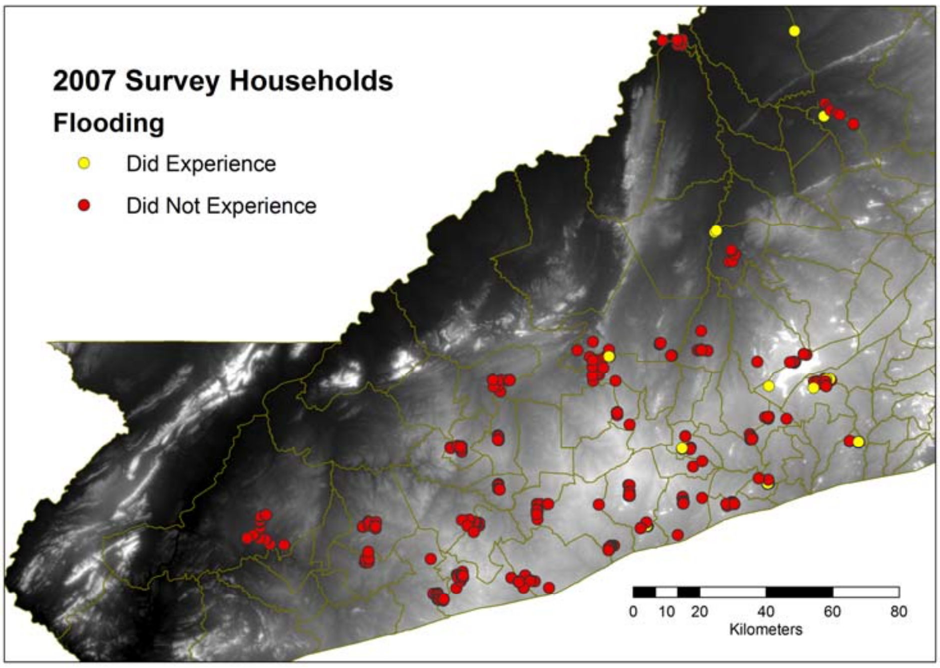

Figure 2. Spatial distribution of households reporting flooding, Eastern Province

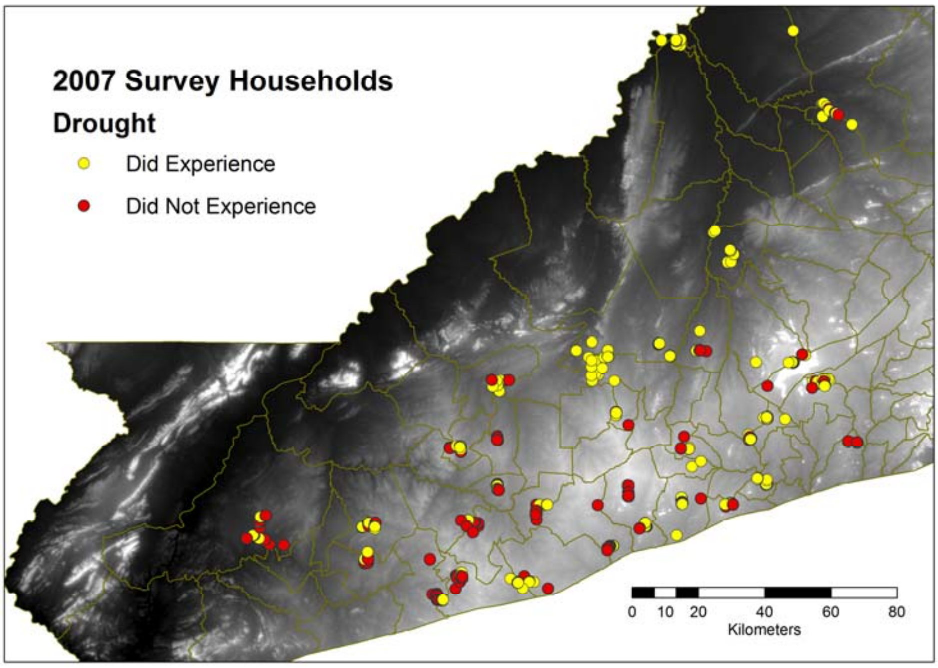

Figure 3. Spatial distribution of households reporting drought, Eastern Province

For those households reporting exposure to drought or floods, we can then explore the spatial distribution of the coping strategies employed. Coping strategies were categorized as internal vs. external strategies to explore how local-level spatial interactions relate to the coping strategy alternatives. Examples of external coping strategies include piecework for other households in the village, piecework for households in other villages or relying on food aid. Internal coping strategies including reducing the number of meals, pulling children out of school to increase labor supply or diversifying crops. Figures 4 and 5 present the spatial distribution of households coping strategies. In figure 4 a majority of the responses are null in the southern area because these households did not report exposure to drought. Figure 5 shows a wide variety of coping strategies with both internal and external strategies evident in different areas.

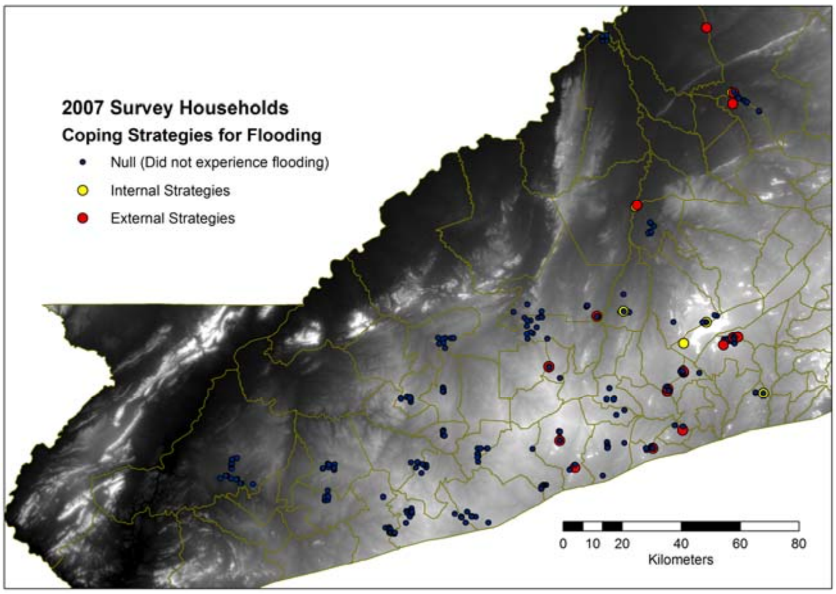

Figure 4. Internal vs. external coping strategies of households reporting flooding, Eastern Province

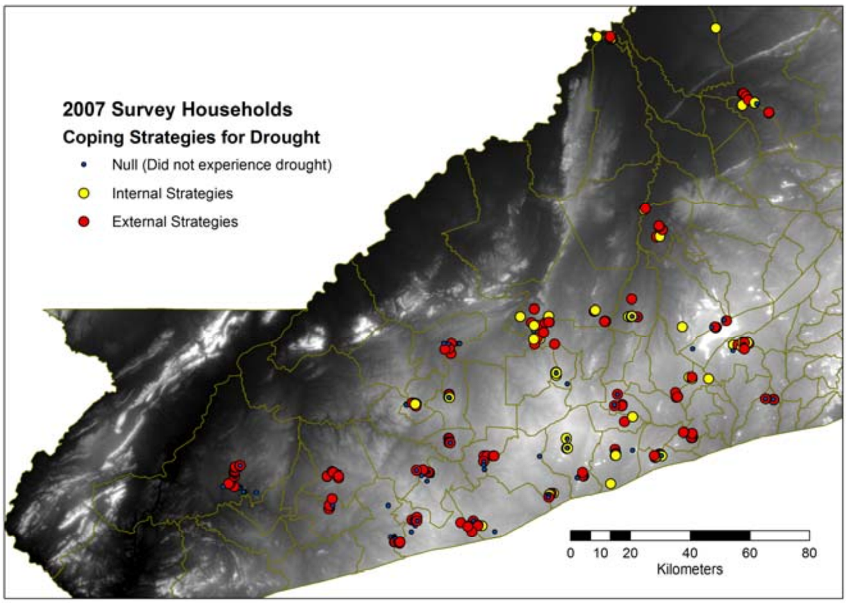

Figure 5. Internal vs. external coping strategies of households reporting drought, Eastern Province

Exposure to drought and flooding is in part a product of the number of land holdings and crop diversification. Figure 6 shows the number of crops planted by household for the 2005/2006 cropping season. There are a large number of households that report planting only a single crop. There is also considerable heterogeneity within local areas with some households reporting 4-6 crops planted in the same areas where other households report planting only one crop. This heterogeneity of crop diversification presents a key question for subsequent analysis. Previous research has demonstrated how in some cases households choose crop diversification over maximizing yields or returns to mitigate against precipitation variability. But this analysis has been conducted at the household level. An unresolved question is the role of household interactions in community level resilience. In other words, households choosing to plant only one crop may not have inherently more risk exposure if they have the option to rely on other households if their crops fail. In this scenario, households may have greater exposure to crop failure, but not necessarily less resilience to climate variability. This is an additional area for future analysis. Again, the extensive survey data use a spatial sampling design that limits the ability to fully characterize the spatial interactions between households. Still, the spatial clustering of exposure, coping and crop diversification can be performed while attempting to control for households that are not part of the survey.

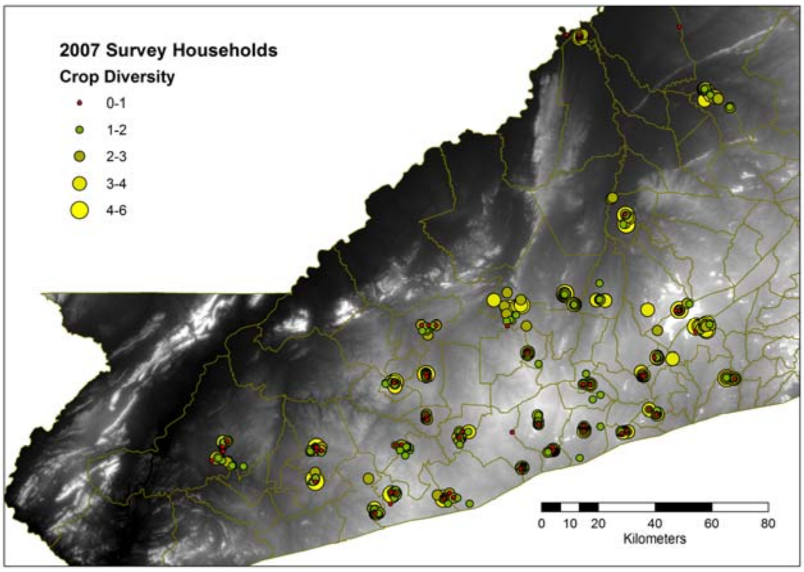

Figure 6. Spatial distribution of crop diversification, Eastern Province

4. Future Work

This report has presented a basic conceptual framework for an analysis of spatial resilience and suggestions for future analysis of the 2007 extensive household survey data. We hypothesize that these climate- and landscape-dependent relationships lead to the development of differential coping strategies in response to climate variability. We also suggest that households develop complex portfolios of coping strategies that are related to the spatial arrangement of resources, but that different households faced with the same shocks may choose different coping strategies depending on their household assets or previous experience. In future work we plan to assess both household level dynamics (land use and labor allocation) and land suitability in a spatially explicit framework to identify the contribution of spatial configuration and spatial interactions in the resilience of smallholders.

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