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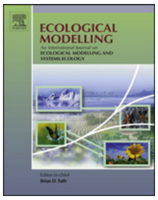

Modeling scale and variability in human–environmental interactions in Inner Asia

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ABSTRACT

Pastoralism represents a complex adaptive system that has existed in Inner Asia for thousands of years. The challenges of environmental change have highlighted the need to assess the potential for long-term sustainability while also considering the characteristics of systems that have the potential to maintain resilience. Here we assess the interaction between slow and fast processes and how interpretations of adaptive capacity and system resilience are affected by the scale at which observations are made. Agent-based modeling is used to identify the social and demographic interactions between landscape and weather variability for pastoralists in Inner Asia at a variety of social scales and from temporal scales of societal change ranging from a few days to 1000 years. Results indicate that the scale of abrupt changes may not be proportional to the severity or duration of the weather event, but is highly impacted by internal social factors. At the scale of individual families, highly interconnected social systems with less mobility and restricted decision making are less effective. When viewed from the vantage point of larger social units, highly interconnected kinship systems and restrictions in access to land may serve purposes that are counterproductive for individual families.

1. Introduction

Studies of complexity, in both ecological and social sciences, point to a series of dynamic interactions that describe adaptive systems constantly undergoing episodic and chaotic change (Gunderson and Holling, 2002; Kohler and van der Leeuw, 2007; Pickett et al., 2005). In this study we explore characteristics of a simulated pastoralist socioecological system (SES) from Inner Asia to develop a better understanding of how transformative change occurs.

Since the 1980s, studies of pastoralists and the rangeland ecosystems in which they live have called into question a variety of earlier assumptions about the environmental impacts of herbivores, carrying capacity, sustainability, and common management practices (DeAngelis and Waterhouse, 1987; Westoby et al., 1989; Sneath, 1998; Robinson et al., 2003). Through these and many other studies a far more dynamic picture has emerged of the environmental implications of sustained use of grasslands. In the human component of interactions with the environment a diversity of buffering mechanisms provide the means of coping with environmental uncertainty and rapid change. However, available buffering mechanisms often cannot accommodate extreme changes. In fact, the non-linear and cross-scale nature of abrupt change has been observed in many ecosystems, ranging from coral reefs to forests (Scheffer et al., 2001). Similar abrupt changes are observed in many social systems, ranging from hunter-gatherer subsistence practices (Halstead and O'Shea, 1989; Bartolome, 1993; Kohler et al., 2000), to the collapse or transformation of entire states and empires (Tainter, 1988:44–51; Macanany and Yoffee, 2009). Given these considerations, we ask two primary questions:

1. Under conditions of high variability how do we assess the potential resiliency of a SES?
2. How does the scale at which we analyze socioecological processes affect our understanding of specific changes?

Using an agent-based model of pastoralists allows exploration of simulated changes that may operate on the scale of decades or centuries. To investigate the implications of abrupt change and scale of analysis, pastoralist adaptations in Inner Asia are analyzed within the framework of two related concepts hypothesized as fundamental to system resiliency—potential for change and connectedness (Holling and Gunderson, 2002:49–52).

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There are many overlapping conditions within an SES related to buffering mechanisms, economic options, the relative rigidity of cultural hierarchies, and even the unique cognitive abilities and foresight of people. The economic potential of a particular environment provides the grounding for assessing the broader potential for change, whether that change is derived from internal or external sources. The connectedness of any system regulates the extent of external influences—whether it is a single organism or an entire society. Connectedness is viewed as a measure of the ability of a system to exert control over outside forces through many mechanisms for mitigating disruptions. Connectedness allows a system to respond rapidly and make use of capabilities for adjustment. Changes in the number of elements and functionality at different scales within the system are hypothesized to be a measure of system resilience (Allen et al., 2005). Human systems interact through networks of kinship, status, class, political hierarchy, formal and informal authority, occupation, and in other ways, however, these forms of interrelationship are not automatically the kind of connectedness that supports system sustainability.

Resilience theory has received wide application in recent years in the study of various “natural” ecosystems and a growing number of SESs (Redman et al., 2009). Resilience specifically refers to “the magnitude of disturbance that can be tolerated before a SES moves to a different region of state space controlled by a different set of processes” (Carpenter et al., 2001:765). Peterson et al. (1998) predicted that a diversity of functions within scales of interaction and redundancy across scales will produce a system with greater connectedness and therefore resilience. Resilient systems are flexible, persist, and are able to maintain key relationships within the ecosystem even when experiencing severe external or internal pressures.

Scale and the implications for resiliency are analyzed here in the context of pastoralist adaptations in Inner Asia. Inner Asia archeological and historical sources provide substantial evidence for both continuity and change in pastoralist societies, including the emergence and collapse of great empires (Honeychurch and Amartuvshin, 2006; Rogers, 2007). The flexibility and lengthy knowledge base of pastoralist adaptation is balanced against the environmental vulnerability to weather events that frequently produce devastating consequences. While contemporary climate change trends are increasingly evident and are having an effect on productive capacity, pastoralists continue to experience change most directly through the extremes of severe weather events, especially winter storms (*zud*) and droughts (Batima, 2006:53; Swift, 2007).

2. Methods

2.1. Model construction

HouseholdsWorld is the agent-based model developed to explore not only the simulation of weather events, but a wide range of social and environmental factors related to pastoralism (Cioffi-Revilla et al., 2011). The model is based on empirical data from ethnology, archeology, paleoclimatology, historical ecology, and rangeland management. These different sources of information are used to validate the model parameters to develop an artificial SES with the key characteristics of Inner Asian pastoralism observed currently and in the past. This form of pastoralism emerged first in central Asia following the domestication of the horse and the emergence of riding technology more than 4000 years ago (Anthony, 2007). Numerous variations on the theme of mobile pastoralism exist, involving the herding of sheep, goats, cattle, yaks, camels, and horses (Benecke and von den Driesch, 2003; Frachetti, 2009; Kohl, 2007). While the model developed here is not derived from any one time it is meant to focus on a social environment that is local, without the existence of overarching state-level social control hierarchies.

Archeologically and historically there is a deep, although not very detailed, knowledge of both local practices and the rise of complex social and political systems. The first steppe empire of Inner Asia, the Xiongnu, became formalized around 200 B.C. (Brosseder and Miller, 2011; Rogers, in press). The model used here does not simulate the emergence of states and empires, however, such work is under development in two additional models, HierarchiesWorld and HunnuLand. These models will be utilized in future studies of particular relevance for archeological analysis of early empires.

The principal model entities in HouseholdsWorld are introduced in Fig. 1. Each entity (a computational object in the simulation model) is described below in separate sections and in Table 1. The model utilizes a suite of simulation tools (MASON) developed at George Mason University and coded in Java (Luke et al., 2005; Cioffi-Revilla et al., 2007; Rogers and Cioffi-Revilla, 2009). The main social units in HouseholdsWorld are households. These agent-units operate within spatial classes on a gridded landscape using a subset of geospatial GIS facilities inherent in the MASON interface. Additional details about the HouseholdsWorld model are provided in Cioffi-Revilla et al. (2011).

2.2. HouseholdsWorld main components

The decision making household-agents in the model belong to lineages, local camps similar to the Mongolian *Khot-Ail* (Bold, 1996), and larger social units, similar to clans. Households have a life cycle, produce offspring households (marriages of children), accumulate herd wealth, evaluate the landscape on a daily basis, move their herds in search of grass, remember their routes to favorable grazing from year to year, form camps, and “friendships” with other households. Marriage partners are identified based on group affiliation and kinship norms. A dowry of herding animals is given by the parent households to the newly formed household. Households may provide a safety net through gifts of animals to relatives in distress. Decisions and opportunities vary and affect accumulation of animal wealth, recovery from unfavorable weather, and survivability. Ethnographic and historical research drawn from numerous sources in Inner Asia, provide the basis for modeling the social structure (e.g., Simukov, 1934; Vreeland, 1957; Vainshtein, 1980).

2.3. Herd dynamics

Contemporary pastoralists in Mongolia follow a long tradition involving a mixed herd strategy, primarily consisting of sheep, followed by different proportions of goats, horses, yaks, cattle, and camels, varying by region. We do not model each species, but instead use the concept of a standard stocking unit (SSU) defined as sheep = 1; goat = 0.9; cattle and yaks = 5; horse = 6; camel = 7 (Humphrey and Sneath, 1999:77). The primary herd dynamics include herd size, the amount of biomass consumed by herd animals, animal birth rates and subsequent herd growth rates, animal starvation rates, miscellaneous animal death rate due to routine hazards (e.g. predators or disease), herd grazing efficiency, and the removal rate (off-take) of animals for consumption or trade (Table 1). Together, these parameters provide a herd mortality profile that compares well with a variety of field observations and experimental results (Cribb, 1991; Natsagdorj and Dulamsuren, 2001; Begzsuren et al., 2004). Pastoralists do not simply herd animals, but also gather, hunt, fish, sometimes practice agriculture, engage in wage labor, among other pursuits (Cooper, 1995; Honeychurch and Amartuvshin, 2007:36–37). These alternative

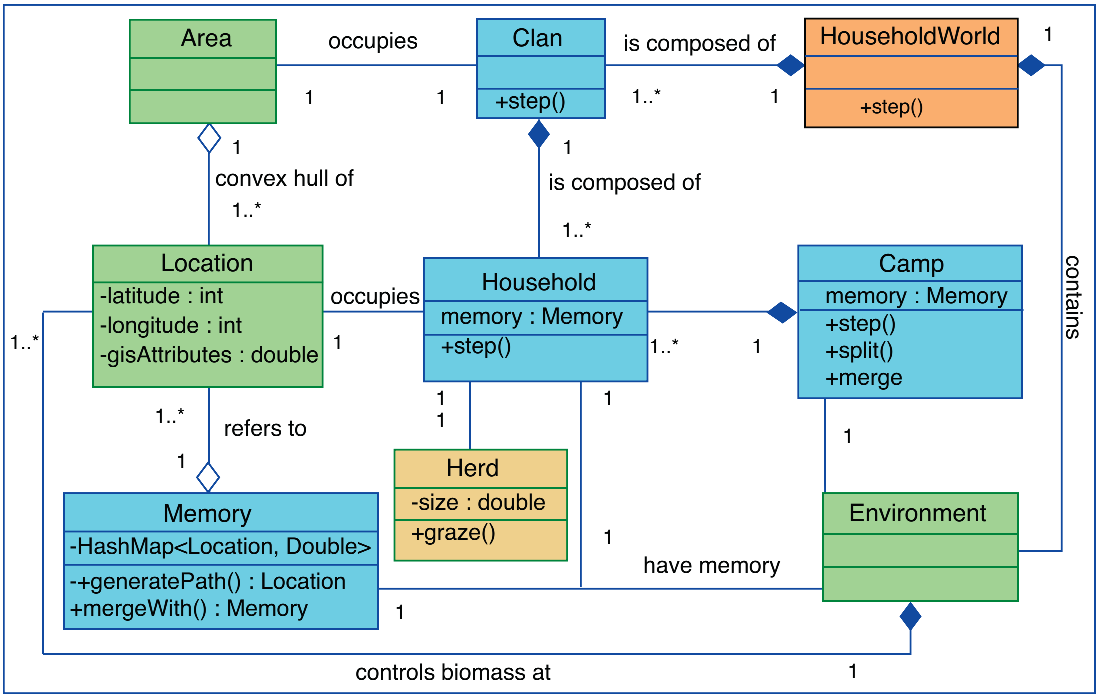

Fig. 1. Unified Modeling Language (UML) class diagram showing the high-level components of HouseholdsWorld and the dynamics of households and camps in relation to environment and herds.

Adapted from Cioffi-Revilla et al. (2011).

economic activities are implicit in the relative benefits attached to several combinations of activities and aspects of the social structure.

2.4. Landscapes

Households “live” on realistically rendered landscapes of 10,000 km^2 that function as a closed system, with no population movements or interactions beyond the borders. In this study we use landscape S-7 in the Egiin Gol region of north-central Mongolia (Fig. 2). The landscape's ground cover is rendered using Normalized Difference Vegetation Index (NDVI) data and specific geomorphic attributes (Hansen et al., 1998, 2000). Monthly NDVI rasters were computed from atmosphere corrected bands in 500 m resolution. The landscapes are classified into 14 land cover types with exponential regressions calculated to produce approximations of edible biomass for the relevant landscape types. Biomass coefficients are drawn from Kawamura et al. (2005) and further supported by a variety of rangeland research in Mongolia and northern China (Committee on Scholarly Communication, 1992; Bedunah et al., 2006; Batbuyan, 2008).

2.5. Weather dynamics

While pastoralists use a variety of mechanisms to buffer against loss of herds, increases and decreases often occur more rapidly than in agricultural societies (Cribb, 1991:24). Throughout the steppe regions of Central and Inner Asia, the *zud* is the most deadly extreme weather event that pastoralists must cope with (Natsagdorj and Dulamsuren, 2001). For example, in Mongolia between 1999 and 2002 over 12 million animals (25% of the national total) were killed primarily through starvation resulting from severe winter storms (*zud*) (National Statistical Office, 2001, 2005:173; Batima et al., 2008:77). In 2009–2010 already dry conditions and winter snow storms caused the loss of at least 4.5 million herd animals in Mongolia, about 10% of the national total. Tens of thousands of herder families were forced to migrate to towns and cities to survive (The Economist, 2010:44). In our model, we simulate the effects of *zud* and droughts by adjusting the abundance and growth rate of edible biomass for a specified duration of days (Table 1).

Droughts typically produce less abrupt consequences, but contribute to severe livestock loss especially when occurring in combination with a *zud*, such as occurred in 1962 (32% loss) and 1983 (24% loss) in Mongolia (Begzsuren et al., 2004:792; Morinaga et al., 2004; Iwasaki, 2006:745). During a good year normal livestock losses range from approximately 1–8% (National Statistical Office, 2005:173; Begzsuren et al., 2004:788).

3. Results—comparing 1000 year histories

The simulation (HouseholdsWorld v. 1.6.3) was run hundreds of times to calibrate the parameters against numerous sources of ethnographic, historical, demographic, and environmental data, as briefly summarized in Table 1. After a set of parameter values was finalized for this study, the simulation was run an additional 20 times to measure the range of variation between runs. Because the simulation output is the result of a dynamic process no two outputs are exactly alike, although they fall within a predictable range of variation. For instance, demographic values for households varied + or −6% to 8% of the mean between runs, depending on the type of simulation. This kind of path dependency (history) is expected and parallels the complexity of decision making processes in the real world, when interactions between variables generate alternative outcomes. The results are presented below in three parts: the baseline simulation, followed by two experiments using variations of the *zud* and drought simulation.

3.1. Baseline

The first set of output results to be analyzed is a baseline history. This simulation produced an abstraction of the carrying capacity of the landscape in the absence of weather variability. The result

Table 1
Characteristics and values for the main properties used in HouseholdsWorld.

Parameters	Value	Notes and sources
Social system		
Number of surviving offspring a household may produce	4	Mean, based on 14 sources of ethnographic data (e.g. Vainshtein, 1980)
Maximum frequency of reproduction	9 months	Threshold for gap between pregnancies
Depth of ancestry remembered by household	3	Memory of 3–4 ancestral generations, based on ethnographic sources
Mean age of households at death	25 years	Based on 20th century life expectancies
Threshold age at which households may die	18 years	Based on 20th century life expectancies
Minimal kinship distance for marriage	6	Marriage partners must be second cousins or more distant
Algorithm for calculating kinship distance	Shortest distance	Produces results similar to ethnographically known kinship systems
Maximal number of animals per household	3000	Rarely exceeded ethnographically by non-elite households
Minimal number of animals per household	60	Threshold below which probability of household failure increases
Animals transferred to offspring households	30%	Portion of existing herd given by one set of parents to newly formed offspring household
Minimal no. of animals required for household to reproduce	300	Value considered necessary for growing household
Household vision range	5 km	Field observations, central Mongolia
Kinship affinity threshold for splitting	12	When clan kinship affinity becomes attenuated the clan my split
Kinship affinity threshold for merging	6	Level of kinship affinity needed for emergence of a new clan
Camp separation probability	0.2/day	Pasture evaluated twice per week. Camps may separate when pasture is insufficient
Maximal camp size	6	Mean (Humphrey and Sneath, 1999; Fernández-Giménez, 2002)
Social group activity	0.001–0.005/day	Probability rules will activate
Group Structure Rules	Version 30	Order of rules determines relative importance
Camp memory	Priority 1	Maintain friendships
Local gradient	Priority 2	Emphasize local relationships
Camp cohesion	Priority 3	Maintain same members
Social group cohesion	Priority 4	Maintain social memberships
Avoid non-members	Priority 5	Avoid non-clan or non-group members
Herds		
Animal consumption amount	1.1 kg/day	Robinson (2001), Shurentuja et al. (2002), Milner-Gulland et al. (2006:26) and Retzer et al. (2006)
Animal growth rate, variable by month	0.0–0.008/day	Results from experimental station
Animal starvation rate, variable by month	Mean 0.0002/day	Tigner and Larson (1997)
Animal misc. death rate, variable by month	Mean 0.0001/day	
Grazing efficiency	89%	Ali and Sharrow (1994) and Leeuw and Bakker (1986)
Removal rate (off-takes)	0.1 SSU/day	36 Standard Stocking Units (SSU) consumed/year or lost through disease, etc. Mean family size = 5.5
Physical environment		
Biomass adjustment rate	Variable	Values extracted from regressions on remote sensing (MODIS) data (Kawamura et al., 2005)
Landscape scenarios	S1–S8	Specific regions, focus on N. Mongolia
Weather		
Zud (blizzard)	Biomass = 0 × days	Three levels of severity, 5, 10, and 15 days
Drought	Biomass = 0.5 × days	20 days

See Cioffi-Revilla et al. (2011) for additional information on the specific structure and function of the properties.

of a specific baseline run (#60) for the Egiin Gol landscape (S-7) is presented in Fig. 3. This figure shows the total number of households plotted over the course of 1000 years. When viewed at this scale, the simulation shows a population that increases and becomes relatively stable, but with patterns of increase and decrease. Following the initial simulation calibration cycle (32 years) a complex history of annual population growth and decline emerges along with additional trends that reflect the consequences of more complex social and environmental interactions on the scale of multiple generations. In spite of occasional down turns, the population increases slowly and continues to do so for hundreds of years. At a level of 2400 households the virtual human population would total 13,200 for a mean of 1.32 inhabitants per km^2. A review of 14 ethnographic studies from rural areas of Mongolia, Russia, and Kazakhstan revealed human population densities for steppe pastoralists ranging from approximately 0.05 to 1.8 people per km^2. The baseline simulation successfully replicates population densities, such as might be expected on a landscape with moderate-to-high rangeland productivity.

Hundreds of years of simulated history produce many stories of the rise and fall of great clans, the wealth and domination of particular households and lineages, and the specific ethnographies of individual families. A close inspection of Fig. 3 reveals complex histories of change in social organization, wealth distributions, and landscape use resulting in population shifts lasting decades. The authority structures above the level of the household produce territories, restricting the movement of households. Social groups fortunate enough to secure favored grazing areas have wealthier households that over time are more successful in producing offspring households. However, when territories remain stable for long periods of time under conditions of population growth there is a tendency for overgrazing. In this simulation stable territories are analogous to patterns seen when grazing landscapes become fragmented (Galvin et al., 2008). The simulation shows complete cycles of territorial formation, growth, and potential decline. The greatest benefits for household survivability as a member of the territorial social unit occurs earlier in the cycle of formation and growth.

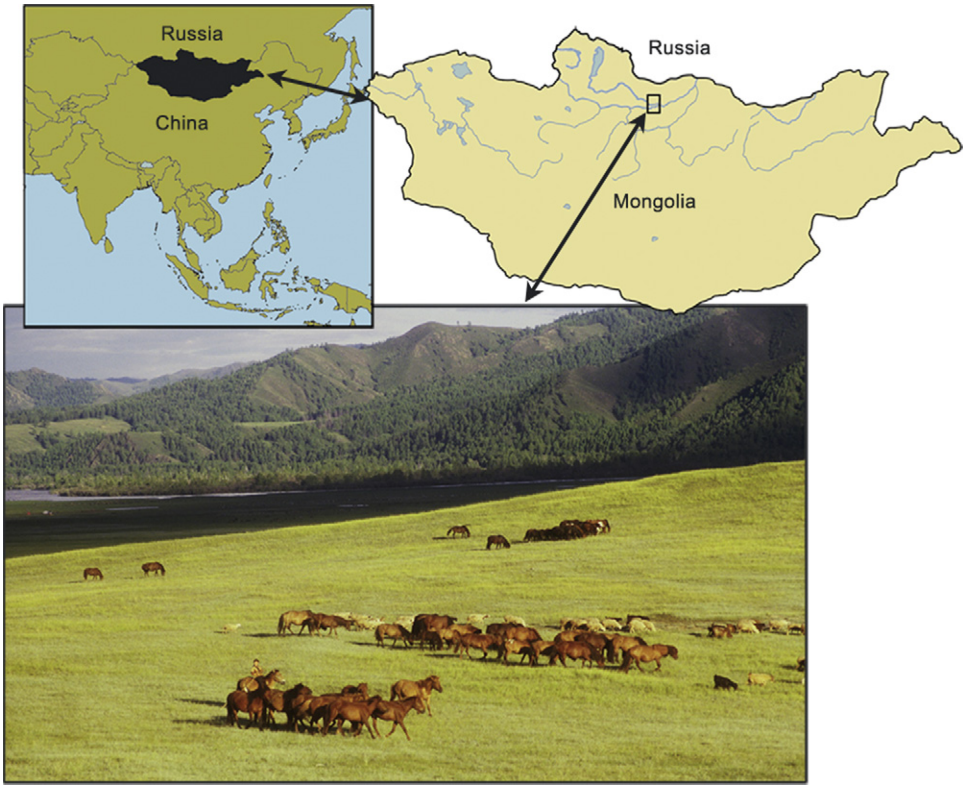

Fig. 2. The Egiin Gol landscape (S-7) used in the study is a well-watered region of 10,000 km^2 with diverse topography located in north-central Mongolia. Photograph by Albert Russell Nelson.

3.2. *Zud* and drought—experiment 1

A second simulation was run (#61) using the same parameter values of the baseline simulation, with *zud* and droughts introduced in random order, at different times of the year, and with differing degrees of severity (mild, moderate, and severe). Using meteorological and historical data from the 19th and 20th centuries on the frequency of *zud* and droughts (see above), it was estimated that a period of 750 years would reasonably include 213 events. Fig. 4 graphs the result for households, with the first weather event, a severe *zud,* introduced in year 248. Compared to the baseline presented in Fig. 3, this new and more realistic history shows the volatility so often described as the hallmark of a pastoralist adaptive system. In essence, the results shown in Fig. 4 provide an estimate of

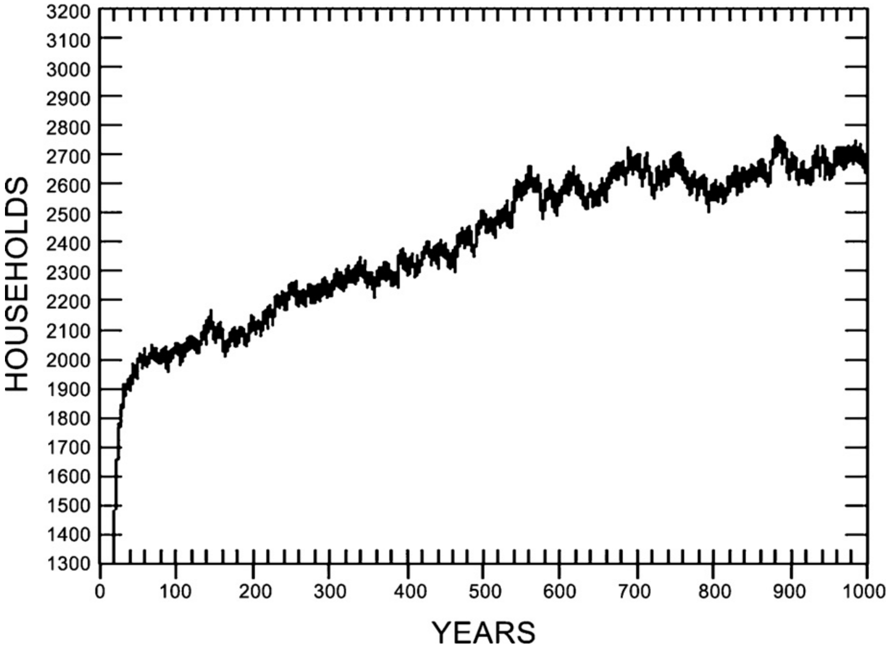

Fig. 3. Baseline simulation (#60), showing household population levels over 1000 years. The baseline simulation represents an approximation of the carrying capacity of the Egiin Gol landscape without *zud* or drought weather events.

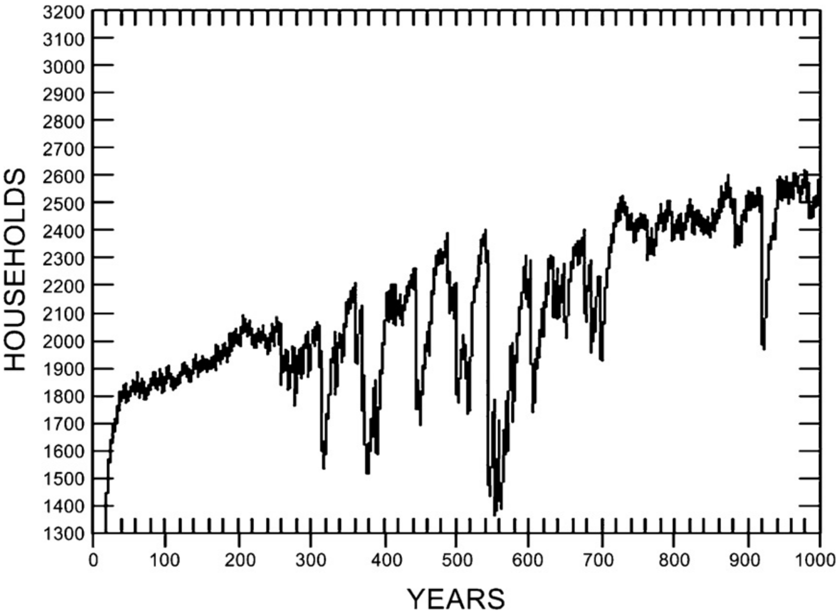

Fig. 4. *Zud* and drought simulation (#61), showing household population levels over 1000 years. Major fluctuations in population are the result of severe herd losses due to external weather events.

the dynamic carrying capacity of this landscape over a long period of time. The volatility highlights the problem of attempting to estimate sustainable values for contemporary rangeland management.

Once weather events are introduced the population levels stay far below those seen in the baseline simulation described in Section 3.1 and Fig. 4. These results show the emergence of multiple steady states while highlighting the non-linear nature of responses to change. We consider a new steady state to exist when the population levels and social changes evident after the end of the external pressure (weather) are maintained for a length of time exceeding a generation, rather than simply rebounding to previous levels. For example, in one instance a particularly devastating combination of weather events causes a 60% loss of herds and a 38% reduction in the number of households (year 543). The proximal cause of the 60% loss was a late spring *zud* that struck when the herds were giving birth, followed by a summer drought causing a 50% reduction in edible biomass for a period of 20 days. Numerous similar combinations of events are noted in the 20th Century weather data. A major loss of households is not necessarily equivalent to a similar loss of human life. When a household goes below a particular herd size (60 SSU) it is generally no longer viable (unless relatives give them a loan of animals) and the members may be absorbed into the households of relatives. Households will "die" when the social safety net is exhausted.

The abrupt changes initiated in 543 have proximal causes, but the scale of the change calls for a deeper analysis. For instance, it would not have been possible to predict the scale of the loss under linear models of reactions to weather events. Under controlled experiments we consistently recorded a herd loss of 30% or less for this type of weather event combination. However, in the dynamic social landscape of the full simulation other factors were clearly at play. Fig. 5 shows a more detailed graph of an 80 year period beginning in 520, showing the period leading up to and following the events of 543. The 543 dramatic loss of population is the equivalent of the type of abrupt transition that drastically alters the social landscape of an SES and effectively moves the system into a new steady state. We hypothesize that the extremely dense populations and fragmented landscape in the years leading up to 543 set the stage for this transitions. In the 2 years following 543 a cascading effect continued to reduce the herd and household population as the social safety net failed, even though the edible biomass had returned to more typical conditions. Interestingly, over the next 32 years 4 major and several minor *zud* and droughts strike, but none produce losses (24% and less) nearly as dramatic as those suffered in 543. We propose that during the post-543 period the system has moved into a new steady state that was less vulnerable to external disruptions. There are three principal reasons: first, large territorial social units began to give way to an increasing number of smaller social units; second, the disruptions of population loss allowed new camp groups to form and new territorial patterns to emerge; and three, the lower population densities produced more opportunities for short-distance mobility with less competition for local grazing.

3.3. Zud and drought—experiment 2

Mobility and the structure of the social system affect herd size and recovery from weather-related losses. The tendency of larger social units to exert control over territories limits mobility in the simulation. This phenomenon is suggestive of issues observed with contemporary rangeland fragmentation and the challenges posed for pastoralist sustainability (Galvin et al., 2008). To test the role of hierarchical social control, another simulation was run in which the clan activity social rules (see Table 1) were implemented on average only once every 3 years, rather than every 8 months as in Experiment 1. This is the equivalent of allowing greater autonomy at the local level.

Fig. 6 presents the results of the Experiment 2 simulation (#63) for human population levels. The results show substantially higher populations and less volatility over the same period of time, thus supporting the idea that increased household autonomy allows for higher survivability. Individual households achieved this outcome by making micro adjustments on a daily basis, but not by traveling greater distances. Territorial boundaries were less distinct, which allowed a wider range of movement choices. With the emphasis on local autonomy, social units above the camp decreased in size. The effects of reduced hierarchical control were also very evident when comparing the same weather events described above. With less hierarchical social control weather had less impact during the actual event and recovery was more rapid.

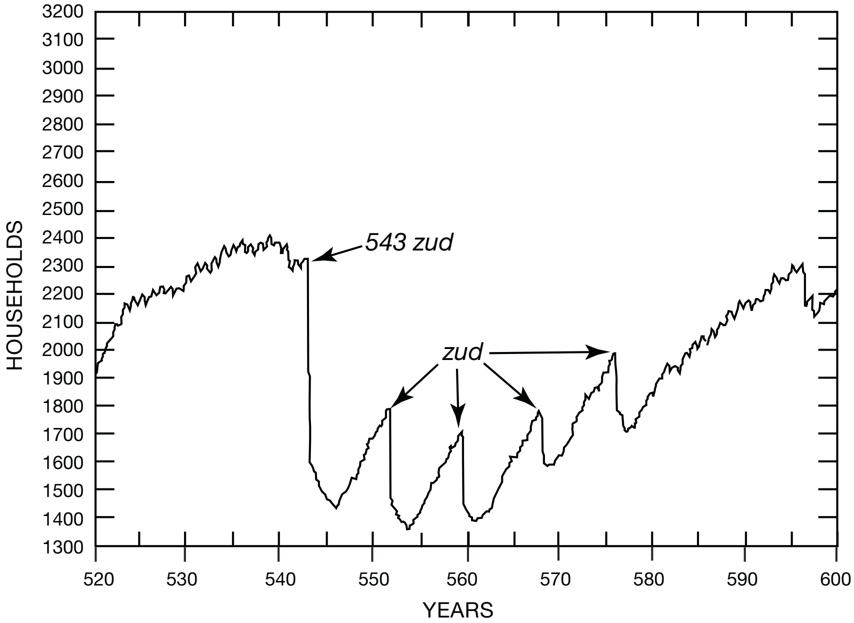

Fig. 5. *Zud* and drought simulation (#61), showing household population levels over 80 years beginning in 520. The *zud* and drought combination of 543 produced an abrupt change that was not repeated by the four following *zud*, even though they were of comparable intensity.

4. Discussion

Weather happens, animals are wealth, and the survivability of the household rests in the balance. As observed ethnographically, our analysis supports the idea that households with larger flocks are generally better positioned to withstand unpredictable weather losses (Cribb, 1991:32). However, herd wealth alone is an insufficient predictor of success or even survivability. The social connectedness and the extent of hierarchical control are also important factors. These are adaptive strategies and incorporate the potential for change, from the view of risk aversion, maximization, and optimization. Ethnographically, there are various types of buffering mechanisms that are scale-dependent, including diversification, mobility, dispersal of herds, accumulation of resources, trade, market-based insurance, and several approaches to building social capital (O'Shea and Halstead, 1989:125). Increasing pastoralist income while minimizing risk has also been the goal of a variety of programs implemented on a broad scale over at least the last 90 years, ranging from the collectivization of pastoralism to more recent locality-based strategies (Humphrey and Sneath, 1999; Fernández-Giménez, 2001; Reynolds, 2006). Fernández-Giménez (1997:10–11) also notes a

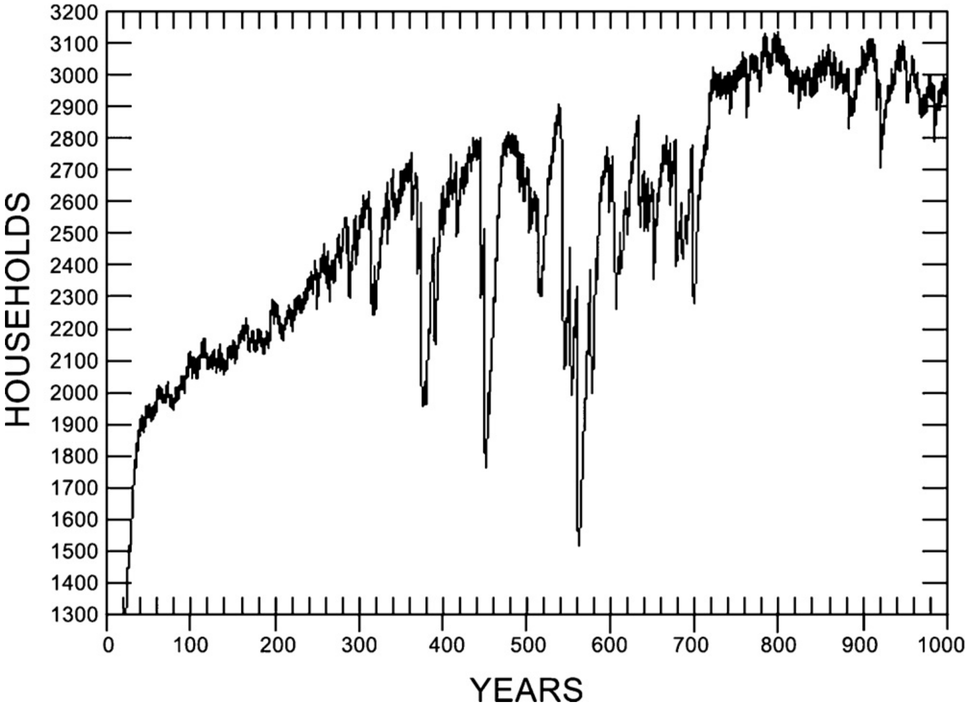

Fig. 6. *Zud* and drought simulation (#63), showing household population levels over 1000 years with clan influence reduced (compare with Fig. 4).

series of social strategies that include traditions of sharing, reciprocity and hospitality; livestock tenancy; group ownership and inheritance; wage labor and self-employment; social networks and patron–client relationships; labor sharing arrangements; institutions such as adoption and fictitious siblings; and rotating credit.

Scheffer and Carpenter (2003) have observed that regime shifts in adaptive cycles, similar to the abrupt changes seen here, are primarily the result of external factors. We agree, however, the scale of the shift is also closely related to internal conditions, which acknowledges the influence of diverse conditions in the emergence of critical thresholds (Garmestani et al., 2009:2). Folke et al. (2004) "found evidence that regime shifts were most likely to occur when ecosystem resilience had been reduced by removing functional [species] groups and associated response diversity, as well as trophic levels, and by altering the magnitude, frequency, and duration of disturbance regimes." Their observations are supported here, at least in terms of reduced response diversity and the scale of disturbances. The emergence of critical thresholds is exemplified by the year 543 events.

Under the conditions of the *zud* and drought simulation it becomes very apparent that the concepts of carrying capacity or sustainability in herd size are moving targets, especially when viewed from the scale of decades or centuries. It might be anticipated that a combination of buffering mechanisms coupled with low herd population densities serves nearly as a definition of sustainability itself (Christensen et al., 2003; Ykhanbai et al., 2004; Kerven et al., 2006). Our results support the idea that system volatility is reduced when populations are low, with significant grazing lands in reserve (cf. Enkh-Amgalan, 1997; Dorligsuren, 2006). There are essentially four explanatory facets to this argument: First, weather events strike abruptly and are wide spread; second, their impacts affect small populations and large populations equally; third, a systemic event operating on a small population may cause enough additional loss to induce an abrupt transition or total collapse of the system, depending on the social structure; and fourth, in small populations social hierarchies are more easily disrupted beyond critical thresholds because each may contain relatively few members.

5. Conclusions

In any kind of model construction—whether operational or representational, whether dynamic or purely descriptive—there is a tension between abstraction and increasingly intricate levels of detail. In many instances a highly abstracted model is all that is needed to develop insights into the fundamental principles of a particular issue. The model utilized in this study, however, is an effort to simulate a wide array of characteristics of an SES. HouseholdsWorld is in essence a complex hypothesis in the mode of what has been called "generative social science", but equally relevant for any field using agent-based models. As Epstein explains (2006:8): Agent-based models provide computational demonstrations that a given microspecification [e.g. households] is in fact *sufficient to generate* a macrostructure [e.g. new steady states] of interest". The resulting explanation is not automatically the best explanation, but when successfully validated using empirical data a variety of hypotheses can be assessed in the search for well justified explanations.

Our model successfully replicates a variety of social, herd, and environmental dynamics observed in other sources of data. Even so, there are several sets of information that are not part of the model but could be included in future versions. First, pastoralists are mobile and although the study plots are 10,000 km^2, each is a closed system not allowing movement, trade, or communication beyond the artificial boundaries. For local interactions the study plots are considered adequate, but interactions beyond the local remain as an unknown. Second, at the other end of the spectrum the movement of individual households on the landscape is arguably overly abstract. For instance, water is a daily necessity for herd animals, but its location is not specifically modeled. Instead, water access is assumed as a function of biomass density and vegetation type. At the level of households herd movement is correspondingly abstracted. Third, the concept of a Standard Stocking Unit is utilized here, however, it is reasonable to suppose that if the behavior and requirements of each herd species was modeled individually that it would be possible to develop a more insightful understanding of land use dynamics. Fourth, issues of labor organization and herd ownership are also important, given what we know about contemporary practices. While the possible ways to "grow" the model are nearly endless, each has to be evaluated against relevance for specific questions and the potential limitations of computing capabilities.

The Section 4 results, comparing the baseline simulation with the *zud* and drought simulations, show a huge disparity in population levels and volatility. Given diverse conditions within the simulations, the timing of random extreme weather events may have an effect on herd and human populations far beyond what might be predicted using linear equilibrium models. An example is the occurrence of a *zud* at a time when herd populations are already declining due to other factors or when population densities are very high. For instance, herders may have less flexibility in their movements due to emerging clan territories or social boundaries emerging from lineage and camp affiliations. The effects of weather events may be nearly doubled in intensity. In these situations the social safety net fails, households "die" and camps disperse. Conversely, the effects of severe weather events may be significantly blunted by positive growth trends, especially when local options for movement are available.

In past ecological research, ecosystems that were thought to be at equilibrium or at a sustainable level through study of carrying capacity, typically assumed that the response of the system was proportional to the degree of disturbance—weather events in this case. Studies of rangelands in Africa, Australia, and Inner Asia have shown that arid and semi-arid landscapes are subject to substantial rainfall volatility and models that assume stability do not work well (Ellis, 1995; Fernández-Giménez and Allen-Diaz, 1999; Li and Huntsinger, 2011). Our results contribute to this rethinking by showing multiple situations in which the response to external factors (weather) is not proportional to the disturbance. Alternative steady states may emerge with both different social and herd dynamics, as happened following the events of 543. We hypothesize an interrelationship between negative and positive feedback in growth and mortality cycles and random effects that may actually be unrelated to population density.

Building on the above conclusions and the capabilities of the model there are two principal directions for future research that we intend to pursue. First, continued exploration of basic principles in socioecological systems, especially in the context of human responses to climate change trends. With relatively little adjustment it will be possible to explore several climate change scenarios for Inner Asia using both paleoclimate data and climatological projections. The results of such analyses would help hypothesize likely consequences for pastoralists.

A second, but related, research direction is the application of the model to specific questions in archeological analysis of change over time. Within HouseholdsWorld there are emergent histories of wealth differentials (resource accumulation) at the household and clan levels and territoriality (spatial social distinctions). Control of wealth and the resources to produce it are understood to be fundamental to the emergence of social hierarchies as seen historically in early states and empires. As noted above, two additional models are being developed. HierarchiesWorld is a model of the development of complex social systems with multiple political hierarchies through the confederation of smaller social units. In this model leaders attempt to amass political power by attacking weaker neighbors, thus garnering additional resources. A third model, HunnuLand integrates HouseholdWorld and HierarchiesWorld into a sub-continental scale model of social and environmental interactions utilizing a million-plus agents. HunnuLand explores the emergence and expansion of empires starting from the basic characteristics of households and herds, as outlined in Section 2. These models are relevant to social theories about the development of complex societies.

At the scale of local landscapes HouseholdsWorld is also potentially relevant for evaluating actual archeological patterning. The archeology of nomadic pastoralism, in Inner Asia and elsewhere, confronts the challenge of a constantly changing social landscape that leaves few traces (Barnard and Wendrich, 2008; Cribb, 1991). Although, pastoralism is not always about movement and the empires of Inner Asia did build settlements, garrison posts, palaces, walls, and other constructions to facilitate the larger agendas of emerging social systems. Even with these built places the greatest portion of the pastoralist adaptation was still that of the individual family and their herds.

In combination with the scant archeological record of pastoralism in Inner Asia is the reality of less-than-ideal dating. Even if camp traces are discovered it may only be possible to attribute them to periods several hundred years in length, if they can be dated at all. This results in a conflated settlement history masking a wide swath of behavioral dynamics. HouseholdsWorld can be used to simulate population movements. Because HouseholdsWorld can utilize any real landscape, known settlement patterns can be compared with simulated patterns. Given the importance of social controls in patterning the movement of households, one set of questions might revolve around observable differences between socially autonomous households and those under the control of overarching political systems. There are several regions in Mongolia (e.g. Baga Gazaryn Chuluu, Egiin Gol, Hovsgol, and Khanuy) and others in Kazakhstan and Russia where detailed archeological survey has produced excellent comparative data sets (Honeychurch et al., 2007; Houle, 2010). Another type of question might involve recognizing a settlement pattern influenced by climate change versus one affected by migrations, war, or local social controls. In essence, it is possible to simulate settlement pattern data along dimensions of social organization, landscape resources, and population to study a variety of questions. The agent-based model used in this study concentrates on the temporal scale to provide a means of viewing overlapping processes operating at different rates. Analysis of change over time is a strength of archeology and one that is well suited to the capabilities of HouseholdsWorld and related models.

While archeological applications represent a future direction, the results of this study illustrate that each social unit in the simulation exhibits functions that are dynamically interconnected and operate asymmetrically between levels of internal social behaviors and external climate and weather events. Cross-cutting events, like *zuds* and droughts, affect all aspects of highly interconnected social landscapes, potentially resulting in cascading effects that may be small or large in scope. To adequately understand the interactions of various events will require additional research to explore individual social and environmental factors, however, our results support the proposition that maintaining a diversity of behavioral options is a key factor in system resilience. Our findings suggest that local autonomy (minimization of social constraints) for households, with the potential for even micro adjustments in mobility are key factors in pastoralist resiliency.

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