Divergences of Two Coupled Human and Natural Systems on the Mongolian Plateau

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Central to the concept of coupled human and natural systems (CHANS), humans and nature are organized into interacting subsystems of a cohesive whole at multiple spatial and temporal scales. Following an overview of the challenges in implementing the CHANS concept, we used widely available measures of social, economic, and ecological systems, including gross domestic product, population size, net primary productivity, and livestock and their ratios to examine CHANS dynamics on the Mongolian Plateau from 1981 to 2010. Our cross-border analysis of coupled dynamics over the past three decades demonstrated striking contrasts between Inner Mongolia (IM) and Mongolia (MG), with policies playing shifting roles in these measures. For prioritizing future research on the CHANS concept, we hypothesize that although the divergence of IM and MG for 1981–2010 was largely driven by market reforms, the importance of socioeconomic forces driving climate changes will gradually decrease in IM while remaining important in MG.

Keywords: CHANS, climatic change, livestock, socioeconomic, Mongolia

Human and natural dynamics have long been understood to influence and to be closely related to each other. An increasing number of studies have shown that human activities and climate change have regulated ecosystems simultaneously, with human disturbances producing much stronger impacts than climate change (e.g., Chen et al. 2013). From human history, we now know that ecosystem services have been affected by human actions, such as wars (Pongratz et al. 2011), emerging and expanding agriculture (John et al. 2009), human settlement and urban expansion (Grimm et al. 2008, Seto et al. 2011), and changing social structures (Diamond 1997). Some examples include the original agriculture in the Fertile Crescent region and its dispersion across the Eurasian continent and later to North America (Diamond 1997). Previous studies on the human–environment interaction have been focused on land-use change (e.g., Meyer and Turner 1994, Foley et al. 2005, Lambin and Meyfroidt 2011). Along the long course of interaction between humans and nature, people have been adapting and modifying the environment through food production (Foley et al. 2011, Goldewijk et al. 2011). The dynamics of population and its spatial distribution, as well as the varieties of foods, reflect the interaction between humans and nature, creating different ethnic groups.

In East Asia, Lattimore (1940) proposed that the physical layout of the mountains (e.g., Altai and Xing'an), the grasslands, and the river systems (e.g., the Yellow River) were responsible for much of the societal structure—including the government, trading, and the frequent wars among them. In contrast, human activities have been increasingly altering the structures and functions of biophysical landscapes. Pongratz and colleagues (2011), for example, concluded that the largest modifications of global, agricultural landscapes and detectable global climate change came from the four largest wars over the past two millennia. However, escalating global climate change and disturbances in recent decades have added to the complexity of these coupled human and natural processes and functions. Since the Industrial Revolution, the human influence on nature has been escalating. In addition to global climatic change through greenhouse gas emissions, the loss of biological diversity, and the volatility in food, energy, and water supplies all point to the need for a better understanding of the mechanisms regulating coupled human and natural systems (CHANS) at various temporal and spatial scales.

Central to our understanding of CHANS is the concept that humans and nature are organized in interacting subsystems that make a cohesive whole at multiple spatial and temporal scales. Empirical evidence strongly indicates that

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biophysical and socioeconomic systems do not operate independently; rather, they interact with one another, often in a nonlinear fashion, varying across spatial, temporal, and organizational scales and yielding emergent behaviors for each system (Agrawal and Lemos 2007, Liu et al. 2007, Alberti et al. 2011). The study of the CHANS concept requires not only examining the complex interactions among the elements of the human system (HS) or natural system (NS) but also—and more importantly—studying the direct or indirect causal relationships between the elements of the HS and NS due to the changes of driving forces from socioeconomic or climatic perspectives (e.g., population increases, institutional and policy changes, economic growth, global climate, and education). Although the CHANS concept has evolved as a promising guideline for interdisciplinary research toward the sustainable management of our society and environment (Entwisle and Stern 2005), successful applications with solid theoretical and empirical foundations at regional scales are rare and usually require dynamic modeling approaches in empirically rich settings. So far, much effort has been placed on the interactions and feedback among the elements within the CHANS; however, there has been an increasing interest in how human activities may shape the ecosystems that provide vital services to societies (i.e., ecosystem services). Regardless of escalating scientific investigations and programs on a global scale, the theories and quantitative models that guide our understanding of the behaviors of CHANS and their management remain undeveloped. They draw from a wide variety of disciplines, but this multidisciplinarity can challenge integrated studies of the CHANS concept. To overcome some of these challenges, we analyze the dynamics and spatial patterns in data representing the economic, social, and ecological characteristics of the CHANS on the scale of the Mongolian Plateau. Combining time-series ecological information derived from satellite observations with available socioeconomic data provides a powerful, contemporary platform for bridging the NS and HS in practice.

The Mongolian Plateau, with its traditionally nomadic culture, is a good case for studying the CHANS concept given the long tradition of the pastoral livelihoods in the region, the present ecological gradients (stretching from the desert in the southwest to the forests in the northeast but dominated by grasslands), the susceptibility to climate change, and the divergent political systems in Mongolia (MG) and in Inner Mongolia (IM), China. The long-term goal of this study is to examine and model the interactive changes of the NS and HS, as well as the feedback in time and space on the Mongolian Plateau, where IM and MG have similar climates, ecosystems, cultures, and traditions but different contemporary governmental structures, land uses, levels of economic development, and demographic changes (e.g., ethnical composition). We use widely available measures of the social, economic, and ecological systems for IM and MG to examine the dynamics of the CHANS.

In the long list of quantitative metrics measuring the economy, human demography ecosystems, gross domestic product (GDP), population size (POP), and net primary productivity (NPP) are the simplest, most widely used metrics for measuring the overall functions of these components, respectively. Livestock (LSK) and its changes over time have been widely used because they are essential for land use, development, and climatic influence (Gutman and Reisell 2004). This is particularly true because of the importance of livestock to the livelihood and economic well-being of people in both IM and MG. In this article, we first explore the coupled dynamics of GDP, POP, and NPP by calculating the ratios of each pair: GDP:POP is known as the GDP per capita, GDP:NPP reflects the economic output per unit of ecosystem production, and NPP:POP indicates the mean natural resource shared by each person.

Here, for the first time, we integrated NPP into ratio-based indices as a way of bridging ecosystem functions (natural capital) with measures of social and economic performance (i.e., POP, GDP, and LSK; figure 1). Whereas NPP:LSK represents the available biomass produced by vegetation available for each livestock on an annual basis, GDP:NPP can be interpreted as the total amount of domestic economic production for the given level of natural productivity (i.e., to measure the importance of natural capital in overall economic production). Although agriculture—which is reliant on natural resources and productivity—dominated economic production prior to the Industrial Revolution (Diamond 1997), this dependence is significantly weakened as other forms of economic production increase and the contribution of natural vegetation to the total economy is reduced. The NPP:POP ratio, meanwhile, is the amount of a specific natural resource (here, appropriately measured as NPP in a pastoral society) shared by each person (i.e., asset). Although NPP can vary with climate and both human and natural disturbances, the ratio is also influenced by population size, such that a larger human population means greater reliance on available productivity. The large population in IM, compared with that in MG, results in a lower average amount of natural assets per person. NPP:POP interacts with NPP:GDP because a decreased reliance on natural productivity for economic output (NPP:GDP) might be expected to coincide with a reduction in NPP:POP, at least in the initial stages of development, as dependence on natural resources reduces and economic productivity declines. Over time, the changes in these ratios reflect the coupled dynamics and interactions among the economic, demographic, and ecological subsystems (figure 1). Livestock has been widely used as an intermediate variable that connects the economic, social, and ecological contributions to the CHANS. Livestock changes play crucial roles in current and future land-cover and land-use changes, which, in turn, determine the levels of ecosystem services and societal well-being. The approach discussed above is consistent with the economic approach in which production is viewed as contributed by natural capital and human capital. In a pastoral society, NPP can be seen as natural capital, population as human capital, and

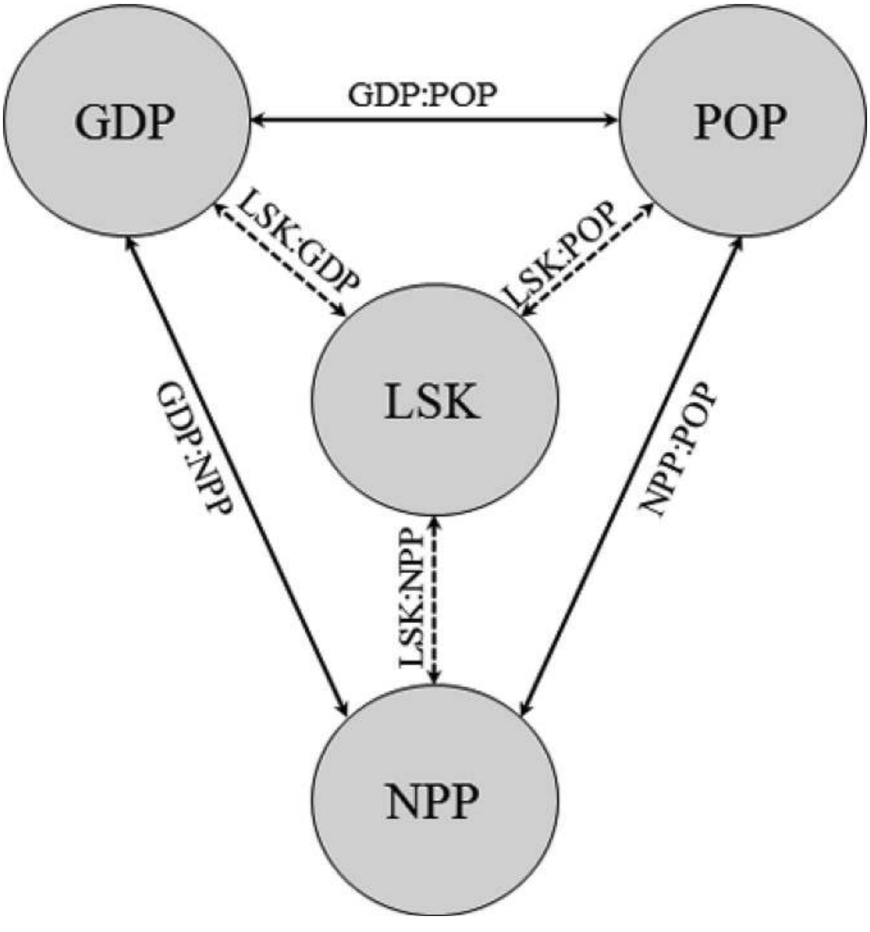

Figure 1. The working framework connecting the dots representing social, economic, and ecosystem functions and land use. The quantitative measure for each dot is population (POP), gross domestic product (GDP), net primary productivity (NPP) of ecosystems, and livestock (LSK), respectively. We focus on the changes in ratios between any two measures in Inner Mongolia (IM) and Mongolia (MG) between 1981 and 2010.

the livestock as production. Both NPP and POP jointly contribute to LSK. NPP and POP can substitute for each other in contributing to LSK. The ratios measure the changes of relative scarcity and contribution to the production.

To compare the dynamics in IM and MG, we calculated the ratios of the above metrics between IM and MG from 1981 through 2010—a period when both countries experienced dramatic policy, institutional, and climatic changes (Chen et al. 2013). This was first done by calculating the relative difference (*D*) for a given year (*i*):

$$D_i = \frac{X_i(IM) - X_i\,(MG)}{X_i(MG)} \tag{1}$$

where *X* is any variable discussed above. To compare the changes among the ratio variables, we normalized each variable to [−1, 1]:

$$ND_i = \frac{D_i - Min\,(D_i)}{\mathrm{Max}(D_i) - \mathrm{Min}(D_i)} \times 2 - 1 \tag{2}$$

where *ND* is the normalized difference between IM and MG. A negative ND_i indicates a lower value in IM than that in MG.

Data used in this article came from several sources. The NPP was obtained from the Advanced Very High Resolution Radiometer–derived global production efficiency model (GloPEM)—that is, the global maps of net primary production with 8-kilometer (km) resolution and 10-day time steps from 1981 to 2000 (*http://glcf.umd.edu/data/glopem/index.shtml*). We also obtained moderate resolution imaging spectroradiometer (MODIS)–derived annual NPP from MOD17A3 at 1-km resolution from the Numerical Terradynamic Simulation Group (NTSG, *www.ntsg.umt.edu/data*; Mu et al. 2011). We extended the GloPEM NPP time series to 2010 by aggregating MODIS NPP to 8-km resolution and rescaling its values using a common year. The GDP, POP, and LSK numbers were taken from the World Bank (*www.indexmundi.com*) for MG and from the Inner Mongolia Statistical Yearbooks for IM. All prices have been converted into PPP (constant 2005 international dollars).

Divergences of IM and MG

The Mongolian Plateau includes two jurisdictions with similar ecological systems but contrasting socioeconomic systems, with 1.14 and 1.56 million square kilometers (km^2) for IM and MG, respectively. The plateau is one of the most sensitive regions to global climate change, next to the Arctic and the Tibetan Plateau (Groisman et al. 2009, Chen et al. 2013). MG is the world's second largest landlocked country. IM and MG both include grassland, forest, and desert biomes, with nearly 88% of MG's land covered by deserts and grasslands (table 1). Both regions exhibit significant variations in biophysical conditions (e.g., climate, biomes) from east to west, resulting in distinct climates, ecosystems, levels of productivity and evapotranspiration, and livelihoods. The political separation of IM and MG in 1921, coupled with Chinese and Soviet influences, has caused a significant divergence in their human demographic and socioeconomic conditions. In 2010, the population density of IM was 21.7 per km^2, which is 12.2 times that in MG, with 55.5% and 63.3% of the population in IM and MG being classified as urban population, respectively. The Mongolian Plateau was predominately inhabited by nomadic Mongolians over the past 3000 years. However, the majority of the pastoral households in both

Table 1. Quantitative statistics of major biophysical and socioeconomic variables for Inner Mongolia (IM) and Mongolia (MG) in 2010.

Variable	IM	MG
Total land area (in 10^6 km^2)	1.14	1.56
Grassland biome (in 10^6 km^2)	0.55	0.69
Desert biome (in 10^6 km^2)	0.37	0.70
Forest biome (in 10^6 km^2)	0.22	0.17
NPP (in g C per m^2 per year)	246.3	216.6
ET (in mm per year)	214.3	208.4
Air temperature (in °C)	6.1	1.5
Precipitation (in mm per year)	311.2	252.9
Drought years	2000–2002, 2009	2000–2002, 2009
Dzud years	2000–2002, 2010	2000–2002, 2010
Extreme low temperature (in °C)	–45 (2010)	–52.9 (2001)
Population size (in 10^6)	24.722	2.780
Population density (in the number per km^2)	21.65	1.78
Urban population (in 10^6)	13.73	1.76
Urban population percentage	55.53	63.30
Urban area (in km^2)	2966	981
Urban area percentage	0.26	0.06
Livestock (in 10^6)	60.29	32.73
Gross domestic product (in $\$10^9$)	265.18	9.97
Major policy shifts	• Economic Reform (1979) • Grain-for-Green Program (1999) • Asian Financial Crisis (2007) • China as a WTO member (2001)	• Atar Programs (Cultivation) (Atar I 1959–1970, Atar II-1970–1980 and Atar III-2008–present) • Collapse of collectivization post soviet union (1991) • Gold mining programs (1992–1996, and 1997–2000)

Note: Biome boundaries were derived from the Ecoregions database of the World Wide Fund for Nature (*https://worldwildlife.org/publications/terrestrial-ecoregions-of-the-world*). Abbreviations: C, carbon g, grams; km^2, square kilometers; m^2, square meters; mm, millimeters; °C, degrees Celsius.

MG and IM began settling around permanent towns or immigrating to large urban centers in recent decades. IM has been increasingly settled by Han Chinese, whereas the population of MG, even though it is under the influence of the former Soviet Union, remains predominantly Mongolian. Although the total land area for grazing (i.e., grassland and desert) in IM is only 66% that of MG, IM's livestock population is nearly double the size of MG's. This divergent land pressure from grazing is likely due to differences in technology, infrastructure, and management (Qi et al. 2012). Nevertheless, the increase in livestock in both IM and MG has been steady and exponential (figure 2). In 2010, the number of livestock in MG reached 33 million—an increase of 15.7% from 2006, with more than 60% of its pastureland being overgrazed (Zhen et al. 2010). A similar change was also observed in the 1980s in IM. These changes play crucial roles in current and future land use, which, in turn, determine the levels of ecosystem services and societal functions.

IM and MG have also developed contrasting political systems since 1979, with much more rapid changes in IM than in MG. As a consequence of the resulting land-use changes, the severities and frequencies of catastrophic events (e.g., droughts, *dzuds*, and dust storms) have been increasing on the Mongolian Plateau (John et al. 2013). Land-use change is expected to be dramatic in upcoming decades because the region is recognized for its rich minerals. In addition, significant increases in air temperature since the 1950s due to global warming have been observed, with the increases varying significantly across the plateau (figure 3; Chen et al. 2013, Wang J et al. 2013). Although warming has dominated the plateau since 1952, we observed a few places where there were no changes or where there were slight cooling trends. However, the IPCC (2007) predicted that this already water-limited region will experience a warming trend above the global mean (3.3 degrees Celsius by 2100; longer, more intense, and frequent summer heat waves), altered summer and winter precipitation patterns, and more extreme precipitation events. These predictions, along with the Mongolian Plateau's geographic characteristics (i.e., high latitude, high elevation, and landlocked), make the plateau an exemplary system for the scientific community interested in the dynamics of CHANS, of which the most serious outcomes

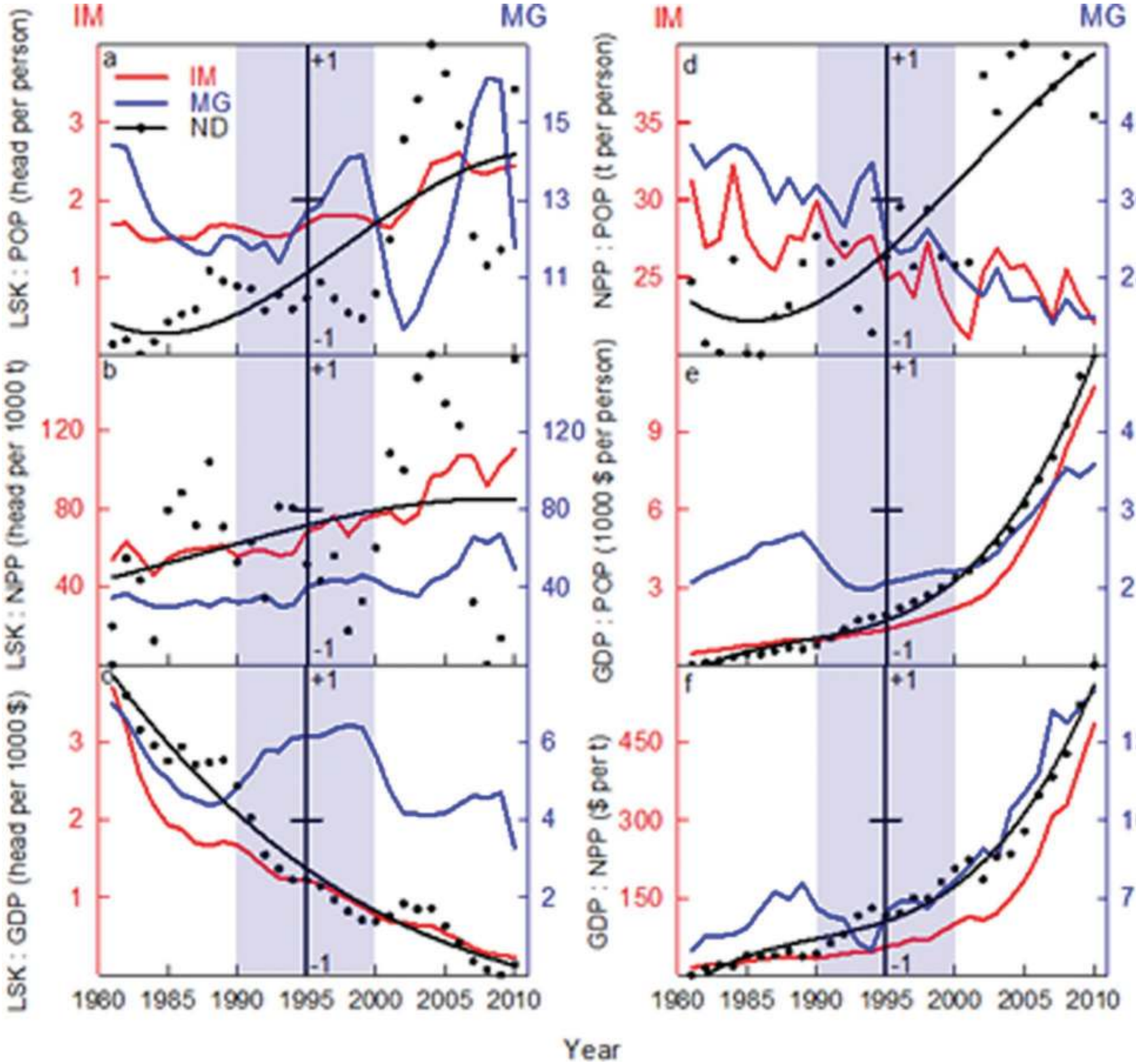

Figure 2. The change (Δ) in the ratio of (a) livestock (LSK) and population (POP), (b) LSK and net primary productivity (NPP), (c) LSK and gross domestic product (GDP), (d) NPP and POP, (e) GDP and POP, and (f) GDP and NPP between Inner Mongolia (IM) and Mongolia (MG) from 1981 to 2010. ND is the normalized difference to [–1, +1] and is shown by the vertical line in the middle of each panel. A negative ND indicates a lower value in IM than in MG. Abbreviations: P, precipitation; T, temperature.

were the consecutive summer drought events of 2000–2002 and the extreme winters of 2009 and 2010 (Tachiiri et al. 2008). Mongolians use the term *dzud* to refer to an extreme winter preceded by summer drought, and it is characterized by extreme cold, heavy snowfall, reduced availability of forage, and the widespread mortality of livestock. Studies suggest that 5-year *dzud* cycles are related to the El Niño Southern Oscillation, whereas the decadal cycles are influenced by Indian monsoons (Morinaga et al. 2003). The 1999–2002 *dzud*, the worst in 50 years and in which 30% of the national herd perished, was dissimilar to historical precedents in MG (Tachiiri et al. 2008, Fernandez-Gimenez et al. 2012). This was followed by the 2009–2010 summer–winter *dzud*, in which 8.5 million livestock—20% of the national herd—perished (Fernandez-Gimenez et al. 2012). Extreme events such as these are expected to increase in frequency and magnitude. Meanwhile, the socioeconomic impacts of *dzuds* on herder households are amplified by a global economic crisis, such as the financial crisis of 2008 (Yuan et al. 2010). For example, the 2007 global financial crisis led to a reduction of about 20% in Chinese exports (including those from IM—one of the largest exporting provinces), a decrease of 7.33% in gross domestic production, and a reduction of 9.21% in energy consumption by the first half of 2009

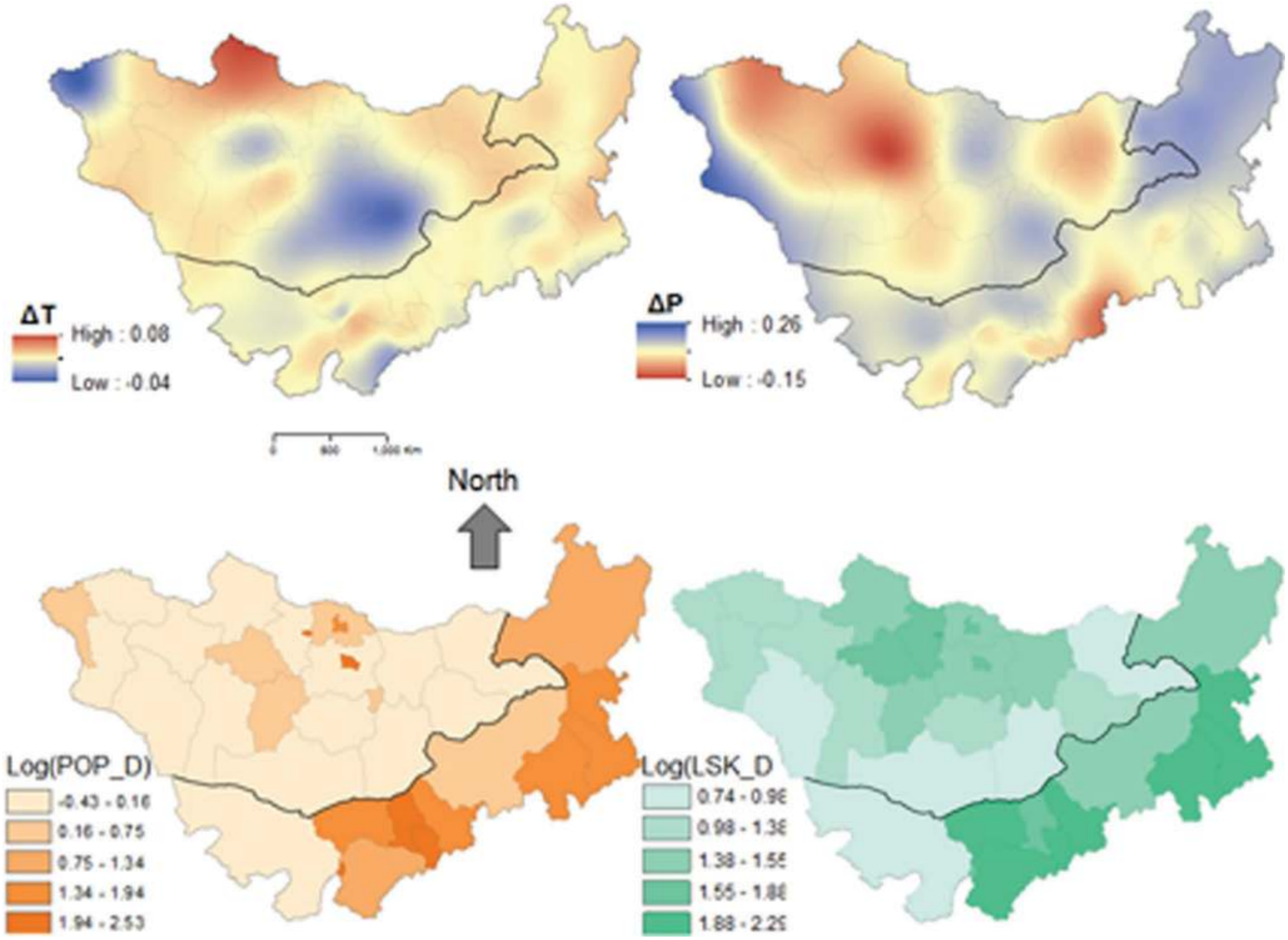

Figure 3. The contrasting distributions of four demonstrative variables on the Mongolian Plateau, showing the mismatches in space and time: (a) the rate of temperature increase (1955–2010), (b) the rate of precipitation change (1955–2010), (c) the log-transformed livestock density of Mongolia (MG) in 2009 and Inner Mongolia (IM) in 2003 (relative values to each country), and (d) log-transformed population density of IM in 2000 and MG in 2010. The nonparametric trends were interpolated using the Mann–Kendall method. Abbreviations: LSK, livestock; NPP, net primary productivity; POP, population; t, tons.

(Yuan et al. 2010). The reduction in economic activity at the macroeconomic level had a major impact on the demand for livestock and its related products.

Climatic extremes, episodic events (e.g., El Niño), and new policies complicate the dynamics of livestock populations that are driven by the market (Qi et al. 2012). Recently, the Chinese government announced several major policies (e.g., subsidy and reward programs for the country's herdsmen over the coming years, implemented to reverse and prevent damages on grasslands). In MG, the policy that relocated rural herdsmen into urban areas since the mid-1990s has resulted in more than 50% of the national population residing in the three largest cities and resulted in more than one-third of rural lands being placed under preservation. As a consequence of the extreme *dzuds* experienced over the last decade, MG initiated a program called Atar 3 (also known as the Third Campaign to Reclaim Virgin Lands), with increased government spending from 2005 to 2009, in order to improve food security and prevent future food crises (Pederson et al. 2013). This increase in the areas of croplands is centered on Mongolia's breadbasket, which includes the provinces of Bulgan, Tov, and Selenge in north-central Mongolia. In comparison, China experienced a recent decrease in the areas of croplands through its Grain-for-Green Program, including in IM, where 330,000 hectares (ha) were converted to grassland or shelterbelts between 1996 and 2000 (Wang J et al. 2012).

Coupled dynamics of social, economic, and ecological systems

Our cross-border analysis of the coupled changes among POP, GDP, NPP, and LSK over the past three decades demonstrates the contrasting dynamics between IM and MG (table 2, figure 2). The change in LSK:POP indicated that MG is inhabited by 6.8 times more livestock per person than IM is, regardless of IM's high livestock size and density

Table 2. Decadal means of major socioeconomic and biophysical variables as well as their ratios in Inner Mongolia (IM) and Mongolia (MG) for the study period (1981–2010).

	1981–1990		1991–2000		2001–2010		1981–2010	
Variable	**IM**	**MG**	**IM**	**MG**	**IM**	**MG**	**IM**	**MG**
NPP (in Gt per year)	0.573	0.735	0.584	0.752	0.585	0.664	0.581	0.717
NPP_D (in t per ha per year)	4.975	4.737	5.073	4.844	5.086	4.279	5.045	4.620
GDP (10^9)	15.737	4.590	35.194	4.801	141.411	7.695	64.114	5.695
POP (10^6)	20.309	1.888	22.861	2.267	24.166	2.595	22.445	2.250
POP_D (in ha)	0.176	0.012	0.199	0.015	0.210	0.017	0.195	0.015
LSK (10^6)	32.242	23.666	38.399	28.855	54.879	32.889	41.840	28.47
LSK_D (in ha)	0.280	0.153	0.334	0.186	0.477	0.212	0.364	0.184
LSK:POP (in the number per person)	1.587	12.594	1.677	12.701	2.269	12.608	1.844	12.635
LSK:NPP (in head per t)	0.057	0.032	0.066	0.039	0.094	0.050	0.072	0.040
LSK:GDP (in head per $1000)	2.222	5.279	1.150	6.005	0.474	4.289	1.282	5.191
NPP: POP (in t per person)	28.209	390.431	25.573	332.415	24.225	256.359	26.002	326.402
GDP:POP (in $1000 per person)	0.768	2.418	1.529	2.115	5.815	2.946	2.704	2.493
GDP:NPP (in $ per t)	27.504	6.236	60.938	6.439	243.889	11.626	110.777	8.100

Abbreviations: NPP, net primary productivity; Gt, gigaton; t, ton; GDP, gross domestic product; POP, population size; ha, hectare.

(table 2). This is obviously caused by the much higher POP in IM (i.e., more than 10 times the POP of MG) rather than the higher livestock density. Interestingly, the change in LSK:POP over the 30-year study period appeared to be more volatile in MG than in IM, reflecting a highly vulnerable CHANS in MG that may be due to less developed economic and management systems and greater exposure to climatic extremes. For example, the extreme *dzud* of 2000–2002 caused a huge drop in livestock in MG but not in IM (figure 2a). However, the normalized differences for LSK:POP switched to positive after 2002 and until 2008, when the global financial crisis occurred (table 1). Placing livestock in the context of NPP, the natural vegetation on the Mongolian Plateau supports about 0.032–0.072 head per ton of carbon, with consistently higher values in IM than in MG (figure 2b). However, there are significantly more purchased fodder inputs to livestock in IM than in MG (Wang J et al. 2013), suggesting that livestock may be entirely less reliant on local production but can be further examined in the context of China or global development. Again, the normalized differences during the 1990s stayed slightly negative but positively increased after 2000. The LSK:GDP reflects the relative weight of the livestock in national economic development: It decreased exponentially in both IM and MG prior to the 1990s but remained as important in MG since 2000. The Soviet Union's exit from MG in 1991 indeed increased the importance of livestock in MG, resulting in a continuous decrease in the normalized difference value of LSK:GDP (figure 2c). This also reflects the strong growth of the Chinese industrial sector and economy, which dwarfs any increases in livestock production in IM (Wang J et al. 2013). NPP:POP, GDP:POP, and GDP:NPP provided additional insights on the coupling effects (figure 2d–f). Although the amounts of natural vegetation production (i.e., NPP) in IM and MG are similar per land base (approximately 4.8–5.1 metric tons per ha per year, table 2), the high human population in IM caused a NPP per capita of approximately 8% of MG (i.e., making it less reliant on NPP). The GDP growth per capita or per unit NPP, however, showed steady exponential increases over the 30-year period, with the ND changing to positive in 2005 (figure 2).

These coupled dynamics are complicated in their spatial distributions across the Mongolian Plateau (figure 3). From a climatic perspective, the plateau has warmed in the past 60 years, although several regions have experienced cooling or insignificant changes in temperature (mostly in MG). The historical precipitation data also indicated that southern IM and northern MG are getting drier, with more land area receiving reduced precipitation in MG than in IM (figure 3b). Regarding the future, the relationship will become weaker as the economies as well as the populations in MG and IM gradually deemphasize livestock. The potential reserves of mining and energy resources will replace the link of GDP and POP with NPP, and the importance of LSK will be replaced by the production of energy or minerals. However, the new economy is still dependent on the NS. More importantly, the capacities of natural supporting systems (like water) will become new factors limiting the economies and populations. As the interactions between the NS and HS change and as technology, capital, income, and prices converge through increased globalization, the ratio of LSK:NPP will likely converge between IM and MG. Most importantly, it is expected that both IM and MG will adopt market economies and will let the markets play major roles in allocating resources.


a. An abandoned village in Inner Mongolia, China

b. Recent establishment in suburban Ulaanbaatar

Figure 4. The most recent decade on the Mongolian Plateau is characterized by migration from rural to urban areas. However, the mechanism in Inner Mongolia (IM) lies within the labor needs and higher incomes in urban IM, whereas the incentive policy is the primary force for abandoning traditional practices in Mongolia.

If we use the livestock statistics in IM and MG as examples, major policy changes in both regions appear to be responsible for the fluctuations in livestock sizes. In IM, the substantial increase in livestock in the late 1980s was largely a result of livestock and grassland tenure reform, whereas the drop in livestock around 2000 was caused by the grassland restoration policy enacted in 1998–1999. The substantial livestock increase since 2004 was likely caused by growing demand driven by fast economic growth and market reform in China. The fluctuations of the relative prices have significantly affected animal grazing behaviors over the past few decades in IM (Zhen et al. 2010), which, in turn, directly affected ecosystems. Clearly, the coupled dynamics of the physical and socioeconomic systems have been fueled by institutional and policy shifts on the Mongolian Plateau. However, including these influences in modeling the CHANS concept for sound adaptation plans awaits investigations by both scientists and policymakers (Brown et al. 2013).

As a result of changing economies, with particularly greater market integration, food production accounts for less and less household time, leading to changes in the interactions between the HS and NS. On the Mongolian Plateau, an obvious change has been the abandonment of traditional nomadic practices of primarily self-subsistence in favor of higher profit and wagemaking practices. For example, we have observed many villages in IM being abandoned while witnessing escalating residential development in suburban MG (figure 4), resulting in accelerated urbanization. However, the migrations in IM and MG were driven by different mechanisms. Our field surveys indicated that the rural–urban migration in IM was primarily from better-paying jobs and advanced education systems in IM cities, whereas the Collectivization Program (1921–1960) and the Gold Program (1992–2000) in MG (i.e., policy-driven changes) were responsible for the herdsmen settling in the suburbs (51.8% of the population of MG is in the city of Ulaanbaatar and in the Darkhan-Uul and Orkhon *aimags*, or provinces, with 45% of the MG population in Ulaanbaatar alone). The growing population is shifting from grazing-based economies to other economies. The Gold Program initiated the boom in mining and energy sectors, which are becoming very important. These economy- and policy-driven processes will likely continue to produce significant consequences for land-use change in rural landscapes, with consequent effects on ecosystem productivity and related services.

With a change in natural and human interactions also comes a change in the coordination among the people in both formal and informal institutional arrangements (Wang J et al. 2013). Land (resource) tenure is one of the most important arrangements because of the intimate relationship between land and livelihoods and because of the risk of overexploitation that follows from the open access of a pastoral society (Hardin 1968). Therefore, collective resource management is often used to combat loss due to open access (Dietz et al. 2003, Ostrom 2005). The changing relative scarcity measured by land area per capita, which is the ratio of land to total population, would induce institutions, such as land tenure change, to capture the increasing value of the land (North and Thomas 1973). The varieties of grazing systems (Shao et al. 2013) and the dramatic changes in land cover on the Mongolian Plateau since the 1980s provide a great opportunity to examine the changes in the institutional arrangements. These changes were partially driven by the relative scarcity of the resources (e.g., NPP:GDP or NPP:POP), political forces, market powers, and technological advancements. Many new policies and institutional arrangements have been applied to regulate the access to land resources and reduce externality problems, such as controlling the maximum livestock number per unit of grassland, prohibiting specific-animal grazing for fragile grasslands or providing incentives to ecosystem service providers (Zhen et al. 2010). These policies and the institutional arrangements designed to carry them out significantly influence the CHANS. In IM, grassland tenure has progressed toward a more privatized form that is designed to increase the values of the resources to individual households. This arrangement has reduced the opportunities in IM—relative to those in MG—to adapt to climatic variability through livestock management (Brown et al. 2013); however, it may be more suited to a more market-driven economic system.

Future CHANS on the Mongolian Plateau

Bringing all of the elements of the NS and HS together provides a great opportunity to contribute to process-based modeling studies for the development of realistic adaptation plans. However, great challenges also lie ahead because some of the spatial and temporal relationships between any two elements have not been thoroughly explored in previous investigations, even though they may have been independently explored. For example, GDP and NPP have been extensively studied in socioeconomic and ecological investigations, respectively. Liu and colleagues (2008) demonstrated that food consumption patterns significantly affect water requirements, with the per-capita water requirement for food increasing from 255 cubic meters (m^3) per person per year in 1961 to 860 m^3 per person per year in 2003 in China, and an additional 407–515 m^3 per person per year will be required in 2030. This diet shift may also have detrimental effects on population health (e.g., MG), as in other developed countries.

Although we do not always anticipate clear causal relationships among the biophysical and socioeconomic variables, a series of questions may arise from these analyses: What are the most meaningful measures for connecting the HS and NS? How should they be interpreted? If climate and land use affect the HS, what is the feedback from changes in the HS to the regional climate and future land-use and land-cover change? IM experienced much higher land-use and environmental stresses than MG did; can this be sustained, and for how long? Will MG follow pathways similar to those of IM? Here, we propose a conceptual framework addressing the coupled effects of climatic and socioeconomic changes that will simultaneously place pressure on land use (figure 5). This conceptual framework aims to understand the drivers, mechanisms, and consequences of socioeconomic and physical changes on the functional changes of the CHANS on the Mongolian Plateau, where IM and MG have headed toward different directions over the past 70 years, after their separation. Land-use change and land-cover change are central variables facilitating such causal relationships, as well as the foundations for their trajectories. Particular efforts are needed to explore the causes, reactions, constraints, and interactions among these driving forces, especially if we are to create the development plans that support adaptation to changing climatic and economic conditions.

People devise a variety of livelihood strategies that reduce the risks associated with variability in their natural and human contexts. These risk-reducing strategies include livelihood diversification (Ellis 2000), mobility, storage, communal pooling, and market exchange (Agrawal and Perrin 2009). These strategies are facilitated by various forms of formal and informal institutional arrangements (Nuijten 2004). Mobile grazing has been a key strategy in pastoral communities on the Mongolian Plateau, but mobility has been reduced in IM because of the changes in land tenure arrangements and in MG because of reductions in available infrastructure (Wang J et al. 2013). Because market integration has increased and land use has become increasingly oriented toward income as opposed to subsistence food production (Zhang et al. 2000), the adaptation strategies have shifted toward livelihood diversification and market exchange in IM, facilitated primarily by governmental and market institutions. Mobility remains a dominant strategy in Mongolia, with communal pooling also being used and facilitated by local communal institutions (Wang J et al. 2013). Another form of mobility has become increasingly important in the form of rural–urban migration in response to the increasing gaps in wages or other opportunities. Such adaptations will have significant impacts on local communities and ecosystems. For example, the opportunity for a NS to be restored presents itself as more rural populations migrate to urban areas (Aide and Grau 2004, Wang C et al. 2011).

The sustainable adaptation of the NS and HS to possible changes in climatic and economic conditions requires jointly considering both ecological and socioeconomic systems. No workable solution can ignore social, economic, or political factors (Perry et al. 2008), suggesting that policymakers need to be leaders in developing sound adaptation plans. A society can adapt to external social or environmental changes using technological solutions, infrastructure investments, planning responses, or a combination of sanctions and incentives that encourage adaptive behavioral choices and land-management practices. Synthesizing science to support such policymaking, however, is extremely challenging (Kareiva and Marvier 2007) because (a) in agile adaptations, uncertainties and risks in

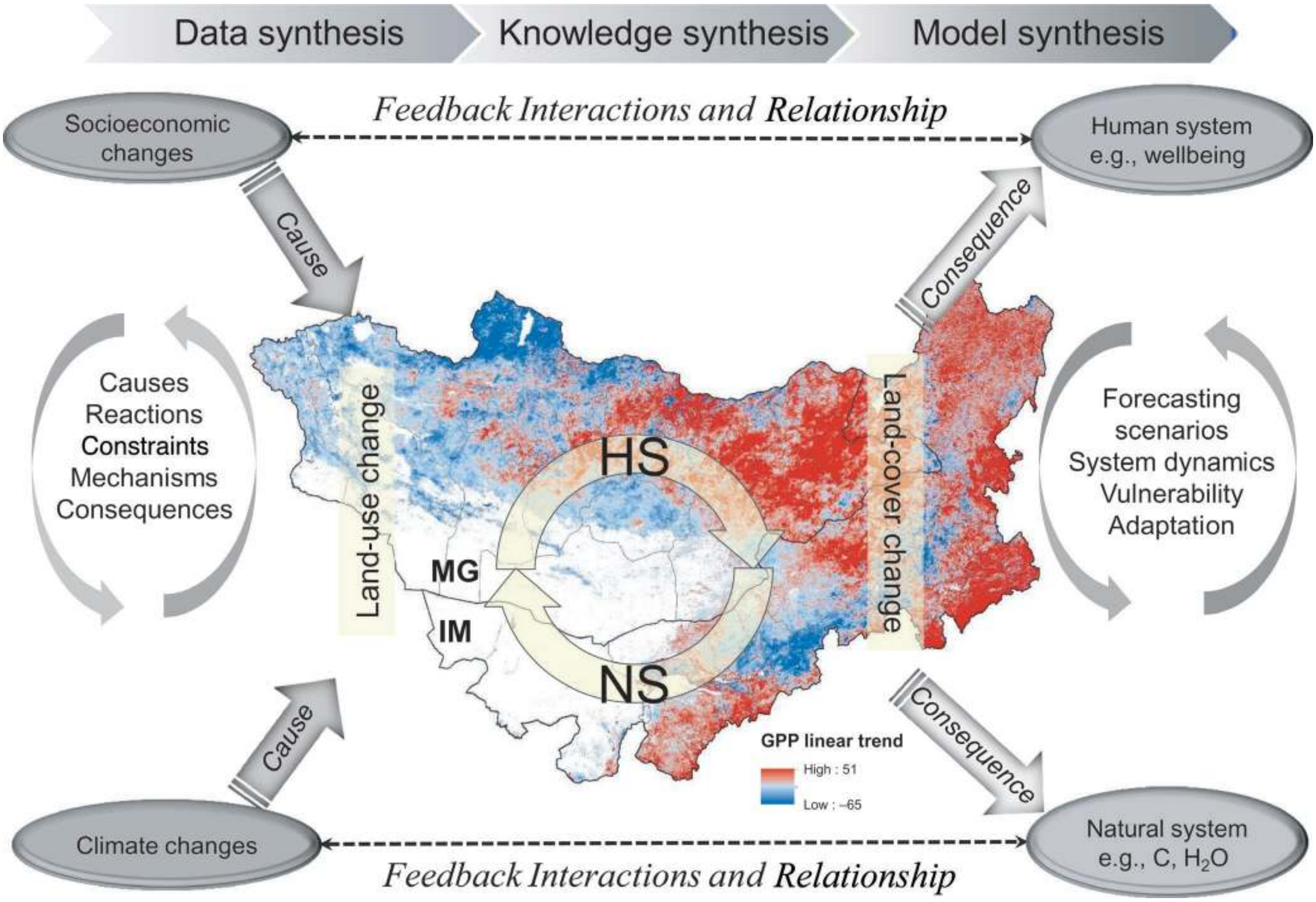

Figure 5. A proposed coupled human and natural systems conceptual framework for understanding the drivers, mechanisms, and consequences of socioeconomic and physical changes on the functional changes of the human system (HS) and natural system (NS) on the Mongolian Plateau. Land-use change and land-cover change can be considered as the intermediate variables facilitating the causal relationships, as well as the foundations for the trajectories. Abbreviations: C, carbon; GPP, gross primary production; H_2O, water; IM, Inner Mongolia; MG, Mongolia.

the broader context of socioeconomic incentives and institutional behaviors need to be considered and (b) managers need to know, in advance, where the greatest vulnerability lies in order to reevaluate priorities and consider triage. In light of understanding the complex CHANS on the Mongolian Plateau, it is reasonable to hypothesize that although biophysical change (e.g., climate) has produced uneven pressures on ecosystems and societies in time and space on the plateau, the socioeconomic changes and their disparities among the administrative units further escalated the complex causal relationships among the elements of the NS and HS (figure 5). We further hypothesize that the human influences on the CHANS exceeded those of the biophysical changes but the significance varies in time, location, and ecological setting (e.g., biome). To test these hypotheses and develop sound adaptation strategies that ensure long-term sustainability under alternative climates, land use patterns, and socioeconomic conditions, we must perform an uncertainty analysis, assess vulnerability, and forecast changes in CHANS functions on various temporal, spatial, and organizational scales. Prior to 1980, it seemed that climatic change was the dominant driver over other changes for both MG and IM. The much greater changes observed in IM than in MG in 1980–2000 were because the market economy and economic reforms were adopted earlier in China than they were in MG (figure 6). In the future, it seems likely that the relative importance of these socioeconomic forces will gradually decrease in IM while it increases in MG (figure 6). The climate change will become an increasingly important driver for grazing and livestock when MG also completes the transition into a market economy. Both the changes and the regulating mechanisms vary by biome because of contrasting resource limitations.

The need for the scientific understanding of CHANS has been recognized for a long time but has gained momentum only in the past two decades. The Man and the Biosphere Programme, the International Human Dimensions Programme, the Millennium Report, and the current initiative of Future Earth all call for the maintenance of ecosystem

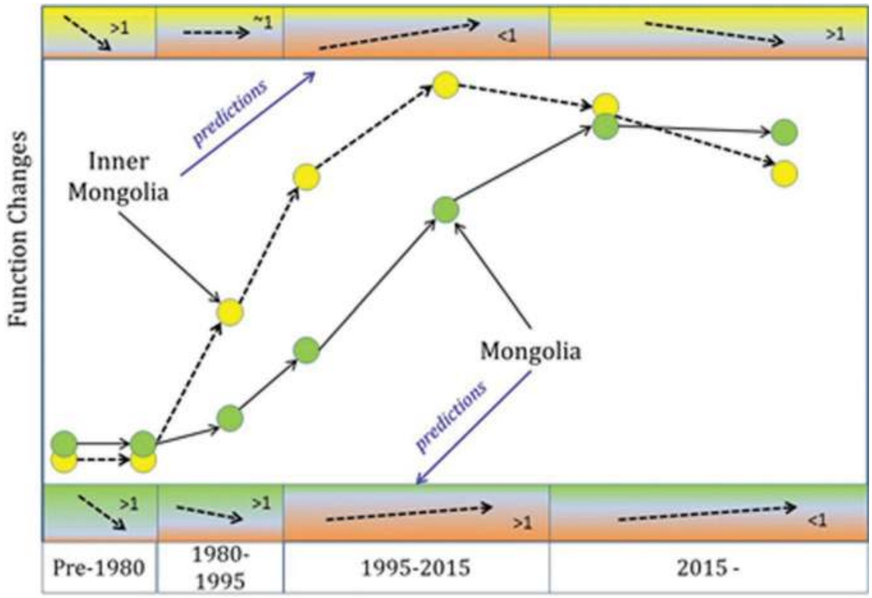

Figure 6. The hypothesized divergence of coupled human and natural systems (drivers, processes, and functions) in Inner Mongolia and Mongolia in different periods. The number in the prediction box indicates the ratio of biophysical to socioeconomic change (i.e., more than 1 refers to those dominated mostly by biophysical changes).

functions while promoting economic development and social values. Here, we initiated efforts to understand the CHANS in two contrasting societies by using the most important metrics of social, economic, and ecosystem functions. Future efforts are urgently needed to explore the detailed mechanisms, such as those illustrated in our working framework, at multiple spatial and temporal scales.

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References cited

Agrawal A, Lemos MC. 2007. A greener revolution in the making? Environmental governance in the 21st century. Environment 49: 36–45.

Agrawal A, Perrin N. 2009. Climate adaptation, local institutions, and rural livelihoods. Pages 350–367 in Adger WN, Lorenzoni I, O'Brien KL, eds. Adapting to Climate Change: Thresholds, Values, Governance. Cambridge University Press.

Aide TM, Grau HR. 2004. Ecology: Globalization, migration, and Latin American ecosystems. Science 305: 1915–1916.

Alberti M, et al. 2011. Research on coupled human and natural systems (CHANS): Approach, challenges, and strategies. Bulletin of the Ecological Society of America 92: 218–228.

Brown DG, Agrawal A, Sass DA, Wang J, Hua J, Xie Y. 2013. Responses to climate and economic risks and opportunities across national and ecological boundaries: Changing household strategies on the Mongolian Plateau. Environmental Research Letters 8 (art. 045011). doi:10.1088/1748-9326/8/4/045011

Chen J, Wan S, Henebry G, Qi J, Gutman G, Sun G, Kappas M, eds. 2013. Dryland East Asia (DEA): Land Dynamics Amid Social and Climate Change. Higher Education Press and De Gruyter.

Diamond J. 1997. Guns, Germs, and Steel: The Fates of Human Societies. Norton.

Dietz T, Ostrom E, Stern PC. 2003. The struggle to govern the commons. Science 302: 1907–1912.

Ellis F. 2000. Rural Livelihoods and Diversity in Developing Countries. Oxford University Press.

Entwisle B, Stern PC. 2005. Population, Land Use, and Environment: Research Directions. National Academy Press.

Fernandez-Gimenez ME, Batkhishig B, Batbuyan B. 2012. Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (*dzud*) in Mongolia. Global Environmental Change–Human and Policy Dimensions 22: 836–851.

Foley JA, et al. 2005. Global consequences of land use. Science 309: 570–574.

Foley JA, et al. 2011. Solutions for a cultivated planet. Nature 478: 337–342.

Goldewijk KK, Beusen A, van Drecht G, de Vos M. 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Global Ecology and Biogeography 20: 73–86.

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM. 2008. Global change and the ecology of cities. Science 319: 756–760.

Groisman PY, et al. 2009. The Northern Eurasia Earth Science Partnership: An example of science applied to societal needs. Bulletin of the American Meteorological Society 90: 671–688.

Gutman G, Reisell A. 2004. Eurasian Arctic Land Cover and Land Use in a Changing Climate. Springer.

Hardin G. 1968. The tragedy of the commons. Science 162: 1243–1248.

[IPCC] Intergovernmental Panel on Climate Change. 2007. Summary for policymakers. Pages 7–22 in Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, eds. Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

John R, Chen J, Lu N, Wilske B. 2009. Land cover/land use change in semi-arid Inner Mongolia: 1992–2004. Environmental Research Letters 4 (art. 045010). doi:10.1088/1748-9326/ 4/4/045010

John R, Chen J, Ou-Yang Z-T, Xiao J, Becker R, Samanta A, Ganguly S, Yuan W, Batkhishig O. 2013. Vegetation response to extreme climate events on the Mongolian Plateau from 2000 to 2010. Environmental Research Letters 8 (art. 035033). doi:10.1088/1748-9326/ 8/3/035033

Kareiva P, Marvier M. 2007. Conversation for the people: Pitting nature and biodiversity against people makes little sense. Many conservationists now argue that human health and well-being should be central to conservation efforts. Scientific American 297: 50–57.

Lambin EF, Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108: 3465–3472.

Lattimore O. 1940. Inner Asian Frontiers of China. International Research Series, vol. 21. American Geographical Society.

Liu J, et al. 2007. Complexity of coupled human and natural systems. Science 317: 1513–1516.

Liu J, Yang H, Savenije HHG. 2008. China's move to higher-meat diet hits water security. Nature 454: 397.

Meyer WB, Turner BL II. 1994. Changes in Land Use and Land Cover: A Global Perspective. Cambridge University Press.

Morinaga Y, Tian SF, Shinoda M. 2003. Winter snow anomaly and atmospheric circulation in Mongolia. International Journal of Climatology 23: 1627–1636.

Mu QZ, Zhao MS, Running SW. 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sensing of Environment 115: 1781–1800.

North DC, Thomas RP. 1973. The Rise of the Western World: A New Economic History. Cambridge University Press.

Nuijten M. 2004. Between fear and fantasy: Governmentality and the working of power in Mexico. Critique of Anthropology 24: 209–230.

Ostrom E. 2005. Understanding Institutional Diversity. Princeton University Press.

Pederson N, Leland C, Nachin B, Hessl AE, Bell AR, Martin-Benito D, Saladyga T, Suran B, Brown PM, Davi NK. 2013. Three centuries of shifting hydroclimatic regimes across the Mongolian breadbasket. Agricultural and Forest Meteorology 178: 10–20.

Perry JL, Brudney JL, Coursey D, Littlepage L. 2008. What drives morally committed citizens? A study of the antecedents of public service motivation. Public Administration Review 68: 445–458.

Pongratz J, Caldeira K, Reick CH, Claussen M. 2011. Coupled climate–carbon simulations indicate minor global effects of wars and epidemics on atmospheric CO_2 between AD 800 and 1850. Holocene 21: 843–851.

Qi J, Chen J, Wan S, Ai L. 2012. Understanding the coupled natural and human systems in Dryland East Asia. Environmental Research Letters 7 (art. 015202). doi:10.1088/1748-9326/7/1/015202

Seto KC, Fragkias M, Güneralp B, Reilly MK. 2011. A meta-analysis of global urban land expansion. PLOS ONE 6 (art. E23777). doi:10.1371/journal.pone.0023777

Shao C, Chen J, Li L. 2013. Grazing alters the biophysical regulation of carbon fluxes in a desert steppe. Environmental Research Letters 8 (art. 025012). doi:10.1088/1748-9326/ 8/2/025012

Tachiiri K, Shinoda M, Klinkenberg B, Morinaga Y. 2008. Assessing Mongolian snow disaster risk using livestock and satellite data. Journal of Arid Environments 72: 2251–2263.

Wang C, Yang Y, Zhang Y. 2011. Economic development, rural livelihoods, and ecological restoration: Evidence from China. Ambio 40: 78–87.

Wang J, Chen Y, Shao X, Zhang Y, Cao Y. 2012. Land-use changes and policy dimension driving forces in China: Present, trend and future. Land Use Policy 29: 737–749.

Wang J, Brown DG, Agrawal A. 2013. Climate adaptation, local institutions, and rural livelihoods: A comparative study of herder communities in Mongolia and Inner Mongolia, China. Global Environmental Change–Human and Policy Dimensions 23: 1673–1683.

Yuan C, Liu S, Xie N. 2010. The impact on Chinese economic growth and energy consumption of the global financial crisis: An input–output analysis. Energy 35: 1805–1812.

Zhang Y, Uusivuori J, Kuuluvainen J. 2000. Econometric analysis of the causes of forest land use changes in Hainan, China. Canadian Journal of Forest Research 30: 1913–1921.

Zhen L, Ochirbat B, Lv Y, Wei YJ, Liu XL, Chen JQ, Yao ZJ, Li F. 2010. Comparing patterns of ecosystem service consumption and perceptions of range management between ethnic herders in Inner Mongolia and Mongolia. Environmental Research Letters 5 (art. 015001). doi:10.1088/1748-9326/5/1/015001

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