Coupled dynamics of socioeconomic and environmental systems in Tibet

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1. Introduction

Our understanding of a region’s stability and sustainability can be approached through the lens of two paradigms: coupled socioeconomic and environmental systems (SES) (Alberti et al 2011, Mayer et al 2014), or coupled human and natural systems (Liu et al 2007, Chen and Liu 2014). The second paradigm was promoted in the 1990s with the realization that increased human activities had resulted in few human-free landscapes across the Earth (Chen 2015), and that ecosystem function and societal development were tightly connected and regulated by the interactive driving forces of physical and anthropogenic changes (Alberti et al 2011, Mayer et al 2014, Chen et al 2015a, 2015b). While there remain many challenges in forming a united theoretical foundation for this new scientific discipline, practical research needs to quantitatively explore the complex relationships, direct and indirect, among the elements of human and environmental matrices across multiple spatial, temporal, and organizational scales. With this knowledge, sound sustainable adaptation and mitigation for the climatic and socioeconomic changes can be developed (Arrow 1996, Ostrom et al 1999, Adams et al 2004, Perry et al 2007, Tallis et al 2008, Wu 2013, Chen et al 2015b).

Following this school of thought, we examined the coupled dynamics of Tibetan SES that is characterized by high elevation, harsh climate, complex terrains, ecosystem sensitivity to global climatic changes, and underdeveloped transporation systems for these relatively-untouched landscapes (figure 1). A pastoralist society has existed for thousands of years on the Tibetan Plateau. Today, livestock (LSK) remains the foundation for society on the plateau, and its economy relies on rangeland vegetation as the primary food source for livestock production. This suggests that ecosystem function (e.g. net primary production, NPP) is directly affected by livestock (LSK) through grazing in addition to the biophysical regulations of climate (e.g. phenology, available water and solar radiation). While our long-term, overarching goal is to tease apart the contributions of climate change and human activities on the relationship between LSK and NPP so that sound policy and mitigation plans can be developed, the specific objective of this study is to quantify the spatiotemporal changes of the LSK~NPP relationship, as well as the causes and consequences of the coupled dynamics.

We simplified our conceptual framework by focusing on the most the direct causes for and consequences of LSK, NPP, and their coupled dynamics (figure 2). In Tibet, LSK is composed of large (yak, horse, etc.) and small (sheep, goat, etc.) livestock (LSK_large and LSK_small, respectively), and is reported in the government’s annual statistics. Its change will have direct effects on the rural labor force (R_labour) and major economic measures (e.g. the industry and grazing production). For NPP, amount of leaf (i.e. leaf area for photosynthetic production) and fraction of photosynthetically-active radiation (fPAR) are the two direct variables determining its magnitude. Meanwhile, NPP dynamics are reflected by the magnitude and changes of water loss through evapotranspiration (ET; a key process for available water for the semi-arid ecosystems) and Albedo (i.e. reflection of solar radiation).

Three pressing issues within this working framework are: (1) What are the most meaningful measures for quantifying the socioeconomic and ecological...
systems in Tibet? (2) How should they be interpreted if we desire to discover the interactive feedbacks between the two systems? and (3) What role may policy shifts, climate, and other anthropogenic activities have in the coupled changes of Tibetan SES? We hypothesize that the LSK~NPP relationship varies significantly across the Tibetan landscapes and during different time periods, due in large part to the uneven changes of driving forces in space, time, and biophysical settings (e.g. biome). We predict that increased
Figure 3. Spatial distribution of land cover type, as well as the annual average normalized difference vegetation index (NDVI), net primary productivity (NPP), fraction of photosynthetically-active radiation (fPAR), evapotranspiration (ET), and Albedo (a)–(f), respectively, during 2000–2014 across the Tibetan Plateau (source: MODIS at http://ladsweb.nascom.nasa.gov/data).

grazing will decrease the vegetation coverage, elevate surface Albedo, and reduce ET. These changes in turn will yield different levels of local energy balance, climate, and economic development.

2. Methods

2.1. Tibet Autonomous Region

The Tibet Autonomous Region (hereafter referred to as Tibet) is one of the two provinces on the Tibetan Plateau \((1.1621 \times 10^8 \text{ km}^2)\) (figure 3). Its complex terrain includes the summit of Mt. Everest (8848 m a.s.l.), deep cut riverine systems (e.g. Brahmaputra River, 2057 km long), and vast pasture lands \(\left(2.39 \times 10^5 \text{ km}^2\right)\). The massive permanent glaciers secure the water resources for the Plateau and its neighboring territories in Southeast Asia, often referred to as the Asian water tower (Viviroli et al 2007) (figures 1(a) and (b)). Dominant land cover types include alpine meadow, steppe, forest, and desert steppe (figure 3(a)).

Tibet is one of the 31 provincial units of China. It is administratively divided into seven prefectures and 73 counties. Tibetans account for the majority of the population at 90.48% (www.xizang.gov.cn/rkmz/51886.jhtml) (figure 1(b)). Lhasa, the capital of Tibet, is the only major city with >560,000 residents and serves as the educational, economic, political and religious (i.e. Buddhism, the Potala Palace) center (figure 1(d)). In 1980, China began to implement a reform and opening-up policy to develop the economy; after 1999, the Chinese government promoted the ‘Go West’ campaign to narrow the gap between the East and West regions. China became a member of the World Trade Organization (WTO) in 2000, which has produced nationwide effects on its socioeconomic conditions. Governmental investments and poverty-alleviating projects, along with nongovernmental organizations and private foundations, brought rapid economic development to the region (e.g. developing ecotourism, service sectors, cultivation of Buddhism, promoting endemic Tibetan
Quantitative modeling exercises conclude that anthropogenic disturbances (e.g. overgrazing) have produced strong impacts on regional climate and ecosystem function (e.g. NPP, Albedo, ET) (Dallmeyer and Claussen 2011, Piao et al 2012, Geldmann et al 2014, Tian et al 2014b). The higher-than-global warming rate on the Plateau paired with frequent extreme weather events in the last decades have had catastrophic consequences for the local wildlife, vegetation, people, and society (Rockstrom et al 2009). The Intergovernmental Panel on Climate Change predicts that temperature and winter precipitation will increase within the next 20 years in most areas of the plateau (2016–2035), having increased by ~10% from 1986–2005 (Van Oldenborgh et al 2013), which will have direct impacts on herder livelihood, nomadic practices, and the ecosystem function.

2.2. Data sources
Our master database was constructed using several sources. For the socioeconomic system, we compiled the annual statistics of the 73 counties from the Tibet Statistics Yearbook (1981–2015) and used the 2010 China census for any missing data. This included information on LSK, primary industry (Primary 1), grazing production (GP), and R_Labor. Both LSK and LSK were converted to livestock unit (LSU) following the protocol of EUROSTATS (http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Livestock_unit_(LSU)). Primary I included gross output values of farming, forestry, animal husbandry, and fisheries. These measurements were selected because they all have direct connections with LSK (Cao et al 2015, Chen et al 2015a, 2015b). The annual values were standardized by each county’s land area.

We chose the normalized difference vegetation index (NDVI) and fPAR as the causal variables for NPP, and Albedo and ET as the direct consequences of NPP. These variables are widely used in ecological studies and were accessed from various remote sensing databases that cover Tibet and the entire study period. NDVI provides estimates of leaf mass of the vegetation; ET is an important measurement that is synchronized with photosynthesis (e.g. NPP); fPAR and Albedo reflect the radiation energy balance across the land surface.

The time series of NPP, NDVI, ET, fPAR, and Albedo were extracted from the moderate resolution imaging spectroradiometer (MODIS) products for 2000–2014, and from the global inventory monitoring and modeling system (GIMMS) and partial GIMMS datasets of AVHRR for 1981–2012 (table 1). The two sets of products had previously been validated for the Tibetan Plateau (Pu et al 2007, Qin et al 2011, Shen et al 2014, Tian et al 2014b, Wu and Yan 2002).

| Variable | Product ID | Resolution | Frequency | Span |
|----------|------------|------------|-----------|------|
| NDVI (0–1) | MOD13Q1 | 250 m | 16 days | 2000–2015 |
|           | GIMMS3g  | 0.05° | 15 days | 1981–2013 |
| Albedo (0–1) | MOD11A2 | 1 km | 8 days | 2000–2014 |
|            | GIMMS    | 0.05° | 15 days | 1981–2000 |
| NPP (gC m⁻² yr⁻¹) | MOD17A3 | 1 km | Annual | 2000–2014 |
|           | GIMMS    | 8 km | Annual | 1982–2011 |
| fPAR (%) | MOD15A2  | 1 km | 8 days | 2000–2014 |
|          | GIMMS3g  | (1/12)° | 15 days | 1981–2011 |
| ET (mm)  | MOD16A3  | 1 km | Annual | 2000–2014 |
|          | GIMMS3g  | 0.03° | Annual | 1981–2012 |

These products were further improved by filtering out noise caused by cloud contamination and topographic differences with the subset tool. For GIMMS products, we masked out any values below 0 and applied the filter using a third-order polynomial and a moving window of three observations prior to data extraction using the county boundaries. Vegetation types were obtained using the archives at the Data Center of Resources and Environmental Sciences (Liu et al 2003).

2.3. Quantitative analysis
Remote sensing products were used to explore the annual spatial distributions of NDVI, ET, Albedo and fPAR. The annual mean NDVI (NDVI_mean) was calculated as:

\[
NDVI_{\text{mean}} = \frac{1}{12} \sum_{i=1}^{12} NDVI_{\text{max}}
\]

where NDVI_mean is the annual average and NDVI_max is the maximum NDVI of each month (i). Annual averages ET_mean, Albedo_mean, and fPAR_mean were calculated as:

\[
I_{\text{mean}} = \frac{1}{12} \sum_{i=1}^{12} I_{\text{mean}}
\]

where I_mean is the annual average of Albedo_mean and fPAR_mean, respectively. The M_mean is the monthly mean. The ET and NPP are the annual total and mean, respectively.

We also examined the ratio between an independent variable of LSK and those of NPP for their changes over the study period, including: LSK:NPP, LSK:ET, LSK:Albedo, LSK:R_Labor, and LSK:small:NPP (figure 5). These changes were explored before/after 2000 when China joined the WTO, which was found to be the most significant policy in shaping the relationship between the natural and human systems in the neighboring Mongolian Plateau (Chen et al 2015b).

We hypothesize that the coupled dynamics between the two stages are very different. A t-test was employed to examine the significant difference prior/post 2000 for the above variables.
2.4. Structural equation modeling (SEM) of SES
SEM uses multiple structural equations to model the hypothesized causal relationships. Since its publication (Jöreskog 1973), it has been extensively used in socioeconomic and physical science (Grace et al. 2010, Tian et al. 2014a, Fan et al. 2016, Park et al. 2017). SEM is normally expressed as path diagrams (figures 6–7). The primary focus of this study was on the coupled dynamics of LSK and NPP. Here, NPP was hypothesized to have a direct causal relationship with ET, fPAR, Albedo and NDVI, whereas LSK has direct relationships with LSK_large, R_Labor, Primary I, and GP (figure 2). Posterior analysis on the uncertainty of LSK and NPP were also performed. The path coefficients, Chi-square value, and P values are reported for SEM results (Fan et al. 2016). The 30 year study period was split into six stages (1981, 1989, 2000, 2005, 2010, and 2014) for our SMEs. Each stage included data from ±2 years before/after the year as input for the same SEM to ensure sufficient sampling sizes (n = 365). However, year 1981 included data from 1981 and 1982 (n = 146), and year 2014 included data from 2013 and 2014 (n = 146). Each county in Tibet was treated as a sample (n = 73) for our SEM. We performed a correlation analysis on all of the variables to finalize the structure of SEMs.

3. Results
3.1 Socioeconomic changes in space and time
Large spatial variations existed in the changes of all six socioeconomic variables among the 73 counties during 1980–2014, with counties around the Lhasa showing high averages (figure 4, S1 available at stacks.iop.org/ERL/13/034001/mmmedia). In general, the average values of these variables were low in the west and high in the south. The average values of LSK, LSK_large, LSK_small, Primary I, GP, and R_Labor were 6.57 LSU km⁻², 5.16 LSU km⁻², 1.41 LSU km⁻², 4.18 km⁻², 1.75 × 10³ km⁻², and 0.84 person km⁻², respectively. The highest LSK was found in Taktse county, whereas Metok county had the lowest (S1). The highest Primary I and GP was found in Dazi county, and the lowest in Motuo county. For R_Labor, its maximum was in Lhasa and the minimum in Ritu. The LSK was primarily composed of LSK_large (80.60%) in the southern and western region (S1), whereas in the eastern region (S1), the ratio of LSK_large to LSK_small was near 1. More importantly, it seems that high LSK was tightly coupled with Primary I, GP, and R_Labor.

The changes in socioeconomic variables also exhibited different dynamics over the study period (figures 5(a), (c) and (d)). The mean LSK decreased during 1981–1983 and increased until 2005, except in 1991–1992 and 2012–2014 when winter snowstorms hit the plateau. LSK composition also shifted, with increased LSK_large and decreased LSK_small in the mid-1990s (figure 5(d)). Additionally, LSK_large appeared more sensitive to the extreme climatic events than LSK_small. For Primary I, GP, and R_Labor, two distinct stages were apparent: 1981–1990 and post-1990. All three measures remained low and stable in the 1980s but they exponentially increased until 1990, with GP lagging behind by 3–4 years (figure 5(c)). The R_Labor increased from 1988–2014, whereas Primary I and GP increased (S1).

3.2. Spatiotemporal changes of ecosystem measures
NDVI decreased from the southeast to the northwest, with the highest NDVI value found in the forest and
Figure 5. Changes in socioeconomic (Primary I, GDP, $R_{Labor}$), climatic (ET, Albedo), ecosystem characteristics (NPP, NDVI) from 1981–2014 on the Tibetan Plateau. Some measurements (e.g. NPP) showed clear periodic dependency, while others appeared more sensitive to extreme climate (e.g. LSK in 1992 and 2012).

alpine meadow (∼0.81) and the lowest value in the alpine steppe and alpine desert steppe (∼0.20) (figure 3(b)), S1). There appeared three distinct periods: 1981–1987, 1988–2001, and 2002–2014. NDVI decreased from 0.226 in 1981–0.224 in 1987 (figure 5(h)). After 1987, it increased until 2001. From 2002–2014, NDVI decreased again and experienced a slight increase after 2008.

NPP of MODIS during 2000–2014 decreased from ∼1700 g C m$^{-2}$ yr$^{-1}$ in the tropical rainforest to 5 g C m$^{-2}$ yr$^{-1}$ in the cold arid meadows (figure 3(d)). For NPP of GIMMS$_{3g}$ (1982–2010), it fluctuated with a range of ∼60 g C m$^{-2}$ yr$^{-1}$, with an increase during 1981–1987. From 2003–2010, NPP decreased. fPAR matched spatially well with MODIS NDVI (figure 3(c)), with a range of 0.50–0.85 for the 2000–2014 period. The annual average fPAR increased slightly from 1981–2011, especially between 1983 and 1990. This rapid increasing trend was observed until 1993 (18.039) before it leveled off until 2011 (figure 5(e)). Interestingly, Albedo demonstrated a different changing trend from NDVI. On average, MODIS Albedo was 0.15–0.85 for 2000–2014 (figure 3(f)) and GIMMS$_{3g}$ was 0.154–0.152 for 1981–2000 (figure 5(f)).

ET during 2000–2014 varied between 180 mm and 1200 mm, with a decreasing trend from the...
northwestern to southeast (figure 3(e)). The annual ET increased from 441.35 mm in 2000–453.38 mm in 2014, with a peak of 474.32 mm in 2013 (figure 5(g)). For 1981–2012, the ET showed two contrasting changes. It decreased from 784.44 mm in 1981–761.70 mm in 1993, with a peak of 826.39 mm in 1984. During 1993–2012, it increased steadily to 832.56 mm in 2012 with a maximum of 860.23 mm in 2009.

3.3. Coupled dynamics of Tibetan SES

Temporal changes of the ratio between socioeconomic and ecological measures during 1981–2014 varied greatly (figure 6). Prior to 2000, LSK:NPP decreased slightly (slope = $-0.008$, $P = 0.046$), with two low values in 1987 and 1992 when an extreme snowstorm and low temperatures spread across the Tibetan Plateau. This ratio was significantly ($P = 0.002$) shifted from 2.874–3.098 after 2000 (7.8% increase) (figure 6(a)). For the LSK:ET ratio, there also appeared an increasing trend prior to 2000 (slope = 0.006, $P = 0.006$) and post 2000 (slope = 0.005, $P = 0.040$) (figure 6(b)), with the mean significantly elevated ($P = 0.001$) from 0.809–0.887 (9.6% increase). LSK:Albedo remained relatively stable in the first stage (slope =0.003, $P = 0.025$), but rapidly dropped to its minimum before an increase (slope =0.003, $P = 0.025$), with the two extreme values in 1998 and 2012 caused by the significant difference between the two periods ($P = 0.000$) (figure 6(c)). LSK$_{large}$:NPP show a similar change to LSK: NPP, with stable changes in both periods, but a small, marginally-significant shift ($P = 0.075$) from 2.193–3.467 (5.8%) (figure 6(d)). Finally, LSK:R$_{Labor}$ in each period remained as steady, variable changes, with a significantly lower value of 2.680 from (2.842) (−5.8%; $P = 0.035$) after 2000 (figure 6(e)).

Our SEM results further confirmed the complex, coupled changes among the SES elements (figure 7). The Chi-square below 10 and $P$ value of $>0.05$ indicate a reliable model conversion. The overall Chi-square of SEMs varied from 4.23 in 2000–8.32 in 1981. The low Chi-square for 1998–2002 (labeled as 2000) may reflect the transitional period (i.e. policy shift) when China became a WTO member (figures 5 and 6). Overall, there existed a negative relationship between LSK and NPP, varying from −0.110 (2000) to −0.265 (2005). In the first stage (1981), the four socioeconomic factors (LSK$_{large}$, R$_{Labor}$, Primary I, GP) were all positively correlated with LSK ($r = 0.786, 0.406, 0.198$ and $0.711$, respectively). After 2000, however, Primary I and R$_{Labor}$ showed negative relationships with LSK (figure 6). The four physical variables (ET, $f$PAR, albedo, NDVI) had a correlation of 0.294, 0.646, −0.726 and 0.561, respectively, with NPP (figures 7–8).

NDVI and $f$PAR showed a decreasing relationship with NPP before 2000. After 2000, NDVI continued this relationship, but $f$PAR began to show a decreasing and then increasing relationship. ET maintained the same relationship with NPP before 2000, but showed a decreasing and then increasing relationship after 2000 (figure 8(a)). The negative correlation between NPP and Albedo diminished in recent years. For LSK dynamics, all causal variables were significant...
Figure 7. Dynamics of structural relationships based on structural equation modeling (SEM) for coupled changes of socioeconomic and environmental variables for the six time periods (1981, 1989, 2000, 2005, 2010, 2014) on the Tibetan Plateau. A one-way arrow indicates a hypothesized causal relationship between the two variables, while a two-way arrow indicates a feedback relationship. Absence of a line between any two variables implies that no hypothesis was proposed in this study. Livestock (LSK) is hypothesized to be influenced by LSK large, R Labor, Primary I, and GP, while ecosystem net primary productivity (NPP) is related to NDVI, f PAR, ET and Albedo (see figure 3). The residuals of LSK and NPP were assessed by the model. The partial regression coefficients indicated the strength and direction of these relationships.

(P < 0.05), with LSK large and Primary I showing a negative relationship for all years except 1990 and 2010 where the correlations were near zero. Interestingly, Primary I had a negative correlation with LSK; R Labor dipped to a negative correlation with LSK, especially after 2000 (figure 8(b)).

4. Discussion

A series of environmental issues on the Tibetan Plateau have emerged due to increased anthropogenic disturbances and climatic change (Piao et al 2012, Zhang et al 2014). A pronounced rise in temperature has been observed over recent decades, with a warming rate of about twice that of the global average for the period 1960–2009 (Hansen et al 2010, Yao et al 2012, Piao et al 2012), and a slightly wetter climate (Van Oldenborgh et al 2013). In addition, overgrazing has been widely cited as the principle culprit for grassland degradation. Alpine meadow and alpine steppe degradation has been caused by tillage and fertilization (Niu et al 2009), the privatization of livestock ownership and rangelands, and the re-settlement of herdsmen (Liu et al 2003, Yan and Wu 2005). An increasing number of ecological studies have observed major ecological shifts in Tibet, including changes in phenology (Piao et al 2011, Zhang 2013), plant abundance and distribution along the elevation gradient (Piao et al 2011, Shen et al 2014), carbon and nitrogen cycling (Zhang et al 2014), ecosystem production, soil carbon loss (Hu et al 2016), and pasture degradation (Cao et al 2015).

The massive investments and immigration projects by the Chinese government are turning Tibet into one of the most dynamic SES on Earth (Horowitz and Yu 2014). The negative relationship between LSK and NPP is clear, although the magnitude of the correlation varied over time (figure 7). The correlate coefficient reached its highest in 2005, likely due to: (1) the fact that LSK increased (figure 5(a)) as the market demand increased under the market economy; and (2) the LSK large increased significantly due to the increasing demands (figure 5(d)). A yak requires much more land than a sheep, which would increase the pressure on vegetation. In 2010 and 2014, the correlation decreased, likely due to policy implementations on
grazing practices (e.g. LSK, figures 5(a) and (d)), population increases, and/or economic advancements leading to increased sources of income for herdsmen. For example, the State Council’s implementation of the ‘retire-livestock-and-restore-grassland’ policy in 2004 (Wei et al. 2012), aiming at the Tibetan’s ecological security through protection and restoration, was a component of the five-year plan that invested ¥15.5 billion for the ecological and environmental protection in Tibet (www.concrete-accessory.com/news/china-invested-tibet-ecological-security-barrier-construction). These policies provided the herdsmen with economic compensation for reducing their livestock (figure 5) and promoting ecosystem functions (Cao et al. 2010, Piao et al. 2011, Shen et al. 2015). While our analysis confirmed the policies’ effectiveness based on LSK and NPP dynamics, we also echo the point by Cao et al. (2009) that continued efforts are needed for the future.

A highly aggregated spatial pattern was found for all six socioeconomic variables in Tibet (figure 4). This may be partially due to intensified local grazing, and/or reduced nomadic practices. Since 1978, policies on land use rights, privatization for businesses, livestock privatization, etc have been promoting land ownership and enforcing grazing boundaries, which has resulted in less migratory grazing (Wu and Yan 2002, Kreutzmann 2011). Coupled with location-dependent changes to population, economic infrastructure (e.g. road networks, railroads, hydro-dams, etc.), local ecosystems with high LSK, and other developments (e.g. urban, industries), these factors would accelerate the changes in LSK and vegetation, in turn accelerating the spatial aggregation.

Through SEMs, we found that the $R_{Labor}$ and Primary 1 were negatively correlated with LSK (figure 7). This was also evidenced by the changing ratios of LSK:$R_{Labor}$ (figure 6). We speculate that this was partially influenced by the national and regional socioeconomic developments that provided more opportunities for herdsmen to find off-pasture jobs after 2004 (Wang et al. 2016b). For example, the urban private and individual enterprises in 2015 provided jobs for 480,000 throughout Tibet (Xizang Statistic Years 2016). This increased livelihood diversity may have weakened the relationship between LSK and NPP. The program of projects alleviating poverty, technology, and poverty in China can revolutionize the lifestyle of local residents. The dual objectives of reducing local poverty and protecting ecosystem resources in rural areas such as Tibet are commendable. For example, the under-developed transportation and trade market in the five southeastern counties (Cuona, Langxian, Motuo, Milin, Chayu) continued to hinder the transport of commodities. In these counties, we found low values of LSK, Primary I, and GP, while their ratios to NPP were high but not their ratios to NPP (figure 4).

The spatial patterns of socioeconomic variables did not always match those of environmental variables (figure 3) and consequently resulted in highly dynamic and variable relationships between LSK and NPP prior/post to 2000, as well as indirect relationships between the elements of LSK and NPP (figure 6). Normally, temperature and precipitation are conventionally used to model the changes in NPP and its drivers (e.g. NDVI, $f_{PAR}$, ET). Here, we advanced the empirical understanding to livestock (figures 5–7). For example, NDVI increased rapidly from 1981–1989, varied substantially from 1990–2000, and decreased steadily after 2000 (figure 5(h)). The ET, especially, increased significantly after 1990 (figure 5(g)), likely due to increased temperatures that increased vapor pressure deficits while maintaining soil moisture—which may have had an increased supply from glacier melt (Viviroli et al. 2007, Van Oldenborgh et al. 2013).

Similarly, climatic extremes can also change these coupled relationships and dynamics (figure 6). In the extremely cold winter of 1990–1991, the combination of heavy snow and low temperature was responsible for the death of 1.27 million heads of livestock in 11 counties in Tibet (Sun 1999). The legacy effects of this event lasted until 2005 (figures 5 and 8). As a result of the increased price of beef and mutton, $R_{Labor}$ and GP immediately increased (figures 5(c) and 7). Their influences on the coupled dynamics of SES elements were also very apparent. For example, LSK:NPP was approximately seven heads of livestock per 10⁴ per kg in 1987 and 1991 (the two extreme winter years in Tibet) (figure 6(a)). This value was reduced by 17.6%
from ~2.8 LSU of livestock per 10^4 per kg, which is a change similar to that in livestock mortality caused by the 1990–1991 dzud in Mongolia (Wang et al. 2016a, Chen et al. 2015b, John et al. 2016). However, the impact of the same extreme climate in 1987 on other relationships (e.g. LSK:ET, LSK:Albedo, LSK:R_Labor; figures 6 (b), (c) and (e)) was not found.

Our findings thus far are based on historical data. With escalated warming, infrastructure expansion (e.g. road development, urbanization, and technological, health-care and educational system advancements) one can reasonably expect new emerging properties within the Tibetan SES that are potentially different from those reported in this study due to different needs of future stakeholders (Allington et al. in review). Due to the sensitive issues facing Tibet’s society (e.g. religion), China has been and will continue investing in more flexible policies for regional stability. One can expect that any new policies implemented in Tibet will continue to influence the spatiotemporal changes of SES elements and, consequently, the functions and dynamics of the system. Nevertheless, including the overarching driving forces from human dimensions (e.g. policy changes) and natural disturbances (e.g. climatic extremes) is necessary because these events can shift the SES to another level.

5. Conclusions

Tibet is a unique case for SES because of its fragile environment and grazing-dependent livelihood. As expected, each measure of the socioeconomic system or the environmental conditions differed from each other over time and across the landscapes. However, these differences may sometimes yield a similar ratio between the elements of socioeconomic variables and the environmental characteristics. A key lesson from this study is that climatic extremes and policy shifts can tip the balance between the socioeconomic and environmental changes. While climatic extremes produced immediate effects on SES dynamics and lasted a few years, policy development may have caused profound long-term consequences. The positive effects from policies on the socioeconomic measures and ecological functions are apparent. Our study, however, is based only on historical data. With rapid economic and technological advancements, high population growth, and dramatic urbanization, unforeseeable outcomes may arise in the future.

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References

Alberi M A et al 2011 Research on coupled human and natural systems (CHANS): approach, challenges, and strategies Bull. Ecol. Soc. Am. 92 218–28

Adams W M et al 2004 Biodiversity conservation and the eradication of poverty Science 306 1146–9

Allington G, Fernández-Giménez R H M, Chen J and Brown D G Combining participatory scenario planning and systems modeling to identify drivers of future sustainability on the Mongolian Plateau Ecol. Soc. submitted

Arrow K 1996 Overview Rights to Nature: Ecological, Economic, Cultural, and Political Principles of Institutions for the Environment ed S S Hanna et al (Washington, DC: Island Press) pp viii–xv

Cao H et al 2015 Grazing intensifies degradation of a Tibetan Plateau alpine meadow through plant-pest interaction Ecol. Evol. 5 2478–86

Cao S X, Zhong B L, Yue H, Zeng H and Zeng J H 2009 Development and testing of a sustainable environmental restoration policy on eradicating the poverty trap in China’s Changing county Proc. Natl Acad. Sci. USA 106 10712–6

Cao S X, Tian T, Chen L, Dong X, Yu X X and Wang G 2010 Damage caused to the environment by reforestation policy in arid and semi-arid areas of China Ambio. 39 279–83

Chen J Q 2015 Editorial: Coupled human and natural system BioScience 65 539

Chen J Q et al 2015a Policy shifts influence the functional changes of the CNH systems on the Mongolian plateau Environ. Res. Lett. 10 085003

Chen J Q et al 2015b Divergences of two coupled human and natural systems on the Mongolian Plateau BioScience 65 599–70

Chen J Q and Liu Y Q 2014 Coupled natural and human systems: a landscape ecology perspective Landscape Ecol. 29 1641–41

Dallmeier A and Clausen M 2011 The influence of land cover change in the Asian monsoon region on present-day and mid-Holocene climate Biogeosciences 8 1499–319

Fan Y, Chen J, Shirkey G, John R, Wu R, Park H and Shao C 2016 Applications of structural equation modeling (SEM) in ecological research: an updated review Ecol. Process 5 19

Geldmann J, Joppa L N. and Burgess N D 2014 Mapping change in human pressure globally on land and within protected areas Conserv. Biol. 28 1604–16

Grace J B, Anderson T M, Olff H and Scheiner S M 2010 On the specification of structural equation models for ecological systems Ecol. Monogr. 80 67–87

Hansen J, Rudoy R, Sato M and Lo K 2010 Global surface temperature change Rev. Geophys. 48 RG4004

Horowitz S and Yu P 2014 Holding China in balance: explaining CCP strategies of rule in Tibet and Xinjiang J. Chinese Polit. Sci. 20 451–75

Hu Y G et al 2016 The temperature sensitivity of ecosystem respiration to climate change in an alpine meadow on the Tibetan plateau: a reciprocal translocation experiment Agric. Forest Meteorol. 216 93–104

John R et al 2016 Differentiating anthropogenic modification and precipitation-driven change on vegetation productivity on the Mongolian plateau Landscape Ecol. 31 547–66

Jøreskog K G 1973 Analysis of covariance structures Multivariate Analysis III ed P R Krishnaiah (NY: Academic)
