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Review

Socio-ecological Interactions in a Changing Climate: A Review of the Mongolian Pastoral System

Kaoru Kakinuma [1,*], Aki Yanagawa [2], Takehiro Sasaki [3], Mukund Palat Rao [4,5] and Shinjiro Kanae [6]

1 Asian Demographic Research Institute, Shanghai University, No. 333 Nanchen Road, Baoshan District, Shanghai 200444, China
2 Environmental Systems and Engineering, School of Science and Engineering, Meisei University, 29-1006, 2-1-1 Hodokubo, Hino, Tokyo 191-8506, Japan; aki.yanagawa@meisei-u.ac.jp
3 Graduate School of Environment and Information Sciences, Yokohama National University, 79-7 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan; sasaki-takehiro-kw@ynu.ac.jp
4 Tree Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA; mukund@ldeo.columbia.edu
5 Department of Earth and Environmental Science, Columbia University, New York, NY 10027, USA
6 School of Environment and Society, Tokyo Institute of Technology, 2-12-1-M1-6 O-okayama, Meguro-ku, Tokyo 152-8552, Japan; kanae@cv.titech.ac.jp
* Correspondence: k.kakinuma0214@gmail.com

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Abstract: Coping with climate change in socio-ecological systems is one of the most urgent issues facing the world. This is particularly true in socio-ecological systems, where climate not only influences social and ecosystem dynamics, but also modulates their interaction. In this paper, we presented a conceptual framework through a literature review and a trend analysis for assessing the impact of climate change that incorporates socio-ecological interactions. In particular, we focused on the Mongolian pastoral system, which has tightly coupled socio-ecological interactions, as a model for describing the framework. Our framework suggests that the flexibility in mobility of herders is the principal factor in determining the vulnerability of the socio-ecological system to climate change. The flexibility varies along a climatic gradient and socio-ecological interactions in each region have evolved to be suited to its local climate regime. Herders in northern and central regions of Mongolia move shorter distances, and less flexible, than those in southern (Gobi) region. Climatic hazards, on the other hand have been increasing across Mongolia with a trend toward warmer and drier conditions since the 1960s. We suggest that further warming and drying would have the greatest impact on northern and central regions due to lower flexibility in mobility among herders there coupled with the much higher livestock density in the regions. The findings support that maintaining flexibility of mobile herding will likely be crucial to reducing the vulnerability of the Mongolian pastoral system to climate change.

Keywords: drought; exposure; flexibility; hazard; pastoralism; vulnerability

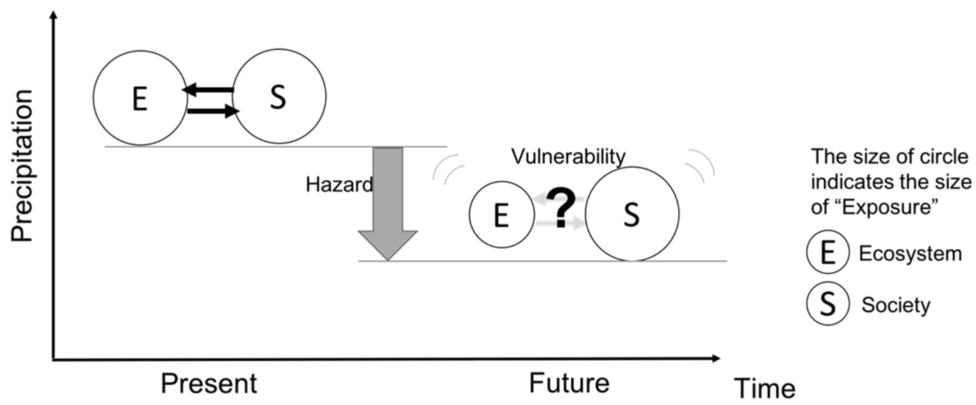
1. Introduction

Climate change represents one of the gravest threats to the world. Clear assessments of how climate change impacts ecosystems and society are crucial for effective adaptation and mitigation [1,2]. Most scientific studies typically examine the impact of climate change on either ecosystems or society, treating the two systems independently. However, in certain regions, the social and environmental systems themselves are tightly coupled [3–6]. This is especially true in the drylands of developing countries, where livelihoods are largely dependent on natural resources [5,7]. In such regions, thorough assessments of climate change, related impacts on socio-ecological systems are necessary to maintain a sustainable relationship between society and ecosystem.

The outcome of socio-ecological interactions in a changing climate may be complex [3,6]. Rangelands have been greatly influenced by political and social changes, such as the introduction of the market economy, land privatization and expansion of agriculture [8,9]. Such conditions often drive the systems to be more susceptible to climate change [8]. The objective of this paper is to propose a framework for assessing the impact of climate change from the perspective of socio-ecological interactions (Figure 1). We used the Mongolian pastoral system as a model for describing this framework because of the unique close interconnectedness between pastoral societies and their ecosystem in Mongolia.

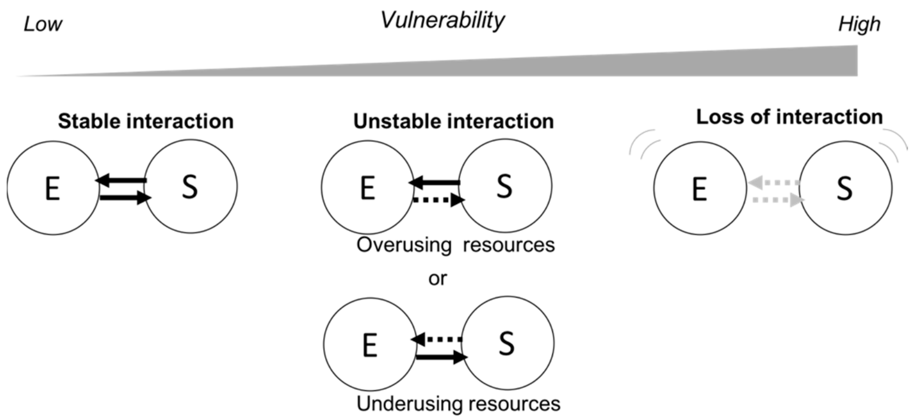
2. Framework for Assessing the Impact of Climate Change on Socio-Ecological Systems

The impact of climate change is often quantified by the contribution and interaction between three primary components: hazard, exposure and vulnerability [1]. Within this three-component interactive framework, physical climatic conditions generally constitute the hazard. The exposure means presence of population, species and assets in places that could be adversely affected [1]. The vulnerability of society to the hazard corresponds to the vulnerability construct. Based on the Intergovernmental Panel on Climate Change (IPCC)'s framework, we introduced a new framework that explicitly incorporates socio-ecological interactions (Figure 1). Future climate change, such as decreased precipitation, may change the ecosystem state (E), for example by reducing ecosystem productivity, and society (S) must adapt to new climatic and ecosystem conditions (Figure 1a). Thus, the degree of vulnerability is determined by the flexibility of the society (S) to adapt to a new interaction state with the ecosystem (E) in the future state (Figure 1b). If the society is not flexible and is unable to establish a stable interaction regime with the new ecosystem, such as continued maintenance of high livestock numbers in less productive grassland during drought, the system will become vulnerable through the overuse of grassland. If the interaction between society and the ecosystem is diminished due to these unstable conditions, such as irreversible land degradation, the system will become highly vulnerable to collapse. In such a situation, many herders would be unable to keep their livestock, and eventually would give up being herders. Climate change would amplify the risk of such poverty or conflict in the situation. Therefore, society's flexible and rapid response to new ecosystem conditions under climate change is key to reducing this vulnerability.



(**a**) Interactions between society and ecosystem in a changing climate

Figure 1. *Cont.*



(**b**) Vulnerability of a socio-ecological system

Figure 1. Framework for assessing socio-ecological interactions under a changing climate. (**a**) Interactions between society and ecosystem in a changing climate. The size of the circle indicates the degree of exposure, which depends on the number of population, species or assets that would be affected by hazard. (**b**) Vulnerability of a socio-ecological system. The black arrows mean that the society (ecosystem) has a strong connection with the ecosystem (society). The dashed black arrows indicate a weak connection, and the gray dashed arrows indicate the loss of a connection. Combinations of arrows determine the strengths of the interactions and vulnerability of the social-ecological system.

3. Study Site

Mongolia, a country located in north-east Asia, represents a coupled socio-ecological system [4,10,11]. Over 70% of Mongolian land is used by agriculture, largely in the form of nomadic pastoralism, which attempts to maximize both temporally and spatially scarce and variable vegetation resources [12,13]. Nomadism has proven to be a sustainable way of life in Mongolia for multiple millennia [14,15]. Importantly, both the Mongolian economy and livelihood herders depend on the natural resources of the ecosystem. In addition, Mongolia has a strong latitudinal climatic gradient, with the northern regions being wetter than the southern Gobi region, and also being characterized by a more stable precipitation regime (Figure 2a, Supplementary Materials Figure S1). Winter temperature also varied along the latitude, with northern regions being colder than the southern region (Figure 2b, Figure S2). Thus, an opportunity exists to examine the relationship between ecosystem and society along a climatic gradient. We divided the country into five regions based on environmental characteristics (Figure 2c). Mean annual precipitation in northern, central, Gobi, eastern and western regions are 31, 22, 12, 22 and 19 mm/month, respectively.

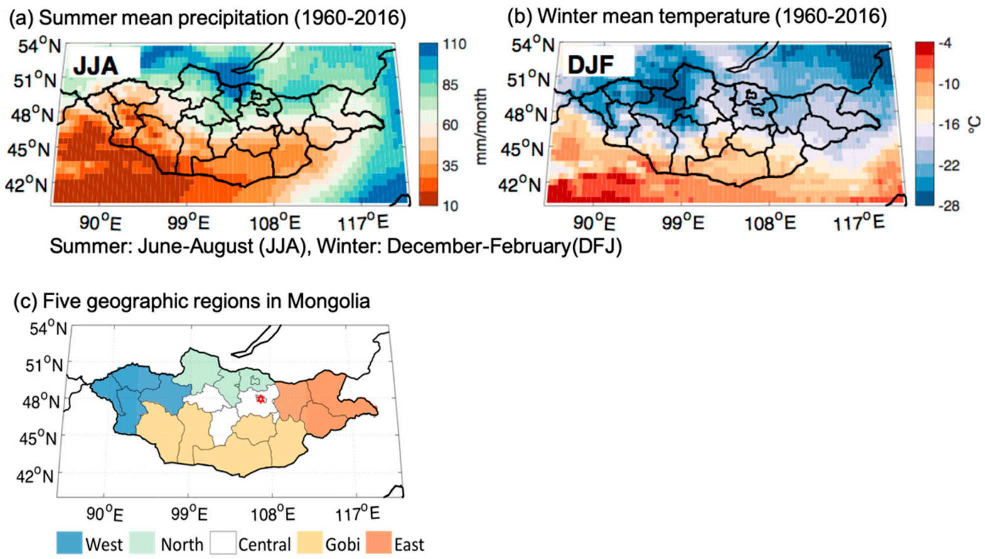


Figure 2. (**a**) Summer mean precipitation between 1960–2016 (**b**) Winter mean temperature between 1960–2016. (**c**) Five geographic regions in Mongolia. The red star indicates the location of Ulaanbaatar, the capital city of Mongolia.

The main vegetation types differ among regions: mountain forest steppe in the northern region, mountain steppe in the western region, steppe in the central and eastern regions and desert steppe in the Gobi region (Figure 3). Grasslands in Mongolia are mainly dominated by perennial grasses, forbs or shrubs [16]. Covers of shrubs are relatively large in desert steppe, and some tree species can be found in mountain forest steppe [16]. Diversity of plant species is higher in the mountain steppe than in the steppe and desert steppe [17].

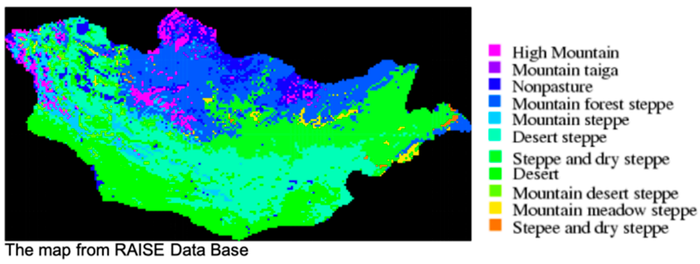


Figure 3. Vegetation map in Mongolia. The map is from the Rangelands Atmosphere-Hydrosphere-Biosphere Interaction Study Experiment in Northeastern Asia (RAISE) Data Base http://raise.suiri.tsukuba.ac.jp/DVD/top/map.htm.

4. Materials and Methods

We first conducted a literature review to describe flexibility of mobile herds along a climate gradient that may relate with socio-ecological vulnerability to climate change (Figure 1). Then, we conducted a literature review and trend analysis to detect trends in climate (hazard), livestock population (exposure) and vegetation (ecosystem). We used the Thomson ISI Web of Science database to identify primary literature sources. We searched using the key words 'trend' and 'Mongolia' and 'climate' or 'vegetation' or 'livestock'. We selected papers focusing on Mongolia (not Inner Mongolia). To describe pastoral mobility, we searched using the key words "herder" and "mobility" and "Mongolia", but this returned few results. Therefore, we utilized other methods to collect relevant references.

For hazard trends, we focused on temperature, precipitation and drought index (scPDSI – Palmer Drought Severity Index). To compute mean temperature and precipitation, and trends in these variables, we used the University of East Anglia's Climate Research Unit's (CRU) Ts v4.01

dataset [18], while for the scPDSI analysis we used the van der Schrier et al. (2013) dataset [19]. Both datasets are globally gridded at a 0.5° spatial resolution and cover the period between 1901 and 2016. The datasets are publicly accessible at CRU: https://crudata.uea.ac.uk/cru/data/hrg/ and scPDSI: https://crudata.uea.ac.uk/cru/data/drought/.

To analyze trends in vegetation, we used the Normalized Difference Vegetation Index (NDVI), as derived from satellite images. The NDVI dataset is part of the global 15-day University of Maryland Global Inventory Monitoring and Modeling System (GIMMS) NDVI 3g.v1 dataset, comprising data for the period 1981–2016 [20,21], and is accessible at https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/. The data are derived from a series of images collected from different National Oceanic and Atmospheric Administration (NOAA) satellites over the period 1981–2015, and have been corrected for calibration, geometrical view, volcanic aerosols (e.g., from El Chichon [1982–1984] and Mt. Pinatubo [1991–1993]) and other effects that are not related to vegetation change, such as cloud cover. The data are available in a 0.0727° × 0.0727° grid format [18,19]. We computed trends in both the climate and NDVI data on a grid-cell-by-grid-cell basis, by first calculating the seasonal means, and then, for each grid-cell, building a linear model and comparing the p-value of its F-statistic against that of a constant model.

5. Society: Pastoral mobility, Flexibility and Their Trends along a Climatic Gradient

Pastoral mobility, or the movement of people together with their livestock, is well adapted to its climate and grassland ecosystem, and its pattern and flexibility vary along a climatic gradient (Table 1; Figure 4). Patterns of mobility were categorized into six types according to geophysical characteristics by the Russian researcher Simukov in 1932 (Table 1) [22–24]. Simukov's classification is adequate for understanding herder mobility in present-day Mongolia, and many features, such as seasonal movement, have been retained since 1932 [23,24]. There are two main forms of mobility practiced: the Khangai type and the Gobi type. The mobility type of herders in high and stable precipitation regions of Mongolia, such as the northern region, is known as the Khangai type. In northern regions, the productivity of pastures is both high and stable, such that herders only need to migrate short distances, and with low frequency. The diameter of the annual movement cycle in such cases is small, typically being around 7–8 km [23]. In some cases, the summer and winter camps are separated by as little as 2–3 km [23]. On the other hand, in the Gobi type of mobility, seen in the desert steppe Gobi region (which experiences low, but also highly variable, pasture productivity), herders tend to travel considerably longer distances, and with greater frequency, especially during drought periods, compared to their Khangai-type mobility counterparts (Figure 4) [23,25]. Long-distance movement is a common strategy to mitigate the effect of drought, as it provides a means by which herders can efficiently forage for resources even under conditions of scarce vegetation. During a drought, herders and herds often migrate 150–200 km from their usual camps in search of good pasture [23,24]. Thus, pastoral mobility types are largely influenced by climatic and ecological conditions; in drier environments, herders tend to have to move more frequently and travel longer distances (Figure 4). Therefore, climate change-related increases in drought frequency or intensity will have large impacts on herders' mobility.

Climate factors affect not only mobility patterns, but also its flexibility through social reciprocity among herders [26–28]. Herders are likely to develop cooperative rangeland management strategies to maintain flexibility of mobile herding [26,28]. Herders tend to accept herders from other villages/prefectures that are experiencing drought conditions. The flexibility enables herders to use alternative rangeland during drought. The Gobi region is characterized by drought-adapted pastoral systems, with reciprocity occurring among herders and showing high flexibility (Figure 4) [27,28]. On the other hand, in stable environments such as northern and central regions, herders are more likely to develop more exclusive management strategies [26]. Such herders do not need to maintain flexibility because they already have them in their possession. In order to maximize their livestock number, cooperation level among herders may become low. Herders in northern and central regions move shorter distances (Table 1), employ more exclusive management strategies and have overall less flexibility (Figure 4). This diversity in rangeland management strategies has evolved based on historical climatic conditions; however, the responses of these different management strategies (exclusive versus cooperative) or the flexibility of mobile herding to future climate change (e.g., increased drought intensity) remains to be seen.

Socio-economic factors have also influenced mobility patterns across Mongolia. Under socialism (1970–1990), the Mongolian government established collectives in which groups of herders moved together; the government determined the direction and timing of these migrations. Thus, the mobility distances were relatively shorter during the period of socialism [22]. Furthermore, the distributions of livestock and herders were managed, and services such as shelters, forage and wells were provided by the government during this period. After the collapse of socialism in 1990, the collective herding system was dissolved, and livestock ownership privatized. The number of livestock has increased after the collapse of socialism (see also 7. Exposure: Changes in Population and Livestock Distributions). Now, herders must decide on the timing and patterns of their migrations independently. Some herders have found it difficult to enter into long-distance migrations, '*otor*' in Mongolian, because of the lack of state support [28,29]. Consequently, the economic conditions of herders can affect their mobility patterns, with economically rich herders being able to travel longer distances and having greater access to vegetation resources than less wealthy herders [30,31]. Therefore, there has been an overall decline in mobility [22], and mobility types have showed greater variety, due to changes in herder economic conditions since 1990.

Table 1. Herder migration distances by region.

Region (See Figure 2c)	Moblie Pattern (Simukov Category)	Annual Movement
Northern	Khangai	7–8 km
Central	Steppe	30–50 km
Western	Western	100 km
Eastern	Eastern	100 km
Gobi	Gobi	250 km
	Ovorkhangai	150–200 km

Data from Honeychurch (2015b) [24]. The Ovorkhangai migratory pattern, seen in the southwestern Khangai Mountains of Mongolia. This region corresponds to the Gobi region investigated in this study. Herders move across distances of 150–200 km to use summer streams and meadows in the upper Khangai Range, and the warmer winter pastures in the lower-altitude Gobi region [24].

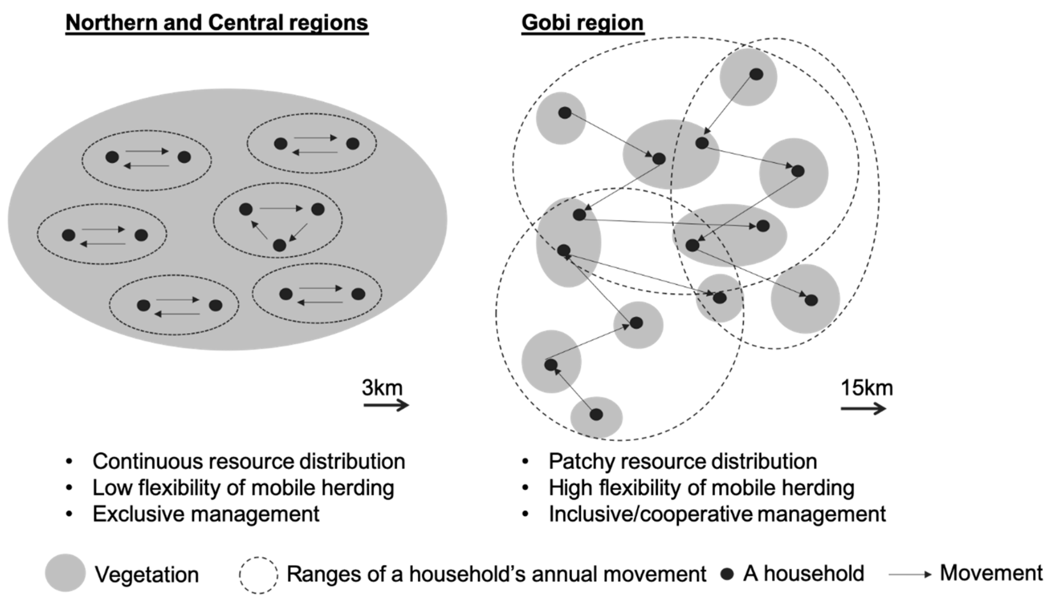


Figure 4. Herder movement types by region.

Herders in the northern and central regions of Mongolia move shorter distances, and less frequently, than those in the Gobi region (Table 1). Thus, the migration range is smaller each year and exclusive management strategies are likely to ensue. In contrast, herders in the Gobi region move larger distances, and with greater frequency. Consequently, they have a larger range that often overlaps with those of other herders, especially during periods of drought. High flexibility is maintained by social reciprocity between herders [26,28]. Thus, the borders of their ranges may be unclear, and inclusive/cooperative rangeland management strategies are favored.

6. Hazard: Climate Trends in Mongolia

Climate trends in temperature and precipitation for the period 1960–2016 across the five regions of Mongolia are shown in Figure 5 and summarized in Supplementary Materials Table S1. Temperature shows a consistent increasing trend ($p < 0.05$) across the entire country, and across all seasons with the exception of winter (Figure 5a, Figures S3 and S4; see Methods for details). Our findings are consistent with previous assessments based on 48 Mongolian meteorological stations, which showed a 2.14 °C increase in mean annual temperature over the last 70 years [32] (IGES 2012), and with other studies showing that annual temperature in all regions (i.e., northern, central, Gobi, eastern and western regions) have increased significantly over the last 30 years [32–35]. In addition to observational data, tree-ring derived reconstructions of summer temperatures over the past millennium also suggest that temperature in the northern region has increased rapidly since the 1900s, and that this increase might be unprecedented in the context of the previous millennium [36–38].

While temperature shows a significant positive trend across Mongolia, precipitation trends are more spatially heterogeneous (Figure 5b). Our analysis shows that summer precipitation has significantly decreased in the northern and central regions of Mongolia since 1960 (Figure 5b). Winter precipitation has increased slightly in the eastern region, while seasonal precipitation levels have remained constant in the Gobi and western regions (Figure S4). However, considering precipitation seasonality, which peaks in the summer (Figure S1), the decrease in summer precipitation is of a greater magnitude than the small increase seen in winter precipitation (Figure S4). We did not detect any significant trends in annual precipitation across Mongolia for the period 1960–2016. These results agree with studies by [39,40], which evaluated mean annual precipitation in Mongolia between the 1980s and 2015 and found no significant trends. Some studies have suggested that annual precipitation has slightly decreased across Mongolia [27,33,41–43]. However, these studies examined data from the 1980s to 2000s, a period during which precipitation was decreasing. Mongolia experienced a positive trend in annual precipitation between 2000 and 2015 [40]. These negative trends in annual precipitation between 1980 and 2000, and the positive trends between 2000 and 2015, may mask trends in annual precipitation across Mongolia during the overall study period (1960–2016).

We examined the trend in drought severity by using the scPDSI (self-calibrating Palmer Drought Severity Index) [19]. The mean summer (June–August; JJA) scPDSI showed a significant negative trend for the central, Gobi and eastern regions since 1960 ($p < 0.01$), suggesting that drought intensity is increasing in these regions (Figure 5c). Tree-ring-reconstructed PDSI suggested that the drought period of 1996–2011 was one of the most severe over the past millennium [44–46]. This drought was characterized by elevated temperatures and reduced precipitation relative to the last 400–900 years [44,45]. Further increases in temperature might lead to increased drought risk [35,44] and severe consequences for both society and the ecosystem (e.g., [47]).

We conclude that the climate in Mongolia has become hotter and drier since the 1960s. This change is most apparent in the summer months (June-July-August or JJA). In addition to gradual climate changes, the intensity of drought has also increased in the central, Gobi and eastern regions of Mongolia. While we found significant warming and drying trends for summer climate, we identified no such trends in winter temperatures or precipitation across Mongolia since 1960.

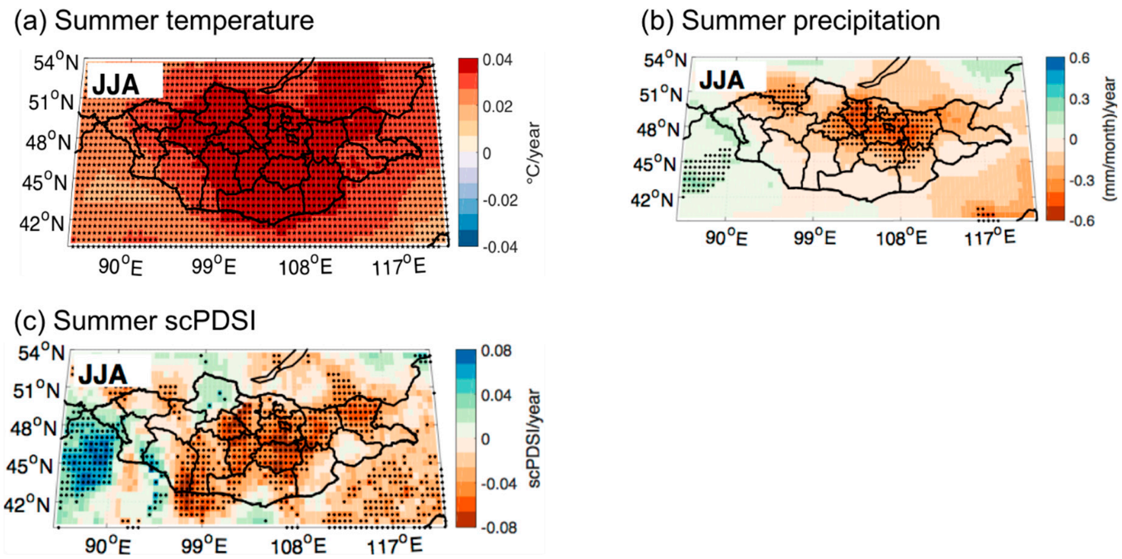


Figure 5. Climate trends between 1960 and 2016 in Mongolia for mean June-July-August (JJA): (**a**) summer temperature, (**b**) summer precipitation, (**c**) summer self-calibrating Palmer Drought Severity Index (scPDSI). Stippling indicates regions where the F-test on the regression model compared to constant model had a p-value of <0.05.

7. Exposure: Changes in Population and Livestock Distributions

We focus on the spatial and temporal distributions of the Mongolian population and livestock numbers to examine trends in the exposure parameter. Livestock increased considerably in number and variety following the collapse of socialism in 1990 [13,40]. Livestock types are mainly sheep, goat, horse, cattle and camel. During the pre-1990 Soviet era, the government owned all livestock. After the introduction of capitalism in 1990, livestock ownership was privatized to individual herders. This prompted a great increase in the total livestock population size (Figure 6a). However, this increase in post-1990 livestock population size has been punctuated by large downturns, occurring in 2000–2001 and 2009–2010 [13]. Such livestock mortality events are known as "*dzuds*", which translates to "winter disaster causing livestock mortality". *Dzuds* are caused by both social and environmental factors [48,49]. The climatic variables most relevant to *dzuds* are cold winter temperatures and summer drought [50], and livestock mortality is associated with snowfall in winter and vegetation conditions in the previous summer [51]. Especially, drought conditions caused reduction of livestock weight, and livestock may not overcome the severe winter after the drought [52]. In addition to these physical factors, socio-economic factors such as regional poverty, weakened collective actions, loss of traditional knowledge and limited numbers of cross-level institutions may lead to poor pasture and animal conditions. Lack of coordinated pasture management and winter preparations may trigger and exacerbate *dzud* impacts [48,53]. Although the frequency of *dzuds* has increased since 1950 [48,49], so too has the number of livestock. Currently, the livestock population in Mongolia is approximately 61 million heads, which is the highest level since livestock census surveys began in 1950, and likely the highest it has ever been (Figure 6a) [13].

The central region of Mongolia contains the highest density of livestock (goat and sheep), measured as the number of livestock per square kilometer (Figure 6b). This distribution relates to the location of cities and access to the road networks. The three biggest cities in Mongolia, the capital Ulaanbaatar, and two other major cities, Eldenet and Orhon, are located in the central region. The accessibility of markets in these cities makes this region attractive to herders desiring to sell their livestock (meat, milk, skin, etc.). These socio-economic advantages help explain why livestock populations and herders are concentrated around big cities.

The number of herders relative to the rest of the population has been gradually decreasing since the 1990s, despite the increase in the total Mongolian population (Figure S5). About 26% of the population is currently a herder, while about 69% of the population lives in urban settlements, primarily in Ulaanbaatar [13]. Although the number of herders has decreased, the total number of livestock in the country has increased. Previous studies report that economically poor herders, who tend to have smaller herd sizes, find it harder to recover their losses compared to richer herders, who tend to have larger herds [54,55]. It is likely that the disparity between the rich and poor herders has increased with the introduction of the free market [22,56].

Livestock numbers have increased since 1970 (Figure 6a), especially in northern and central regions. This increase relates to socio-economic factors, such as easier access to roads and transportation [57], and environmental factors, such as access to better quality rangelands [48,49]. However, it remains unclear why the frequency of *dzuds* has been increasing since 1950 [49], and how climate trends will affect the frequency and intensity of *dzuds*. To clarify the impact of climate on livestock populations, studies should explore the complex interactions among climate, ecosystem, livestock and society.

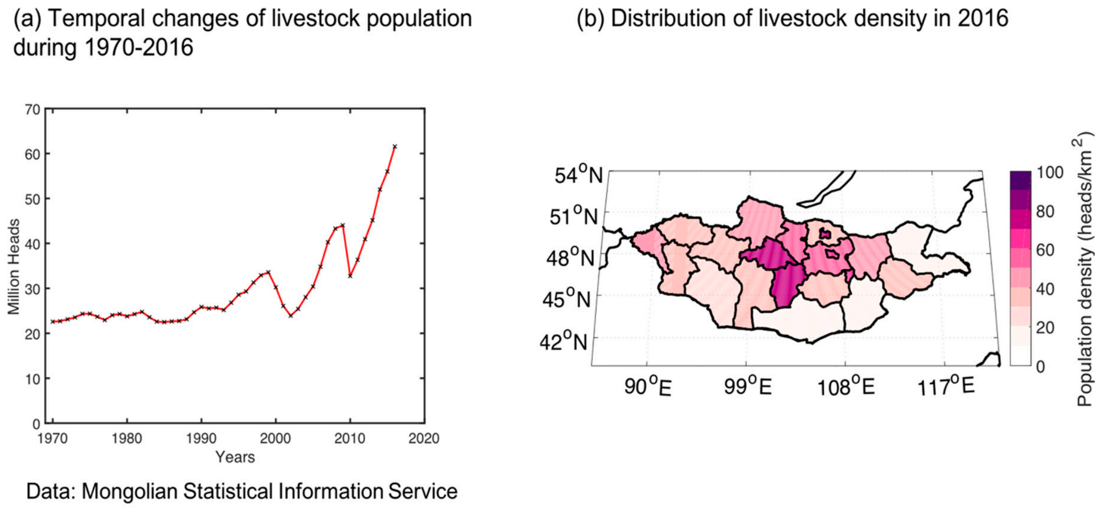


Figure 6. Temporal changes and spatial distribution of livestock population.

8. Ecosystem: Vegetation Trends along a Climatic Gradient

8.1. Regional and Country Level

While hazard and exposure trends have increased significantly, vegetation trends are unclear. Several studies have examined vegetation trends at the country and regional levels using satellite imagery (e.g., [34,40,42,58–60]). At the country level, no significant trends in vegetation resources were observed between 1982 and 2012 [34,42,58], when using the NDVI [61]. There is no consensus regarding regional trends between 1982 and 2012 [34,40]. Our analysis revealed a significant increasing trend in NDVI at the country scale ($p < 0.01$), and for the eastern region ($p < 0.05$), between 1982 and 2015 (Figure 7). However, the more recent increase in NDVI between 2010 and 2015 may have influenced the results. We did not detect a significant trend in NDVI for the northern, central, Gobi or western regions between 1985 and 2015 (Figure 7).

The NDVI in Mongolia is well-correlated with climatic factors [34,42,59,62]. Annual precipitation, summer precipitation and NDVI exhibit a strong positive correlation in all vegetation types, whereas annual mean temperature and NDVI do not correlate, except in the case of forest-steppe vegetation [34,42,59,62]. Across most vegetation types (meadow, steppe, desert steppe) there is a positive correlation between summer/annual precipitation and NDVI [34,42]; only in the forest-steppe, which is mainly distributed in the northern region, has a negative correlation between summer precipitation and NDVI has been observed [34]. In contrast to Bao et al. [34], Hilker et al. [59] suggested that only densely vegetated areas (mean NDVI > 0.60: forest steppe) show a significant positive relationship between NDVI and precipitation anomalies. Although there is little consensus regarding the interactions among different vegetation types, precipitation and NDVI, it is clear that precipitation and NDVI are positively correlated, and that temperature changes play only a minor role in explaining NDVI trends across Mongolia (e.g., [34,42,59,62]). Future studies will be necessary to clarify the mechanism underlying vegetation trends. Currently, the cause and effect relationship between climate and vegetation is unclear. To understand this complex interaction, future studies should combine satellite imagery analysis with observational field experiments, to evaluate the relationships among precipitation, temperature and plant species composition and abundance.

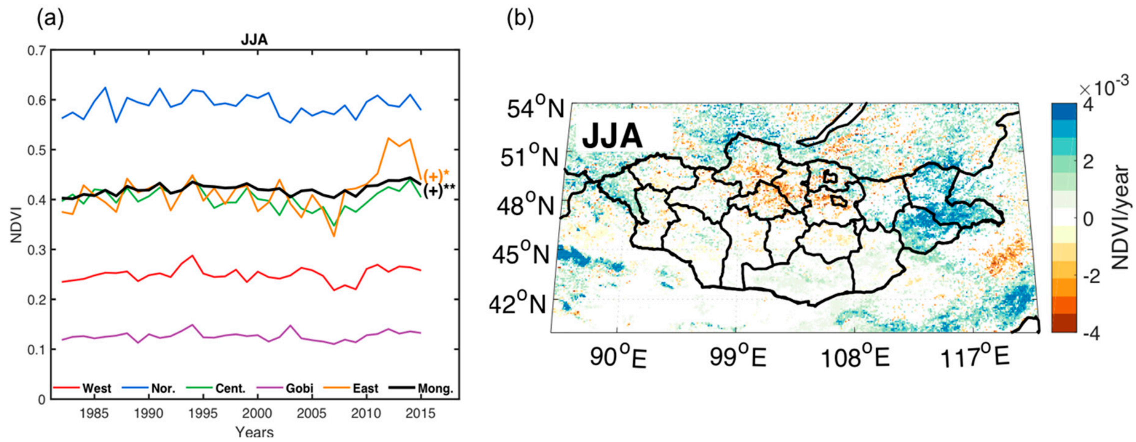


Figure 7. Trends in Normalized Difference Vegetation Index (NDVI) (June–August) between 1982–2015 (**a**) trends averaged across the five spatial regions (West—red, North—blue, Central—green, Gobi—purple and Eastern Mongolia—orange) and across all of Mongolia (in black) (**b**) and spatially across the Mongolian domain.

8.2. Community Level Analysis

Relatively few studies have examined long-term trends in plant species and abundance at a community scale, but those that have done so suggest that the plant aboveground biomass and the number of plant species have declined across various regions of Mongolia [39,63–66]. Nandintsetseg et al. [64] used time series field data to show that the plant aboveground biomass significantly decreased (by 10.8 g/m^2) across regions of Mongolia during the period 1974–2010. They suggested that drought during the plant-growing season (April–August) reduced pasture production. In a monitoring study, Sheehy and Damiran [63] suggested that species richness and plant production declined between 1997 and 2008 in the north, central, Gobi and western regions. Khishigbayar et al. [39] reported that species richness has declined, while plant biomass and cover have remained steady or even increased, between 1995 and 2013 in mountain-steppe, steppe and desert-steppe habitats. National report on the rangeland heath of Mongolia [67] showed that grasslands in Arhangai, Tuv prefectures (Central region), Selenge prefecture (North region) and Dundgobi prefecture (South region) has been shifted to higher degradation level during 2014-2016.

Several field experiments have suggested that climate change may affect plant species composition, phenology and growth in Mongolia (e.g., [68–71]). Spence et al. [71] showed that an increase of precipitation enhanced forb biomass and species richness in the northern region. In contrast, the interaction of increased temperature and grazing has reduced the richness of flowering plant species in this region [70]. Shinoda et al. [72] conducted a drought experiment in the central region and showed that drought drastically reduced aboveground biomass, and that some species did not recover after exposure to drought conditions. Such changes in plant communities and their phenology may negatively impact the persistence and functioning of grassland ecosystems in the face of ongoing environmental changes.

These field studies were based on short-term data and provide only a snapshot compared to multi-decadal datasets. To accurately determine climate change-induced fluctuations, as well as trends in vegetation resources and phenology at a regional scale, it is critical to gather data for extended periods, as this allows for a wider range of climatic cycles and patterns to be analyzed. While studies on plant abundance and diversity in Mongolia are sparse, it appears that overall species richness has declined [39,63]. It is therefore urgent that we continue to monitor trends in plant species across Mongolia, to understand climate change impacts.

The vegetation response to climate change is complex, where vegetation dynamics are influenced by both biotic and abiotic factors [72]. It is well recognized that external disturbances (particularly livestock grazing) cause vegetation composition to change abruptly from perennial grasses and forbs to unpalatable forbs and weedy annuals [73]. Such nonlinear vegetation responses can generally be observed from northern to southern Mongolia. The nonlinear vegetation changes that result from livestock grazing directly impact crop nutritional value and herbage yield, which has direct implications for human activities [74]. We consider it likely that plant communities would also respond to climate change in a nonlinear fashion (e.g., [75]). Previous studies have suggested that variability in rainfall patterns greatly impact vegetation biomass and cover across the region [76,77]. Ecological modeling studies also suggested that plant communities in dry environments are especially vulnerable to grazing in Mongolia [78].

It is essential that future studies examine how facets of climate change, such as increasing temperature and decreasing precipitation, affect interactions between plants and livestock grazing. Prior studies have suggested that reduced biodiversity increases vulnerability to extreme climatic events (e.g., [79,80]). In that sense, any reduction in plant species richness due to heavy livestock grazing (e.g., [81]) may negatively impact ecosystem function and increase ecosystem vulnerability. To clarify these dynamics, a long-term dataset for climate, vegetation, livestock and human migration is needed. Improving collection of these data using field survey methods is also important. Statistical analyses, such as convergent cross-mapping, a time series analysis tool to identify cause-and-effect relationships [82], may be useful to examine complex interactions once a long-term dataset becomes available.

9. Climate Change Impacts on the Socio-Ecological System in Mongolia

Pastoral mobility historically has been variable across regions with socio-ecological (pastoral society and grassland ecosystem) interactions traditionally being stable and adapted to the local certain climate regime (Figures 4 and 8). On the other hand, climatic hazards are increasing across Mongolia with a trend toward warmer and drier conditions since the 1960s (Figure 5), which may affect the socio-ecological interaction especially in Northern and Central regions (Figure 8). Flexibility of mobile herding has traditionally been maintained in Gobi region in response to scarce and variable vegetation resources during drought, while it is less flexible in North and Central regions (Figure 4, Table 1). A continuation of hotter and drier trends would have the greatest impact on northern and central regions due to their less flexibility because it is difficult to use alternative grassland during drought. The exclusive management system that characterizes the northern and central regions relies on stable precipitation patterns to maximize livestock numbers. However, the climate trend is most prominent in the central region, wherein the summer temperature has increased (Figure 5a), while summer precipitation for JJA has decreased by ~17.74 mm (Figure 5b) and drought severity has increased since 1960 (Figure 5c). Moreover, livestock number has rapidly increased and high density in Central and Northern regions since the 1990s (Figure 6). That means many herders may get stuck in hazardous grassland with large number of livestock during drought, and that may cause unbalance interaction between herding society and ecosystem (Figure 8). For these reasons, we suggest that social-ecological systems in the northern and central regions are more vulnerable to an increase in drought intensity. Therefore, maintaining flexibility in mobility of herders during disaster periods will be an important measure to mitigate climate change impacts especially in northern and central regions of Mongolia.

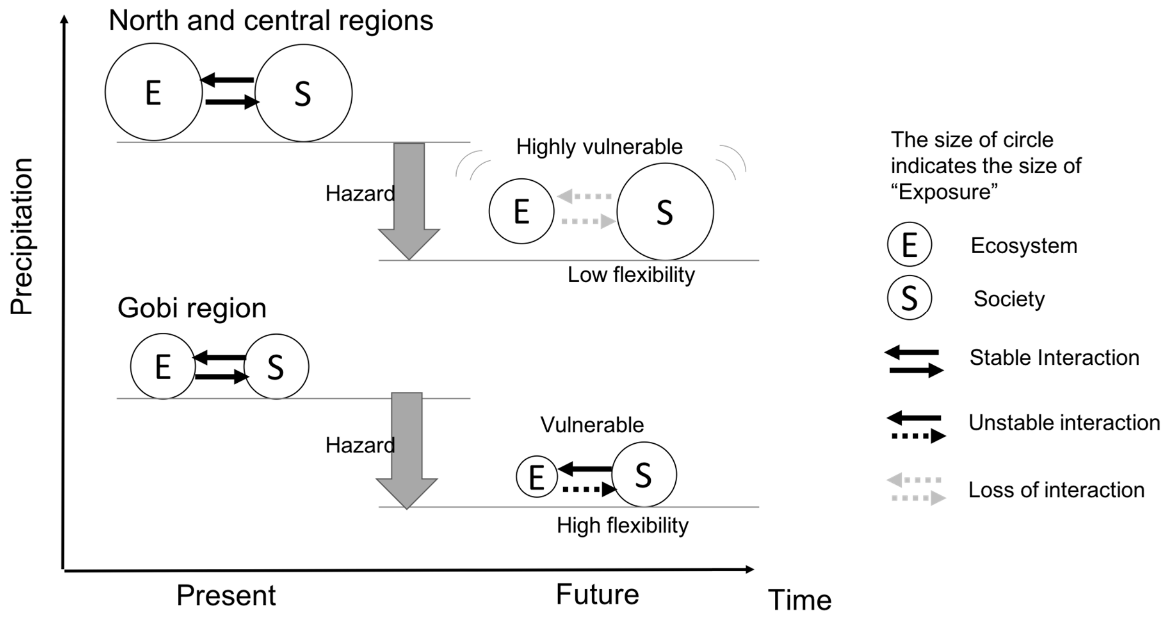


Figure 8. Impact of climate change on socio-ecological systems in Mongolia.

Low flexibility of mobile herding in northern and central regions may cause the socio-ecological system to be highly vulnerable to future climate change. The Gobi region includes high flexibility to alternative grassland during drought. If people can maintain this flexibility, it would reduce the system's vulnerability to future climate change.

While climatic hazard and exposure are increasing significantly in Mongolia, the trends in vegetation resources are not clear (Figure 7). Although some studies have attempted to examine vegetation patterns using satellite imagery, the resulting NDVI trends from 1982 to the present have been equivocal [34,42,58]. Assessment at the community level is challenging given the limited number of studies available. Although there are currently no significant clear trends for vegetation resources, temperature and drought conditions have increased significantly (Figure 5). Drier conditions may cause a reduction in vegetation and soil moisture, and that may in turn lead to an increase in dust outbreaks [83,84]. It will therefore be important for future studies to examine the effect of increased temperatures and drier conditions on the Mongolian rangeland ecosystem.

In addition to vulnerability, "resilience" also plays a role in determining the impacts of climate change [85]. Resilience is defined as the capacity of an ecosystem to resist and recover rapidly from environmental perturbations and still maintain its function [85,86]. Resilience of ecosystems can be expected to decrease from northern to southern areas in Mongolia, because biological diversity and soil quality generally decrease along this same geographical gradient. However, resilience can be modulated by the self-reinforcing mechanism of ecosystems. In plant communities in the Gobi region, for example, drought avoidance and tolerant traits would be selected for under conditions of severe aridity. Despite lower levels of biological diversity in this area, drought-adapted populations would likely show extreme tolerance (resilience) to drought stress. Studies have yet to examine the inherent variations in ecosystem resilience, or how climatic and anthropogenic factors may influence such resilience. Furthermore, we know little about how the ecological resilience of communities might mitigate the impacts of climate change, or to what extent resilience is necessary to sustain ecosystem functioning in the future. In Mongolia, efforts to understand resilience should focus on semi-arid regions, wherein drastic changes in plant communities would be a major threat to human livelihood. The northern and central regions are characterized by a large number of livestock and high plant productivity, thus, it is likely that they have relatively higher resilience to climatic hazards. In summary, future studies should consider resilience, and not just vulnerability, when evaluating regional responses to climate change.

10. Conclusions

Developing comprehensive strategies to cope with climate change is a challenging yet essential task. Human societies are tightly coupled to the ecosystem [3,5], and an understanding of the complex socio-ecological interactions is necessary to predict responses to climate change [6]. We suggest a conceptual framework that captures socio-ecological interactions to assess climate change impacts (Figure 1). We focused on the Mongolian pastoral system as a model for describing the framework. The socio-ecological system in the northern and central regions would be highly vulnerable to continued climate hazards, due to their low flexibility, which makes it difficult for herders to access alternative grassland during drought (Table 1, Figures 4 and 8). Climatic hazard is increasing, as it is getting warmer and drier across Mongolia (Figure 5). Thus, maintaining the flexibility of mobile herding will be an important strategy to mitigate climate change impacts. The framework proposed herein provides a rationale for the inclusion of socio-ecological interactions in future efforts aimed at determining the impacts of climate change, especially in regions showing tight socio-ecological coupling.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/21/5883/s1, Figure S1: Seasonal mean precipitation over Mongolia in 1960–2016, Figure S2: Seasonal mean temperature over Mongolia in 1960–2016, Figure S3: Spatial temperature trends by season in 1960–2016, Figure S4: Spatial precipitation trends by season in 1960–2016, Figure S5: The number of pastoralist and non-pastoralist households, Table S1. Summary of climate trends in each region of Mongolia in 1960–2016.

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