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To cite this article: Mukund Palat Rao *et al* 2015 *Environ. Res. Lett.* **10** 074012

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Dzuds, droughts, and livestock mortality in Mongolia

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Abstract

Recent incidences of mass livestock mortality, known as dzud, have called into question the sustainability of pastoral nomadic herding, the cornerstone of Mongolian culture. A total of 20 million head of livestock perished in the mortality events of 2000-2002, and 2009-2010. To mitigate the effects of such events on the lives of herders, international agencies such as the World Bank are taking increasing interest in developing tailored market-based solutions like index-insurance. Their ultimate success depends on understanding the historical context and underlying causes of mortality. In this paper we examine mortality in 21 Mongolian aimags (provinces) between 1955-2013 in order to explain its density independent cause(s) related to climate variability. We show that livestock mortality is most strongly linked to winter (November-February) temperatures, with incidences of mass mortality being most likely to occur because of an anomalously cold winter. Additionally, we find prior summer (July-September) drought and precipitation deficit to be an important trigger for mortality that intensifies the effect of upcoming winter temperatures on livestock. Our density independent mortality model based on winter temperature, summer drought, summer precipitation, and summer potential evapotranspiration explains 48.4% of the total variability in the mortality dataset. The Mongolian Index Based Livestock Insurance Program (IBLIP) uses a threshold of 6% mortality to trigger payouts. We find that on average for Mongolia, the probability of exceedance of 6% mortality in any given year is 26% over the 59-year period between 1955-2013.

1. Introduction

Climate and society are inextricably linked (1), for example, droughts impact agricultural productivity and lead to food shortages (2). In semi-nomadic Mongolia, the connection between climate, human, and animal populations is exceedingly clear. The land features a varying topography and an continental climate, with long and harsh cold winters, short warm summers, and low annual precipitation, most of which falls between the months of June to August (figure 1). Mongolia is vulnerable to extreme climate events, and is often affected by episodes of anomalously cold winters and droughts. Such climatic extreme events are particularly deleterious to livestock (goat, sheep, cattle, camel, horses), and often cause high mortality, and are known locally as ‘dzud’ (or ‘zud’ - зүд) (3-6). This term is unique to pastoral communities in Central Asia, and can be caused by a combination of summer drought, heavy snowfall, and high winds in concurrence with extremely low winter temperatures which combine to cause unsustainable conditions for animal survival (4). Mortality is caused by a combination of starvation because of

being unable to graze and access fodder due to heavy snow, ice or drought, freezing due to extreme cold temperature, exposure to storms and wind, and a weakened immune system response due to exposure (4, 5, 7).

Livestock numbers in Mongolia rose precipitously following the collapse of the Soviet Union in the 1990s (figure 2). This indirectly increased the vulnerability of herders and livestock to climate extremes (8, 9). Four mass mortality events have occurred since 1999 and have thrown many Mongolians into a period of great economic hardship and poverty. Three events occurred in successive years between 2000-2002. During this period livestock numbers declined drastically, from over 33 million head in 1999 to 23 million in 2003. This led many herders to migrate to urban centers and join the ranks of the urban poor (10). Recently, during the exceptionally harsh winter of 2009-2010, livestock numbers were again severely impacted, and dropped by 9.7 million animals or 20% and in some areas, herders were left without a single animal (8).

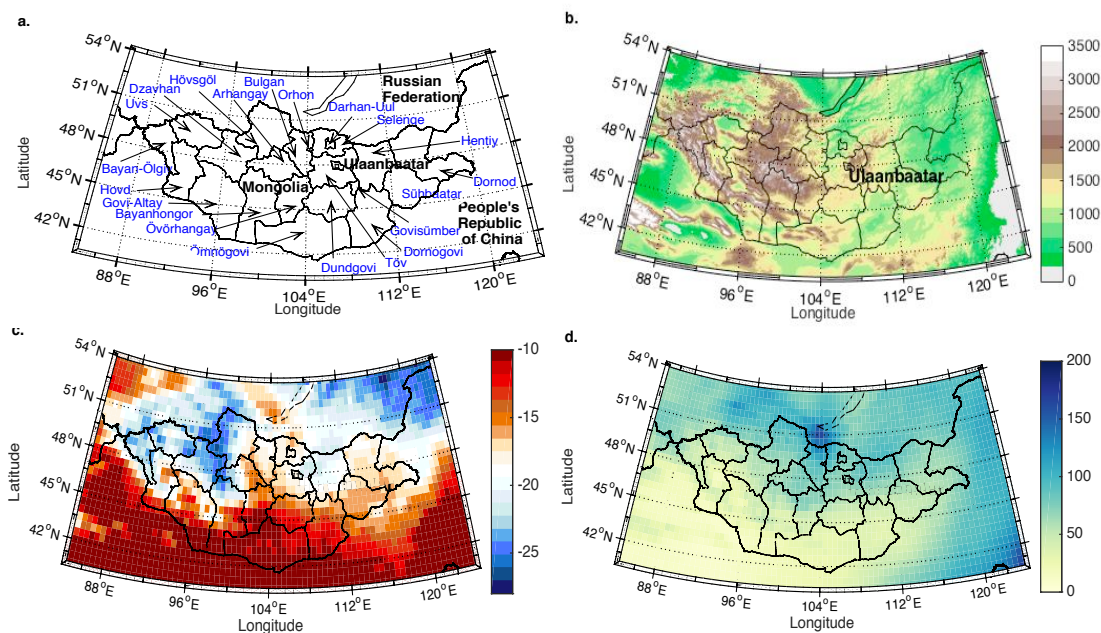


Figure 1 Map of Mongolia showing **a.** Names of aimags (provinces) **b.** Elevation (meters) **c.** November-February (ndJF) mean average monthly temperature ($^{\circ}\text{C}$) (1951-2011). Mean average ndJF temperature for all of Mongolia is -19°C **d.** June-August (JJA) mean monthly precipitation (mm/month) (1951-2012), also showing southwest to northeast increasing gradient of precipitation. 75% of annual precipitation over the country occurs in JJA.

Mongolian society has historically been herding-based and nomadic. Even now, herding provides the primary source of income for many Mongolians. Agriculture, 80% of which is accounted for by herding, is the second largest contributor to the economy after mining. It accounts for about 19% of the national GDP, but employs a disproportionately large (36%) of the working

population (11, 12). With such a large percentage of the working population and their kin depending directly on herding for their primary source of income, understanding the linkages between climate, droughts, dzuds, and livestock mortality is vital if they are to be successful in adapting to and mitigating the impacts of extreme climate on their livestock and livelihoods.

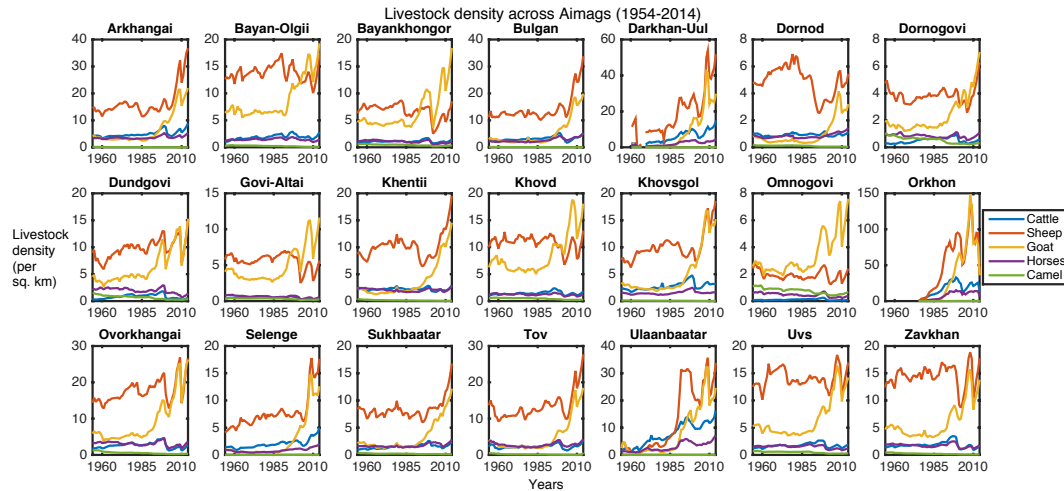


Figure 2. Total livestock density per square kilometer (cattle - blue, sheep - red, goat - yellow, horses - purple and camel - green) across 21 Mongolian aimags between 1954 and 2014. Herd size increases drastically after the 1990s dissolution of the Soviet Union following herd de-collectivization (see section 3.1). Note varying scale and that yak is counted as cattle in the annual census [ref. (13)].

Interest in building societal resilience to dzud and extreme climate has grown significantly both among public and private institutions through programs such as index-based insurance. While evidence of academics writing about index-based insurance spans nearly 100 years [e.g ref. (14)], global programs to implement them in developing nations outside of India began only about 15 years ago (15). The first ever index-based livestock insurance program (IBLIP) targeted at providing financial solution to herders facing climate-related livestock deaths was started by the Government of Mongolia via a World Bank loan in 2005 (11, 16, 17). The IBLIP was institutionalized with the passage of legislation only recently in the summer of 2014. Overall, such programs have shown promising results (11, 18-20). Yet, their preparedness faces a number of challenges. Key among them is the lack of scientific understanding of the history of past events and the forcing mechanisms behind them (e.g. climate variability and change, varying ground conditions such as pasture quality and snow characteristics) (20, 21).

The index in the current program uses past population statistics to inform about livestock loss risk and determine exceedance threshold for payouts (22). The IBLIP program pays indemnities to insured herders when adult mortality in a localized area exceeds a certain specified threshold

(most commonly 6%). A supposed advantage of such a program is that it incentivizes herders to minimize individual losses, as payments are based on area losses and not on individual losses (16). In other words a herder is rewarded for their competitive success in minimizing losses vis-à-vis other herders when local regional mortality is high. This program is based purely on past livestock population statistics and is not ‘weather-based index insurance’ where evolution of climatic variables are also tracked and payouts triggered based on the exceedance of certain climatic thresholds. The reason for this decision was that climatic drivers (and ecological drivers such as pasture health) were determined to be too complex to model, and data available was of substandard quality (22). However, as climate is one of the factors that implicitly drive the population statistics used in the IBLIP we think it is a worthwhile exercise to try and directly model the direct impact of climate on mortality. We undertake this here in this study. More details about IBLIP can be found at <http://www.iblip.mn>, and in refs. (11, 16, 22, 23)

In this paper we analyze annual livestock data collected by the Government of Mongolia from all 21 aimags, available from 1954 to 2014. The data is collected in a comprehensive livestock census conducted every December by the National Statistical Office of Mongolia (NSO). We use the data to understand the spatial and temporal variability of dzud damage, and the physical relationships between climate variability and livestock mortality to further the information available for planners and decision makers to develop mitigation strategies. We build a linear regression model using a stepwise regression framework to understand the overall influence of climate (temperature, drought, precipitation, and potential evapotranspiration) as a density independent driver of mortality.

1.1 Dzuds and droughts

Mongolian herders commonly classify dzuds into five types depending on the characteristics of the severe winter weather: 1) *white dzud*, deep heavy snow and cold temperatures; 2) *black dzud*, freezing temperatures and the absence of surface water and forage; 3) *combined dzud*, deep snow with a sudden drop in temperature; 4) *iron dzud*, impenetrable ice cover over the forage area; and 5) *storm dzud*, high winds and heavy snow (5, 7, 24). Due to the lack of reliable wind and snow data for Mongolia, differentiating between dzud types for an extended period of record is not possible. Since cold winters are a prerequisite for any kind of dzud, here we use the term dzud to refer to a cold winter that results in livestock loss.

Apart from cold winters, droughts also affect livestock (7). Droughts (extended periods of deficient rainfall (25)) deplete pasture, emaciate animals, and result in increased vulnerability to harsh winters (24). Begzsuren et al. (7) found that, in the Gobi Three Beauty National Park, dzud (defined as a cold winter which causes high mortality) and not drought is the dominant cause of mortality, but droughts exacerbated the effect of dzud on livestock. Sternberg (26), also suggests that in the southern Gobi, droughts and dzuds are decoupled in their impact on mortality. Here we use a combination of both instrumental and proxy based drought datasets, along with gridded precipitation and potential evapotranspiration datasets to conduct these analyses.

2. Methods and data

2.1 Data

Climate data for temperature, precipitation and potential evapotranspiration was derived from the University of East Anglia, Climate Research Unit (UEA, CRU) Ts 3.21 dataset (27). Palmer Drought Severity Index (PDSI– (25)) comes from the Cook et al., Dai et al., Schrier et al., datasets (28–30). The National Statistics Office (NSO), Government of Mongolia (<http://www.nso.mn>), undertakes the annual census of livestock. The data collected in this census is used to calculate mortality. Elevation data used in Figure 1b was extracted from the National Oceanic and Atmospheric Administration (NOAA) 1km Digital Elevation Model (31) which was downloaded from the International Research Institute for Climate and Society/Lamont-Doherty Earth Observatory (IRI-LDEO) climate data library (<http://iridl.ldeo.columbia.edu>).

2.2. Percentage Mortality

The feed requirement of each type of livestock is different. To standardize for this requirement, livestock numbers were first converted to equivalent ‘sheep forage units’ (SFU). 1 SFU expresses the feeding requirement of 1 sheep for one year (365kg/year or 805 lb/year of forage) (32). Following this convention of treating different livestock on a forage equivalency basis, each livestock head was converted to an equivalent number of SFU as follows: 1 sheep – 1 SFU, 1 camel – 5 SFU, 1 cattle – 6 SFU, 1 horse – 7 SFU, 1 goat- 0.9 SFU (32, 33). Percentage mortality for each aimag was then calculated as the ratio between the total SFU that died in a particular year and the total SFU at the beginning of that year. Figure S1 shows the percentage mortality in each of the aimags individually between 1955 and 2013.

2.3 Principal Components Analysis

To examine the broad spatial pattern of variability in the mortality data we performed an unrotated principal component analysis (PCA- ref. (34)) on the percentage mortality data for each aimag between 1955-2013 calculated in section 2.2. The data used is the percentage mortality for each aimag on a ‘sheep forage unit’ (SFU) basis, with time as an independent variable and percentage mortality as a dependent variable. The PCA therefore tells us about the dominant patterns of covariability in the mortality data. The overall variance explained by the first, second and third PCs were 55.8%, 13.8% and 8.5% respectively (total 78.1%). Mortality in aimags of Western and Central Mongolia show a positive loading for Empirical Orthogonal Function 1 (EOF1), while aimags of Eastern Mongolia load negatively on EOF2. Figure S2 shows the loadings coefficients of for EOFs 1 through 3 for the mortality data in each aimag, the corresponding variance explained, and the PC 1 through 3 time-series respectively.

2.4 Climate mean, and livestock population trends

CRU (27) climate data between 1951-2012 was averaged for November-February (ndJF) temperature, and June-August (JJA) precipitation respectively. This average is shown in figures 1c, and 1d. Raw livestock numbers for cattle, sheep, goat, horse and camel, in each aimag between 1954-2014 were downloaded from the NSO website for each aimag. These numbers were converted to livestock density, by dividing this value by the area of the corresponding aimag (in km²). The livestock density for each aimag between 1954-2013 is plotted in figure 2. Percentage livestock mortality data based on SFU for the years 1968, 2000, 2001, and 2010 are shown in figure 3.

To create figure 4a percentage mortality in SFU for each aimag calculated was plotted (in dotted lines) between 1955-2013. The averaged percentage mortality for each aimag of Mongolia is plotted as the solid black curve. A linear trend line was then fit to this curve and added to the plot. Figure 4b shows a box plot with the interquartile range (IQR), and outliers in the mean mortality data. Figures 4c shows the probability density estimate of the mean mortality for each of the 21 aimags (dotted lines), and mean mortality (solid black), based on a normal kernel function. The cumulative distribution function of mean mortality is shown in figure 4d.

To determine the relationship between mortality and climate (temperature, PDSI, precipitation, and potential evapotranspiration) we calculated monthly correlations between the two for a period spanning from prior year January to current year December. We found the strongest relationship between temperature and mortality for the months of November through February (ndJF). Based

on this result, figure 5a was created by computing a point-by-point Pearson correlation between mean ndJF temperature for each latitude-longitude grid point in the domain from the CRU (ref. (27)) dataset and average percentage mortality for all of Mongolia. Correlations where $P > 0.05$ (2-sided test for $n=59$, 1955-2013) are masked in the figure. Temperatures from the CRU dataset for a gridbox only covering Mongolia were then averaged for ndJF, and correlated with mortality in each individual aimag (figure 5b) and then plotted against the percentage mortality averaged for all of Mongolia (figure 5c). Both timseries were converted to 'zscores', by subtracting out their mean and dividing by their respective standard deviations. Using a similar procedure we found that PC1 of July through September (JAS) precipitation that loaded negatively on all of Mongolia (figure S5) showed the highest positive correlation with mortality (figure 5d). For figure 5d, June-August (JJA) PSDI from the Cook et al. (ref. (28)) dataset was averaged for the years 1999-2001. Similarly we also tested the relationship between PDSI, and PET as predictors of mortality, and found that JAS PC1 and PC3 of both PDSI, and PET correlated positively with mortality (figure S6-S7).

2.5 Stepwise multiple regression model

Analyzing all the months that showed the highest correlation with mortality we determined that ndJF temperature, and prior year PC1 and PC3 or JAS precipitation, PDSI, and PET might be potential predictors of mortality. Using this result, we developed a stepwise multiple regression model using each of these climate timeseries as potential predictors for mortality. We included interaction terms, and squared terms in our model that was built separately for each aimag. The final model was chosen when the Akaike information criterion (AIC) was minimized. The adjusted R squared from the model fit of actual mortality is shown in figure 6, and the final model for each aimag is listed in Table S1. Figure S9 shows the model fit of mortality against the actual recorded mortality. Adjusted R squared values were higher when AIC was used instead of the Bayesian information criterion (BIC).

2.6 Assumptions and caveats

1. For the purposes of this study we treat our study region (Mongolia) as a non-equilibrium system. A non-equilibrium system is one where ecosystems and plant productivity are influenced by climate alone, and not through density dependent feedbacks such as herbivore grazing (35, 36). While Fernandez-Gimenez and Allen-Diaz (13) concluded that non-equilibrium systems do in fact persist over the Mongolian desert-steppe and steppe, they find that the mountain-steppe ecosystem behaves along the lines of the conventional range conditions model.

There is no doubt that (population) density dependent factors impact mortality through feedbacks such as rangeland deterioration and disease (37-41). However, the objective of this paper is only to examine the impact of climate as a density independent driver of livestock mortality. Hence, we do not consider, for example, the impact of over grazing, or stationary versus nomadic rearing practices on mortality.

The scale of our study is at the aimag level. Most Mongolian aimag span an area greater than 60,000km². Additionally, the resolution of the mortality data used here is annual. Due to this spatial and temporal resolution of our study we are unable to resolve mortality caused by increasing herd size, inexperienced herders, and loss of pastureland to competing interests. In addition to this livestock densities vary vastly between aimags (figure 2), and pasture dynamics too vary considerably over different ecosystems (e.g. Gobi – desert, grassland steppe, and forests). Hence it is not possible to ascribe mortality to any particular event (e.g. a single snow storms) that might cause local spikes in mortality. At regional scales of analysis these factors definitely play a role in influencing mortality, and at times might be more important than cold winters and summer drought, but even in such cases their influence is over and on top of the impact of broad scale climate on mortality.

2. We assume that reported mortality is related to climate, disease or other factors like predation and not due to old age. This is because in herding communities livestock are usually slaughtered before they die of old age, and these deaths are not counted in the census. The census specifically only counts ‘un-natural’ death. We do not analyze the impact of disease and predation here.
3. We assume that as each herder tries to maximize their success, mortality reported is due to an externality (e.g. drought, climate, predation, hunger) and not due to a herder taking insufficient care of their herd.
4. Mortality data is compiled in December of each year. Therefore, observed mortality can be either a factor of the prior year or current year’s climate, in this case prior year drought, and winter temperatures.
5. No information is available on the age structure, or sex ratio of the herd. Therefore, it is not possible to determine if certain groups are more vulnerable to climate variability than other groups.
6. We do not have an estimate of the uncertainties in mortality data. Therefore, in this study we cannot correct any induced biases in mortality data due to incorrect reporting.

3. Results

3.1 Trends in livestock density (1955-2014)

The livestock data show increasing total livestock densities (per sq. km), especially since after the collapse of the Soviet Union in the 1990s (figure 2). During this period a transition to private ownership of herds was made, and the restrictions placed during the post 1960s era of collectivized herding were abandoned (42, 43). The abandonment of collectivization, removal of related restrictions, and the sudden loss of state sponsored livelihoods which caused people to return to the traditional practice of herding, were the main reasons responsible for the increase in livestock populations (also see refs. (42, 43), and chapter 5 in ref. (44)). Today over 95% of livestock is privately owned, and the greatest increases have been in the number of sheep and goats, due to a growing cashmere industry (39, 45, 46). Among the different livestock species, camel numbers have traditionally been low across aimags and have been declining consistently since the mid-1950s. The decrease in the number of camels is mostly a result of the increasing availability of motorized transport to move camps, carry baggage and pull carts (39). The density of sheep, the most commonly reared livestock animal, is highest in the north central and north western aimags of Ovorkhangai, Tov, Bulgan, Arkhangai, Khovsgol, Zavkhan, and Uvs. The density is much lower in the south central, and eastern aimags of Omnogovi and Dornogovi, probably because of the much drier climate regime prevalent in this region (figure 1c).

3.2 Spatial and temporal patterns of mortality (1955-2013)

Overall, barring the recent high mortality years of 2000-2003, and 2009-2010, during the 57 year record there has been a steady decline in mortality when averaged across all aimags (linear trend in figure 4a). One reason for this decline could be the unusually extended period of warmer than normal weather conditions between 1988-1998 (see next section on climate and mortality). Another contributing factor for the decrease is the de-collectivization of herds leading to a greater incentive among herders to avoid mortality. However, this de-collectivization was accompanied by a dismantling of safety nets like fodder storage structures, which during adverse climatic events had the potential to lessen the impact of climate on livestock (8). Prior to the 1990s these herding collectives were responsible for subsidized transportation for herders, veterinary healthcare for livestock, maintenance of watering wells, coordinated 'haymaking' for winter forage, and for providing a market for livestock (42, 43).

The percentage of mortality in each year, overall mean mortality for Mongolia, and a best-fit linear trend are plotted in figure 4a. Years where all aimags recorded high mortality (i.e. greater than 6%) are 1966, 1967, 1968, 1977, 2000, 2001, 2002, 2003 and 2010. The worst mortality events in our period of analysis were in 2001, and 2010 when 17%, and 20% of total livestock perished respectively. These events were especially severe in the northwestern aimags of Zavkhan, Arkhangai, and Khovsgol in 2001, and Ovorkhangai, Zavkhan, Dundgovi, and Govi-Altai in 2010 (figure 3). IBLIP has been using a mortality rate of 6% to trigger payments by soum (county) and species. Using this definition, 1980, 1983, and 1993 do not cross the 6% threshold when averaged across all of Mongolia, even though, these events still saw a high loss of livestock (figure 4a). The most severe continuous mortality event occurred between 2000-2003, whereas 2009-2010 was the most severe single event. In fact, the 2009-2010 event is ranked as the most severe mortality event in Mongolia since 1944-1945 when the national mortality rate was 33% (3, 43). A box plot of the mean mortality time series from figure 4a is shown in figure 4b, along with its kernel density estimate in 4c (solid black line), and cumulative distribution function (cdf) in 4d. Dotted lines in 4c are the kernel density estimates for each of the 21 aimags. From figures 4b through 4d we surmise that the mean mortality timeseries shows skew, most years clustered around a low mortality of ~3.7%. However, high mortality events such as those greater than 10% show non-negligible probabilities. The probability of exceedance of 6% mortality in any given yaer (used to trigger insurance payouts) for all of Mongolia is 26%. Approximately 50% of the time mortality is below 4.2%, and the exceedance probability of 8.7% mortality is 10%.

3.3 Climate and mortality

3.3.1 Temperature

We find an inverse relationship between temperature and mortality. Mean percentage mortality in Mongolia is significantly inversely correlated to preceding winter temperatures between November and February ($P < 0.05$, 2-sided t-test, 1955-2013, figure 5a). This inverse response is spread across much of Central and East Asia. Thus, cold winters in the prior season are linked to increased incidences of mortality, recorded during a census of animals in December of the current year. The region of strongest correlation to temperature is very similar to the first Empirical Orthogonal Function (EOF) mode of winter temperatures for Central and East Asia shown by Yatagai and Yasunari (47), possibly indicating coherence in winter temperature variability in this broad region.

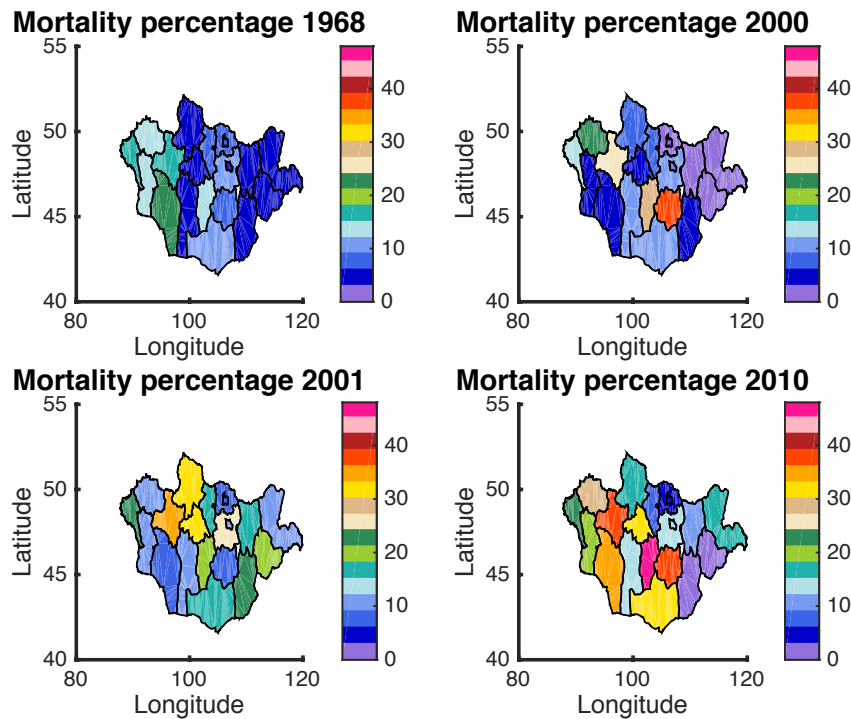


Figure 3. Total percentage mortality of livestock in an aimag for that year as recorded by a census in December for major events in 1968, 2000, 2001 and 2010.

When ndJF temperatures for a grid box covering all of Mongolia are averaged, they show a significant inverse relationship with mortality. The correlation of percentage mortality in each aimag and prior ndJF temperature is shown in figure 5b. The strongest negative correlations are seen over Khovsgol, Arkhangai, Tov, and Dornogovi. When percentage mortality is averaged over the entire country the correlation between ndJF temperature and mortality was found to be -0.44 ($P=0.0004$, 2-sided t-test, 1955-2013). Almost every year where high mortality was recorded (1957, 1960, 1966, 1967, 1968, 1977, 2001, 2010) was preceded by a colder than normal winter or dzud (figure 5c). Interestingly the period in the 1990s where livestock numbers saw an almost exponential increase also coincided with the warmest decade of winter temperatures over the previous half-century. The average winter ndJF mean temperature between 1988-1998 was -17.52°C , more than 1.5°C warmer than the -19.12°C average winter temperature between 1954-2012. This was also the warmest decade of the entire twentieth century (figure S3). However, the winters of 1999 and 2000 were much colder than those of the previous decade (figure 5c). This sudden drop in temperature, coupled with the dramatic increase in livestock numbers, along with summer droughts (see following subsection on drought), contributed to the widespread mortality observed during these years, as many of the new inexperienced herders were unaccustomed to such harsh weather (10) (see discussion), and the lack of safety nets (42, 43). The year 2009-2010 has been documented as the most severe mass mortality event in recorded in the history of

Mongolia, exceeded only by the 1944-1945 event (3, 43). Average temperatures between November-February 2009-2010 were -22.05°C, almost 3°C colder than the 1954-2012 average of -19.12°C. While 1944-1945 is outside the timeframe of our analysis, in fact the winter of 1944-1945 appears to have been the coldest winter in Mongolia ever recorded in the instrumental data over the entire twentieth century, though instrumental stations in this region are few and sparse prior to the 1930s (figure S4).

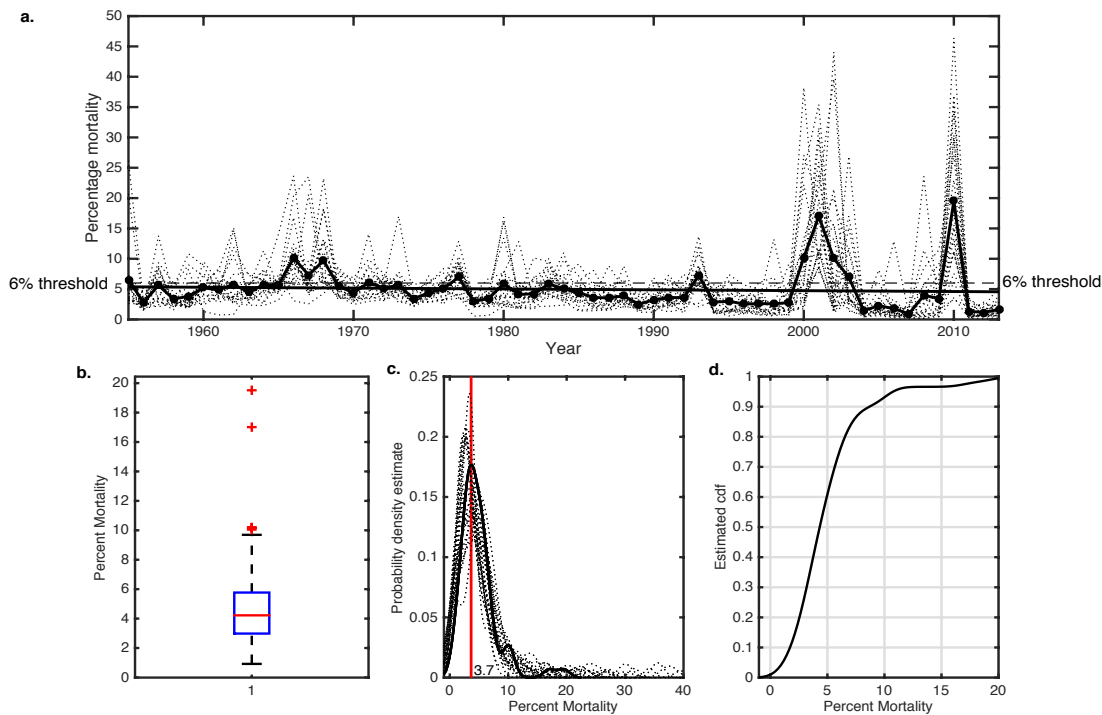


Figure 4. (a.) Percentage mortality (1955-2013) across each of the 21 aimags (dotted black), and mortality averaged across all aimags (bold black), with best-fit linear trend line. Insurance payouts by the index-based livestock insurance program (IBLIP) at the soum (county) level are triggered when mortality exceeds 6%. (b.) Box plot showing interquartile range (IQR) and outliers for mean mortality data (bold black line from part a). (c.) Probability density estimate based on normal kernel function for each of the 21 aimags (dotted black), and mean (solid black), and (d.) is the estimated cumulative distribution function (cdf) of the mean mortality. Parts (b), (c), and (d), show that low mortality of ~3.7% is most common, but high mortality i.e. >10% has non-negligible probability.

3.3.2 Precipitation, drought, and potential evapotranspiration

In addition to occurring following a period of anomalously cold winters, the high mortality recorded in the years 2000, 2001, 2002 and 2003 also followed one of the worst large-scale droughts in instrumental records. Three successive years of summer drought occurred between 1999-2001, and this drought was especially severe in the mid-latitudes regions of Central and East Asia (48-50). The underlying process of animals surviving a very short summer with poor

growing conditions (drought), and then needing to face the harsh Mongolian winter, followed by drought again, very likely explains the sequence of mortality from 2000 to 2003. Following the 1997 El Niño, the strongest of the twentieth century (51), the 1998-2002 period saw protracted cold La Niña conditions in the eastern equatorial Pacific, and concurrent anomalous warming in the Indo-Pacific (48). Lotsch et al. (52) noted that these extended La Niña conditions, which caused much of the precipitation deficits, were also reinforced by a documented phase shift of the Pacific Decadal Oscillation (PDO) into a negative (cold) episode.

We found that the PC scores of EOF1 of prior year July through September (JAS) precipitation which loaded negatively on all of Mongolia (figure S5) and explained 24.2% of the total variance of precipitation in these months correlated positively with mortality in aimags of southern and western Mongolia (figure 5d). This indicates that dry conditions also drive mortality. The extreme positive values of PC1 between 2000-2002 (figure S5) shows that the severity of the drought during this period is unprecedented compared to the previous century. The severity of the drought over Mongolia is also illustrated in figure 5e, by the July-September (JAS) Palmer Drought Severity Index [PDSI-ref. (28)] conditions. The PSDI is an index of soil moisture conditions, where negative values indicate drought like conditions, and positive values wet conditions. During 1999-2001, the JJA PDSI was below negative four over Mongolia and Northeast Asia signifying extreme drought. PC1 and PC3 of JAS precipitation, PDSI, and PET also showed a similar relationship to mortality (figure S5-S7).

A comparison of the severity of the 1999-2001 drought with tree-ring based paleoclimate reconstructions (28, 53, 54) and instrumental records (29, 30) showed this to be one of the worst droughts for all of Mongolia in the past half millennium (figure S8). This drought had a severe impact on available freshwater resources, causing critical lakes to dry up (55). Forage resources became extremely scarce, and combined with the unusually colder winters this led to the widespread livestock mortality (56).

3.4 Stepwise multiple regression model

In section 3.3 we found mortality was most strongly linked to cold winters (ndJF temperature) and summer drought conditions (PC1 and PC3 of each PDSI, precipitation, and PET). Based on this result we developed a stepwise multilinear regression model using each of the above as a potential predictor. Our model was allowed to contain an intercept, linear terms, interactions, and squared terms. Interactions were included to remove potential redundancy from using PDSI,

precipitation, and PET as predictors when each of them might be highly correlated to each other. We started with all possible predictors, and allowed both forward and backward iterations till the Akaike information criterion (AIC) score was minimized. A separate model was developed for each aimag to gauge the varying influence of climate of mortality. The adjusted R squared (for degrees of freedom) based on this model is shown in figure 6. Median adjusted R squared for the entire country is 48.4%. Adjusted R squared values are greater than 50% for Arkhangai (67.3 %), Ulaanbaatar (60.1%), Khentii (58.1%), Dornod (56.4%), Khovsgol (56.1%), Sukhbaatar (53.7%) Orkhon (53.6%), Bulgan (52.7%), Tov (52.2%), Zavkhan (51.7%). Details on the final predictors retained can be found in Table S1. Figure S9 shows model fit plotted against the actual percentage mortality data.

4. Discussion

We have found that livestock mortality in Mongolia is strongly related to winter temperature variability, and this relationship has been stable over time. Every major mortality event (1945, 1957, 1966, 1967, 1968, 1977, 2000, 2001, and 2010) has been recorded following an anomalously cold winter. The decade of 1988-1999, one with extremely low mortality, was the warmest period of time in winter temperature in the entire twentieth century. The winter of 2009-2010 was the coldest since 1944-1945, and consequently led to the second worst recorded livestock mortality event in Mongolia. Despite the fact winter temperatures have warmed by over 2.5°C over the last century over Mongolia (albeit stabilized recently – figure S3), the recent spate of high mortality events over the past decade reemphasizes that even in a period of general warming, year-to-year climatic variability and extremes impact livestock mortality.

We also find that there are important regional differences in mortality, and that mortality in the provinces of central Mongolia (Tov, Arkhangai, Khovsgol, Dornogovi, Zavkhan, Khenti), that have the highest densities of livestock, are most sensitive to extreme cold-winter type dzud events (figure 5b). Prior year JAS precipitation on other hand shows the highest relationship with mortality in the relatively more arid south and southerwestern aimags of the country (figure 5d). Furthermore, the high mortality recorded between 2000-2002 occurred following a series of drought years between 1999-2001, suggesting exacerbated effects on available forage and fresh water resources during consecutive droughts (55-57).

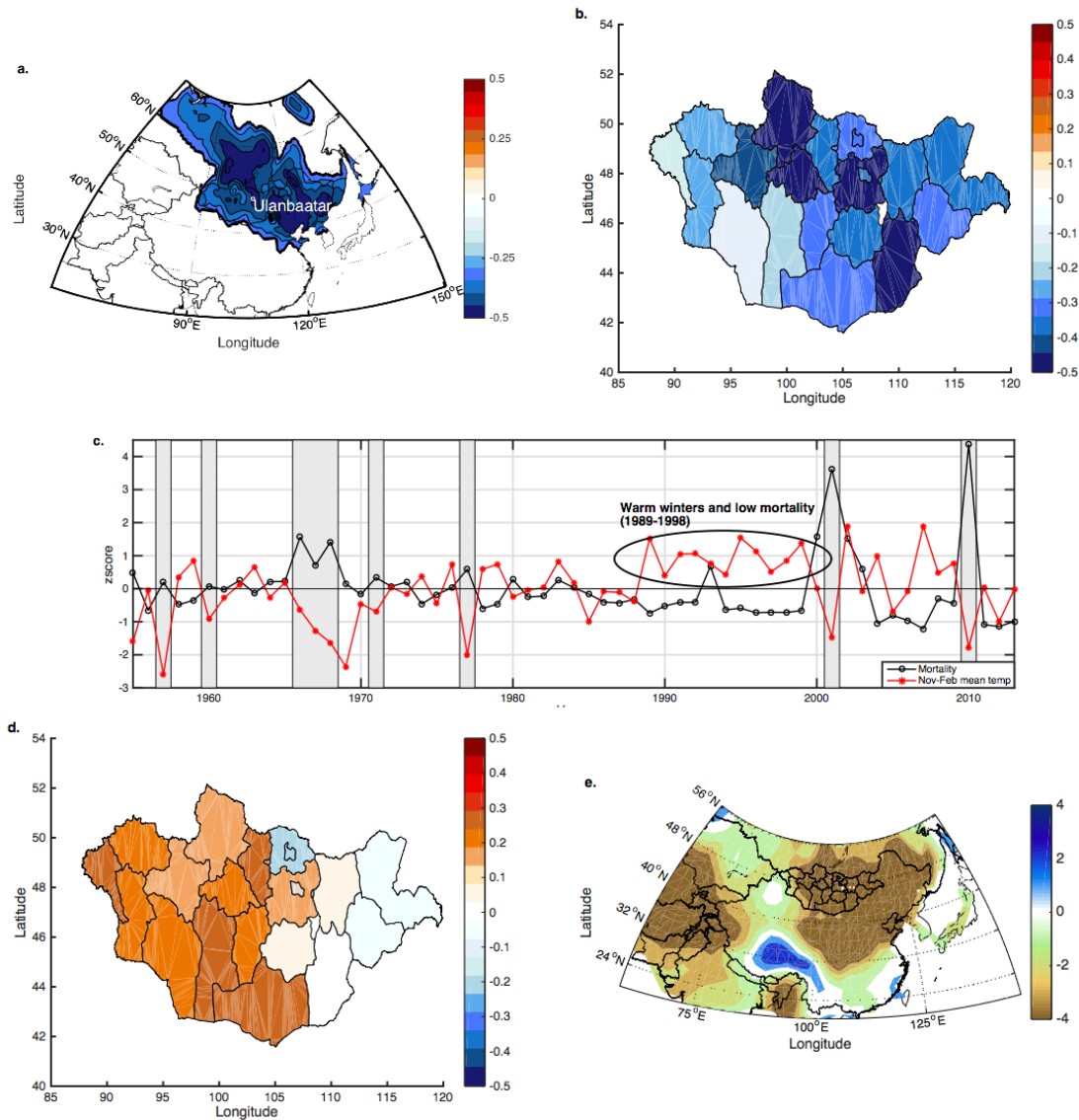


Figure 5a. Map showing spatial pattern of correlation between November-February (ndJF) to mean temperature and mean percentage mortality timeseries ($p < 0.05$, 2-sided t-test, 1955-2013). Red-positive correlation, blue-negative correlation. An inverse relationship is seen between mean percentage mortality and NDJF temperatures. **5b.** Correlation between ndJF temperature and mortality in each aimag. Correlations are significant when the absolute value is greater than 0.26 (2-sided t-test, $n=59$). **5c.** Timeseries of standardized anomalies of mean livestock mortality, and NDJF mean temperatures ($r = -0.44$, $p = 0.0005$, 1955-2013, 2-sided t-test). Grey bands indicate anomalously cold winters with coincided with high mortality events. Note that each November-February mean temperature is marked according to the calendar year starting January. For example, the mean temperatures between November 1955-February 1956 is referred to as 1956. **5d.** Same as 5b but for PC1 for July-September (JAS) precipitation of the prior year. **5e.** Spatial pattern of average June-August Palmer Drought Severity Index (PDSI) between 1999-2001 computed from the Cook et al. PDSI dataset (ref 23.). Brown-increasing drought conditions, blue-increasing wet conditions. Most of Mongolia has PDSI values exceeding -4 signifying extreme drought conditions.

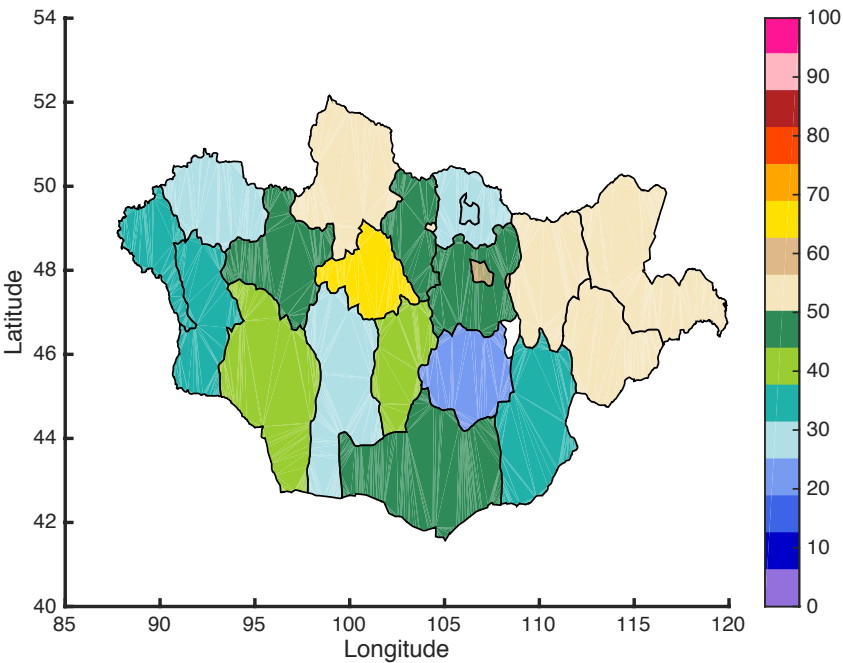


Figure 6 Adjusted R squared (for degrees of freedom) from model fit of percentage mortality based on stepwise linear multiple regression model with interaction using ndJF temperature, PC1 and PC3 of each JAS precipitation, PDSI, and PET. Median value of adjusted R squared is 48.4%.

Based on the results of our stepwise multiple regression model we show that climate is an important driver of mortality. The model, which uses ndJF temperature, and PC1 and PC3 of precipitation, PDSI, and PET as potential predictors of mortality, has a median adjusted R square of 48.4% for Mongolia. We find that while temperature is the dominant driver of mortality for all of Mongolia precipitation and summer drought are also important drivers especially in southern and western Mongolia. Studies have shown that the twentieth century has been one of the wettest of the past millennium over Mongolia (54, 58, 59), with the exception of the drought between 1999-2001. Hence, a potential shift to a more arid climate regime in the future due to increases in evapotranspiration with climate warming might increase the vulnerability of livestock to drought.

The 1990s also overlapped with an exponential increase in the absolute numbers of livestock. The sharp increase of livestock number during this period was directly related to the increasing market price of livestock products like meat and cashmere. After the collapse of the Soviet Union many Mongolians returned to the traditional practice of herding, but many of these herders were inexperienced (17, 39). Thus, it is possible that inexperience together with increasing numbers of animals and the lack of safety nets, left herders extremely unprepared for the extreme climatic events discussed above. Fernandez-Gimenez and Khishigbayar (10) have also noted that the turn

of the century dzud events not only devastated livelihoods, but also caused many of these inexperienced herders to give up herding completely, which resulted in a mass migration to urban centers like Ulaanbatar. This reveals the huge human cost of mortality, where climate not only has caused the mortality of livestock but also contributed to the loss of livelihoods, and culture.

The Government of Mongolia is undertaking important policy measures, both to promote industrial activities such as mining, and for environmental conservation through the demarcation of ‘protected areas’ (33, 60). These policies have been in direct conflict with herding. For example mining has now become one of the largest consumers of freshwater resources in this arid landscape, and has also resulted in large tracts of land becoming unavailable for foraging (61). At the same time, many traditional grazing areas are now ‘protected’, and thus no longer accessible to herders (33). As access to freshwater and pasture is the staple of livestock rearing and Mongolian culture, and there is a potential for increasing drought risk in this region (58, 62, 63), it will be critical to find a sustainable balance between these competing economic and political interests. Likewise, there is an urgent need to concurrently develop resilience to harsh winter weather through climate early warning systems and fodder storage structures. In fact, doing so is even more pertinent when considering that recent severe Eurasian winters is likely a product of Arctic sea-ice melt, and that this trend is projected to continue into the near future (64, 65). Lastly, an improved baseline understanding of mortality and its forcing has potential to improve products like the recently introduced IBLIP.

5. Conclusions

Our study shows that widespread mass mortality of livestock in Mongolia is caused primarily by anomalously cold winters. We also find that preceding summer drought can also exacerbate mortality. Based on this result we develop a stepwise multiple regression model to examine the role that climate plays as a density independent driver of mortality. A better understanding of this relationship between mortality and climate is critical to both predict and mitigate the impacts of future climatic events on the lives of herders and the livestock themselves. The current Mongolian index-based livestock insurance program (IBLIP) only uses past population statistics to determine payouts to herders. We feel that based on the relationship between climate and mortality shown in this study climate information temperature and drought information have potential considered as potential as climate indices in the IBLIP. The 6% mortality rate used by the to trigger payouts was found to have a probability of exceedance of 26% per year. While in this paper we only examine the impact of climate on mortality, population density dependent

factors such as over-grazing often exacerbate the effect of climate. Therefore, understanding these complex relationships both independently and in conjunction with climate will be critical for help mitigate future mass livestock mortality.

Acknowledgements

The authors thank the four anonymous reviewers. The authors are grateful to the Government of Mongolia and all individuals involved in collecting and recording the livestock records. Without these detailed collections every year it would have been impossible to conduct these analyses. The authors thank Dr. Upmanu Lall, (Columbia University) for suggestions with statistical analysis. M.P.R thanks Dr. Benjamin I. Cook (NASA-GISS) for assistance in generating figures. The authors dedicate this paper to the memory of Dr. Gordon C. Jacoby. We acknowledge NSF AGS award #1137729. LDEO contribution number: XXX

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