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Biophysical variability and politico-economic singularity: Responses of livestock numbers in South Mongolian nomadic pastoralism[1]

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Abstract: We analyzed a unique data set of livestock numbers in the Mongolian southern Gobi. In a novel approach, we combined biophysical data on precipitation and pasture biomass productivity with data on fine wool prices from 1981 through 2015 to investigate dynamic patterns and responses of livestock numbers in Mongolia's southern Gobi. Using piecewise

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structural equation modeling enabled us to disentangle the effects of biophysical and politico-economic factors on livestock numbers and species composition, paying particular attention to the singular transition from centrally planned to free-market economy that happened in Mongolia in 1992. Our analysis reveals that biophysical and politico-economic factors were both important determinants of livestock numbers, and highlights the politico-economic singularity of 1992 as the single-largest driver of livestock dynamics in the period investigated.

Keywords: productivity; nomadic herding; Gobi; precipitation variability; post-soviet Mongolia; extreme events, piecewise structural equation modeling

1. Introduction

In any system, extreme events, or singularities, are relatively rare. In spite of their rarity, singularities play an important role in shaping the natural, socio-economic or social-ecological systems they take place in (Sornette 2006). Extreme events can be divided into human-made such as financial crises, prolonged stock market rallies and wars, and natural such as droughts and climatic anomalies (e.g., the Medieval Warm Period). Extreme events may also be a combination of both such as documented by the 2011 nuclear disaster of Fukushima-Daiichi. With regard to social-ecological and socio-economic systems and natural drivers, many contributions have pointed out the impact of biophysical variability (Lybbert et al. 2004; Quaas et al. 2007; von Wehrden et al. 2012; Pinho, Marengo and Smith 2015; Engler et al. 2018).

A prime example for combined occurrence of both natural and human-made extreme events in a social-ecological system is the grazing system of Mongolia's south Gobi region. In Mongolia, the collapse of the Soviet Union in 1990 triggered a substantial politico-economic transition from a centrally planned to a free-market economy in 1992. Among the consequences of this shift in politico-economic system for herders were the privatization of livestock, abolishment of collectives, deregulation of rangeland use and stocking rates, with all production risks remaining with herders and their families (Fernández-Giménez 1999; Johnson et al. 2006). Shortly after, Mongolia had become the world's second largest producer of cashmere wool (World Bank 2002). In addition, biophysical stochasticity in the form of high precipitation variability between years, which causes high variability in productivity, is a major climatic feature of Mongolia (Wesche and Retzer 2005). Lastly, periods of extreme cold during winters (‘dzud’) regularly cause substantial losses in animal numbers to herders (Middleton 2016; Otani et al. 2016; Engler et al. 2018). The frequency of dzud events has risen from one in five years in the period 1950–1970 to one in every 2.8 years in the period 1990–2010 (Fernández-Giménez, Batkishig and Batbuyan 2012). Still, Mongolia’s nomadic pastoral production system has been in place for at least 1000 years, and possibly for as long as 4000 years (Fernández-Giménez 1999; Johnson et al. 2006).

The non-equilibrium theory of rangeland ecology postulates that inter-annual rainfall variability is the main driver of rangeland dynamics in semi-arid regions rather than absolute precipitation levels. High inter-annual rainfall variability implies that high-rainfall periods frequently alternate with droughts. During droughts, herbivore populations decline considerably and typically need several years to recover, whereas pasture vegetation more quickly recovers under sufficient levels of precipitation, consequently leading to a non-equilibrium of animal numbers and available biomass. Thus, if rainfall variability is large enough, typically at a $C_v > 33\%$, non-equilibrium theory proposes that rangelands are less prone to deterioration in biophysical variables (often referred to as “degradation”) due to overgrazing by large herbivores (Ellis and Swift 1988; Fernández-Giménez and Allen-Diaz 1999). Reviews of the available evidence suggest that the non-equilibrium theory of rangelands is empirically well supported (von Wehrden et al. 2012; Engler and von Wehrden 2018).

The peculiar combination of driving factors and well-documented repeated occurrence of extreme events in the Mongolian nomadic herding system has led to debates in ecology and geography about the relative importance of biophysical and politico-economic controls (Berger, Buuveibataar and Mishra 2013, 2015; von Wehrden et al. 2015). This debate can also be put into the wider context of rangeland ecology and long-term sustainable use and management in human ecology and ecological economics (Sullivan and Rohde 2002; Vetter 2005; Campbell et al. 2005; Gillson and Hoffman 2007; Sayre et al. 2017; Engler and von Wehrden 2018). Some scholars also have explicitly pointed out ‘a lack of connection’ between social, economic and natural science rangeland research (Campbell et al. 2005: 75).

We contribute to these debates by compiling and analyzing a unique data set from Mongolia’s South Gobi (Umnugobi) province, which contains data on total livestock numbers, livestock species, pasture productivity, precipitation, occurrence of dzud and fine wool prices from 1981 through 2015. Based on animal numbers in 2015, Umnugobi accounts for 3.5% of Mongolia’s total livestock (head count) and 5.7% of its cashmere production (own calculations, based on Erdenesan 2016). We address the following research questions: (1) how did livestock numbers change over time (by individual species and in total) in the period 1981–2015, and what factors might explain the dynamics observed? (2) What is the relative contribution of biophysical and politico-economic factors to these changes in livestock numbers? (3) What is the relationship between these factors?

We use piecewise structural equation modeling (Grace 2006; Lefcheck 2016) to quantify hypothesized causal relationships between multiple predictor and response variables in a social-ecological network characterizing nomadic pastoralism in southern Mongolia. In order to formulate our model, we combine the available theory from rangeland ecology and economics. For example, we hypothesize that precipitation had a direct positive effect on both livestock numbers and bio-productivity, but also an indirect positive effect that was mediated by bio-productivity. Economic cornerstone hypotheses in our model are that market prices for fine wool and the change of politico-economic system from planned to free-market economy both had a positive effect on livestock numbers. Thus, our study contributes to the growing body of literature that seeks to understand what drives and mediates change and stability in social-ecological systems (e.g., Chen et al. 2015; Dorresteijn et al. 2015; Sanderson et al. 2017).

2. Material and methods

2.1 Study area

Our study area covers some 165,000 km² in the South Gobi Aimag (Umnugobi Province) in southern central Mongolia. It comprises 15 administrative units; 14 of these are equivalent to a county (called "*sum*" in Mongolia); the other is the separately treated district capital Dalanzadgad. The vegetation of the region is characterized by grass dominated desert steppes and shrub dominated semi-deserts. The traversing mountain ranges of the eastern Gobi Altay host more productive mountain steppes dominated by grasses (von Wehrden et al. 2006; 2009).

For the study period 1981–2015, annual mean precipitation levels varied between 86 mm (1st quartile) and 187 mm (3rd quartile). In general, rainfall levels tend to be higher in the eastern part of the region compared to the west, and they increase with elevation (Figure 1). Inter-annual rainfall variability, as measured by the coefficient of variation (C_v) of annual rainfall totals, increases with increasing dryness of sites (von Wehrden and Wesche 2007). Most areas show a $C_v > 34\%$ (cf. white iso-variability lines in Figure 1), implying that the entire study area is comprised of rangelands characterized by non-equilibrium conditions.

Plot-level measurements show that biomass productivity in southern Mongolia is low and highly variable at 200 to 700 kg/ha in the prevailing desert steppes (Wesche and Retzer 2005). This is confirmed by remotely sensing-based data analysed from 1981-2000 (von Wehrden and Wesche 2007) and other sources (Zhang et al. 2009; Eckert et al. 2015). According to our analysis, the long-term normalized differential vegetation index (NDVI) in the study area ranged from 0.078 (1st quartile) to 0.092 (3rd quartile).

Semi-nomadic pastoralism is the most important form of land use in our study area. Animals are kept in mixed, privately owned herds on public land. Main livestock species are, in decreasing number of importance, goats, sheep, camels, horses, and cows (Table 1). Grazing land is mainly owned by the government and herders are allowed to move relatively freely (Fernández-Giménez and Batbuyan 2004). Herders regularly migrate over distances of several kilometers in the course of the year, with long-distance migrations (>100 km) taking place in years of drought (Retzer 2007). Access to markets is generally difficult and production of milk and meat for family subsistence is still a main motivation of herders. The land use practice together with the high levels of inter-annual precipitation variability qualify the study area as a 'subsistence non-equilibrium system' according to the social-ecological typology of rangelands proposed by Engler et al. (2018). There is, however, the exception of Cashmere wool that is widely traded and represents the main source of cash income for the majority of herders (Addison and Brown 2014), in spite of poor market access and infrastructure (Fernández-Giménez et al. 2015).

2.2 Data collection

We base our analysis on a combination of official government data, remote-sensing data and publicly available wool price data from 1981–2015. We extracted herd size numbers as the main response variables from official government statistics (see acknowledgements). Herders elect representatives on the community level and these collect the information on herd sizes. These representatives have very good knowledge of the respective local situation and the livestock numbers reported can be regarded as reliable. We extracted the wool price data from 1981 through 2015 from the Australian Wool Exchange monthly spot quotes provided by the

International Monetary Fund (IMF 2017), from which we derived annual mean prices for the standard commodity of 19-micron fine sheep wool (mainly Merino wool) in US-cents per kilogram. The Australian Wool Exchange data is the only available data that covers the entire study period, and correlated ($r_{spearman} > 0.6$) with the cashmere price for the period 1987–2006 for which we were able to obtain cashmere price data. The recent dip in correlation between wool and cashmere prices only started in 2018 and hence does not affect the results of our analysis.

Precipitation and biomass availability are closely correlated in the Mongolian drylands (Munkhtsetseg et al. 2007; von Wehrden and Wesche 2007), and precipitation is the main predictor variables in modeling of productivity. The National Agency of Meteorology and Environmental Monitoring of Mongolia runs standard climate stations in every county centre, and we acquired monthly values for precipitation totals for the period 1981–2015. We double-checked each data record individually and extrapolated missing values based on long-term means and spatially weighted values of close-by climate stations. Because field measurements of biomass productivity are available for only few sites in the region (Wesche and Retzer 2005; Munkhtsetseg et al. 2007), even less so for the entire time period of interest, we relied on remote-sensing based mean annual Normalized Difference Vegetation Index (NDVI) values provided by NASA, which are freely available and date back long enough[3]. NDVI values are good proxies for rangeland productivity in Mongolia, even in the drier parts (Kogan 2004; Yu 2004). Lastly, we searched the available literature on livestock grazing in Mongolia and classified each year with respect to dzud occurrence (Begzsuren et al. 2004; Fernández-Giménez, Batkishig and Batbuyan 2012; Middleton et al. 2014; Rao et al. 2015).

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[3] Please see https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/ and https://nex.nasa.gov/nex/projects/1349/ for more info.

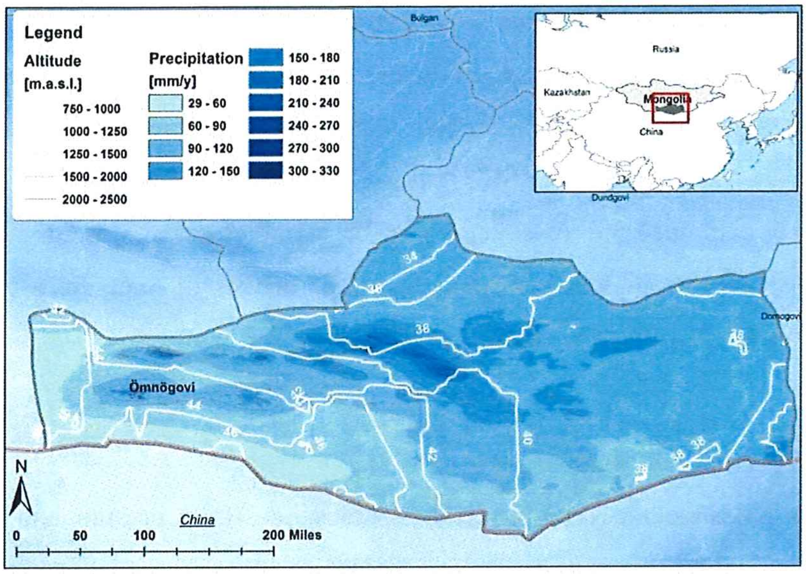

Figure 1: Map of the study area, south Mongolia's Umnugobi Province, along with annual precipitation volumes, inter-annual rainfall variability (% *Cv*, thick white lines) and altitude (thin grey lines).

2.3 Variables used for modeling

Our data set consists of biophysical and socio-economic data. The annual average of NDVI, annual total precipitation in millimeters ('presum'), head counts of the five most common herding animals, camel, cow, goat, horse and sheep, and a dummy variable for dzud (which takes the value 0 in years with no dzud and 1 in years of dzud) constitute the biophysical variables. Socio-economic variables comprise the average annual fine wool price in U.S. Dollars and a dummy for politico-economic system (0 for socialism, 1 for free-market economy). All variables except for the wool prices have records for each of the 15 administrative units of the South Gobi Aimag (Umnugobi) for each year in the period from 1981 to 2015. From these data, we constructed variables that indicate values of the same variable in the last and second-last year, e.g. in the data row for the year 1990 in a given county, the variable NDVI1 indicates the average annual NDVI value in 1989 in that county, and NDVI2 the respective NDVI-value in 1988. We conducted this procedure for the variables NDVI, presum and the fine wool price to be able to demonstrate the role of time in explaining responses. For analysis of aggregate livestock numbers, we used Sheep Forage Units (SFU) to account for the different feed requirements of livestock species when pooling them into one aggregate livestock number index. Rather than analyzing the total number of livestock heads, the conventionalism of using SFU thus bases livestock comparisons on the average amount of forage consumed by the respective species. Based on this forage equivalency metric, livestock heads were converted to an equivalent number of SFU as follows: 1 sheep – 1 SFU, 1 camel – 5 SFU, 1 cattle – 6 SFU, 1 goat – 0.9 SFU, 1 horse – 7 SFU (Bedunah and Schmidt 2000). The resulting data set contained 556 observations of 23 variables and represents what we believe are some of the main ecological and socio-economic drivers of nomadic pastoralism in the southern Gobi from 1981 through 2015.

2.4 Modeling

Explanatory variables include (i) biophysical variables, i.e. NDVI, presum, and their respective values in the last and second-last year, and (ii) politico-economic variables, i.e. wool and the politico-economic dummy variable. Independent variables are aggregate livestock numbers (Sheep Forage Units, model 1), and herd sizes of the individual species, which are camel, cow, goat, horse and sheep (model 2). We use piecewise structural equation modeling (SEM) to analyze and disentangle the relative importance of biophysical and politico-economic variables in explaining herd size dynamics in the study area before, during and after the transition from socialism to free-market economy in Mongolia. In general, SEMs are networks of variables connected through paths, which represent hypothesized causal relationships (Grace 2006; Lefcheck 2016). Mathematically, SEMs are represented by a system of linear equations. Here, we follow a strictly confirmatory approach in that we formulate hypothesized relationships between variables based on *a priori* knowledge about the system, and try to quantify the relative strength of these relationships. Naturally, the results cannot be taken 'as a proof of causal claims, but instead as evaluations or tests of models representing causal relationships' (Grace et al. 2015: 173). In SEM, a variable can take the role of a predictor in one or several equations of the system, and that of a response in one of those equations where it is not a predictor. Particularly, in piecewise SEM, local estimation of parameters allows for a wide range of statistical modeling approaches (Shipley 2000; 2009).

We construct our piecewise SEM from generalized linear mixed-effects models (GLMMs, cf. Bolker et al. 2009) with a Poisson error structure for individual species and aggregate livestock and a Gamma error structure with log-link for NDVI as response variable. We modeled the fine wool price using a generalized linear model (GLM) with a Gamma error structure with log-link. The pseudoreplicated structure of our data with repeated measurements on the same statistical units – the 14 South Gobi Aimag counties plus the district capital Dalanzagdad – calls for a mixed-effects model, since, by design, annual measurements of NDVI, precipitation, and animal numbers are nested within these administrative units, i.e. counties and the district capital (cf. Crawley 2007). Hence, we included 'county' and 'year' as nested random factors, with 'year' nested within 'county'. In all models for animal numbers, fixed effects include NDVI measurements, precipitation variables, wool prices and the politico-economic and dzud dummy variables.

From the final fitted models, we obtained path coefficients by exponentiation of the estimates, which enabled expression of path coefficients as percentage change in the response if the predictor changed by one reference unit, while all other predictors are being held constant at their respective mean values. The procedure aimed at increasing the interpretability of model outputs, because due to the log-link functions used in some parts of the statistical modeling process, raw coefficients were not all straightforward to interpret. In addition, we report marginal (R^2_m) and conditional (R^2_c) R^2 values for each constituting model to quantify the proportion of variance explained by the full model (R^2_c) and by the fixed factors alone (R^2_m, cf. Nakagawa and Schielzeth 2013). Lastly, we indicate whether or not the 95% confidence intervals around path coefficients include zero. All statistical analyses were performed within the R environment (R Development Core Team 2019), making use of the 'PIECEWISESEM' package (Lefcheck 2016). We drew all diagrams with the web-based visualizing tool 'draw.io' (www.draw.io).

2.5 Model description

Generally, SEMs need to be informed by and rely on *a priori* knowledge about the system under study. In Figure 2, we illustrate the basic conceptual idea of all our models that we present here. We base our model on two main pillars: economics and rangeland ecology.

As to economic drivers (right half of Figure 2, yellow boxes), we use the finding that a centrally planned economy is less efficient than a free market economy, which leads to a misallocation of economic resources (e.g., Mankiw 1998). Upon realizing that the size and composition of their herds could be optimized after being granted free choice of animal numbers following 1992, we assume that herders adjusted herd size and composition. Note that we do not need to assume further that herders aimed at financial benefits by optimizing expected net present value, although such behavior might certainly have occurred. Other mechanisms might be at least as relevant, such as shifting to larger herd sizes with a higher proportion of small livestock as a risk management strategy. This kind of risk management is well documented, especially for subsistence-oriented systems with frequent extreme weather events that carry the risk of severe losses (cf. Mace and Houston 1989 and references therein). We hypothesize that mechanisms like these have led to higher aggregate animal numbers, i.e. we expect a positive response of livestock numbers to the factor 'politico-economic system'. It has been suggested that the post-1992 increase of goat numbers in Mongolia has been driven to some extent by rising world-wide demand for cashmere wool (Saizen, Maekawa and Yamamura 2010; Berger, Buuveibaatar and Mishra 2013; Liu et al. 2013), which we take up here as a hypothesized path. Overall, we assume two effects of politico-economic system change on livestock: a direct effect, the dynamics of which we have laid out above, and an indirect effect with the fine wool price as intermediary variable. That is, controlling for everything else, Mongolia's entry into the world market as a major cashmere producer should generate a drop in fine wool price. Moreover, we hypothesize that there was a direct effect of politico-economic system on pasture productivity and speculate that this impact was negative, because the system of rearing private herds on common land that herders found themselves in after 1992 is the archetypal 'tragedy of the commons' situation (Hardin 1968; Lloyd 1980 [1833]). While we acknowledge that the 'tragedy of the commons' framework has been challenged on various grounds (e.g., Ostrom 1999; 2009), it is still part of the economics debate on sustainable management of public-good resources. Moreover, reports of degradation in various parts of Mongolia make it seem like a reasonable null hypothesis in our SEM approach (Fernández-Gimenez and Allen-Diaz 1999; Sasaki et al. 2008; Eckert et al. 2015).

As to ecological links (left half of Figure 2, green boxes), we expect a direct positive effect of precipitation on pasture productivity, which is well documented for arid and semi-arid ecosystems (e.g., Yan et al. 2015). We also expect a direct positive effect of precipitation on livestock numbers, assuming that higher precipitation translates to more abundant drinking water availability for livestock, mainly through rivers and wells. In turn, we assume a direct positive effect of productivity on animal numbers, which means that our model assumes an indirect positive effect of precipitation on livestock numbers mediated by productivity. Lastly, we expect the occurrence of dzud events to negatively impact livestock numbers (Pinho, Marengo and Smith 2015; Rao et al. 2015), but do not expect a causal link between precipitation and dzud, in line with what Sternberg (2018) finds. The evidence on the role of dzud events for productivity in Mongolia has been inconclusive so far (Vova et al. 2020), so we remain agnostic in this regard and refrain from adding a path from dzud to productivity for the purpose of this study.

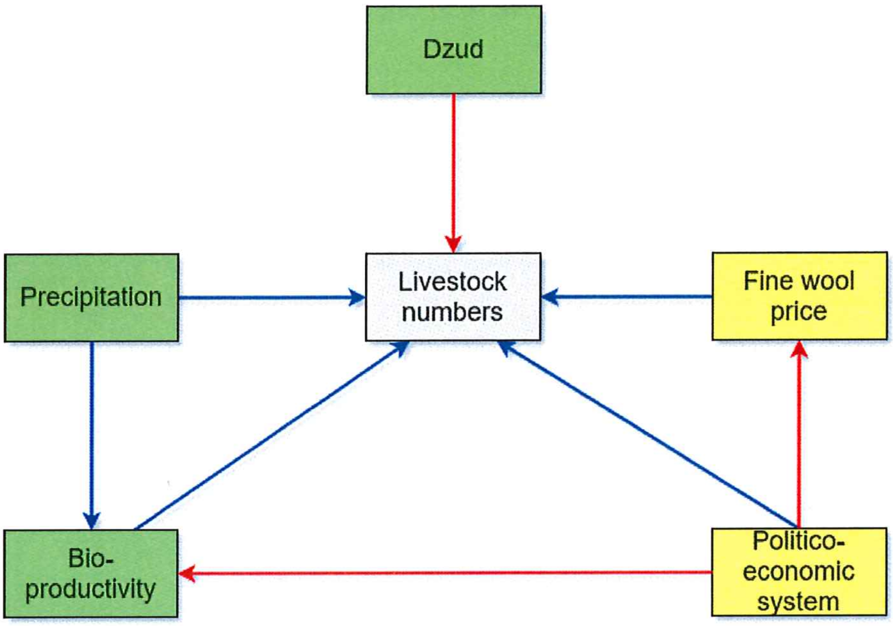

Figure 2: Hypothesized conceptual model of factors controlling livestock numbers in South Gobi nomadic herding. Blue paths indicate hypothesized positive relationships between variables; red paths indicate hypothesized negative relationships, the direction of which is indicated by the arrow.

3. Results

3.1 Descriptive statistics

We report some descriptive statistics for the parameters of interest in the study area for the 34-year period 1981–2015. Figure 3 illustrates the temporal dynamics of livestock numbers and ratios. Total livestock numbers have risen quite steeply to a head count of 2 million in 2015 after hovering just below the one-million mark until 1992 (Figure 3, upper panel and Table 1). In terms of percentages, all species declined over time except for goats, the percentage of which increased from 44.6% in 1981 to 68.0% 34 years later (Figure 3, lower panel). While all other species decreased in percentage, there were large differences. Sheep dropped from 30.6% to 21.7% (−8.9 percentage points, referred to as pp hereafter), camels from 14.4% to 5.8% (−8.6pp), horses from 8.1% to 3.6% (−4.5pp) and cows from 2.1% to 0.9% (−1.2pp). In spite of these relative changes over time, the relative ranking of livestock species has prevailed. The dzud events from 1999 to 2002 (1.6 million to 0.9 million, −44.3pp) and 2009/10 (1.75 million to 1.0 million, −42.8pp) generated clear signals in the data. Sternberg (2018) reports that the 2009/10 dzud killed about 25% of livestock in Mongolia and led to a 4.4% reduction of GDP.

	Camel [heads]	**Cow [heads]**	**Goat [heads]**	**Horse [heads]**	**Sheep [heads]**	**Total [heads]**	**Precipitation totals [mm/a]**	**NDVI**	**Fine wool price [$/kg]**
Min	61035	5386	299861	32216	175786	708543	2.0	0.064	4.63
Max	122282	36633	787147	101977	383949	1385382	509.0	0.121	15.49
Mean	87998	19423	528845	58778	260639	955682	146.3	0.086	8.23
Median	81549	20381	535879	54419	247787	911847	128.6	0.086	7.34
Std. deviation	21027	9194	179464	19530	58466	220717	84.2	0.009	2.55

Table 1: Descriptive statistics of animal numbers, biophysical variables and fine wool prices for 1981–2015

Annual precipitation and pasture productivity showed a couple of notable features in the period under study (Figure 4). Quite strikingly, the years 1993–1999 featured precipitation levels well above the values seen from 1985–1992, with NDVI values mirroring this. Moreover, the period 1988–1999 featured the warmest winter temperatures over the entire twentieth century (Rao et al. 2015). Thus, it is not a priori clear to what extent changes in livestock numbers and composition in the years following 1992, particularly in the period 1993–1999, can be attributed to changes in the politico-economic system (Retzer and Reudenbach 2005). Secondly, the years 2000, 2001 and 2005 were the driest in the post-1992 era partly coinciding with a series of severe and consecutive dzud events from 1999–2002 (Tachiiri et al. 2008; Fernández-Giménez, Batkishig and Batbuyan 2012; Otani et al. 2016). A relationship between drought and dzud has often been asserted or implicitly assumed, but does not hold up to scrutiny (Sternberg 2018). For example, 2005 was exceptionally dry, yet it was not a dzud year. Dzud years were obtained from Sternberg (2018: S30). During the study period, dzud years were: 1986/87, 1993/94, 1996/97, 1999–2002, 2009/10. In terms of livestock mortality in the entire country of Mongolia, the dzud events of 1999–2002 and 2009/10 have been by far the worst on record, with over 10 million dead livestock each, in agreement with livestock losses in the study area.

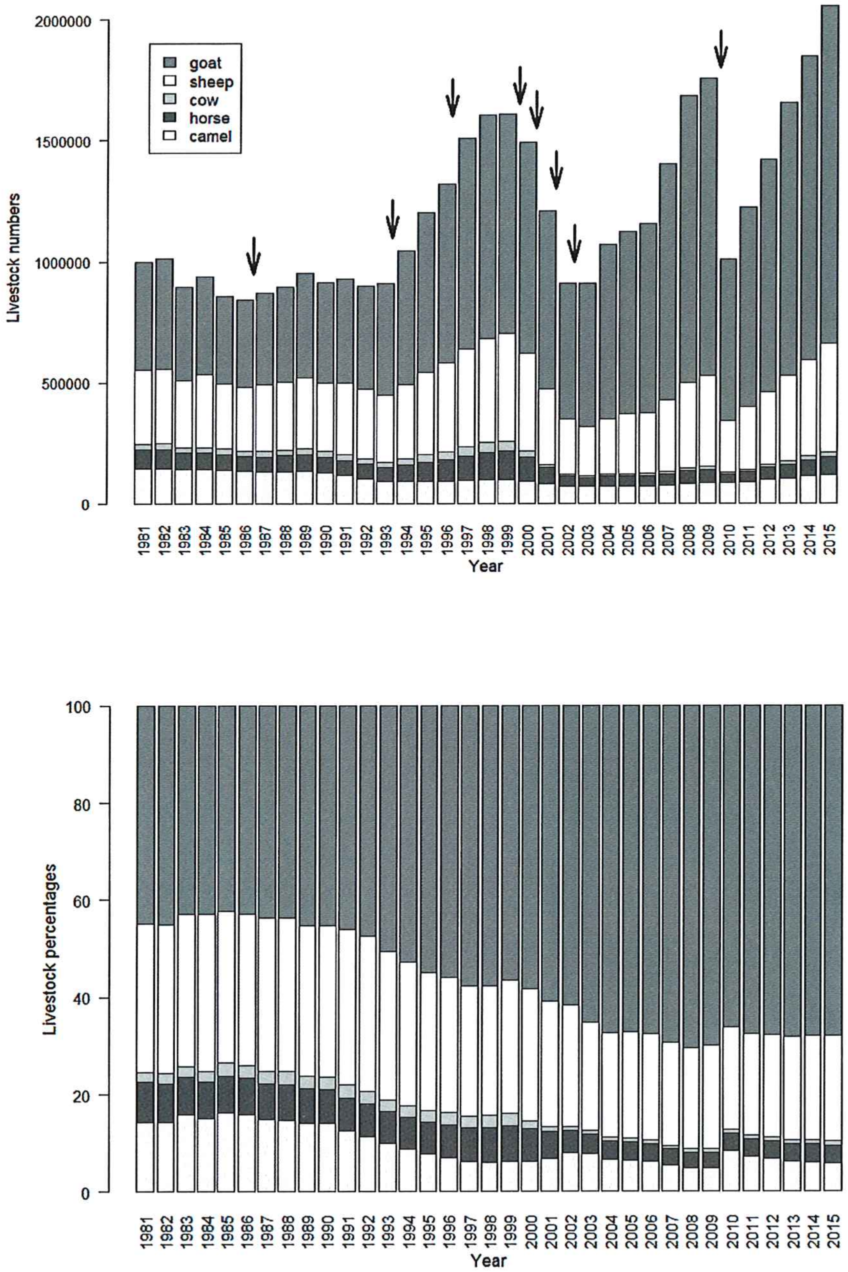

Figure 3: Temporal change of total livestock numbers (upper panel, years of dzud indicated by black arrows) and livestock species percentages (in terms of head counts, lower panel) in the 15 counties studied from 1981–2015.

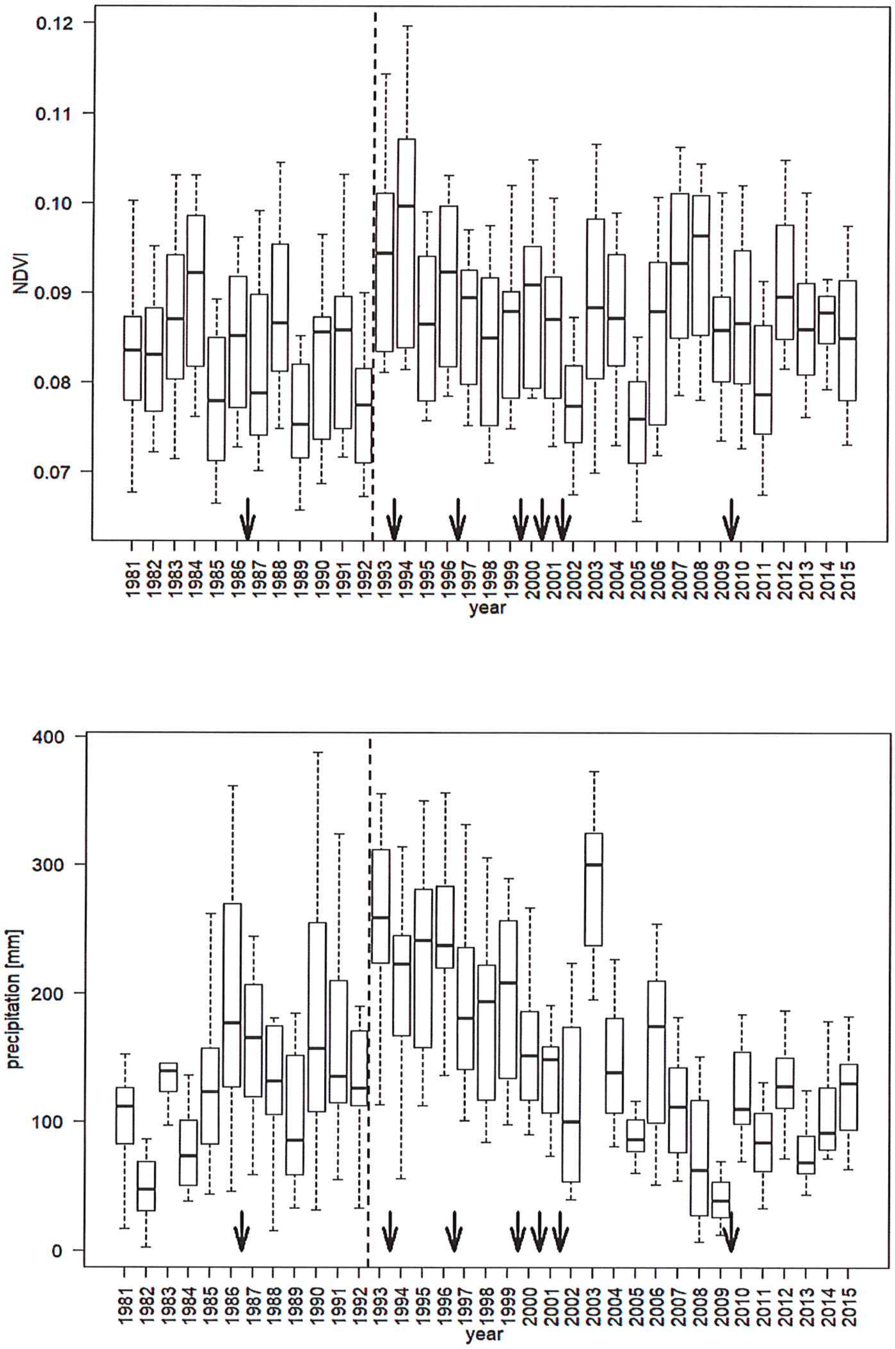

Figure 4: Temporal dynamics of precipitation (upper panel) and NDVI (lower panel) for the study area for the period 1981–2015, with the advent of politico-economic transformation in 1992 and dzud years marked (dotted line). The first couple of years with a free-market economy coincide with rainfall amounts well above the long-term mean, which in turn resulted in above-average NDVI values.

3.2 Aggregate livestock numbers

Figure 5 shows the result of our piecewise SEM for aggregate livestock numbers. Fit statistics indicate that the hypothesized model provides a plausible description of the data, both with respect to overall model fit ($p = .08$, Fisher's $C = 14.14$, RMSEA(df = 8) = 0.041) and variance explained in individual regressions ($R^2_m = 11.9\%$ and $R^2_c - R^2_m = 88.1\%$ for livestock numbers in SFU, $R^2_m = 11.8\%$ and $R^2_c - R^2_m = 88.2\%$ for NDVI, and $R^2 = 0.31\%$ for fine wool price).

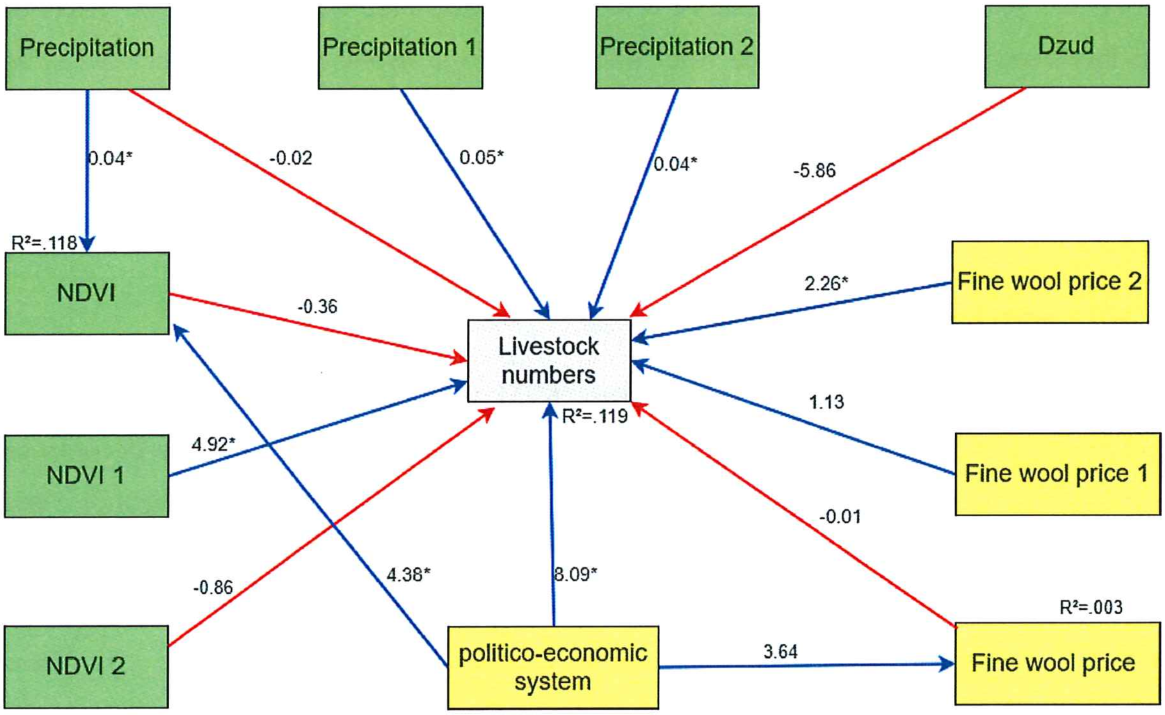

Figure 5: Final piecewise structural equation model quantifying hypothesized relationships between biophysical (precipitation, pasture cover/NDVI, livestock numbers; green) and politico-economic (politico-economic system, wool price; yellow) factors in southern Gobi nomadic herding. Path coefficients are expressed as percentage change implied by a change in predictors by one reference unit, controlling for all other factors. In case of dummy variables, the path coefficients express the percentage change implied by a change in the dummy from 0 to 1. Reference units are ±1mm (precipitation), ±1$/kg (wool price), ±0.01 (NDVI). Asterisks indicate that the 95% confidence interval around the estimate does not include zero.

Of the 14 directed relationships that we assumed, seven were found to be likely non-zero. In accordance with our hypothesized conceptual model, pre-preceding-year fine wool price (path coefficient = 2.26) and politico-economic system change (8.09) had a significantly positive impact on livestock numbers as did the biophysical variables of precipitation and productivity (NDVI). As expected, precipitation had a positive effect on NDVI (0.04). In contrast to our a priori hypothesis, politico-economic system change had a positive effect on productivity (4.38). Even though the occurrence of dzud had a negative effect on aggregate livestock as measured in SFU (−5.86), which is in line with our hypothesis, the 95% confidence interval around the estimate included zero. As to direct effects on livestock numbers, we found that change in politico-economic system had the single strongest direct effect on livestock numbers, followed by productivity of the preceding year (4.92). The only non-zero price variable was the fine wool price two years ago (2.26). In contrast to our hypothesis, there was no significant effect of politico-economic system on fine wool price. All of the hypothesized indirect effects, as indicated by the connection of two variables via a mediating variable, were practically zero. In terms of time lags of responses in livestock numbers to biophysical and politico-economic drivers, there is a tendency of greater effects for preceding and pre-preceding-year variables.

3.3 Individual livestock species

Figure 6 shows the results of our piecewise SEM for individual livestock species. The conceptual model as illustrated in Figure 2 remains unchanged, except that we now decompose 'livestock' into individual numbers for the main livestock species camel, goat, sheep, horse and cow to analyze impacts of politico-economic (Figure 6a) and biophysical (Figure 6b) variables on individual livestock species. For the sake of better readability, we provide separate graphs instead of showing all paths in one graph. For the same reason, we only show those paths where the 95% confidence interval around the estimate does not include zero, which is the case for 38 out of 58 paths assumed in the model.

Fit statistics indicate that the hypothesized model provides an adequate description of the data, both with respect to overall model fit ($p = .12$, Fisher's $C = 17.85$, RMSEA($df = 12$) = 0.033) and variance explained in individual regressions ($R^2_m = 16.0\%$ and $R^2_c - R^2_m = 84.0\%$ for camels , $R^2_m = 34.7\%$ and $R^2_c - R^2_m = 65.3\%$ for goats, $R^2_m = 26.2\%$ and $R^2_c - R^2_m = 73.8\%$ for sheep, $R^2_m = 40.4\%$ and $R^2_c - R^2_m = 59.5\%$ for cows, $R^2_m = 25.8\%$ and $R^2_c - R^2_m = 74.1\%$ for horses, $R^2 = 0.31\%$ for fine wool price, and $R^2_m = 11.8\%$ and $R^2_c - R^2_m = 88.2\%$ for NDVI).

Change in politico-economic system had a direct negative effect on camel (−38.60) and cow numbers (−50.41), and a direct positive effect on goat numbers (105.00). As expected, we found a positive effect of the pre-preceding year fine wool price on goat numbers (3.93), but also on all other livestock species, albeit to a lesser extent (camel: 1.08, sheep: 2.69, horse: 1.99, cow: 3.51). We found negative effects of current-year wool price on sheep (−1.73), horse (−2.41) and cow (−5.00).

Overall, productivity (NDVI) consistently had a stronger impact on livestock species than precipitation with 13 out of 15 paths from productivity variables having a strong positive effect on all respective species. Horses and cows generally responded stronger to changes in productivity than camels and goats (Figure 6b). In fact, the response of cows to changes in NDVI variables was the strongest among all responses of species to changes in biophysical variables (16.00, 19.93 and 11.80). Goats were exceptional, in that we found an effect from productivity in the preceding year (9.56), but no significant effects else. We found a tendency for precipitation variables to affect sheep, horse and cow, except for current-year precipitation, which also had an effect on camels (0.04) and goat (−0.05), the only negative response that we found for any precipitation variable on any species. We found the largest precipitation response with cows (0.14, 0.16 and 0.17) followed by horse (0.09, 0.01 and 0.08). There were indirect positive effects of precipitation on all species mediated by productivity. Regarding the impact of dzud events, goats were the only livestock species affected significantly, and as expected this impact was negative (−13.55).

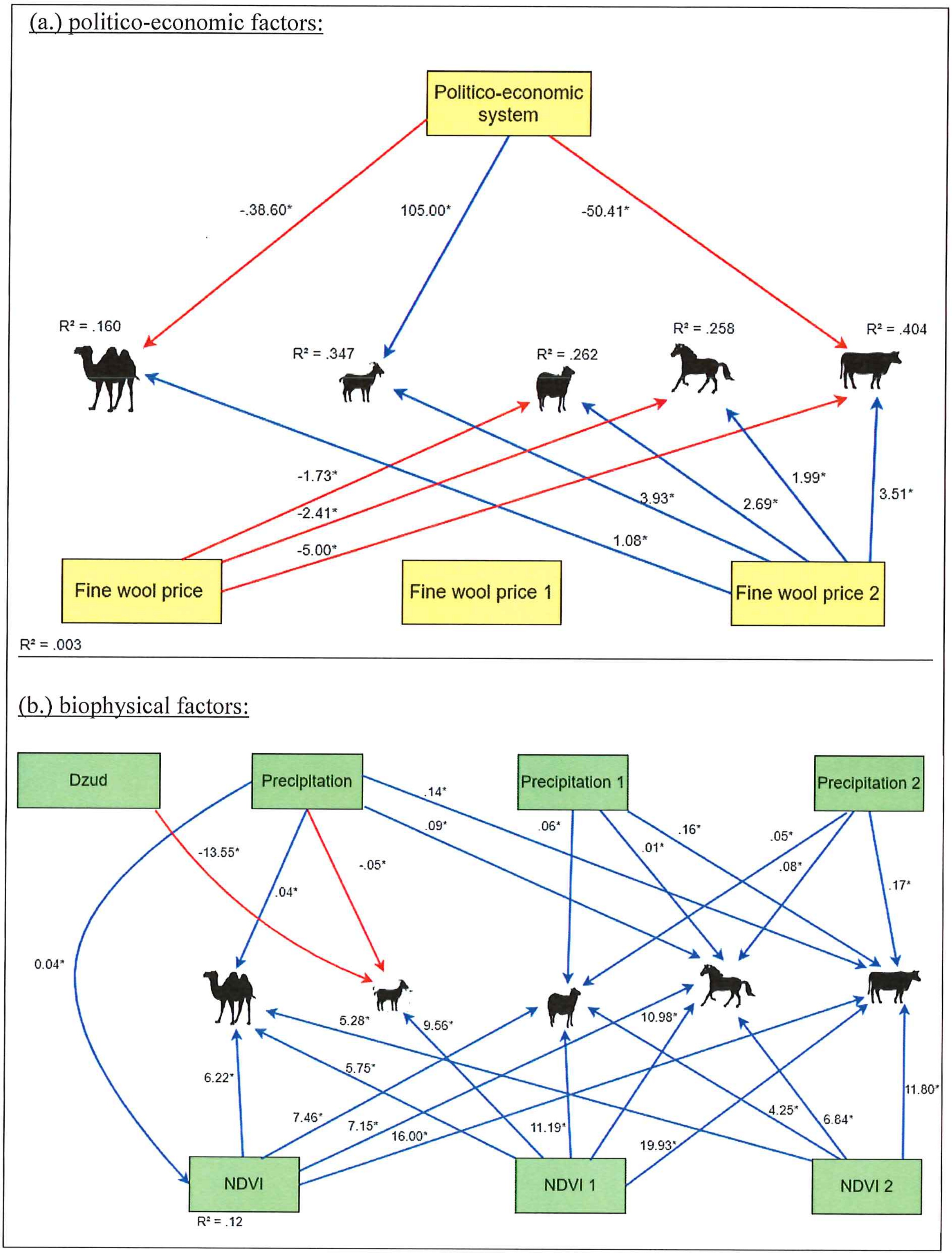

Figure 6: Final piecewise structural equation model quantifying hypothesized relationships between politico-economic (panel a.) and biophysical (panel b.) factors and livestock numbers in southern Gobi nomadic herding. Path coefficients are expressed as percentage change implied by a change in predictors by one reference unit. In

case of dummy variables, the path coefficients express the percentage change implied by a change in the dummy from 0 to 1. Reference units are ±1mm (precipitation), ±1$/kg (wool price), ±0.01 (NDVI). We only show those paths where the 95% confidence interval around the estimate does not include zero (numbers given with asterisks).

4. Discussion

Our analysis aimed at quantifying the drivers of change in livestock numbers as well as livestock species composition in Mongolia's South Gobi (Umnugobi) province. Particularly, we addressed the question of relative weight of biophysical and politico-economic drivers in this social-ecological system, which has been a veritable source of discussion (Berger, Buuveibaatar and Mishra 2013, 2015; von Wehrden et al. 2015; Sayre et al. 2017). In what follows, we discuss the implications of the fits of the structural equation models that we constructed based on our *a priori* knowledge of ecology and economics of rangelands. As will be discussed, we have good reason to be confident about these implications, but highlight that goodness-of-fit and *p*-values are not indicators of actual model 'truth' in reality.

Overall, we found that, based on the available data from 1981–2015 and using piecewise structural equation modeling, biophysical factors such as precipitation, productivity and the occurrence of dzuds were important explanatory factors for livestock numbers in the study area. However, we also found that changes in politico-economic system characteristics following 1992, and gradual fine wool world market price changes played an equally important role in driving system dynamics. In terms of livestock species composition, we found that all livestock species were significantly driven by biophysical factors, i.e. by precipitation, productivity and dzuds, while the politico-economic shift only had an impact on camels, cows and goats, however quite considerably so. Interestingly, we found that pre-preceding-year fine wool prices seem to have been a positive driver for all livestock species, not just for goats. Our analysis also confirmed the important role of extreme events in shaping the dynamics of social-ecological rangeland systems.

Regarding model fit, all fit statistics indicated good fits, both in terms of fit of overall structural equation model and individual regressions constituting the network of variables that represents the structural equation model. For the aggregate livestock model, R^2_m values were relatively small (~12%) compared to R^2_c values. In contrast, fixed factors in the individual species model explained relatively larger shares of the variability in the data (~12% to ~40%). In general, a large part of the variability in the data was residing in the random effects ($R^2_c - R^2_m$) and residuals, i.e. was due to idiosyncrasies of single counties and years, which ultimately corroborates our GLMM approach to the data set.

4.1. Responses of livestock to politico-economic factors

Change in politico-economic system formally means the transition from a centrally planned economy with little or no private proprietorship to a capitalistic free-market economy. Practically, this transition had many implications for herders and their families, because there no longer were collectives to provide infrastructure, additional fodder and access to veterinary services; herders had to take responsibility for all entrepreneurial decisions and risks associated (Johnson et al. 2006).

The model for aggregate livestock numbers confirmed several hypothesized relationships between variables. We found non-zero positive responses of livestock numbers to the fine wool price two years ago and to the politico-economic system dummy variable, the latter of which was the strongest direct effect on livestock in the model. Our individual species model revealed that goats, and, to a lesser extent, all other livestock species, positively responded to changes in fine wool price two years ago. The change in politico-economic system had a strong positive effect on livestock numbers in general (Figure 5) and on goat numbers in particular (Figure 6a). Our results confirmed hypotheses that had been phrased earlier in the literature but that had not yet been subject to quantitative tests (e.g., Saizen, Maekawa and Yamamura 2010; Berger, Buuveibaatar and Mishra 2013; Liu et al. 2013). Furthermore, our finding that the pre-preceding year price of fine wool caused a positive response in livestock numbers confirmed our hypothesis that livestock numbers reacted with a time lag to observed fine wool price changes. As to effects of the transition from socialism to capitalism, the negative responses of camels and cows were apparently overcompensated by the strong positive response of goats, corroborating that herders indeed gradually switched from large to small livestock, possibly as a risk management strategy, a profit maximization strategy, or both (Mace and Houston 1989; Lybbert et al. 2004). In any case, this process only started after 1992, and only gradually. Lastly, horses and sheep did not respond to politico-economic change, which reflects that herders keep these animals as food source (sheep) and mount (horses), with horses also being important symbols of status in Mongolian culture.

While the indirect effect of politico-economic change on livestock mediated by current-year NDVI was close to zero, the strong positive response of current-year productivity to politico-economic system was unexpected in light of recent mixed reports on the state of Mongolian rangelands in general (Hilker et al. 2014; Khishigbayar et al. 2015; Fernández-Gimenez et al. 2017; Densambuu et al. 2018; McLaughlin 2019). We had hypothesized a negative response, in agreement with the 'tragedy of the commons' hypothesis (Hardin 1968). In line with what Lybbert et al. (2004) report for smallholder farmers in Ethiopia, we do not find evidence for the tragedy of the commons hypothesis based on our model and data. Several explanations for this finding are possible. First, our study was concerned with Umnugobi province, while reports about overgrazing tend to refer to Mongolia in general, or to its central parts in particular (Fernández-Giménez et al. 2017). Indeed, Hilker et al. (2014: 418) found that decline in productivity over time was largest 'in the transition zone between grasslands and the Gobi desert'. Moreover, Fernández-Gimenez et al. (2017) point out that most recent studies on Mongolian rangelands reporting some form of decline of rangeland quality in some of their study areas also find large patches of rangeland with no decline or even qualitative improvements. Second, as Ostrom (1999; 2009) has pointed out, not all of the assumptions that warrant a Tragedy of the Commons outcome necessarily hold in all social-ecological systems. Resource users might self-organize depending on variables such as the size of the system, number of resource users or norms. Indeed, various forms of self-organization, termed community-based natural resource management, have been reported for pastoralist communities in Mongolia (e.g., Fernández-Gimenez et al. 2015). Lastly, it is also possible that this finding is to some extent an artifact originating from the coincidence of a succession of relatively wet years following the transition in 1992 as compared to the period 1981–1992 (cf. Figure 4).

4.2 Responses of livestock to biophysical variables

The model for aggregate livestock numbers confirmed that biophysical variables play an important role in south Mongolian nomadic herding (Figure 5). We found non-zero positive responses of livestock to preceding and pre-preceding-year precipitation and to current and preceding-year productivity variables. Direct responses to productivity were stronger than direct or indirect responses to changes in precipitation. These results seem to corroborate the theory that herders likely used conditions of preceding years as one easily available decision heuristic. Such behavior is in agreement with known psychological patterns of human thinking such as the 'recency effect' (Deese and Kaufman 1957) and, the availability heuristic (Tversky and Kahneman 1974). Another factor that would contribute to the patterns observed is the time lag imposed by the reproduction cycle of animal species.

Our findings are in agreement with our hypothesis that there is a time lag in some of the responses to signals from biophysical and politico-economic drivers, while other responses happen more directly. For example, there is a positive response of productivity to precipitation in the current year, while livestock response to increased levels of productivity is strongest for preceding-year NDVI values. This result is in agreement with the non-equilibrium theory of rangelands, which posits an immediate reaction of productivity to precipitation, but a time lag in livestock response to productivity (Wesche and Retzer 2005). Regarding livestock species, our results highlight that each species reacted differently to biophysical signals (Figure 6b). Particularly, our results confirmed the grouping of livestock species by Mongolian herders into 'warm' and 'cold' species (Fernández-Giménez 2000). From 'warm' to 'cold', these are camels, goats, sheep, horses and cows. While camels can graze even in drier semi-deserts, goats already depend on daily access to drinking water, and are thus restricted to grazing areas with access to water sites. All other species are more selective regarding their habitat, with sheep being more adaptable than horses and cows, which are restricted to oases and mountain habitats in our study region. Indeed, we found strong positive effects of precipitation variables on cows and horses. The response pattern to productivity variables consistently showed stronger responses for 'cold' species and weaker responses for 'warm' species, in line with the classification by Mongolian herders.

There is a negative response of livestock numbers to the occurrence of dzuds in both models, as expected (Figures 5 and 6b). However, the negative effect of dzud seen in the overall model (95% confidence interval includes zero) seems to be due to the strong negative response of goats that we find in the individual-species model (95% confidence interval does not include zero, Figure 6b). The disproportionately strong response of goat numbers to dzud occurrence is in agreement with findings of Fernández-Giménez et al. (2015) for the province of Bayankhongor, which neighbors Umnugobi province to the west and thus features similar climatic and socio-economic characteristics. Goats generally have less body fat than sheep and are thus neither as good at coping with extremely cold temperatures nor as hardened as sheep when it comes to sustaining their bodies when there is only little or no feed available. Moreover, the increase in inexperienced herders over the study period, especially in the post-1992 years until the early 2000s, which saw many Mongolians returning to traditional pastoralism to make a living (cf. Rao et al. 2015) might be an explanatory factor for this pattern. We speculate that many of these inexperienced herders lacked the geographical, ecological and traditional knowledge that could have alleviated mortality rates in years of dzud. In particular, lack of experience and a focus on cashmere goats as a cash crop could have led to insufficient livestock diversification, which is a major risk management strategy against dzud (cf. Fernández-Giménez et al. 2015).

4.3 Other effects and limitations

We could not find any evidence for our hypothesis that Mongolia's entry into the Cashmere world market had a negative effect on the fine wool price. In fact, our analysis suggests that the effect was likely zero (+3.64, 95% confidence interval includes zero), in agreement with the finding that very little of the variability in fine wool prices was explained by our models.

Our analysis did not account for migration in and out of the study area. Long-distance migratory movements ('otor') are relatively common in Mongolian pastoralism. According to previous research, 'otor' mostly occur during or after severe drought and dzud events. For example, Fernández-Giménez et al. (2015: 55) report for their 2010 sample of central and south Mongolian pastoralist families that roughly one in five herder households were planning on some form of outmigration following dzud. In contrast, Bedunah and Schmidt (2004) report very little mobility in their 1998 – 2000 study of N = 73 households in Umnugobi's Gobi Gurvansaikhan National Park, with more than 80% of respondents indicating to move their camps less than 20 kilometers per year, but hint at longer travels of 150 to 200 kilometers in case of drought (ibid: 179f). Thus, in years where dzud occurred, some of the variance unexplained by the fixed factors in our data might be due to migration in and out of the study area.

Legacy effects were included in the models only to the extent that they were in agreement with non-equilibrium theory. Our approach is in line with general recommendations on how to approach confirmatory – as opposed to exploratory – structural equation modeling (Grace 2006). Hence, while this deliberate modeling decision fits well with the confirmatory nature of our analysis, it also implied not considering other potential legacy effects such as, e.g., of annual precipitation on productivity.

4.4 Relative weights of biophysical and politico-economic drivers

The discussion on the relative weights of biophysical and politico-economic drivers needs to be split in two. On the one hand, there the phenomena of dzud and politico-economic regime shift, which occur as singular extreme events. On the other hand, there are the more continuous drivers such as the fine wool price, annual precipitation and productivity. In both cases, conclusions may not be seen as absolute, but critically dependent on one's persective.

As to the singular extreme events, dzuds had a strong negative impact on aggregate livestock numbers (−5.86, Figure 5), which however mainly stemmed from their impact on goats (−13.55, Figure 6b). At face value, this seems to be considerably less than the impact of the politico-economic transition following 1992 (+8.09, Figure 5), which is again composed of various effects on the species level, most notably the stark effect on goats (+105.00, Figure 6a). Hence, from the viewpoint of comparing effects of single events, the effect of the politico-economic transition was stronger. However, these numbers could also be viewed from a risk perspective. Notably, we observed eight dzuds from 1981 through 2015 and only one politico-economic regime shift. Hence, while both types of events qualify as extreme, for all that we know the risk of dzud occurrence was considerably larger than the risk of another politico-economic transition. To compare the impact of dzuds to those of the politico-economic transition over the entire study period, one could compare the compound losses of eight dzuds to the impacts of the one politico-economic transition that happened. In this perspective, dzuds could be considered the stronger driver at least in terms of aggregate livestock losses. Looking only at goats, the comparison is more of a tossup.

With the more continuous drivers, a comparison of relative strength of effects comes down to a close observation of the variable scales involved. If we assumed for the moment that a change of one standard deviation (σ) in the fine wool price predictors was comparable to a one-σ change in any of the other predictor variables of interest, we could compare the relative weight of biophysical and politico-economic drivers based on this assumption.[4] For aggregate livestock numbers, this would imply that a one-σ change in preceding-year precipitation (+84mm) had roughly the same effect as a one-σ change (+0.009) in preceding-year NDVI (+4.20 as compared to +4.43), which is however smaller than the increase implied by a one-σ change (+2.55$/kg) in fine-wool price two years ago (+5.47). Hence, in this view, the fine-wool price two years ago was the stronger driver, but only slightly so. At face value however, we would conclude that preceding-year NDVI (+4.26) was a stronger continuous driver than the fine-wool price two years ago.

5. Conclusion

Our study of pastoral dynamics in southern Mongolia supports the need for a better integration of ecological, economic and political perspectives when analyzing rangeland systems. For our study area, Umnugobi province in south Mongolia, we find that biophysical variables are important explanatory factors for livestock dynamics, because they ultimately limit what pastoralists can work with. However, based on our analysis of the period 1981–2015, which saw Mongolia's transition from planned to market economy and several extreme winters as well as drought periods, we conclude that biophysical factors might have been outweighed by some of the politico-economic factors at work in this system, albeit this critically depends on one's perspective on the results. In any case, our analysis highlights the role that singular events, such as extremely harsh winters and politico-economic regime shifts, play in shaping the systems they occur in, despite the rarity of their occurrence. Changes in fine-wool price had a significant effect on goat numbers and livestock numbers in general, albeit with a time lag of two years and relatively modest effects when compared to responses of livestock numbers to biophysical variables. This finding highlights that while price signals matter, they are not the strongest explanatory variable for livestock dynamics in south Mongolian nomadic pastoralism. Overall, our study highlights the need for and usefulness of interdisciplinary approaches to analysis and understanding of rangeland dynamics.

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[4] Grace and Bollen (2005: 286) suggest that such ‚standardization' and the comparisons based on them be excecuted with caution

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Appendix

A.1 Pearson correlation among explanatory variables

We show Pearson correlations of all explanatory variables in Table 1. As could be expected, correlations of wool prices with those of succeeding years are highly positive. Successive-year NDVI values are moderately correlated. All correlation values remain below 0.80. Hence, we retained all variables in our analysis. Additionally, the variance inflation factor (VIF) was below 3 for all predictor variables except for the 'wool price1' variable, which attained VIF = 4.51, which is still below the generally recommended threshold value of 5.

	NDVI	NDVI1	NDVI2	presum	presum1	presum2	wool	wool1
NDVI								
NDVI1	0.59							
NDVI2	0.50	0.59						
presum	0.30	−0.01	0.16					
presum1	0.23	0.30	0.00	0.39				
presum2	0.05	0.23	0.31	0.31	0.39			
wool	0.01	0.03	−0.05	−0.30	−0.18	−0.26		

wool1	−0.06	0.01	0.03	−0.31	−0.26	−0.16	0.71	
wool2	−0.08	−0.06	0.01	−0.24	−0.28	−0.24	0.38	0.70

Table 2: Pearson correlation matrix of predictor variables

A.2 Results of full individual species model

	Camel	Goat	Sheep	Cow	Horse
~presum	0.0004*	−0.0005*	0.0002	0.0014*	0.0009*
~presum1	0.0001	0.0003	0.0006*	0.0016*	0.0010*
~presum2	0.0001	0.0003	0.0005*	0.0017*	0.0008*
~NDVI	6.0393*	1.1784	7.1970*	14.8410*	6.9071*
~NDVI1	5.5951*	9.1261*	10.6087*	18.1772*	10.4192*
~NDVI2	5.1489*	0.1239	4.1648*	11.1580*	6.6138*
~wool price	−0.0009	0.0097	−0.0174*	−0.0475*	−0.0244*
~wool price1	0.0088	0.0107	0.0112	0.0217	0.0133
~wool price2	0.0107*	0.0385*	0.0265*	0.0158*	0.0197*
~poli	−0.4877*	0.7178*	0.0179	0.0647*	−0.1639*
~dzud	0.0246	−0.1456*	−0.0360	0.0744	0.0150

Table 3: Full model results for the individual species model. Asterisks indicate that the 95% confidence interval around the estimate does not include zero. Coefficients for NDVI and wool price do not change in comparison to the aggregate animal numbers model (Figure 5).

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