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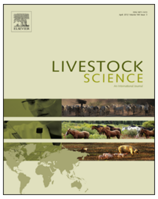

A mathematical model of the dynamics of Mongolian livestock populations

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ABSTRACT

Subsistence livestock herding is an important component of livestock production in Mongolia. However, pasture degradation, extreme weather, desertification, livestock overpopulation, infectious diseases and limited government support increasingly threaten this livelihood. To better assess these afflictions, understanding the population dynamics of livestock is critical. Towards this goal, we developed a model of Mongolian livestock populations. Using the Leslie–Gower difference equation competition model, a discrete analog of the continuous Lotka–Volterra 2-species model, Mongolian livestock population dynamics were simulated in MATLAB. The model encompasses four species and is stratified by age and sex. Calibration of parameters is accomplished using official population data from 1970 to 2010; a turbulent time period that includes the socialist to capitalist market transition and two growth periods both followed by two dzuds (severe winter storms). Herders were surveyed and herd structures were sampled for parameter and model initial value estimation. The current model simulates the Töv aimag (province) goat, sheep, cattle and horse populations. However, with more data collection, the intention would be to simulate all species populations in any aimag or soum (province subdivision). A ten-year simulation of future livestock populations predicts a more than two-fold increase in goat and sheep populations, a slight increase in cattle populations and a slight decline in horse populations. Preliminary validation with 2011 population data shows accurate estimation. Furthermore, a stable future livestock population was attained with the implementation of more than double the current culling rate. The model can be integrated in infectious disease transmission modeling, used as a tool for predicting the economic potential and support requirements of the livestock sector and used to illustrate the urgency of fostering sustainable management of livestock populations in Mongolia. This story of Mongolian pastoral life presents an excellent opportunity to study a social-ecological system as well as to contribute in creating a sustainable, healthy and efficient Mongolian livelihood.

1. Introduction

Pastoralism in Mongolia is a subject to the harsh environment of the continental northern latitudes. Additionally, in recent history erratic environmental conditions and human activity have increased pressure on the pastoral life.

From around 1960 until 1990, the Mongolian livestock sector was organized into collective-based agricultural systems (Mongolian Society for Range Management, 2010). Planning, maintenance, training, infrastructure development and all general support were managed centrally. After the political change to a market economy in 1990, farming collective workers were given their share of the dismantled collectives in the form of livestock and jobless factory

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workers moved to the countryside. This sharp increase in inexperienced herders with little government support and oversight combined with universal constitutional rights of free access to all land and a new need for individual subsistence led to a rapid increase in livestock populations from 1992 until 1999 (Jamsranjav, 2009). A test of this fledgling livestock system came with two successive dzuds (harsh winters) during the winters of 1999–2000 and 2000–2001 where 11 million cattle, sheep and goats were lost. Most losses were due to a lack of access to food trapped under a frozen snow cover (Mahul and Skees, 2006). Too many animals were competing for scarce resources, especially after no institutions remained to manage reserve pasture grounds and emergency fodder (Jamsranjav, 2009). The effects of dzuds on the people of Mongolia are great, considering that 1 million people, or more than one-third of the total population, depend on livestock farming for their livelihood (Mongolian Society for Range Management, 2010).

These dzuds struck while overpopulation was beginning to accelerate pasture degradation and disease transmission. Pasture degradation is estimated to approach 70% (Trachtenberg, 2009). In 1991, 0.8% of the cattle population was infected with brucellosis and by 2002 the average prevalence was 2%. Zinsstag et al. (2005a) describe in their livestock–human brucellosis transmission model that in the year 2000, the Mongolian authorities started a mass vaccination of their ruminants. However, the onset of the vaccination campaign coincided with consecutive snow–storm disasters in the winters 1999–2002, the loss of millions of animals, and a break down in veterinary services.

The herders rallied with the help of more mild weather and from 2002 to 2009 Mongolia's small ruminant and cattle population grew by 84% (National Statistical Office of Mongolia, 1970–2011). Another more devastating dzud during the 2009–2010 winter caused 9.7 million animal losses out of a record high of 44 million Mongolian livestock (Swiss Agency for Development and Cooperation in Mongolia, 2011). Many herders lost their entire herd and Mongolia‘s urban population has continued to swell, piling more stress on an already strained nation (National Statistical Office of Mongolia, 1970–2011; Swiss Agency for Development and Cooperation in Mongolia, 2011).

The study of species population dynamics has accelerated since the mid-20th century. Competitive exclusion was studied by Thomas Park in respect to his experiments with two species of flour beetles (Park, 1948, 1954, 1957). The dynamics of fish populations were described mathematically in discrete, age-structured fashion by Beverton and Holt (1957). Leslie et al. (1968) and later Edmunds et al. (2003) honed the modeling of species competition in discrete time. More recently, interspecies competition was modeled by Pathikonda et al. (2009) in the context of wetland Irises.

Mongolian agriculture has been supported by models for vegetation growth, pasture productivity and brucellosis transmission (Center for Natural Resource Information Technology, 2011; Zinsstag et al., 2005a). The latter included a simple model for livestock population dynamics, which was fitted to official data from 1990 to 1999, but utilized no carrying capacity. A subsequent model analyzed the effect of mass vaccinations and carrying capacity on transmission dynamics (Alonso, 2007).

Since infectious diseases such as brucellosis are transmissible between different livestock species, an understanding of multiple livestock population dynamics is important to understand disease transmission. Zinsstag et al. (2005a) extended this even to humans. In Mongolia, sheep, goats, cattle and horses usually graze together, using the same pasture. To assess the use of pastoral resources by livestock, a multi-species demographic model considering respective pastoral use in terms of reference livestock units are more appropriate than that of single species models. Our objective was to develop an age and sex specific demographic model to simulate past and predict future Mongolian livestock populations while considering varying socio-political and environmental factors.

2. Methods

2.1. Model description

We model livestock population dynamics with difference equations with discrete time steps of one year. The model is based on the Leslie–Gower competition model which uses a modification of the Beverton–Holt function and is a discrete analogue of the Lotka–Volterra two species differential equation competition model (Cushing et al., 2004; Leslie and Gower, 1958). The model includes four species (goats, sheep, horses and cattle) with a constant migration rate, constant per-capita birth and culling rates, and density-dependent mortality rates.

We assume that the effect of a dzud on livestock populations is density dependent, while population dynamics during relatively stable environmental conditions are dominated by density independence. While normally population changes due to extreme weather are considered to be density independent, we believe that the dzud presents an exceptional case. Herders report a lack of access to food that was trapped under layers of ice and that animal losses were due to starvation. Therefore, most animal losses were as a result of competition over a constrained resource.

We denote the state variables at time t for females and males by X and Y respectively. We use two subscripts: the first subscript 1–3 denotes the age groups newborn, juvenile, and adult respectively and the second subscript (g, s, c, h) describes the species (goat, sheep, cow, or horse) respectively. Goat and sheep newborns, juveniles, and adults remain so from age 0–1, 1–2 and >2 years old respectively. Cattle and horses spend two and three years, respectively, in the juvenile class, so cattle newborns are of age 0–1, juveniles of age 1–3, and adults are of age >3, and similarly horse newborns are of age 0–1, juveniles of age 1–4, and adults are of age >4. We represent the additional juvenile classes with a third subscript, (a, b, c) to represent the first, second, and third (for horses) year of the juvenile stage respectively. Therefore, for example, X_{2ca} would represent female juvenile cattle of age 2, and $Y_{3\,s}$ would represent adult male sheep. Fig. 1 is an example graphical representation of the model dynamics of goats.

The four species follow a birth pulse pattern so that each age class models a cohort born around the same time. This is mainly due to the climatic conditions which favor