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Assessing both ecological and engineering resilience of a steppe agroecosystem using the viability theory

R. Sabatier[a,*], F. Joly[b,c], B. Hubert[d]

[a] INRA, Université Paris-Saclay, UMR SADAPT, 16 rue Claude Bernard, 75005 Paris, France
[b] Association pour le cheval de Przewalski: TAKH, Station Biologique de la Tour du Valat, Le Sambuc, 13200 Arles, France
[c] ABIES/AgroParisTech, 19 avenue du Maine, 75015 Paris, France
[d] INRA, UR Ecodéveloppement, Domaine Saint-Paul, 84000 Avignon, France

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ABSTRACT

The high dependence of rangeland-based livestock farming systems to environmental uncertainty makes the resilience of these systems as important as production. Quantification of resilience is however difficult to conduct in real systems due to their low reproducibility. In this study, we develop a modeling approach to quantify both engineering resilience (return time after a perturbation) and ecological resilience (magnitude of a perturbation that a system can bear) of a mixed herd livestock farming system in Mongolian steppes. The model, build within the framework of the viability theory, captures the dynamics of the herd and its management. The system has the particularity to be impacted by agro-climatic events called *dzuds* that induce massive mortalities when harsh climatic condition and high stocking densities are met. Results show that (i) resilience non-linearly depends on herd composition and the level of underground biomass of the system, (ii) contrasted management strategies may be followed to cope with the risk of *dzud* and (iii) according to their herd composition most herders of the area can absorb climate shocks unless they compete for forage with other herders. Results are discussed regarding the impact of forage resource sharing on the resilience of these grazing systems.

1. Introduction

A common issue in rangeland-based livestock farming systems is the high environmental uncertainty (i.e. unpredictability of environmental conditions) on which forage production and animal performances depend (Pickup and Smith, 1993). Due to the high unpredictability of environmental conditions, properties such as robustness, flexibility and resilience of the system become as important as more straight-forward dimensions such as the average level of production (Carande et al., 1995; Berkes et al., 2000; Vetter, 2005). However quantifying such properties in the real world remains a challenge. Studying the ability of a system to deal with uncertain events indeed requires studying the system over the long term and in a wide set of environmental conditions, which is hardly achievable in the field. Modeling approaches, therefore appear to be a good alternative to approximate such properties. Models, by simplifying reality and making explicit the point of view given on the system are a powerful tool to capture complex behaviors and asses non-trivial properties such as resilience. Especially, recent development of the mathematical framework of the Viability Theory (Aubin, 1991) made it possible to compute metrics such as robustness (Anderies et al., 2004, Accatino et al., 2014, Sabatier et al., 2015b), flexibility (Sabatier et al., 2015a, Mathias et al., 2015), vulnerability (Rougé et al., 2015) or resilience (Martin, 2004, Martin et al., 2011, Rougé et al., 2013) in a wide range of semi-natural systems such as forests, grasslands, savannahs or lakes. The viability theory is a mathematical framework that applies to the dynamics of state-control systems. It aims to look for the set of initial situations and management options that make it possible to maintain the system within a set of constraints through time.

In the current study we intend to apply the viability theory framework to the quantification of two forms of resilience of a rangeland-based livestock farming system depending on highly variable environmental conditions. Holling (1996) indeed distinguishes two forms of resilience: (i) engineering resilience relates to the time that a system needs to come back to a steady state (or more generally to a desirable area) after a perturbation; (ii) ecological resilience relates to the magnitude of the perturbation that a system can absorb before shifting to another behavior. These two forms of resilience therefore characterize the ability of the system to recover after a perturbation (engineering resilience) or to absorb it (ecological resilience).

We apply this approach to mixed-livestock farming systems of the steppe regions of Mongolia. These systems are particularly illustrative

* Corresponding author.
E-mail address: rodolphe.sabatier@agroparistech.fr (R. Sabatier).

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of the impact of environmental uncertainty on rangeland dynamics. Beyond the overall harsh climatic conditions (low rainfall, low temperatures in winter) observed in these systems, they are characterized by a high level of climatic uncertainty resulting in unpredictable bioclimatic events locally called *dzuds*. These *dzuds* qualify bioclimatic catastrophes in which a convergence of low forage availability and particularly harsh winters lead to massive mortalities in herds. This is a non-linear effect characterized by a threshold effect on mortality that depends on both exogenous (climate) and endogenous (grazing intensity) factors (Tachirii, 2008).

After presenting the case study in more details, we develop a dynamic and stochastic model of a mixed-herd Mongolian livestock farming system within the framework of the viability theory. The objective of the model is to capture the key agro-ecological dynamics so as to help understanding the behavior of a real system while remaining simple enough to remain comprehensible. It shall therefore not be considered as an illusory attempt to produce a faithful reproduction of the real system, but rather as a simplification of it so as to understand its main properties. This model is then used to characterize both ecological and engineering resilience of the set of possible herd compositions. Results are finally compared and discussed regarding the herd-composition of real farmers from the study area.

2. Material and methods

2.1. Case study

The model is based on a case study of livestock farming-systems of the Mongolian Gobi, in the region of Khomyn Tal. The case study is fully detailed in (Joly et al., 2012, Joly et al., 2013, Joly, 2015) and we will only focus here on a few key elements at the basis of the model we built.

The study area, is located on the western part of Mongolia. Khomyn Tal is a vast plain of 2900 km^2 delimited by natural borders (sand dunes in the south, lakes at the west and river in the east), which makes it a (relatively) closed system. Its substrate is mostly made of wind and lake deposits, at a mean altitude of ca 1250 m. There is a small rocky range culminating at 1666 on its southeast. Approximately 50 herders live there with their livestock and statistics obtained from the local Durvuljin office of the National Statistical Office of Mongolia (NSOM), indicate that they had in 2013 a total of 10,000 goats, 7400 sheep, 1600 horses, 700 cattle and 400 camels.

On the climatic point of view, the system is characterized by harsh conditions with low annual rainfall (95 mm), and cold winters (mean temperature − 18 °C from December to February). It is also characterized by high climatic uncertainty leading to specific bioclimatic events locally called *dzud* that corresponds to a sudden mortality of a high proportion of the herd due to a conjuncture of low food availability and a harsh winter resulting in a large share of the herd not being able to make it through the winter. A *dzud* is characterized by both endogenous and exogenous factors, its occurrence indeed depends both on the state of the forage resource regarding the size of the herd and on climatic conditions (cold temperatures and/or high snowfalls in winter). It is a partly stochastic process that introduces non-linearity to the dynamics of the system. Due to this both endogenous and exogenous origin of the *dzud*, one shall distinguish the climatic hazard from the *dzud* itself since it is therefore possible that a dzud does not occur in bad climatic conditions due to good livestock-forage ratio.

On the farming point of view, the main specificities of the livestock farming systems of the area are transhumance and association of multiple herbivore species. The system is transhumant in the sense that farmers use different areas in the different seasons but come back to the same places every year (Joly et al. 2013). This system relies on mixed herds composed of sheep, goats, cattle, horses and camels. Herders regroup the animals in two functional types locally called *bod* and *bog* characterized by different properties and functions. The *bog* type regroups the two species of small animals (goat and sheep). These species have in common to be a reliable and regular source of income for the farmer (especially the goat which wool is sold as cashmere) but are on average more sensitive to *dzuds* than *bods*. The *bod* type regroups the three species of big animals (cattle, horses and camels). They have a high commercial value per animal and constitute a strong capital. Beyond this monetary value these species fulfill several additional functions within the system. Cattle are used for milk production (for self-subsistence). Horses have a strong cultural value and are still partly used for herd management. Camels used to be the main source of draft power but this task is being progressively transferred to 4WD vehicles in modern systems and remaining camels correspond more to a cultural heritage in current systems. Due to their bigger size (and their higher level of body reserves), *bods* on average resist better to *dzud* than the *bogs* do. Due to their high monetary value and their strong resistance to dzuds, they therefore fulfill an insurance function within the farming system. This distinction between these two functional types (animals able to resist climatic hazards and animals with a high growth rate) is a common feature in arid and semi-arid livestock farming systems (Blench and Marriage, 1999).

2.2. Model

2.2.1. Qualitative description of the model and viability approach

To assess the resilience of the system, we define a discrete time state-control model of herbivore-biomass interaction at the scale of one livestock farming system. The model (Fig. 1) is stochastic in the sense that it accounts for uncertainty on climatic events and is defined on a yearly time step and in finite time (horizon T = 20 years). It accounts for livestock herd and plant biomass dynamics. To limit the number of dimensions of the system, livestock is described using two state variables corresponding to the two functional types mentioned above: *bog* and *bod*. This involves a simplification compared to the real system but basing this simplification on functional categories of animals (instead of considering only two species for example) is the best trade-off that we could find between reducing the size of the state space and describing accurately the system. The characteristics of these functional types (reproduction rates, mortality, etc. …) are calibrated as the mean of the characteristics of the different species they regroup, weighted by their average proportions as observed in herds of the case study. Forage biomass is characterized by above and underground biomass. Regarding forage, only the underground biomass is explicitly defined as a state-variable, above ground biomass only depending on the underground biomass and summer rainfall of the current year. The dynamics are controlled by two control variables representing the number of

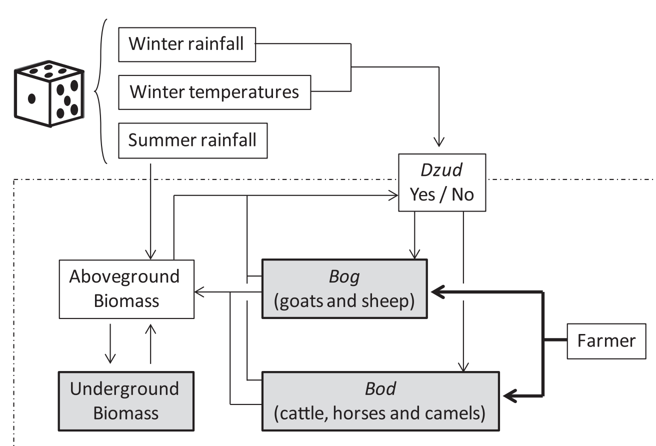

Fig. 1. Conceptual diagram of the model. Grey boxes stand for the states of the system, white boxes are the intermediate variables. Bold arrows stand for the controls. The dice illustrates climate stochasticity.