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Sensitivity analysis of the recovery dynamics of a cattle population following drought in the Sahel region

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ABSTRACT

Dynamics of cattle populations in arid and semi-arid tropical Africa are highly influenced by droughts, which can create dramatic drops in herd sizes as well as disturbances in sex-and-age structures. The Sahel region is particularly affected by such climate shocks. Successive major droughts are assumed to have effectively decreased the cattle stock and strongly influenced the evolution of pastoral and agro-pastoral systems in the past 40 years and probably before. Demographic resilience, i.e. the ability to recover from significant losses, is a key parameter for the sustainability of livestock populations in systems regularly perturbed by demographic shocks, and thus for prospective studies of the livestock sector, in particular for cattle that are more vulnerable to feed shortage than small ruminants and have a slower biological turnover. Here, a simple mathematical herd growth model is used to simulate the post-drought dynamics of a hypothetical Sahelian cattle population taken as example. A set of scenarios describing the drought severity, herd performances and management practices was considered in a global sensitivity analysis. The resilience was measured by the probability to recover, the recovery time of the population and its annual growth rate during the recovery period. An important finding of the study was the extreme variability of the recovery time. This variability challenges the common postulate according to which 10–15 years are needed for a cattle population to recover after a 'severe' drought. This also emphasizes the difficulty of obtaining reliable recovery predictions from inaccurate estimates of demographic parameters. Simulations showed that the proportion of population size decline due to the shock, the calving rate and farmers' offtake strategy after the drought are overall the most influential factors for recovery dynamics. Simulations also showed that the recovery time can be highly influenced by the transient regime of the herd growth model when the post-drought sex-and-age structure is non-equilibrated. In particular, the sensitivity analysis confirmed that large losses of breeding females during shocks considerably delay herd regeneration.

1. Introduction

Dynamics of cattle populations in arid and semi-arid tropical Africa are highly influenced by droughts (Tacher, 1975; Dahl and Hjort, 1976; Bekure et al., 1991a; Coppock, 1994). Droughts cause animals' mortalities through starvation, emergency slaughtering and sales, or definitive herds' migrations, that can create severe drops in cattle population sizes as well as disturbances in sex-and-age structures (Tacher, 1975; McCabe, 1987; Coppock, 1994; Oba, 2001a). Disease outbreaks frequently interfere with undernutrition to aggravate mortalities (Rodgers and Homewood, 1986; Cossins and Upton, 1988a; Grandin, 1991; Scoones, 1992; Oba, 2001a), further delaying population recovery. Like other dry areas, the Sahel region is particularly affected by such climate shocks. In particular, the 1972–1973 and 1983–1984 major droughts are assumed to have decreased the cattle stock and strongly influenced the evolution of pastoral and agro-pastoral systems (Toulmin, 1986; Pradère, 2007). Although unpredictable and not periodically cyclical, droughts are considered as recurrent events in dry areas (Bekure et al., 1991b; Ndikumana et al., 2000; Brooks, 2004).

Understanding and modeling cattle population dynamics in arid and semi-arid rangelands is a complex issue. Environmental conditions, including feeding and animal health constraints, are strongly variable even in absence of drought. The question of the main drivers of rangelands and herbivores dynamics, e.g. the relative importance of unpredictable environments vs. density-dependent mechanisms, has been discussed for long (Illius and O'Connor, 1999, 2000; Desta and Coppock, 2002) and is still actively debated (Vetter,

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2005). One issue that has less been tackled is the 'demographic resilience' of cattle populations, i.e. their ability to recover from significant losses in animal numbers. Resilience is a key parameter for the sustainability of livestock populations in systems regularly perturbed by demographic shocks, and thus for prospective studies of the livestock sector. Two resilience indicators are of particular importance: the time needed for the population to recover after a drop in size, and the population growth rate during the recovering period.

These two indicators are very uncertain for most of the tropical cattle populations, principally due to the difficulty of getting reliable time series on herd sizes in pastoral and agro-pastoral systems. This situation affects particularly the Sahel region. This is illustrated in Table 1 where resilience estimates that we found in literature mainly come from the Horn of Africa. Furthermore, even when documented, most of the estimates in Table 1(a and b) have been obtained from sparse incomplete time-series collected from ground or aerial censuses, approximate retrospective data collected by farmers' interviews and their recall of long-term herd demography, or hypothetical simulations by herd growth models. Administrative national data on livestock numbers and the derived FAO statistics are generally unhelpful for studying recovery dynamics in the Sahel since they are most frequently based on hypothetical annual growth rates arbitrarily set by national services or FAO. For instance, annual growth rates used for building the 1985–2000 recovery period of the cattle population in Chad, Mali and Niger following the 1983–1984 drought were assumed almost constant and around 2% per year (except 1 year at 12%), 2% per year and 6% per year, respectively (FAO, 2011). Another difficulty when analyzing time series of animal numbers is that recovery dynamics are generally interrupted by new shocks or changing environments and thus rarely observed on the entire cycle.

In spite of such uncertainties, the variability of recovery dynamics has been little tackled in the past. In an East African context, Cossins and Upton (1988a) claimed that cattle population recovery after severe droughts may take 10–15 years. This seems to have been taken for granted for arid and semi-arid areas (Toulmin, 1986; Ndikumana et al., 2000). Nevertheless, preliminary model results from Tacher (1975) in Chad after the 1972–1973 drought tend to show much higher variability of recovery time. In the present work, we expanded the sensitivity analysis of Tacher on the demographic resilience of a hypothetical Sahelian cattle population following a drought event. A simple mathematical herd growth model was used to simulate the population dynamics depending on twelve factors of variations (against two in Tacher, 1975) describing drought severity, herds' biological performances and farming practices. The resilience was measured by the recovery time of the population after the drought and its growth rates during the recovery period. A first objective of the sensitivity analysis was to estimate the variability of the demographic resilience. A second objective was to identify the most influential factors on the demographic resilience of cattle population.

2. Materials and methods

2.1. The herd growth model

A Leslie matrix model (Leslie, 1945; Caswell, 2001) was used to simulate the cattle population dynamics at a 1-month time step. Dynamics were defined by:

$$x(t+1) = B \times x(t)$$

where $x(t)$ and $x(t+1)$ represent vectors of numbers of animals (by sex and 1-month age class) living in the population at months t and $t+1$, respectively. B is the 1-month projection matrix containing the monthly calving and survival rates by sex and 1-month age class. Lesnoff (1999) and Lesnoff et al. (2000) illustrated the structure of such projection matrices for livestock dynamics.

In each month interval $(t, t+1)$, births are calculated as:

$$b = f_{\mathrm{calv}} \times n_{\mathrm{r}}$$

where $n_{\mathrm{r}}(t)$ is the number of reproductive females (defined as females older than a given age class) present at time t, and f_{calv} the net calving rate (i.e. the expected number of calves born alive per month and reproductive female). The survival of each sex-and-age class i is calculated as:

$$x_{i+1}(t+1) = (1 - p_{\mathrm{dea},i} - p_{\mathrm{off},i}) \times x_i(t)$$

where $p_{\mathrm{dea},i}$ and $p_{\mathrm{off},i}$ are the probabilities of natural death and net offtake for class i, respectively. Net offtake represents animals leaving definitely the population, e.g. by slaughtering, sales, gifts or outmigration.

2.2. Simulation principle

The general principle was to simulate the dynamics of a cattle population after a pre-defined shock. The shock was assumed to have two direct impacts: a population size decline (proportion of animals' losses) and an eventual disturbance of the sex-and-age structure of the population. Structure disturbances have frequently been observed in cattle herds after droughts (Tacher, 1975; Rodgers and Homewood, 1986; McCabe, 1987; Cossins and Upton, 1988a; Coppock, 1994; Angassa and Oba, 2007). They are due to specific mortalities, slaughters and sales for defined animal sexes and ages, and to the low calving rate during drought which deflates the proportion of calves in herds.

After the shock, it was assumed that no animals are imported from outside the population for accelerating the recovering. Thus, the model represented endogenous population dynamics. For simplification, demographic rates (reproduction, mortality and offtake) were assumed to remain constant after the shock: for instance, rates were not enhanced by the relieved competition for resources following the drop in population nor deflated by eventually limiting feeding or watering resources when the population increased. Furthermore, no additional shocks were simulated after the initial one. This enables complete recovery when resilience is positive. In other words, for a given simulation (i.e. a population recovery trajectory), the matrix B was constant across all the time intervals $(t, t+1)$. The sensitivity analysis involved varying the decline in population size, the sex-and-age structure just after the shock and the rates in matrix B.

Each matrix-B value considered in the analysis represented a mean year, discarding seasonal variations and averaging the basal between-years variability (i.e. without drought) of demographic rates. The values of these mean rates depended on two sets of factors: the herds' biological performances and the management practices (both during the post-drought period). In the sensitivity analysis, these values were randomly sampled from probability distributions as explained in Sections 2.5 and 2.6.

2.3. Model outputs

For each recovery trajectory, three outputs were calculated from the model when the population was able to recover. If $t = 0$ is the starting time for the simulation (i.e. the time just after shock), the population size at any time $t \geq 0$ is

$$n(t) = \Sigma_i x_i(t)$$

If n is the population size just before the drought, the value

$$1 - \frac{n(0)}{n}$$