A viability model to assess the sustainability of mixed herds under climatic uncertainty.

Jocelyne J. Porcher, Bernard Hubert, Luc Doyen, Didier Genin

To cite this version:

Jocelyne J. Porcher, Bernard Hubert, Luc Doyen, Didier Genin. A viability model to assess the sustainability of mixed herds under climatic uncertainty.. Animal Research, 2004, 53, pp.405-417. 10.1051/animres:2004024 . hal-02675580

Anim. Res. 53 (2004) 405–417

DOI: 10.1051/animres:2004024

Original article

A viability model to assess the sustainability of mixed herds under climatic uncertainty[1]

Muriel TICHIT[a*], Bernard HUBERT[b], Luc DOYEN[c], Didier GENIN[d]

[a] UMR INRA SADAPT – INAPG, 16 rue Claude Bernard, 75231 Paris Cedex 05, France
[b] INRA SAD, 147 rue de l'Université, 75007 Paris, France
[c] CNRS – CIRED, Campus Jardin Tropical, 45 bis avenue de la Belle Gabrielle,
94736 Nogent sur Marne, France
[d] IRD, Laboratoire Population, Environnement, Développement, UMR-IRD- Université
de Provence 151, Centre St Charles, Case 10, 13331 Marseille Cedex 3, France

(Received 11 June 2003; accepted 26 February 2004)

Abstract – On the Bolivian arid highlands, breeders' strategies combining herd diversification (llamas and sheep) and the control of breeding rate were assessed under unpredictable environmental conditions. A survey of 14 farms made it possible to characterise practices in llama flocks (controlled and uncontrolled breeding practices) and in sheep flocks (high care and low care practices). The efficiency of these practices was evaluated using annual numerical productivity indexes. To assess the effectiveness of these practices, a dynamic model of mixed herds, based on the mathematical framework of the viability theory, was developed. The model made it possible to analyse the long-term interactions between management practices and climatic uncertainty on livestock system sustainability. Numerical productivity at weaning was found to be significantly lower in llama flocks managed with controlled breeding compared to uncontrolled breeding (44% and 70% respectively). For sheep, numerical productivity at weaning of high-care flocks was not significantly higher than that of low-care ones (83% and 69%, respectively). It was not possible to conclude whether high-care practices were more efficient in increasing numbers than low-care ones. On a long-term perspective, the dynamic analysis showed that the control of the llama flock breeding rate stabilises the evolution of the mixed herd only when a low offtake rate can satisfy a minimum income. Thus, foregoing short-term yield can be a sound strategy to insure mixed herd viability in an extremely harsh and unpredictable environment. However, the effectiveness of this practice is closely related to wealth (herd size). The model is discussed in terms of its heuristic value for assessing management practices and sustainability of pastoral systems.

mixed herd / dynamic modelling / viability theory / uncertainty

Résumé – Viabilité de cheptels mixtes sous incertitude climatique. Ce travail évalue les stratégies des éleveurs des hauts plateaux boliviens confrontés à un environnement incertain. Celles-ci combinent la diversification de la composition du cheptel (lamas et ovins) et le contrôle du rythme de reproduction. Un suivi conduit dans 14 élevages caractérise les pratiques dans les troupeaux de

---

[1] This study was conducted at the French Institute of Research for Development (IRD).
* Corresponding author: tichit@inapg.fr

lamas (pratiques de reproduction « contrôlée » et « non contrôlée ») et dans les troupeaux d'ovins (« gardiennage rapproché » et « laisser faire »). L'efficacité de ces pratiques est évaluée à l'aide d'un indicateur de productivité numérique. L'effectivité des pratiques est évaluée à l'aide d'un modèle dynamique de cheptel multi-espèces basé sur le cadre théorique de la viabilité. Le modèle permet d'analyser l'effet des interactions entre les pratiques de conduite et l'incertitude climatique sur la durabilité du système d'élevage. La productivité numérique au sevrage est significativement plus faible dans les troupeaux de lamas dont le rythme de reproduction est contrôlé comparativement aux troupeaux non contrôlés (respectivement 44 % et 70 %). Dans le cas des troupeaux d'ovins, les différences de productivité numérique au sevrage pour les deux types de pratiques identifiés ne sont pas significatives (respectivement 83 % et 69 %). L'analyse dynamique montre que le contrôle du rythme de reproduction du troupeau de lamas stabilise l'évolution du cheptel multi-espèces uniquement dans les situations où un revenu minimum peut être assuré à partir d'un faible taux d'exploitation. Renoncer à un profit dans le court terme constitue une stratégie de précaution assurant la viabilité du cheptel dans un environnement difficile et non prévisible. Cependant, l'effectivité de ces pratiques est étroitement dépendante de la taille du cheptel. Le modèle de viabilité est discuté au regard de sa valeur heuristique pour évaluer des pratiques de conduite et la durabilité du système d'élevage.

cheptel mixte / modélisation dynamique / théorie de la viabilité / incertitudes

1. INTRODUCTION

Pastoralism often takes place in variable environments such as drylands and breeders adopt strategies to anticipate the impact of droughts [33]. Herd diversification is one such strategy that allows coping with uncertainty. The holding of several species provides securities in the event that conditions could be unfavourable to a given species [22, 24]. The question of which and how breeders' practices are likely to promote system sustainability by anticipating uncertainty has been a matter of controversy. Roth [29] and Sandford [30] argued that in order to avoid herd destitution, pastoralists should maximise the breeding rate of their herd between two droughts. Conversely, empirical data reported some breeding practices consisting in reducing herd growth rate [6]. Using modelling techniques, Mace [23] demonstrated that the reduction of the breeding rate in East African pastoralists' herds can be interpreted as a strategy to maximise long-term family survival. In our opinion, these apparently contradictory arguments are related to the problem of the long-term assessment of the performance of livestock systems and to risk integration [1].

The Bolivian highlands are a typical example of a harsh and arid environment. Breeders hold mixed herds of llamas and sheep, which are managed with large variation with regards to breeding practices of llamas [35]. Even with good range forage availability, some breeders slow the breeding rate of llamas by controlling the number of females that are allowed to mate. These practices are likely to influence annual herd production as well as its long-term dynamics. Breeders applying such practices may be driven by a precautionary behaviour. Evaluating these management practices is riddled with methodological difficulties in the identification and assessment of their long-term effects on performances. Researchers who have adopted a systems approach have underlined that the performance of any system needs to be assessed from the dual perspective of efficiency and effectiveness [20, 21]. Efficiency relates the total output produced to the level of input used. This notion cannot adequately capture the system's adaptation abilities. The effectiveness, in turn, allows the assessment of system performances by relating the system behaviour to its aim. It demands to assess practices in terms of effects that may be felt several years ahead. However these effects are difficult to measure in field situations, since they require monitoring of herd performances over several production cycles. Dynamic modelling is therefore an appropriate tool to explore long term interactions between breeders' practices and performance.

The aim of this paper was to assess the sustainability of mixed herds under unpredictable climatic conditions. The objectives were the following: (i) to evaluate the effect of breeding practices on annual flock productivity, (ii) to develop a dynamic model of mixed herd management in order to analyse long-term mixed herd dynamics under management events in the specific conditions of the Bolivian highlands.

2. MATERIALS AND METHODS

2.1. The livestock systems of the Bolivian highlands

Research was conducted at Turco (17°57'S, 68°15'W), located in the western part of the department of Oruro, Bolivia. Elevation ranges from 3800 to 4500 m. The mean annual temperature is 7.6 °C. Frosts are common (almost 300 days per year) and crop production is therefore extremely limited. Mean annual rainfall is 333 mm and is monomodally distributed (95% fall from December to March). However, interannual variation in rainfall is high and unpredictable (150 to 800 mm) and is the major determinant of the year-to-year variation a family may face in livestock yields.

Livestock systems were analysed at the farm level, which is the herd ownership and the decision-making unit for herd management. These systems have several peculiarities [35]. The capital invested in the animals represents the most important input, since animals are range-fed on rangelands. The herd is also the main source of output for the subsistence of breeders. Both species have a particular sensitivity to between-year variations in rainfall. When forage availability is not a constraint, sheep flocks have a higher increase in numbers than llamas. In case of drought, they are liable to heavy losses, whereas llamas survive better. For both species, all young females are retained as replacements for the breeding flocks and this retention is subject to high between-year variations. To secure their subsistence requirements during any one year, breeders either slaughter for consumption or sell young male stock. Young male offspring are usually insufficient to cover subsistence and a varying proportion of breeding females of each species is culled for consumption and sales.

2.2. Numerical productivity as an indicator to assess the efficiency of breeding practices

A survey was designed to identify the variables and estimate parameters that influence herd dynamics under climatic uncertainty. Data were collected on a monthly basis during 1995 and 1996 from 14 farms [35]. No statistical sampling methodology was used in choosing the farms surveyed, but an attempt was made to cover the diversity of herd composition and management practices observed in previous typology [36]. It involved the accurate herd recording of a population of 800 llama females and 1500 ewes and a quantification of economic requirements of families representing the annual cash value necessary to cover current expenses [27]. To assess flock yield, estimates of production traits (such as fecundity, mortality) were calculated. Breeding practices applying to each species were evaluated using the numerical productivity index. It expresses the number of offspring weaned per year as a percentage of the number of breeding females.

2.3. The mixed herd model

The viability theory was used to analyse long-term mixed herd dynamics under uncertainty. Basically, the viability approach focuses on inter-temporal feasible paths. This mathematical framework developed by Aubin [2] deals with the control of uncertain dynamic systems under state and control constraints. It first requires the identification of a set of constraints that represents the survival or by extension the "good health" of a system. The viability of a dynamic system is related to the maintenance of these conditions at any time, including both the present and future. Similar analyses in other contexts have been proposed by Béné [5], Bonneuil [7] and Doyen [11].

2.3.1. Model structure

The system modelled was a family's herd consisting of two flocks of breeding females: llamas and sheep. The structure of the model was based on the herd composition model developed by Mace [24]. The model relies on a state-space representation of the problem [25]. The state variable is the total family's wealth $x(t)$ composed of the numbers of $y_i(t)$ breeding females in each flock: $y_1(t)$ llamas and $y_2(t)$ sheep. Total wealth is expressed in monetary units by weighting the number of females of each species by its sale price: $x(t) = p_1 y_1(t) + p_2 y_2(t)$. Three control variables represent the breeder's management decisions: (1) the total offtake rate of females $e(t)$ according to the family's needs, and (2) the herd composition $u(t) = (u_1(t), u_2(t))$, through which the breeder can manipulate the proportion of each species. Only adult females are sold or slaughtered, all young females are kept for replacement in the breeding herd. These management decisions closely determine the rate of growth of numbers within the herd.

No density-dependent regulation for the natural rate of growth of female numbers is assumed since the density of the animals is relatively low in this region [15]. However, this parameter is influenced by rainfall variability since droughts are likely to be severe enough to cause adult female and offspring mortality. The impact of rainfall variability is represented for each species i by a natural growth rate $r_i(\gamma(t))$ which depends on a climatic variable $\gamma(t)$.

Wealth evolution may then be described by the differential equation (1):

$$\dot{x}(t) = \frac{dx}{dt}(t) = x(t)\left(\sum_{i=1,2} u_i(t) r_i(\gamma(t)) - e(t)\right),$$

where is $u_1(t) = \frac{p_1 y_1(t)}{x(t)}$ the proportion of wealth allocated to llamas and $u_2(t) = \frac{p_2 y_2(t)}{x(t)}$ is the proportion of wealth allocated to sheep. Herd composition is a decision that might not be radically changed as long as herd viability is not at stake. It is assumed that current total offtake $e(t)$ is bounded through the relation (2): $0 \le e(t) \le e_{\max}$. The upper bound on the total offtake variable makes it possible to consider the relatively low offtake rate applied since breeders do not maintain their herds at a constant size but aim at an increasing herd size [35].

Furthermore, the breeder needs to secure a minimum income C at any time. It represents the cash value needed to secure the annual family's subsistence requirements when all male offspring have been sold. This is a fixed value, estimated for a reference family [35]. The highest offtake rate on females does not lead the herd to extinction. This means that offtake decisions are determined by the need to meet a minimum income without jeopardising herd existence in the future. Therefore, the minimum income constraint reads as follows (3): $e(t)x(t) \ge C$, $\forall t \ge 0$ where $C > 0$, thus the viable offtake of females at every point in time depends on the current wealth. The minimum income constraint (3) mixed with inequality (2) provides the state constraint $x \sup_{0 \le e \le e_{\max}} [e] \ge C \Rightarrow e_{\max} x > C$, which induces a minimum wealth level $x_{\min} = \frac{C}{e_{\max}}$. To summarise the state constraints, K denotes the constraint set defined by (4): $K = [x_{\min}, +\infty[$ and control constraints are summarised by (5): $\frac{C}{x(t)} \le e(t) \le e_{\max}$ and $0 \le u_i(t) \le 1$, $\sum_{i=1,2} u_i(t) = 1$.

Moreover, it is assumed that climatic variable $\gamma(t)$ fluctuates within a given bounded Γ set of two extreme values (6): $\gamma(t) \in \Gamma \ \forall t \geq 0$. Thus Γ stands for the possible climatic scenario at each time. The model is not limited by the need to provide any statistical data on the distribution of the climatic variable. The need for that is eliminated by the adoption of a worst case and totally risk-averse approach related to robust control and differential games [3, 8]. This robust framework is specified in the following paragraph.

2.3.2. Dynamical analysis: a robust viability framework

The compatibility between system dynamics and constraints needs to be studied in a robust framework. The identification of decisions and states that ensure the satisfaction of viability constraints at all times is required, despite uncertainties that may exist. The aim was to identify all the initial wealth levels (i.e., herd size) at which the breeder can secure his minimum income by female offtake at every point in the future, and this for every possible scenario. This refers to the computation of the viability kernel [2] in a robust framework. The viability kernel is the set of initial wealth levels x_0 from which there exists decisions $(e(t), u_1(t), u_2(t))$ that yield wealth evolutions $x(t)$ associated with dynamics (1) such that the whole constraints (5) holds true for every time. However due to the presence of exogenous uncertainty $\gamma(t)$, careful attention has to be paid to the strategy used in the decision variables. Here, non anticipative strategies are considered, which means that current decisions $e(t), u_1(t), u_2(t)$ depend on the past and present realisation of uncertainty $\gamma(.)$, but not on its future values which are unknown and unpredictable (see [8] for more mathematical details).

In a robust framework with such strategies, the viability kernel *Viab* is defined by the set of initial wealth levels x_0 from which there exists a non-anticipative strategy for current decisions such that any possible climatic scenario (6) generates wealth trajectories $x(t)$ of the dynamics (1) that satisfy constraints (5) for every time. This definition of robust viable wealth or viable herd means that in a long-term horizon, there exists decisions such that, despite climatic perturbations, the herd remains viable (i.e. beyond the threshold at which female offtake satisfies a minimum income without compromising future herd evolution).

3. RESULTS

3.1. Description of breeding practices

Our survey showed that breeding practices varied greatly between both species and among flocks for a given species. Breeding practices are defined as the combination of mating practices and caretaking practices (breeder's intervention on the mother- young relationship at parturition).

Mating practices, varied among llama flocks. Some breeders bred all adult females each year ("uncontrolled flocks"). Others selected for mating two-year-old females, females that did not produce any offspring in previous years and females that had lost their offspring within their first weeks of life ("controlled flocks").

No particular trend was observed for the mating practices among sheep flocks, but two types of flock caretaking were observed for this species. Some breeders induced the ewes to remain near their lambs to facilitate the formation of bonds ("high care flocks"). Others had low flock supervision at lambing and many lambs were abandoned a few hours after birth. In order to control the mortality of these lambs, breeders usually have to bottle-feed them ("low care flocks").

3.2. Flock numerical productivity at weaning as an indicator to evaluate breeding practices

Uncontrolled llama flocks reached higher annual numerical productivity than controlled ones (70% and 44%, respectively). Due

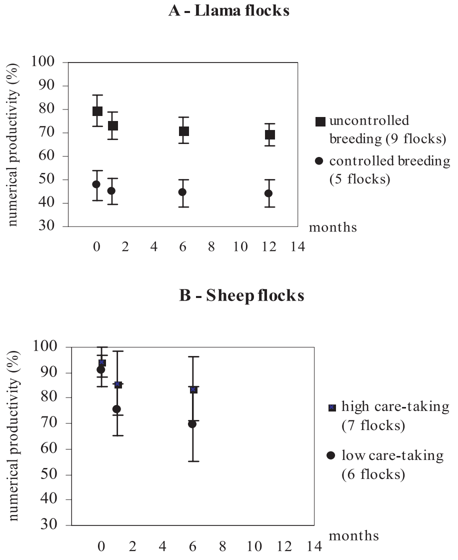

Figure 1. Evolution of numerical productivity index between parturition (0) and weaning (respectively 6 and 12 months) in llama (A) and sheep flocks (B). For Llama flocks, all means are different between the two types of breeding practices ($P < 0.05$). For sheep flocks, differences between the 2 types of care-taking practices are not significant.

to a lower fecundity rate (47% versus 80%), controlled llama flocks produced 37% less offspring each year than uncontrolled ones (Fig. 1A). This difference is significant ($P < 0.05$), indicating that uncontrolled breeding practices were more efficient than controlled ones.

In the case of sheep, numerical productivity at 6 months of high-care flocks was higher than that of low-care ones (83% and 69%, respectively). However this difference is not significant (Fig. 1B). Both sheep flocks started with the same fecundity rate. The higher decrease in numerical productivity during the first month after lambing in low-care flocks illustrated that bottle-feeding was insufficient to control lamb mortality. The wide variation of this parameter among flocks indicated that our categorisation of caretaking practices was too crude to analyse the multiple factors influencing lamb mortality. In further analysis, differences between both breeding practices will not be taken into account for this species.

Controlled breeding in llamas reduced the number of male offspring for sale as well as the number of females for replacement (in both cases, about half of numerical productivity at weaning, assuming a sex-ratio of 50%). Since numerical productivity influences the natural rate of growth of female numbers, it was difficult to understand why some breeders reduced the breeding rate even in a good year with abundant range forage availability. However, numerical productivity is likely to be extremely variable between years in this area. This situation highlighted that the efficiency of management practices, on the basis of their annual outcomes, only provided a partial assessment, which was inadequate to understand why some pastoralists chose to reduce their annual numerical productivity. It was necessary to take into account the influence of climatic variability over the natural rate of growth of female numbers.

3.3. Effectiveness of management related to family wealth

3.3.1. Influence of climatic variability on flock growth parameters

The difference between the replacement rate and adult female mortality rate allowed the calculation of a crude estimate of the natural rate of growth of female numbers [37]. To determine the variation set of this parameter for each species, our measures of production traits were used for good years and interviews with breeders who reported flock performances during 1983 and 1992 droughts were used for bad years.

In good years, the natural growth rates of the number of females were 30% for uncontrolled llamas, 19% for controlled llamas and 34% for sheep. In bad years, breeders involved in controlling the breeding rate of

Table I. Parameter values used in the simulations.

Minimum income (US$)	$C = 600$
Maximum offtake rate (%)	$e_{\max} = 0.20$
Rate of growth of female numbers:	$r_i(\gamma(t)) = r_i \pm \sigma_i \gamma(t)$
uncontrolled llama flock	$r_1(\gamma(t)) = 0.16 + 0.14\gamma(t)$
controlled llama flock	$r_1^{\#}(\gamma(t)) = 0.12 + 0.07\gamma(t)$
sheep flock	$r_2(\gamma(t)) = 0.16 - 0.18\gamma(t)$
Exogenous uncertainty	$\gamma \in [-1, 1]$
Time (years)	$t \in [1, 20]$

their llamas stated that this practice is aimed at preserving females during bad years. It resulted in a rate of growth of female numbers higher in controlled flocks than in uncontrolled flocks (estimated respectively at 5% versus 2%). In uncontrolled flocks, they reported that lactating females showed reduced survival during drought periods. This qualitative information was congruent with field observations during the 1992 drought where some breeders killed llama offspring in order to save the mother [34]. Conversely, there were no reports that breeding practices could influence the rate of growth of ewe numbers. These were liable to heavy loss during bad years and their rate of growth of female number was always lower than that of llamas (–2%).

In order to take into account the existence of a continuum of possible outcomes between good and bad years, natural growth rate parameters depending on a climatic variable were specified as follows: $r_i(\gamma(t)) = r_i \pm \delta_i(\gamma(t))$ (see Tab. I for values). It should be noted that the actual average growth rate over all years will depend on drought frequency (which is unknown). By choosing a lower value r_i for controlled llama flocks than for uncontrolled ones or sheep flocks, it is assumed that average growth rate in controlled llama flocks will be lower than in uncontrolled ones. This is congruent with the fact that drought years are less frequent than good years. Another fundamental assumption for the flock growth rate parameter is that, whatever the climatic variable γ is, there exists at least one species (llamas) with a positive rate of growth of female numbers.

3.3.2. Analytical results

The viability kernel was characterised for the situations where maximum offtake rate was higher than the combined rate of growth of numbers for both species in drought years: i.e. $e_{\max} \geq \inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i(\gamma)) > 0$.

Under the previous assumptions on flock growth parameters, the viability kernel turned out to be the set $Viab = [x^*, +\infty[$, with the viability boundary defined by $x^* = \dfrac{C}{\inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i(\gamma))}$ (see Appendix 1 for the sketch of the proof and Doyen [12] for the whole proof). This means that for any wealth (herd) x_0 greater that the threshold x^*, the herd is viable in the sense that the income C can be guaranteed along time and for every climatic scenario. Conversely, for any wealth smaller than this viable threshold x^*, a catastrophic climatic scenario might transform every decision into non sustainable situations violating the income constraint.

According to the hypothesis on growth rates, the combined growth rate of a mixed herd with a controlled llama flock resulted in being lower than that of a mixed herd with an uncontrolled llama flock:

$$\inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i^{\#}(\gamma)) < \inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i(\gamma)).$$

This is explained by the fact that controlled llama flocks have a lower average growth rate than controlled ones even if on bad years, their growth rate is higher than that of uncontrolled ones. In this situation, the viability kernel was defined by the set $Viab = [x^{\#}, +\infty[$, with

$$x^{\#} = \frac{C}{\inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i^{\#}(\gamma))} > x^*.$$

Analytical results showed that practices controlling the breeding rate of llama flocks strengthened the evolution of the mixed herd only when the herd was large enough so that a relatively low offtake rate satisfied the minimum income. They also indicated that on the minimum viable thresholds of the viability boundaries $x^* > x_{\min}$, the breeder needed to anticipate the dynamics in order to secure the system viability. Otherwise, offtake decisions could become a negative factor in the herd dynamics, comparable to climatic events. Thus, the only deterministic situation appeared at these critical thresholds i.e. when herd size was on the viability boundary and γ was such that herd yield only ensured a minimum income: $x^* \max_{i=1,2}(r_i(\gamma)) = C$. In this case, the breeder's decisions were reduced to $e^* = \frac{C}{x^*}$ and $u^* = (u_1^*, u_2^*)$ such that he had to exchange all his wealth for the species with the highest growth rate $\sum_{i=1,2} u_i r_i(\gamma) = \max_{i=1,2}(r_i(\gamma))$. The latest decision has been described for several pastoral systems, it is referred to as "upstocking" [24]. In relation to this case study, the exchange of wealth from one species to another is not likely to occur, mainly because the market for immature females is nearly non-existent even on good years. Thus, another decision to avoid herd destitution, which is not taken into account in this model, would be the restriction of consumption. This has been reported by Barth [4] as a way to compensate for income fluctuation.

3.3.3. Simulations

The analytical results are illustrated here with two simulations performed with Mathematica software 3.0 [38]. They made it possible to test the effect of breeding practices and herd composition on mixed herd evolution. Simulations were based on the same climatic scenario which influences the proportional rate of growth of numbers for both species (Fig. 2). By dividing his total wealth between both species (with 60% llamas), the breeder secured long-term herd evolution. Figure 3 shows that the breeder who did not control the breeding rate of his llama flock secured a minimum income at each time period with an initial herd composed of 36 llamas and 76 sheep (i). Conversely, the breeder who chose to control the breeding rate of his llama flock even in good years, needed a larger mixed herd (27% larger in wealth) in order to secure herd viability: 46 llamas and 97 sheep heads ((iii) - Fig. 4). All trajectories starting below the discriminating boundary (a wealth of respectively 3571 and 4478 US$) left the constraint set in finite time (ii & iv). Given that the culling rate depends on herd size, it decreased as herd size increased. Thus, to satisfy the minimum income, rich breeders adopted a lower culling rate than poor ones. For any other situation, within the discriminating kernel, several viable regulations were possible. Figure 4 shows that $e^* = C/x^*$

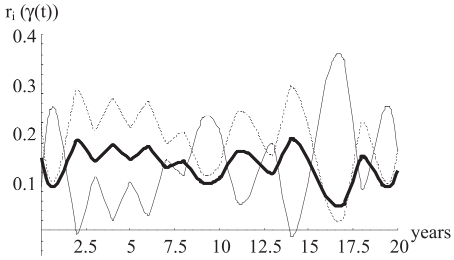

Figure 2. Variability of the rate of growth of female numbers $r_i(\gamma(t))$ for a given climatic scenario. Solid line (sheep), dotted line (llama uncontrolled breeding), thick solid line (llamas controlled breeding). The combined rate of growth of numbers for a mixed herd can be numerically deduced. It stands at the intersection of sheep and llama growth parameter curves (controlled or uncontrolled). It should be noted that it is always lower in a mixed herd with a controlled llama flock [$\inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i^{\#}(\gamma)) = 0.13$] than in a mixed herd with an uncontrolled llama flock [$\inf_{\gamma \in \Gamma} \max_{i=1,2}(r_i(\gamma)) = 0.17$]. See Table I for parameter values.

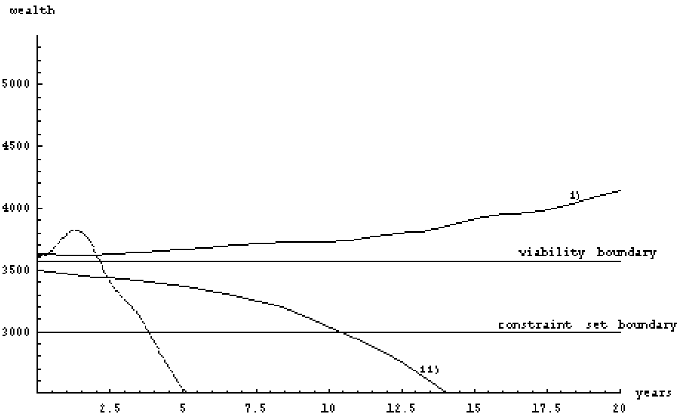

Figure 3. Wealth evolution in a mixed herd with an uncontrolled breeding rate of the llama flock. (i) Strongly viable wealth evolution: initial wealth is $x_0 = 3630$ US\$, herd structure is made up of 60% of llamas and offtake rate on females satisfies a minimum income at every point in time $e(t) = C / x(t)$. See Table I for parameter values. The viability kernel boundary is $x^* = 3571$ US\$ and the constraint set boundary is $x_{\mathrm{min}} = 3000$ US\$. (ii) Non viable wealth evolution. Dotted line: non viable wealth evolution of a mixed herd composed of 10% llamas.

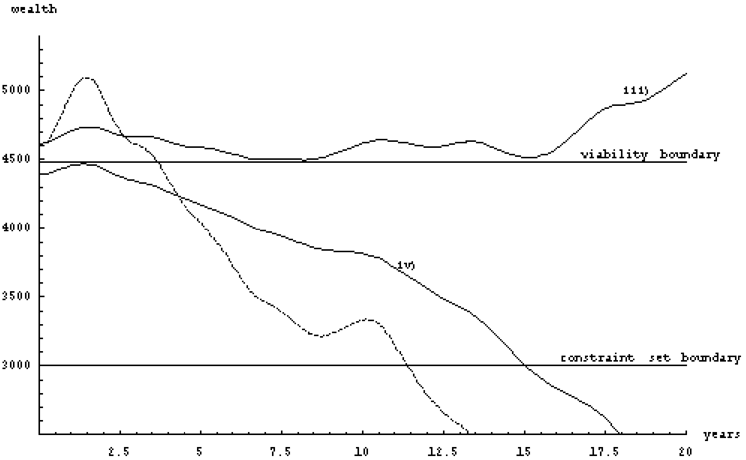

Figure 4. Wealth evolution in a mixed herd with a controlled breeding rate of the llama flock. (iii) Strongly viable wealth evolution: initial viable wealth is $x_0 = 4618$ US\$, herd structure is made up of 60% of llamas and offtake rate on females satisfies a minimum income at every point in time $e(t) = C / x(t)$. See Table I for parameter values. The viability kernel boundary is $x^{**} = 4478$ US\$ and the constraint set boundary is $x_{\mathrm{min}} = 3000$ US\$. (iv) Non viable wealth evolution. Dotted line: non viable wealth evolution of a mixed herd composed of 10% llamas.

was a robust decision allowing the trajectory (iii) to remain tangential with the discriminating kernel at $t = 7.5$ years. Below the discriminating kernel boundary, the female offtake rate itself triggered an irreversible de-capitalisation.

Both simulations also showed non-viable wealth evolution (dotted line) of a mixed herd composed of 10% of llamas. This means that for this particular scenario in which between years 2 and 7, the climatic scenario is unfavourable to the dominant species (sheep), the offtake rate necessary to satisfy the minimum income induced an irreversible de-capitalisation. The contrary would also be true for a mixed herd with 90% llamas in another climatic scenario. In earlier work, it was shown that a mixed herd with a close proportion of each species allows overcoming any possible climatic scenario and that a monospecific herd can also be viable but at higher herd size [12, 35].

4. DISCUSSION

The evaluation of controlled breeding practice in the llama flock demonstrates that foregoing short-term yield favoured mixed herd viability in the long-term. The short-term restraint illustrated by controlled breeding shows that management practices can play a role in terms of anticipating uncertainty. However, the effectiveness of this practice is closely related to wealth level. These qualitative results are similar to those found by Mace [23] for East African sheep flocks using an optimality approach. However, since constraints are technically difficult to tackle, the optimal solution may correspond to situations where the minimum income constraint is not satisfied at least for a while. Furthermore, viability allows assigning an equal weight to every time period avoiding the discussion with respect to the discount factor. This may appear to be a relevant way to perform an intergenerational equity [5].

The model is a highly stylised representation of reality, but can be used to illustrate the principles at work. For further insights, some part of the hypothesis should be reconsidered. In particular it would be interesting to include minimum income dynamics in order to tackle the fact that family subsistence requirements and wealth are not independent. However, data on parameters such as minimum income and herd growth rates in droughts for both llama and sheep species are still scarce.

The model, in its present stage of development has no predictive value: the frequency of droughts is a major determinant of the actual rate of growth of numbers, but it is largely unpredictable in this environment. Its strength lies in the qualitative analysis of relations between variables and parameters, which allows us to dispense with assumptions regarding the numerical value of parameters. Thus, uncertainty in the estimation of some parameters does not alter the interpretation of structural relations between variables and parameters. In a previous work, herd composition was investigated in relation to herd size among 93 breeders [36]. The results indicate that specialised herds are much larger in size than mixed herds. This brings some elements of validation for the results derived from this analysis as far as the relation between wealth level and herd composition is concerned. However, no data is available to validate the results referring to the influence of breeding practices. Therefore, the model is to be perceived as a heuristic tool to assess management practices that can only be understood by adopting a long-term perspective. Several studies [18, 28] have analysed the efficiency and effectiveness of management practices on herd performances, but most of them do not report the cumulative and compensatory effects that occur in the long term. These have been underlined by Cournut [10] who examined the lifetime reproductive performance of individuals within sheep flocks. This author took into account these effects by analysing the trade-off between reproductive function and longevity and underscored the relation between physiological functions of individuals and herd management. Consequently, the model underscores the relevance for local research to study the breeding practices in llama flocks. In particular, it is necessary to get a better evaluation of llama flock yield in drought years and to investigate for llama females the trade-off that may occur between reproduction success and survival. The higher parental care in llama females than in ewes is likely to improve the fitness of their offspring. However, as underlined by Clutton-Brock et al. [9] in red deer, such behaviour may reduce any aspect of the female's fitness. Controlled breeding practice in llama flocks indicates that breeders appreciate these differences: this may allow them to play on the reproductive costs of individuals in terms of either future survival or fecundity. It is interesting to note that since the 1990s, survival in relation to reproductive costs is also a critical parameter for intensive dairy herds [13, 14].

By assessing short-term and long-term effects of management practices, the model provides some insight into the pastoralists' foresight capacity when confronted with uncertainty. A mixed herd enables breeders to take advantage of opposed species-specific traits. Llamas behave as a stabilising component due to their ability to thrive during environmental perturbation, whereas sheep, which have a faster growth rate in good years, promote rapid recovery from drought. At this stage, our results are likely to contribute to the debate about maximising strategies, since these need to be related to the livestock system sustainability. Policies that advocate destocking, assuming that the ecological carrying capacity is being exceeded, are increasingly common especially in drylands [31]. If sustainability (related to family survival) is a common goal to pastoralists, since all of them are not wealthy, they are likely to develop differentiated strategies according to their wealth level [32]. If rich breeders can afford to develop precautionary behaviour, poor breeders have to take risks. For the latter, rapid herd growth when forage is available is likely to remain a sound practice to avoid destitution when droughts occur. While unable to master exogenous uncertainty, breeders can anticipate and mitigate it thanks to particular breeding practices. These practices are directly linked to the set of constraints facing each pastoralist and to his assets, and therefore cannot be standardised to the overall community. Moreover, they have to be viewed on a larger time-scale than the immediate or annual ones. The choice of animal species to breed and their management, assume great importance in the functioning of Andean pastoral systems since llama and sheep are not interchangeable species and have effects both on the short-term domestic economy and on the long-term sustainability of the enterprise. Finally, due to different grazing behaviour, llamas and sheep allow for better utilisation of the overall available forage [16, 17]. They also play a complementary role in the spatial use of the ecological diversity, as well as in the products they supply to the family.

5. CONCLUSIONS

Since the late 1980s, most research and analyses on pastoralist strategies have adopted dynamic optimality approaches [19, 22, 26]. The viability theory framework approach differs from these optimisation techniques by focusing on the viability constraints themselves. Specifying constraints upon decision variables, instead of attributing a law of change to these variables, is sufficient to identify the set of decisions that prevents the system from violating its viability constraints, thus to enhance the understanding of the system dynamics. This representation avoids a certain amount of determinism that would conceal the complete uncertainty in the breeder's behaviour allowing a perfect prediction of the system. In that sense, several trajectories are possible if they fit the same dynamic and meet the same constraints. This enlarges the diversity of possible policies far beyond the unique solution identified in the dynamic optimality approach [5]. This approach appears to be promising for evaluating the efficiency and effectiveness of livestock management practices at a long-term scale, and hence could concretely contribute to sustainability evaluations.

ACKNOWLEDGEMENTS

This work was initially carried out within a collaborative research programme between the Bolivian Institute for Agropastoral Technology (IBTA) and The French Institute of Research for Development (IRD). We are grateful to the people of the Turco community for their assistance in the fieldwork. We thank Daniel Sauvant and Rami Zurayk for helpful comments and discussion; and Laurence de Bonneval for reviewing the English manuscript.

Appendix 1

Sketch of the proof for the value of x^*. Refer to Doyen [12] for a detailed proof. We proceed in two steps:

We first prove that the set $[x^*, +\infty[$ is viable in a robust framework since for $x_0 = x^*$, for any $\gamma \in \Gamma$ there exists (u, e) satisfying (5) such that

$$\dot{x}(t) = \frac{dx}{dt}(t) = x(t)\left(\sum_{i=1,2} u_i(t)r_i(\gamma(t)) - e(t)\right) \geq 0.$$

Symmetrically, we can prove that, for any $x_0 < x^*$, there exists a climatic scenario $\gamma(t)$ and a time $T \geq 0$ such that, despite any admissible (satisfying (5)), regulation $(u(.), e(.))$, $x(T) < x_{\min}$. This means that x_0 is not viable. Therefore the set $[x^*, +\infty[$ is the maximal viable set.

REFERENCES

[1] Anderson J.R., Response and risk assessment in rural ecosystems: from models and plots to define universes, Agric. Ecosyst. Environ. 82 (2000) 261–271.

[2] Aubin J.P., Viability theory, Birhaüser, Boston, 1991.

[3] Aubin J.P., Dynamic economic theory: a viability approach, Birhäuser, Springer-Verlag, 1997.

[4] Barth F., Nomads of South Persia, Oslo University Press, Oslo, 1961.

[5] Béné C., Doyen L., Gabay D., A viability analysis for a bio-economic model, Ecol. Econ. 36 (2001) 385–396.

[6] Bernus E., Le contrôle du milieu naturel et du troupeau par les éleveurs touaregs sahéliens, in: Équipe Écologie et Anthropologie des sociétés Pastorales (Eds.), Production Pastorale et Société, Cambridge University Press, Maison des Sciences de l'Homme, Paris, 1979, pp. 67–74.

[7] Bonneuil N., Malthus, Boserup and population viability, Math. Popul. Stud. 5 (1994) 107–119.

[8] Cardaliaguet P., A differential game with two players and one target, SIAM J. Appl. Math. 34 (1996) 1141–1460.

[9] Clutton-Brock T.H., Albon S.D., Guinness F.E., Fitness cost of gestation and lactation in wild mammals, Nature 337 (1989) 260–262.

[10] Cournut S., Le fonctionnement des systèmes biologiques pilotés : simulation à évènements discrets d'un troupeau ovin conduit en trois agnelages en deux ans, Thèse de doctorat, Université Claude Bernard – Lyon 1, 2001.

[11] Doyen L., Béné C., Sustainability of fisheries through marine reserves: a robust modelling approach, J. Environ. Manage. 69 (2003) 1–13.

[12] Doyen L., Tichit M., A viability analysis of mixed herd management in uncertain climatic environments, Cahiers du Centre de Recherche Viabilité Jeux Contrôle (1999) 1–25.

[13] Ducrocq V., Statistical analysis of length of productive life for dairy cow of the Normand breed, J. Dairy Sci. 77 (1994) 855–866.

[14] Ducrocq V., Survival analysis, a statistical tool for longevity data, Proceedings of the 48th Meeting of the European Association for Animal Production, Vienna, 1997, pp. 223–225.

[15] Genin D., Alzerreca H., Resena de la vegetacion de la zona de Turco, in: Genin D., Picht H.J., Lizarazu R., Rodriguez T. (Eds.), Waira Pampa. Un Sistema Pastoril Camélidos – Ovinos del Altiplano Arido Boliviano, ORSTOM – IBTA – CONPAC, La Paz, 1995, pp. 35–56.

[16] Genin D., Tichit M., Degradability of Andean range forages in llamas and sheep, J. Range Manage. 50 (1997) 381–385.

[17] Genin D., Villca Z., Abasto P., Diet selection and utilization by llamas and sheep in a high altitud-arid rangeland of Bolivia, J. Range Manage. 47 (1994) 245–248.

[18] Girard N., Lasseur J., Stratégies d'élevage et maîtrise de la répartition temporelle de la production. Exemple des élevages ovins allaitants en montagne méditerranéenne, Cah. Agric. 6 (1997) 115–124.

[19] Jacquet F., Pluvinage J., Climatic uncertainty and farm policy: a discret stochastic programming model for cereal-livestock farms in Algeria, Agric. Syst. 53 (1997) 387–407.

[20] Landais E., Recherche sur les systèmes d'élevage. Questions et perspectives, INRA SAD 87, 1987.

[21] Lemoigne J.L., La Théorie du Système Général. Théorie de la Modélisation, PUF, Paris, 1983.

[22] Mace R., Pastoralists herd composition in unpredictable environments: a comparison of model predictions and data from camel-keeping groups, Agric. Syst. 33 (1990) 1–11.

[23] Mace R., Nomadic pastoralists adopt subsistence strategies that maximize long-term household viability, Behav. Ecol. Sociobiol. 33 (1993) 329–334.

[24] Mace R., Houston A., Pastoralists strategies for survival in unpredictable environments: a model of herd composition that maximizes household viability, Agric. Syst. 31 (1989) 185–204.

[25] Mangel M., Clark C., Dynamic modeling in behavioral ecology, University Press, Princeton, 1988.

[26] Milner-Gulland E.J., Mace R., Scoones I., A model of household decisions in dry-land agropastoral systems, Agric. Syst. 51 (1996) 407–430.

[27] Morlon P., Montoya B., Channer S., Dix ans dans la vie de paysans des rives du Titicaca, in: Morlon P. (Ed.), Comprendre l'Agriculture Paysanne dans les Andes Centrales, INRA, Paris, 1992, pp. 331–364.

[28] Moulin C.H., Performances animales et pratiques d'élevage en Afrique sahélienne. La diversité du fonctionnement des troupeaux de petits ruminants dans la communauté rurale de Ndiagne (Sénégal), Thèse de doctorat, Institut National Agronomique Paris-Grignon, 1993.

[29] Roth E.A., Traditional pastoral strategies in a modern world: an example from northern Kenya, Hum. Organ. 55 (1996) 219–223.

[30] Sandford S., Management of pastoral development in the third world, John Wiley & Sons, Chichester, 1983.

[31] Scoones I., Why are there so many animals? Cattle population dynamics in the communal areas of Zimbabwe, in: Behnke R.H. Jr., Scoones I., Kerven C. (Eds.), Range ecology at desequilibrium. New models of natural variability and pastoral adaptation in African Savannas, Overseas Development Institute, London, 1993, pp. 62–76.

[32] Sieff D.F., The effects of wealth on livestock dynamics among the Datoga pastoralists of Tanzania, Agric. Syst. 59 (1999) 1–25.

[33] Thurow T.L., Taylor C.A., Viewpoint: the role of drought in range management, J. Range Manage. 52 (1999) 413–419.

[34] Tichit M., L'association camélidés – ovins dans un système pastoral de l'altiplano désertique de Bolivie, Master of science, CIHEAM, 1993.

[35] Tichit M., Cheptels multi-espèces et stratégies d'élevage en milieu aride : analyse de viabilité des systèmes pastoraux camélidés – ovins sur les hauts plateaux boliviens, Thèse de Doctorat, Institut National Agronomique Paris-Grignon, 1998.

[36] Tichit M., Genin D., Factors affecting herd structure in a mixed camelid – sheep pastoral system in the arid puna of Bolivia, J. Arid Environ. 36 (1997) 167–180.

[37] Upton M., Livestock productivity assessment and modelling, Agric. Syst. 43 (1993) 459–472.

[38] Wolfram S., Mathematica, le livre, International Thomson Publishing Company, France, 1997.