Sustainable goat production: modelling optimal performance in extensive systems

O.F. Godber[1], M. Chentouf[2] and R. Wall[1]

1. Veterinary Parasitology & Ecology Group, University of Bristol, Bristol, BS8 1TQ, U.K.

2. INRA regional centre of Tangier, Bd Sidi Mohamed Ben Abdalah 78, 90010 Tangier, Morocco.

Abstract. Strategies for achieving greater ruminant livestock productivity are essential to meet the food demands of growing populations, but sustainable changes are difficult to identify given the inherent complexity of such systems. Here a systems model for ruminant production in an extensive Mediterranean environment is constructed, which allows management factors influencing multiple aspects of the system to be incorporated. The model is parameterised with data collected over three years for goat holdings in northern Morocco. Scenario analysis techniques are applied to explore the strategies that optimise performance under climate and feed price challenge. Results indicate that meat production is particularly important during periods of drought when increased meat yields can counteract the expected significant reduction in milk yields, to protect human food security, prevent excessive rangeland degradation and preserve natural nutritional resources. Feed price shocks during drought can have significant negative impacts on the system and zero feed input is shown to be a more sustainable strategy than reliance on high price feed during drought. Any alternative feed sources need to have a high forage component to reduce grazing periods significantly and promote rangeland preservation. This model allows improved insight to management strategies which could optimise animal husbandry performance in goat subsistence systems.

Additional Keywords: systems model; sustainability; ruminants; livestock; marginal systems

Corresponding author; Email: richard.wall@bristol.ac.uk

Introduction

Population growth will increase food demand, particularly in developing nations, exacerbating food security concerns (Godber & Wall, 2014). Livestock intensification will inevitably need to play a role in meeting these requirements (UN 2011; Enahoro *et al*. 2019). However, there is concern relating to the environmental impact of livestock production, particularly in rangeland, which is impacted by both rising livestock numbers and climate change (Berkat and Tazi 2006; Dickhoefer *et al*. 2010; Özkan and Cullen 2015). Nevertheless, the identification of novel strategies which are able to optimise production while minimising impacts is difficult, given the inherent complexity of any livestock system, which must consider the abundance and value of the livestock, the nature of the grazing system, socio-economic pressures with evolving trade flows and between-year variability in weather conditions (Lara and Rostagno 2013; Skuce *et al*. 2013). One effective approach to capturing complexity and exploring the behaviour of such systems is the development of systems models (Bosman *et al*. 1997).

Systems models are valuable tools that can be used to explore the potential enhancements in animal production that might be achieved through improvements in animal health, feeding, breeding and management (Bosman *et al*. 1997). Although all models are, inevitably, only partial reflections of the real world, when used with discrimination they can contribute to a consideration of the impacts of exogenous constraints and technology (Morand-Fehr *et al*. 2004), the wider value chain (Rich *et al*. 2011) and policy impacts (Matthews *et al*. 2006). Holistic models which incorporate all these aspects and that could be used universally across all production systems, could also help to overcome many of the current problems associated with the study and development of sustainable livestock production systems. However, to be effective, models must attempt to include the entire production chain - from the impact of changes in environmental conditions on livestock health and productivity to the economic consequences of this (Özkan *et al*. 2016). Models which cover the entire production system and can be adapted for use in different production systems and with different livestock species would be particularly valuable, but inevitably more general models are relatively less precise.

One key hindrance to the development and evaluation of effective models is a lack of good quality data across different production systems and countries. Differences in measurement methods and terminology between research groups and regions can affect the comparison and use of data and modelling outcomes and different countries may not be easily comparable. Data availability largely determines the type of model developed (Özkan *et al*.

2016). A lack of data is a particularly limiting factor for good model development in developing countries where basic information on agricultural systems is not routinely collected (Brooks-Pollock *et al*. 2015). In the short term, predictions can be made in developing regions with limited data by using modelling approaches which can cope with sparse data sets (Gubbins *et al*. 2014), strengthened with the advances in geo-spatial surveying techniques for observations of environmental variables and land use (Jamison *et al.* 2015). On the other hand, it has also been noted that too much detailed data, such as that available from some intensive European livestock systems, can also provide challenges relating to data synthesis (Brooks-Pollock *et al*. 2015).

The aim of the work presented here was to build a systems model for ruminant production under extensive Mediterranean conditions, to allow identification of the management factors that drive overall system performance, with particular focus on animal health and welfare, the contribution of products to human food security, the contribution of production to financial security, and the potential impact of production on rangeland degradation. The model is parameterised using existing long-term data collected for goat holdings in northern Morocco (Godber *et al*. 2016) and then scenario analysis techniques are used to explore the management strategies that optimise overall system performance under both normal and drought conditions. The existing available data included biological indicators (kid mortality rate, reproduction rate, milk yield for human consumption, and meat yield for human consumption), financial indicators (income from meat sales, income from dairy sales, feed expenditure, veterinary and medicine expenditure, and gross margin) and management factors (production objective, herd size, labour input, level of supplementary feeding, length of grazing period, anthelmintic treatment frequency, and doe replacement rate). The overall aim was to develop a model that could be used as a support tool for farmer groups and technical advisors, by providing advice which could improve goat management strategies.

Materials and Methods

Initially, a conceptual comprehensive stock-and-flow model of a representative Mediterranean goat production system was constructed. The stock and flow model was then used to identify informative indicators that would represent the overall technical and economic performance of the system and for which data could be obtained. The biological indicators selected were: kid mortality rate, reproduction rate (the product of the proportion of kids born that survive to weaning and the ratio of kids born to the number of females, indicating the ratio of kids surviving to weaning to the total number of does in the herd; Pittavino *et al*. 2014), milk yield for human consumption and meat yield for human consumption. Reproductive performance and kid survival are vital for continued lactation and dairy production, and to produce offspring for meat production, respectively (Bartl *et al*. 2009; Capper 2013). They can also indicate the overall health and welfare of the goats. The volumes of milk and meat provided for human consumption were taken as measures of goat productivity and their contribution to food security. In addition, financial indicators were selected to assess the financial performance of holdings: the income from meat sales, the income from dairy sales, feed expenditure, and veterinary and medicine expenditure. Fixed costs were not considered as both labour and rent expenditure are negligible. Labour consists almost exclusively of unpaid family members and minimal areas of land are rented (Godber *et al*. 2016). From the difference between the income and expenditure financial indicators, gross margin (or profitability) of the holding can be calculated. This was taken as an overall indicator of the system's performance.

Management factors under the close control of the farmer were selected to assess their effect on technical and economic performance: production objective (commercial cheese producers, commercial milk producers or non-commercial dairy producers), herd size, labour input, level of supplementary feeding (almost exclusively concentrate feed; Godber *et al*. 2016), length of grazing period (grazing intensity), anthelmintic treatment frequency, and doe replacement rate. The production objective indicates the relative importance of dairy production to the financial and food security of the holding. It may also account for breed differences on the commercial and non-commercial dairy holdings which cannot be explicitly accounted for. Many commercial dairy holdings in the region cross local goat breeds with Andalusian buck breeds imported from Spain (Boujenane 2005). Herd size affects the total volume of inputs required and outputs achieved and can lead to pressures on the availability of resources, such as land, feed and labour inputs. Labour availability may act as a constraint and has been shown to limit herd size (Chentouf *et al*. 2006) and intensification (Bosman *et al*. 1997). While mechanisation of milking may be important in the intensification of some Mediterranean goat production systems, it was not in the system studied here. The level of supplementary feeding can have effects on milk and meat yield, or growth potential, reproductive parameters and mortality (Alexandre *et al*. 2010; Ben Salem and Smith 2008; Jénot 2006). It is also a useful indicator for the level of intensification of the system. In the system studied, the length of the grazing period was considered to be a useful indicator for how extensive the system is, and its reliance on the local natural environment for nutrition, although this may not be the case in all Mediterranean systems. Anthelmintic treatment frequency was included here as an indicator of overall veterinary input, as treatment is administered routinely, rather than in response to a confirmed helminth infection. This may again indicate how intensive the production on a holding is, and how accessible veterinary services are. Finally, doe replacement rate gives the turnover rate of the herd and can be an indicator of problems, such as high mortality or cull rates due to health issues.

Potential explanatory variables (fixed effects) were the selected management factors: production objective; herd size; grazing intensity; annual consumption of supplementary feed by does; anthelmintic treatment frequency; annual hours of labour input per doe; and doe replacement rate. As there is a significant relationship between herd size and labour utilisation (Godber et al., 2016), annual hours of labour per doe were included rather than total hours of labour. Quadratic terms were considered for all continuous fixed effects.

The continuous fixed effects are recorded on very different scales. Therefore, to reduce excessive influence of any particular variable due to dimensional effects (Frey and Patil, 2002), they were all divided by the likely achievable maximum value. Holding identity was specified as a random effect to account for the repeated measures taken throughout the study period.

The general model structure was:

$$Y_i = X_i \, \beta_{i^\wedge} + Z_{i,j} \, b_i + \varepsilon_i, \qquad \text{(Equation 1)},$$

where *i* is a vector of observations; *j* is a vector of holdings; Y_i is the response for observation *i*; X_i is the production objective (when interaction with holding type is considered) of observation *i*; β_i is the regression coefficient for observation *i*; $Z_{i,j}$ is the random effect of holding *j* for observation *i*; b is the random intercept for observation *i*, and ε is the random error term for observation *i*.

Data collection

The model was parameterised using data collected from ten small-scale goat holdings representative of the northern Moroccan region of Tangier-Tetouan (Godber *et al*. 2016). The farms were selected based on their production objective: three commercial cheese producers, four commercial milk producers and three non-commercial dairy producers. The region has a Mediterranean climate (Köppen classification Csa) and the environment is characterised by both mountains and plains. Goat production is predominantly extensive, relying on grazing of pasture and rangelands throughout the year to provide nutrition. For meat systems, supplementation may be offered. Dairy systems are all semi-extensive, but most goats receive routine concentrate supplementation in their diets. Data were collected by interviewing farmers monthly between September 2009 and August 2012. The questionnaire used to collect the information was based on the FAO-CIHEAM technical and economic indicators, a full description of which can be found in Toussaint *et al*. (2009).

Sub- and system model construction and scenario analysis

Separate linear mixed effects models were fitted by restricted maximum likelihood (REML) using the R *lme4* package (Bates *et al*. 2014) for each of the selected performance indicators: kid mortality rate, reproduction rate, annual milk yield per doe, annual meat yield per doe, annual income from goat sales per doe, annual income from dairy sales per doe, annual feed expenditure per doe and annual veterinary and medicine expenditure per doe. These models are referred to as sub-models (Table 1); full details of the sub-model construction and scenario analysis are presented in supplementary material.

The sub-models were run for all possible combinations of inputs within a wide range of constraints (Table 2). The total volumes of milk and meat produced by the herd and annual gross margin (the difference between total annual income and expenditure) were calculated. The variance due to holding identity was retained as a random effect in all sub-models with a common slope, but different intercepts were used to account for the repeated measures experimental design. The management factors retained as fixed effects in each minimal adequate sub-model are shown in Table 1.

Scores were assigned to kid mortality rate (to represent goat health and welfare), total milk volume and total meat volume (which together represent food security), gross margin of the herd (to represent financial security) and rangeland preservation. An aggregated score for the overall performance of the system was then calculated for each holding: the sum of the scores for goat health and welfare, food security, financial security and rangeland preservation was calculated. The higher the score, the better the overall performance of the system on that holding since it incorporates aspects of goat health and welfare, food security, financial security and environmental preservation.

The fitted values for the minimal adequate financial sub-models were used to estimate total annual income per doe (the sum of the annual income from goat sales per doe and the annual income from dairy sales per doe), total annual expenditure per doe (the sum of the annual feed expenditure per doe and the annual veterinary and medicine expenditure per doe) and annual gross margin (the difference between the total annual income and the total annual expenditure) both per doe and per holding. These are referred to as system models (Fig. 1). The quality of fit of the estimates from the system models to the observed data was assessed through the adjusted conditional R^2. It was not possible to determine the amount of variance associated with the fixed effects (management factors) in comparison to the random effects for the system models. Therefore, the marginal R^2 was not calculated.

The impact of drought was simulated under two scenarios. Initially, no supplementary feed was input to the system. Then, simulations were run with feed prices inflated by 100%. These scenarios assume that the primary effect of drought is on feed availability and price. Scenarios were compared by fitting linear mixed effects models with restricted maximum likelihood (REML). Scenario or measure of performance was specified as the fixed effect. Holding identity was specified as a random effect to account for repeated observations, and production objective (commercial cheese, commercial milk or non-commercial dairy) was also specified as a random effect to account for differences between systems. When current and optimised performance scenarios were compared, this was also specified as a random effect.

Results

Scenario analysis

Table 3 shows the required changes in management practices predicted by model simulations to optimise overall performance of goat systems in the northern region of Morocco under normal conditions and drought conditions (zero feed input or high feed price). When overall performance was optimised, financial security score increased significantly by approximately 100% on average (QCV=18.63, P<0.001) as a result of significantly increased meat and dairy incomes of over 50% (QCV=2.049 and QCV=21.92 respectively, P<0.01 for both) when compared to current performance. Meat yields also increased by approximately 40% on average (QCV=1.919, P<.05) and rangeland preservation was significantly reduced by approximately 25% (QCV=1.967, P=0.001). When considering changes to management factors, there was an increase of over 150% in doe replacement rate (QCV=1.447, P<0.05), with almost 10% less supplementary feed to does (QCV=9.519, P<0.01), over 20% shorter grazing periods (QCV=1.804, P<05) and 3.5% less labour input (CV=5.856, P<0.05).

Table 4 shows the changes in different aspects of performance under current and drought conditions (zero feed input or high feed price). When the current performance of the system was compared to the expected effects of an extreme drought scenario in which no supplementary feed was available (zero feed input), on average, food security was significantly compromised by approximately 25% (CV=0.972, P<0.001) due to significantly reduced milk yields of over 55% (over 2000 litres per year, QCV=0.602, P<0.001). This also significantly reduced dairy and total income by approximately 55% and 18% respectively (QCV=0.731, P<0.001 and QCV=1.703, P<0.01), whilst veterinary and medicine expenditure increased by over 65% (QCV=2.973, P<0.01). Overall performance was significantly compromised by approximately 12% (CV=0.935, P<0.001). When the current performance of the system was compared to the expected effects of drought resulting in a high feed price shock with no other changes to current management factors (Table 4), financial security was significantly compromised by over 35% on average (QCV=0.801, P=0.001), milk yields were reduced by approximately 20% (QCV=1.653, P<0.05) and dairy income subsequently fell by over 25% (QCV=1.529, P<0.01). Feed costs and total costs both increased significantly by almost 35% (QCV=1.312, P<0.01 and QCV=1.222, P<0.01 respectively), resulting in a significant decrease in overall performance of over 8.5% (QCV=0.879, P<0.05).

When comparing a zero-feed input and high feed price scenarios with current management practices (Table 4), financial security was almost 35% lower on average in the high feed price scenario (QCV=0.966, P<0.01) whilst food security was almost 30% lower in the zero-feed input scenario (QCV=0.966, P<0.01). Milk yields and dairy income were significantly higher in the high feed price scenario (104.6%, QCV=1.029, P<0.001 and 36.60%, QCV=1.879, P<0.05 respectively), as were feed costs and total costs (236.8%, QCV=1.756, P<0.01 and 144.1%, QCV=1.027, P<0.001). In contrast, veterinary and medicine costs were significantly higher in the zero-feed input scenario (38.98%, QCV=0.689, P<0.01).

When performance was optimised under the zero-feed input and the changes compared to the current scenario (Table 3), financial security and goat health and welfare significantly improved (62.52%, QCV=2.843, P<0.001 and 15.25%, QCV=1.254, P<0.001), meat yields and incomes significantly increased (63.91%, QCV=1.057, P<0.001 and 80.24%, QCV=1.322, P<0.01) and doe replacement rate and reproduction rate also increased significantly (166.7%, QCV=1.383, P<001 and 30.85%, QCV=1.687, P<0.001). However, the grazing period and labour input also increased significantly (15.51%, QCV=2.429, P<0.001 and 59.07%, QCV=1.060, P<0.001) resulting in a significant reduction in rangeland preservation of almost 75% (QCV=0.727, P<0.001).

Comparing optimised performance under a high-feed price scenario to the current scenario (Table 3), milk yields and dairy income were reduced by over 30% and 80% respectively (QCV=3.329, P<0.05 and QCV=0.806, P<0.001) whilst meat yields and income both increased significantly by over 25% and over 30% respectively (QCV=3.543, P<0.05 and QCV=4.482, P<0.01) with doe replacement rate and reproduction rate also increasing significantly by approximately 125% and 15% respectively (QCV=2.108, P<0.01 and QCV=2.252, P<0.001). Surprisingly, feed costs were reduced significantly by approximately 20%

(QCV=3.776, P<0.01) due to a significant decrease in the level of supplementary feeding per doe of over 90% (QCV=0.601, P<0.001) which resulted in a significant decrease of 10% in total costs (QCV=3.609, P<0.05). Herd size was significantly reduced by approximately 5% (QCV=6.562, P<0.001) and grazing period by approximately 25% (QCV=2.763, P<001) allowing for a significant reduction in labour input of approximately 10% (QCV=2.853, P<0.05).

When the optimised zero-feed input and optimised high feed price scenarios were compared (Table 3), financial security, food security and goat health and welfare were all significantly higher in the zero feed input scenario (28.03%, QCV=2.999, P<0.001; 7.440%, QCV=5.954, P<0.001 and 2.175%, QCV=4.578, P<0.001). Meat yields and income were both significantly higher by over 15% (QCV=2.834, P<0.01 and QCV=2.416, P<0.01), as was total income (10.62%, QCV=4.547, P<01), whilst total costs were significantly lower (278.6%, QCV=9.298, P<0.001). When management practices were compared, the optimised zero-feed input scenario had significantly bigger herd sizes (3.226%, CV=12.83, P<0.001), a significantly higher doe replacement rate (16.67%, QCV=1.200, P<0.001) and significantly higher reproduction rate (7.806%, QCV=1.680, P<0.001). Furthermore, grazing period and labour input were over 40% and 50% significantly higher in the optimised zero-feed input scenario (QCV=1.667, P<0.001 and QCV=0.609 P<0.001 respectively), resulting in rangeland preservation being significantly lower by approximately 45% in the zero-feed input scenario (CV=4.388, P<0.01).

Discussion

Optimising performance under standard conditions

Approaches to optimising overall performance of goat production systems are considered here through the development of a holistic-like system model. In the optimised scenario under normal conditions (no drought scenario), improved financial security was achieved when meat yields were increased by increasing doe replacement rate, grazing periods were shortened, and feed input decreased. An additional benefit of this is increased rangeland preservation. The implication is that farmers should maximise income from meat sales which do not require high supplementary feed inputs.

Potential management strategies during drought

Climate changes are expected to increase the occurrence of drought in the region (Schilling et al., 2012). Simulations explored potential mitigating strategies to minimise the reduction in performance during drought seasons. Under the extreme drought scenario, no supplementary feed was given (zero-feed input). This represented all supplementary feed being reserved for human food security rather than being available for use as livestock feed (Schilling et al., 2012), or crop failure. When management was optimised, the model forecast that the grazing period would need to be significantly extended to compensate for the lost nutritional input from supplementary feed. Furthermore, because the nutritional quality of the rangeland will be reduced under periods of drought (Blache et al., 2008), animals will need to travel longer distances, or forage over a longer period of time, to receive adequate nutrition (Schilling et al., 2012). This would be expected to increase the degradation of rangeland and compromise its nutritional quality in future years (Jouven *et al*. 2010; Köchy *et al*. 2008). The extent of any of these changes will be influenced by the frequency of drought events.

The simulations suggest that higher replacement and reproduction rates, providing increased meat yields under the extreme drought scenario, could replace the lost revenue from dairy sales so that financial security could be maintained. Increasing meat yields could also support immediate human food security, which is expected to be affected by reduced milk yields during drought. Therefore, a sustainable long-term approach could be to increase culls to reduce herd sizes and increase the meat available during drought. Indeed, in Morocco, farmers tend to reduce the size of herds during drought to keep only the number of animals for which they can provide adequate feed. Reduced herd sizes can also minimise pressure on the rangeland. As goats are usually the most prolific domesticated ruminant and fast reproducers, herd sizes should quickly recover (Aziz, 2010). This recovery period could also allow rangeland quality and feed availability to re-establish following the drought period (Ben Salem and Smith, 2008). Rangeland would be further preserved if some supplementary feed is still provided under the high-feed price scenario.

The high feed price scenario is also representative of a feed price shock to the system. This is considered to be one of the main environmental pressures in agricultural systems (Viglizzo, 1994). As farmers become more commercially orientated, reduced grazing periods and increased dependence on supplementary feed input could result in environmental constraints becoming less of a priority. Feed price shocks, however, could have a bigger impact on the system (Lorent *et al*. 2009). This may mean that drought periods are less of an issue, but feed price shocks would be more common. Furthermore, the beneficial effects of increasing supplementary feed to reduce the grazing period and preserve rangeland will have its limits. If supplementary feeding is increased to a level which allows grazing periods to be shortened significantly, it could result in more sedentary grazing practices, increasing localised rangeland degradation (Jouven *et al*. 2010; Ben Salem 2010). Another consequence would be to generate less typical products and non-terroir products. Therefore, the adaptive grazing schemes discussed by Godber *et al*. (2016), which combine alternative feed resources with strategic or conservative rangeland grazing, could be relevant here. There are many sustainability arguments supporting the use of alternative feed resources, in addition to the financial benefits. This could strengthen the assurance of livestock feed resources being available during food crises (Alexandre *et al*. 2010).

Although a supply-orientated approach could be considered the most sustainable in terms of utilisation of resources, it does not necessarily meet the human food demands of the region or achieve sustainability at a larger scale. Therefore, taking a wider perspective is essential. The intention of this study was to develop a holistic model, but the fact that wider animal, crop, environmental and socio-economic considerations were not included here is a limitation and highlights the complexity inherent in attempting to capture reality in abstract models. Such developments in the future may require a multi-disciplinary approach to further extend the holistic approach taken here. Including a social element relating to stakeholder uptake and highlighting how this can lead to conflicting policy objectives, could also prove useful (Tourki *et al*. 2013). These aspects all support the need for participatory research in the region of northern Morocco, and comparable environments, which incorporates all stakeholders in the value chain and multiple areas of expertise. This will also require the support of extension services for education, training and the uptake of any policy changes, whilst any interventions will need to consider the impact at the herd, farm, community and national scales.

Optimal management strategy

It has been suggested that a diverse management strategy with a mixed meat and dairy semi-intensive production objective, rather than a specialised dairy system, would increase the technical performance of goat production for greater financial returns and financial viability of intensification (Ben Salem and Smith 2008; Godber *et al*. 2016), whilst helping to meet the increasing demand for, and consumption of, meat. The model simulation results presented here support this conclusion; maintaining meat production was necessary to optimise performance.

One implication from the scenario analysis is that inputs are acting synergistically. This highlights the dynamic complexities of livestock production systems (Tedeschi *et al*. 2011) and the difficulties associated with selecting the most appropriate management decisions. Even small changes could have significant impact. Furthermore, under some scenarios presented here, a compromise is made to some aspects of performance, despite an improvement to overall performance. Therefore, it may be difficult to disseminate the benefits of these strategies to farmers without the appropriate support. Further scenario analysis within a participatory approach, which includes a social element relating to stakeholder uptake, power and how this can lead to conflicting policy objectives, could be useful (Tourki *et al*. 2013).

In conclusion, the model presented here has suggested that meat production is particularly important during periods of drought when increased meat yields can counteract the expected reduction in milk yields and help to protect human food security, prevent excessive rangeland degradation and preserve natural nutritional resources. Feed price is shown to be a particularly important limiting factor and zero feed input is shown to be a more sustainable strategy than reliance on high price feed during drought. Overall, the model helps to improve our understanding of goat management in northern Moroccan grazing systems and wider application could contribute to optimising goat husbandry performance in other subsistence systems. However, it also demonstrates the difficulty of constructing a truly holistic model since, to be practical, such abstract constructs must necessarily be bounded; parameter selection and the limits to the boundaries imposed are inevitably critical.

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Table 1. The management factors retained in the minimal adequate sub-models and system models of technical and economic performance on northern Moroccan goat holdings. The conditional R^2 is a measure of the variance in the dependent variable explained by the model as a whole (both fixed and random effects), whilst the marginal R^2 is a measure of the variance explained by the fixed effects alone.

Sub-model / **Management factor**	Production objective	Herd size	Grazing intensity	Annual labour	Anthelmintic treatment	Level of concentrate feeding	Doe replacement rate	R^2	Adjusted conditional R^2	Adjusted marginal R^2
Kid mortality rate	✓	✓				✓		0.559	0.418	0.418
Reproduction rate	✓	✓				✓		0.436	0.257	0.257
Milk yield per doe						✓		0.547	0.514	0.401
Meat yield per doe							✓	0.542	0.508	0.389
Dairy income per doe	✓			✓		✓		0.895	0.862	0.256
Meat income per doe						✓		0.508	0.472	0.426
Feed expenditure per doe			✓		✓	✓	✓	0.884	0.854	0.854
Veterinary and medicine expenditure per doe.		✓		✓	✓	✓		0.797	0.732	0.732

Table 2 The constraints applied to the management practice variables input to the system model for scenario analysis and the scale factors used to place all inputs on a comparable scale from zero to one. The scale factor was guided by the maximum expected value for that management practice (see Godber et al. 2016).

Management practice	Minimum input	Maximum input	Interval	Scale factor
Annual grazing period	Zero hours per day	14 hours per day	One hour per day	14 hours per day
Anthelmintic treatment frequency	One treatment per year	Three treatments per year	One treatment per year	One treatment per year
Doe replacement rate	0.00	1.00	0.10	1.00
Herd size	-50 % of current herd size	+200 % of current herd size	One goat	250 does
Labour input	10 hours per doe per year	Current total labour hours input per year, calculated per doe		200 hours per doe
Level of supplementary feeding	0 kg per doe per year	200 kg per doe per year		200 kg per doe

Table 3. The required changes in management practices predicted by model simulations to optimise overall performance of goat holdings in the northern region of Morocco under normal conditions and drought conditions (zero feed input or high feed price). CQV=coefficient of quartile variation calculated from the interquartile range (Q3 – Q1) divided by the median (Q1 + Q3); level of significance is indicated by asterisks: * = P<0.05, ** = P<0.01, *** = P<0.001; ns = not significant.

	Difference between current management and optimised management under non-drought conditions			**Difference between current management and optimised management with zero feed input (extreme drought scenario)**			**Difference between current management and optimised management with high feed price**			**Difference between optimised management with zero feed input (extreme drought scenario) and optimised management with high feed price**		
	Median change	**QCV**		**Median change**	**QCV**		**Median change**	**QCV**		**Median change**	**QCV**	
Overall performance	+ 1.486%	18.63	ns	- 1.420%	34.29	ns	+ 12.01%	5.702	ns	+ 0.000%	10.62	ns
Financial security	+ 104.6%	1.454	***	+ 62.52%	2.843	***	+ 1.350%	153.4	ns	- 28.03%	2.999	***
Food security	+ 9.052%	8.463	ns	- 3.765%	18.28	ns	- 11.77%	-9.480	ns	- 7.440%	5.954	***
Goat health & welfare	- 2.767%	8.051	ns	+ 15.25%	1.254	***	+ 3.117%	6.191	ns	- 2.175%	4.578	***
Rangeland preservation	- 25.93%	1.967	***	- 73.34%	0.727	***	- 31.29%	4.151	ns	+ 44.74%	4.388	**
Milk yield	+ 2.843%	21.92	ns	- 32.55%	3.000	*	- 31.59%	3.329	*	- 1.203%	44.60	ns
Meat yield	+ 39.10%	1.919	*	+ 63.91%	1.057	***	+ 27.51%	3.543	*	- 15.12%	2.834	**
Dairy income	+ 52.46%	3.386	**	- 100.0%	0.470	**	- 83.71%	0.806	***	+ 5.867%	2665	***
Meat income	+ 56.62%	2.049	**	+ 80.24%	1.322	**	+ 32.39%	4.482	**	- 17.50%	2.416	***
Feed costs	- 9.649%	5.712	ns	- 100.0%	0.000	ns	- 21.05%	3.776	**	+ 5580%	3.297	***
Vet and med costs	- 7.274%	15.57	ns	+ 64.25%	5.804	ns	+ 26.47%	9.704	ns	- 36.64%	3.700	ns
Total income	+ 76.76%	1.438	***	+ 12.95%	8.775	ns	- 5.485%	24.71	ns	- 10.62%	4.547	**
Total costs	- 5.777%	5.380	ns	- 75.01%	0.414	***	- 10.38%	3.609	*	+ 278.6%	9.298	***
Herd size	- 4.072%	1.692	ns	- 1.064%	2.022	ns	- 5.475%	6.562	**	- 3.226%	12.83	***
Labour	- 3.534%	5.856	*	+ 59.07%	1.060	***	- 10.02%	2.853	*	- 51.61%	0.609	***
Grazing period	- 21.63%	1.804	*	+ 15.51%	2.429	***	- 25.41%	2.763	***	- 42.86%	1.667	***
Supplementary feed	- 9.086%	9.519	**	- 100.0%	0.000	ns	- 92.47%	0.601	***	+	QCV =	***
Doe replacement rate	+ 153.3%	1.447	*	+ 166.7%	1.383	***	+ 123.0%	2.108	**	- 16.67%	1.200	***
Reproduction rate	+ 6.025%	1.652	ns	+ 30.85%	1.687	***	+ 14.46%	2.252	***	- 7.806%	1.680	***

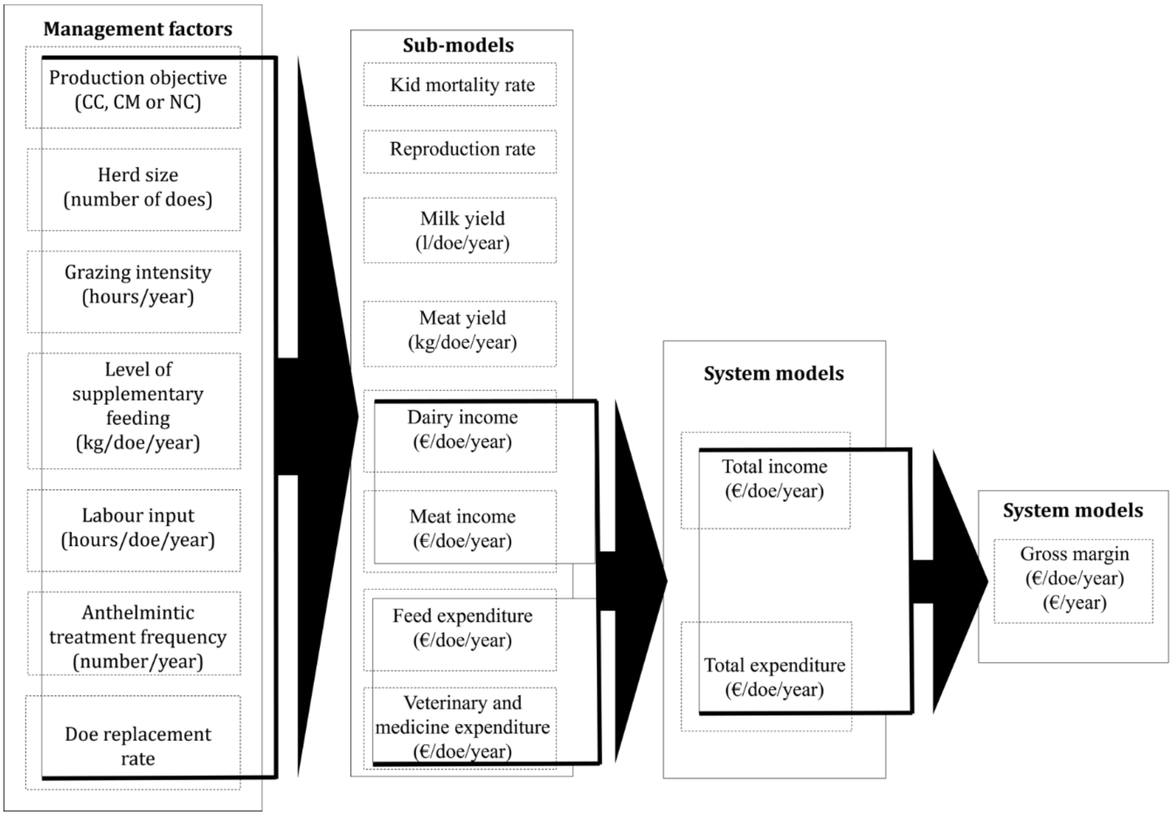
Table 4. The changes in different aspects of performance on goat holdings in the northern region of Morocco under drought conditions (zero feed input or high feed price) compared to current performance. CQV=coefficient of quartile variation calculated from the interquartile range (Q3 – Q1) divided by the median (Q1 + Q3); level of significance is indicated by asterisks: * = P<0.05, ** = P<0.01, *** = P<0.001; ns = not significant.

	Difference between curren management and current management with zero fee input (extreme drought scenario)			Difference between curren management and current management with high feed price			Difference between current management with zero feed in (extreme drought scenario) ar current management with hig feed price		
	Media chang	QC\		Media chang	QC\		Media chang	QC\	
Overall performanc	- 12.	[illegible]	**	- 8.6	[illegible]	*	+ 5.2	[illegible]	ns
Financial security	+ 2.9	[illegible]	ns	- 36.	[illegible]	***	- 33.	[illegible]	**
Food securit	- 26.	[illegible]	***	- 9.5	[illegible]	ns	+ 28.	[illegible]	**
Goat health a welfare	+ 9.7	[illegible]	ns	+ 5.1	[illegible]	ns	- 4.1	[illegible]	ns
Rangeland preservatio	- 0.0	[illegible]	ns	- 0.0	[illegible]	ns	- 0.0	[illegible]	ns
Milk yield	- 57.	[illegible]	***	- 20.	[illegible]	*	+ 10	[illegible]	***
Meat yield	+ 0.6	[illegible]	ns	+ 0.3	[illegible]	ns	+ 0.0	[illegible]	ns
Dairy incom	- 55.	[illegible]	***	- 26.	[illegible]	**	+ 36.	[illegible]	*
Meat income	+ 2.0	[illegible]	ns	+ 0.5	[illegible]	ns	- 3.9	[illegible]	ns
Feed costs	- 63.	[illegible]	***	+ 33.	[illegible]	**	+ 23	[illegible]	***
Veterinary a medicine co	+ 66.	[illegible]	**	+ 23.	[illegible]	ns	- 38.	[illegible]	**
Total incom	- 17.	[illegible]	**	- 9.5	[illegible]	*	+ 6.2	[illegible]	*
Total costs	- 42.	[illegible]	***	+ 34.	[illegible]	**	+ 14	[illegible]	**

Figure legends

Figure 1. The structure of the sub- and system models for the technical and economic performance of goat farms in Northern Morocco. Management factors are specified as fixed effects in the sub-models. The outlined sub-models feed into the system models. CC=commercial cheese producer, CM=commercial milk producer, NC=non-commercial dairy producer.

Fig 1.


Management factors
Production objective (CC, CM or NC)
Herd size (number of does)
Grazing intensity (hours/year)
Level of supplementary feeding (kg/doe/year)
Labour input (hours/doe/year)
Anthelmintic treatment frequency (number/year)
Doe replacement rate
Sub-models
Kid mortality rate
Reproduction rate
Milk yield (l/doe/year)
Meat yield (kg/doe/year)
Dairy income (€/doe/year)
Meat income (€/doe/year)
Feed expenditure (€/doe/year)
Veterinary and medicine expenditure (€/doe/year)
System models
Total income (€/doe/year)
Total expenditure (€/doe/year)
System models
Gross margin (€/doe/year) (€/year)

Supplementary material

To build a systems model for ruminant production under extensive, Mediterranean conditions informative indicators that represent the overall technical and economic performance of the system and for which data could be obtained, were identified from an initial stock and flow model (Fig S1). Sub models were used to build the systems model which was then used for scenario analysis, as described below.

Sub-model inference

Due to the large number of potential models, the R function *dredge()* from the package *MuMIn* was used to rank all possible models (including those with quadratic terms and interactions) based on the second-order Akaike Information Criterion ($AICc$), which adjusts AIC for small samples sizes. The use of AIC_c is equivalent to performing the leave-one-out-cross-validation method, and avoids the need to exclude data for model validation at a later stage (Fang, 2011). This is particularly useful in this instance as the sample size is small (n=30).

The five models with the lowest AIC_c score were evaluated. First, the residuals of the models were assessed for normality through visual inspection using histograms and Q-Q plots. If normal, the model was compared to the null model and retained if there was a significant ($P<0.05$) change in deviance. Change in deviance was based on log-likelihood estimates: a chi-squared value equalling twice the difference between the log-likelihood of the two nested models and the degrees of freedom for the chi-squared distribution were taken. Finally, the adjusted coefficient of multiple determination, R^2, for the fixed effects (the marginal R^2, or R^2_m) and the model as a whole (the conditional R^2, or R^2_c; Nakagawa and Schielzeth, 2013), were calculated from the R^2_m and R^2_c returned from the *r.squared.GLMM()* function of the R package *MuMIn* to provide an absolute value for the goodness-of-fit. The conditional R^2 is a measure of the variance in the dependent variable explained by the model as a whole (both fixed and random effects), whilst the marginal R^2 is a measure of the variance explained by the fixed effects alone:

$$\text{Adjusted } R^2_m = 1 - (1 - R^2_m) * ((n - p)/(n - p - 1)) \qquad \text{(Equation S1)}$$

$$\text{Adjusted } R^2_c = 1 - (1 - R^2_c) * ((n - p)/(n - p - 1)) \qquad \text{(Equation S2)}$$

where n is the number of observations used to construct the model; p is the number of parameters in the model; R^2_m is the marginal R^2 (for the fixed effects only), and R^2_c is the conditional R^2 (for the model as a whole). The minimal adequate model was then subjectively chosen based on the $AICc$ and adjusted R^2_m and R^2_c.

Scenario analysis

To use scenario analysis to explore the effects of different management strategies on each aspect of performance, the models were run for all possible combinations of inputs within a wide range of constraints (Table 2), guided by the literature of the discussion of Godber et al. (2016). All management factors were scaled from zero to one by division by the maximum expected value (herd size = 250 does; annual grazing period = 5000 hours; annual labour per doe = 200 hours; annual supplementary feeding per doe = 200kg; doe replacement rate = 1.00; anthelmintic treatment frequency = 3; Godber et al., 2016). The total labour and supplementary feed required by the herd were then calculated to account for changes in herd size: total labour for the herd and concentrate feeding were limited to a 100% increase. The labour required in addition to the grazing period (the difference in labour per day and daily grazing period, to account for time spent herding goats and labour requirements on the holding) was calculated, and results where the total labour did not exceed this required minimum input were excluded. Furthermore, total expenditure was limited to the current expenditure observed and gross margin had to equal or exceed that currently observed. Results not complying to these constraints were excluded. The constraints to expenditure were applied to account for limited financial sources being available, and those applied to gross margin accounted for the profit required for maintenance of the holding and expenditure by the family. By applying these constraints, the model represents the recommended supply-driven approach as opposed to a demand-driven approach (Alexandre et al., 2010).

All possible combinations of the above limits were run for the three years of data held for each holding (number of runs = 30), using the *predictInterval()* function from the R package *merTools* (Knowles and Frederick, 2015) with 100 simulations per run to obtain a mean score with upper and lower confidence intervals. To maintain herd size, results where the reproduction rate was less than double the doe replacement rate were removed. The total volumes of milk and meat produced by the herd were calculated.

In the dairy income sub-model, only the level of supplementary feeding received by does (rather than the whole herd) is of relevance. This has a strong, significant relationship with that received by the herd as a whole (d.f.=20.24, t=16.86, P=<0.001) and therefore, to maintain consistency between the models, the level of supplementary feeding received by does alone was included in all sub-models. The level of supplementary feeding and doe replacement rate both differ significantly between production objectives (Godber et al., 2016) and therefore the interaction of these indicators with production objective were also considered as potential fixed effects.

Scores were assigned to kid mortality rate, total milk volume, total meat volume, gross margin of the herd and rangeland pressure. The score for kid mortality rate was calculated by subtracting the kid mortality model outcomes from one, and represents the health and welfare of the goats in the system. The scores for total meat and milk volume were calculated by dividing the model result for each holding by the maximum result achievable on that holding under the constraints found in Table 2. This rescaled the scores from zero to one for comparison. The sum of the meat and milk volume scores represents the productivity and contribution to food security of the system. The score for financial security was calculated by dividing the model result for total gross margin on each holding by the maximum result achievable on that holding under the constraints found in Table 2, again to rescale the scores from zero to one for comparison. Finally, the potential pressure of production on the rangeland was calculated by taking the inverse of the product of the herd size and grazing period, divided by the minimum product of herd size and grazing period achievable on that holding, putting the score on a scale of zero to one for comparison. An aggregated score, referred to as the overall performance of the system, was then calculated for each holding by taking the sum of the scores for goat health and welfare, food security, financial security and rangeland preservation. Each score had equal weighting as it is not possible to apply objective weightings to the individual scores. The higher the aggregated score (referred to as the overall performance score), the more optimal the overall performance of the system on that holding since it incorporates aspects of goat health and welfare, food security, financial security and environmental preservation. It is a holistic, and arguably the most sustainable, measure of performance to optimise.

Comparison of scenarios

Scenarios were compared by fitting linear mixed effects model with restricted maximum likelihood (REML) using the R package *lme4* (Bates et al., 2014). Scenario or measure of performance was specified as the fixed effect. Holding identity was specified as a random effect to account for repeated observations, and production objective (commercial cheese, commercial milk or non-commercial dairy) was also specified as a random effect to account for differences between systems. When current and optimised performance scenarios were compared, this was also specified as a random effect.

Inference was based on analysis of variance with F-tests, based on Satterthwaite's approximation to degrees of freedom as recommended by Bolker et al. (2009), using the R package *lmerTest* (Kuznetsova et al., 2014). If significant, simultaneous tests for general linear hypotheses were run using Tukey's honest significant difference with P-values adjusted using the single-step method to account for multiple comparisons and decrease the chance of type I error. The significance level was set at P=0.05 for all tests.

The impact of drought was then simulated under two scenarios which assume that the primary effect of drought is on feed availability and price. Initially, all inputs were held at observed levels except for supplementary feed, which was set to zero representing a scenario in which no supplementary feed was available to the farmer. Simulations were then run with feed prices inflated by 100%. The inflated feed price scenario could represent a drought scenario in which feed is in limited supply and a premium must be paid for it, or one in which high cost forage is sought as a supplementary feed.

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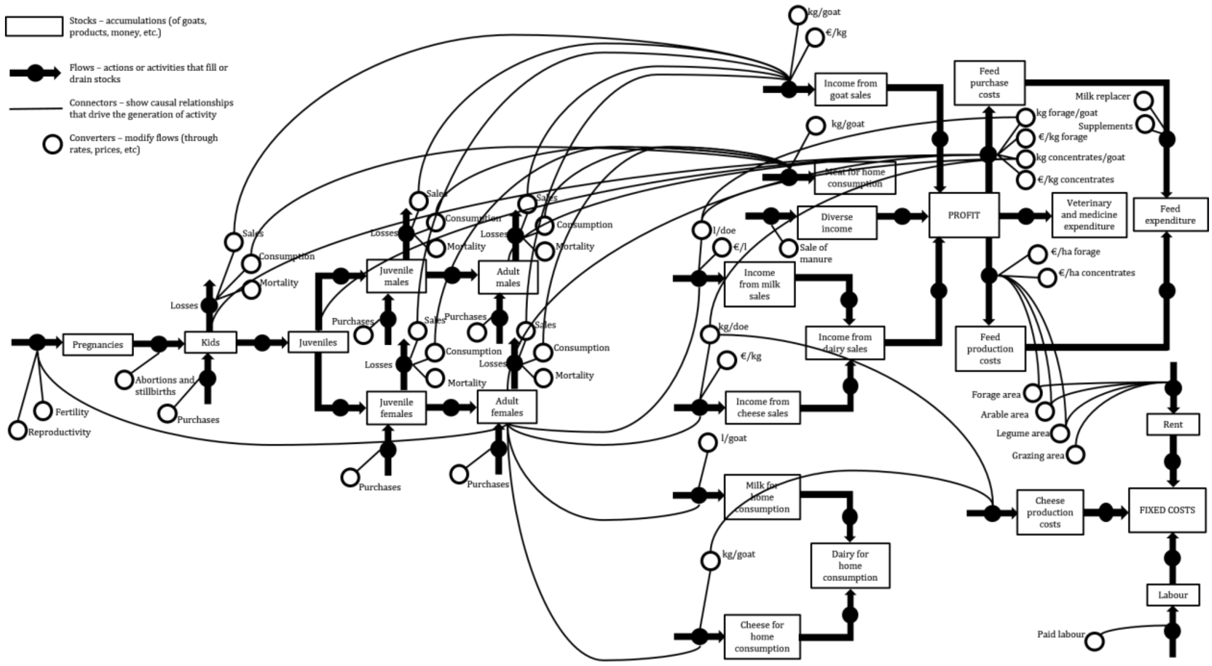

Figure S1. A conceptual model of a typical northern Moroccan goat production system, based on data collected using the FAO-CIHAEM technical and economic indicators (Toussaint et al., 2009).