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Sustainable goat production: modelling optimal performance in extensive systems

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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 (AIC*c*), 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:

Adjusted $R^2_m = 1 - (1 – R^2_m) * ((n - p)/(n – p - 1))$ (Equation S1)

Adjusted $R^2_c = 1 - (1 – R^2_c) * ((n - p)/(n – p - 1))$ (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 AIC*c* 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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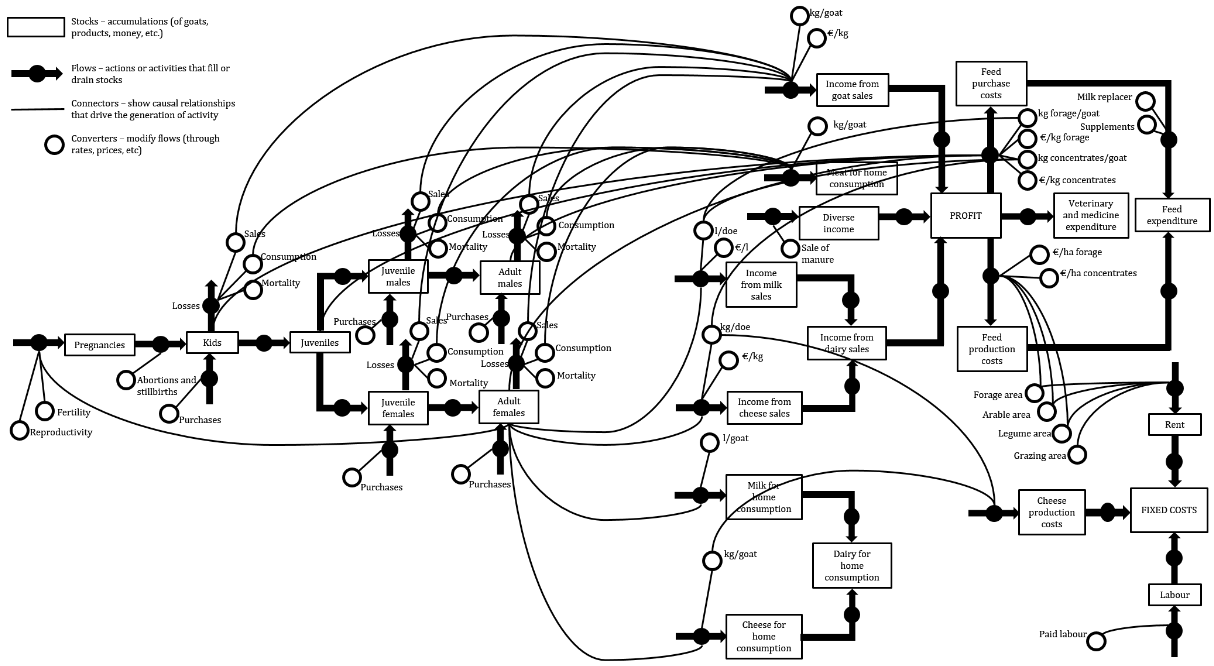

Figure S1. A conceptual model of a typical northern Moroccan goat production system, based on data collected using the FAO-CIHAEM technical and economic indicators (Toussaint et al., 2009).