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Development and validation of a bioeconomic simulation model for estimating economic values in South American camelids

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Introduction

Alpacas (*Vicugna pacos*) and llamas (*Lama glama*) are fundamental to Andean production systems, with Peru hosting approximately 3 million alpacas and over one million llamas (MINAGRI, 2023). These species provide fiber, meat, and breeding stock income for thousands of rural families at 3,800-5,000 m altitude (Barrantes et al., 2018). However, limited genetic improvement programs constrain productivity (Wurzinger and Gutiérrez, 2022). Effective breeding programs require economic values that quantify trait impacts on system profitability (Hazel, 1943; Wolfová et al., 2009). While bioeconomic models successfully estimate economic values in cattle and sheep (Conington *et al*., 2004), South American camelids lack comprehensive models addressing their unique characteristics: extreme altitude conditions, multiple marketing systems, and long reproductive cycles (Quispe et al., 2011). This study developed and validated a bioeconomic simulation model for camelid systems, estimating marginal and relative economic values (MEV, REV) for 15 breeding objective traits across four production scenarios.

Materials & Methods

Model structure and calibration. A deterministic–stochastic bioeconomic model was implemented in Microsoft Excel, adapting the ECOWEIGHT/EWSH1 conceptual framework (Wolfová *et al.,* 2009). It comprises six modules: input parameters, herd dynamics, progeny dynamics, biophysical production, economic evaluation, and economic values (Fig. 1).

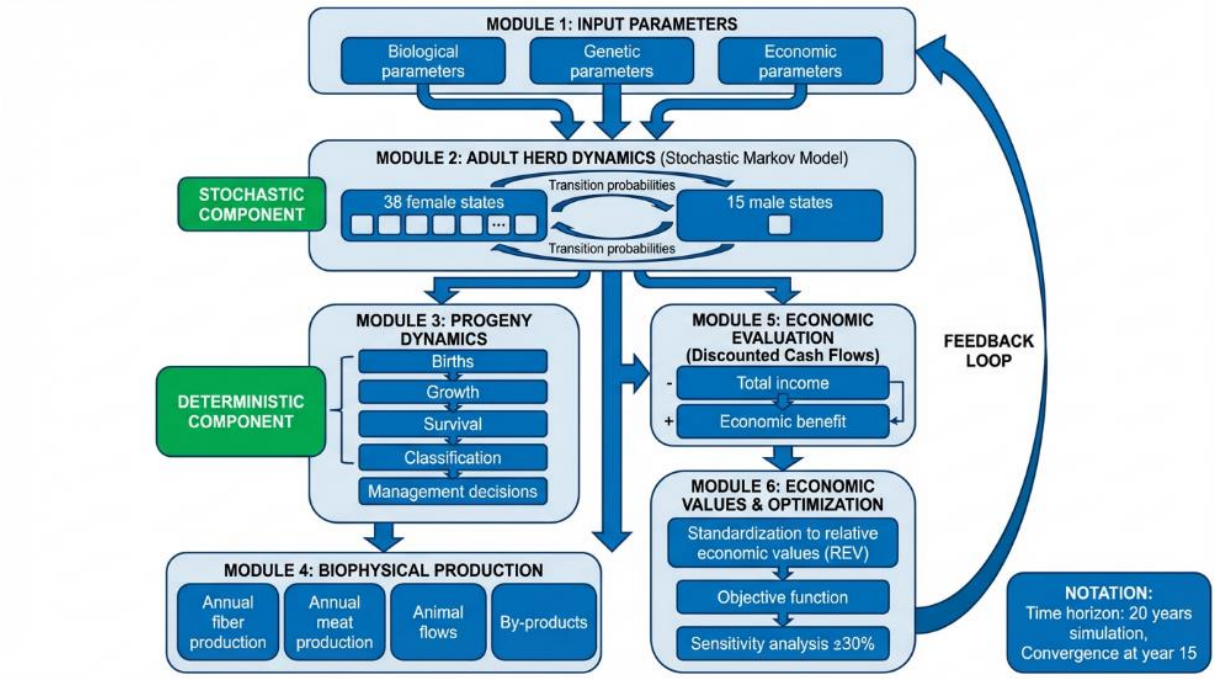

Figure 1. Bioeconomic model structure showing six sequential modules.

Stochastic Markov chains simulated herd dynamics to steady state over a 20-year horizon, while subsequent modules applied deterministic calculations for biological and economic flows. The model was calibrated using five years (2013–2017) of records from Cooperativa Comunal San Pedro de Racco (Pasco, Peru; 4,253–4,446 m a.s.l.), including 1,300 alpacas and 300 llamas. Structural validation compared simulated and observed herd structures (Alpacas: $x^2 = 12.34$, $P = 0.652$; Llamas: $x^2 = 9.87$, $P = 0.827$). **Herd dynamics and traits.** Females were classified into 38 reproductive-status states and males into 15 states; steady state was achieved when transition probabilities stabilized. Progeny were simulated deterministically from birth to destination (replacement, meat, breeding), applying multiphasic growth and stage-specific survival rates. Fifteen breeding traits were evaluated across growth: birth weight (BW), daily gain from birth to weaning (DG-BW), daily gain from weaning to 1 year (DG-W1), daily gain from 1 to 2 years (DG-12), and adult weight (AW); carcass yield (CY); fiber traits including greasy fleece weight (GFW) and fiber diameter (FD); animal category (AC); and functional traits: inter-calving interval (ICI), conception rate of young females (CR-YF), conception rate of adult females (CR-AF), survival from birth to weaning (S-BW), survival from weaning to 1 year (S-W1), and productive lifespan (PL). Animal category (AC; R–S classification) was included because breeding prices depend directly on category. To allow its use in the bioeconomic model, AC was transformed into a quantitative trait by assigning ordinal scores (R=1, C=2, B=3, A=4, S=5). Based on the frequency distribution of animals across categories, a weighted average category score at herd level (Ppf) was calculated and used as the quantitative representation of the trait; fiber quality predominates in alpacas (90%), whereas conformation predominates in llamas (90%). **Economic evaluation and values.** Income sources included fiber, breeding and live sales, carcass, and by-products; costs included feeding, health, labor, shearing, breeding purchases, and fixed costs. Values were expressed in USD (3.35 Soles = 1 USD) and discounted at 8%. Economic benefit was defined as discounted income minus discounted costs per breeding female per year. Marginal economic values were calculated using the finite difference quotient method (±0.5% trait variation): as MEVl = (Benefith - Benefitl) / (Traith - Traitl), where for AC the trait corresponds to Ppf; categorical traits were evaluated using a 0.05 SD threshold shift. Relative economic values were computed as $REV_l = (|MEV_l \times \sigma g_l| / \Sigma|MEV \times \sigma g|) \times 100$. Sensitivity analysis varied key prices and costs by ±30%. Scenarios. Four scenarios were evaluated: Alpacas I (bulk fiber, base), Alpacas II (categorized fiber), Llamas I (base), and Llamas II (−10% conception rate).

Results

Economic performance. Table 1 presents economic performance across scenarios.

Table 1. Economic performance (USD per breeding female per year) across four production scenarios.

Income/Cost Source	Alpacas I	Alpacas II	Llamas I	Llamas II
Total Income	**27.65**	**28.14**	**48.80**	**44.24**
Fiber	14.99	15.48	-	-
Live animal sales	9.54	9.54	17.71	14.35
Breeder sales	1.71	1.71	26.56	25.92
Carcass	0.84	0.84	3.77	3.31
Hides	0.58	0.58	0.76	0.66
Total Costs	**25.06**	**25.06**	**35.44**	**33.97**
Net Benefit	**2.60**	**3.09**	**13.36**	**10.27**
Profitability (%)	**10.36**	**12.34**	**37.69**	**30.32**

For alpacas, fiber categorization (Scenario II) increased total income by 1.8% (from $27.65 to $28.14) and net benefit by 19.0% (from $2.60 to $3.09), raising profitability from 10.36% to 12.34%. Fiber sales dominated income (54-55%), followed by live animal sales (34%). For llamas, a 10% reduction in conception rate (Scenario II) decreased total income by 9.4% (from $48.80 to $44.24) and net benefit by 23.1% (from $13.36 to $10.27), reducing profitability from 37.69% to 30.32%. Income was dominated by breeder sales (54-59%) and live animal sales (32-36%).

Economic values. Table 2 presents MEV and REV for all traits across scenarios. For alpacas, GFW showed highest MEV (7.33-7.57/kg), while FD showed strong negative MEV (-1.94/µm in Scenario II). AC showed moderate MEV ($0.77/unit). Among functional traits, PL ($1.43-1.47/year) and CR-AF ($0.16-0.18/%) demonstrated substantial importance. In Scenario II, fiber traits dominated REV (FD 33.07%, GFW 14.34%), followed by CR-AF (12.51%) and ICI (7.48%). In Scenario I, GFW showed highest REV (21.89%), followed by CR-AF (18.10%) and ICI (11.65%). For llamas, AC dominated MEV ($8.85-9.06/unit) and REV (35.11-36.31%), followed by PL ($1.93-2.07/year; 9.04-10.30% REV) and CR-AF ($0.22-0.23/%; 20.06-20.73% REV). The 10% conception rate reduction (Llamas II) increased relative importance of AC (36.31%), CR-AF (20.73%), and PL (10.30%).

Table 2. MEV (USD/unit) and REV (%) for key traits.

Trait	Unit	Alpacas I		Alpacas II		Llamas I		Llamas II	
		MEV	REV %	MEV	REV %	MEV	REV %	MEV	REV %
BW	kg	0.16	0.39	0.16	0.24	0.18	1.20	0.14	0.99
DG-BW	g/d	0.03	7.73	0.03	4.90	0.04	5.69	0.03	4.67
DG-W1	g/d	0.02	1.85	0.02	1.17	0.03	5.97	0.02	4.92
DG-12	g/d	0.05	7.97	0.05	5.06	0.06	7.35	0.05	6.20
AW	kg	0.04	1.09	0.04	0.69	0.04	1.83	0.04	2.06
CY	%	0.01	0.67	0.01	0.43	0.07	0.29	0.06	0.27
GFW	kg	7.33	21.89	7.57	14.34	-	-	-	-
FD	µm	-	-	-1.94	33.07	-	-	-	-
CR-YF	%	0.05	5.21	0.07	4.57	-0.01	0.44	-0.03	2.39
CR-AF	%	0.16	18.10	0.18	12.51	0.23	20.06	0.22	20.73
S-BW	%	0.10	5.23	0.12	3.81	0.15	6.06	0.12	5.14
S-W1	%	0.12	5.12	0.13	3.61	0.18	5.95	0.14	5.13
PL	year	1.47	8.69	1.43	5.32	1.93	9.04	2.07	10.30
ICI	day	-0.02	11.65	-0.02	7.48	-0.04	1.02	-0.04	0.91
AC	unit	0.77	4.41	0.77	2.79	9.06	35.11	8.85	36.31

Discussion

This study presents the first comprehensive bioeconomic model for South American camelid systems, incorporating Markov chain dynamics across multiple production scenarios. Fiber categorization in alpacas substantially increased profitability (19%, $0.49/female/year) by capturing premium prices for fine fiber, while shifting breeding emphasis toward FD (33% REV). This demonstrates the critical importance of fiber quality improvement, consistent with market realities where extra-fine fiber commands 2-3× prices of coarse fiber (Frank et al., 2006). In bulk systems, GFW dominates (22% REV), suggesting breeding objectives must align with marketing strategies. For llamas, AC dominance (35-36% REV, $8.85-9.06/unit MEV) reflects substantial economic importance of phenotypic quality in breeding markets (Wurzinger et al., 2013). The impact of reduced conception rate (23% benefit reduction, from

$13.36 to $10.27) underscores reproductive efficiency as critical in llama systems where breeder sales constitute 54-59% of income. Functional traits showed substantial importance across scenarios (CR-AF: 12-21% REV; PL: 5-10% REV), exceeding beef cattle (15-25%) but similar to dairy cattle (25-40%) (Wolfová et al., 2005), reflecting reproductive efficiency importance in systems with long generation intervals and low reproductive rates. Sensitivity analysis demonstrated moderate fiber trait sensitivity to prices, while functional traits showed high robustness, supporting consistent emphasis even with imprecise economic data.

Conclusions

A comprehensive bioeconomic model was successfully developed and validated for South American camelid systems, providing systematic economic value estimation for 15 traits across four scenarios. Fiber categorization in alpacas increased profitability 19% and shifted breeding emphasis toward FD (33% REV, MEV -$1.94/µm). Reduced conception in llamas decreased profitability 23%, highlighting reproductive efficiency importance. AC dominated llama objectives (35-36% REV, MEV $8.85-9.06/unit), while fiber traits dominated alpacas (47% combined REV in categorized systems). Functional traits contributed substantially (30-40% combined REV), exceeding beef cattle systems. The model provides a practical tool for defining breeding objectives adapted to diverse contexts.

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