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Economics, risk analysis, and sustainability of minimum module for pasture-based beef production: a case study in Campo Grande, MS, Brazil

Michael Allim Jorge[1]*, Durval Dourado Neto[1], Roberto Daniel Sainz[2], Lucilio Rogerio Aparecido Alves[3], Sila Carneiro da Silva[4], Sergio de Zen[3], Klaus Reichardt[5]

[1] Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Departamento de Produção Vegetal, Piracicaba, SP, Brasil.
[2] University of California, Department of Animal Science, Davis, California, United States of America.
[3] Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Departamento de Economia, Administração e Sociologia, Piracicaba, SP, Brasil.
[4] Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Departamento de Zootecnia, Piracicaba, SP, Brasil.
[5] Universidade de São Paulo, Centro de Energia Nuclear na Agricultura, Piracicaba, SP, Brasil.

***Corresponding author:**
rhallim.michael@usp.br

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ABSTRACT - This study quantified production risks and economic feasibility in tropical pasture-based beef systems by integrating a rule-based Minimum Module (MM) framework with Monte Carlo simulation (@Risk 8.0) in Excel 365 using a Microsoft Visual Basic 6.0 algorithm. Twelve scenarios combining low (0.5 animal unit [AU] ha^{-1}), medium (1.0 AU ha^{-1}), and high (1.5 AU ha^{-1}) stocking rates across 2017–2020 were each run with 10,000 stochastic iterations to identify the smallest viable herd size and pasture area that ensured non-negative net present value (NPV ≥ 0). Intensification increased per-hectare productivity from 3.3 to 9.8 arrobas ha^{-1} yr^{-1} ($P<0.001$) and reduced minimum grazing area by 53–63 percent ($P<0.001$). Risk profiles remained favorable, with negative gross margin in only 0.25% of iterations and negative total profit in 15.55% of iterations. Fixed-cost share declined from approximately 74% in low-intensity to approximately 48% in high-intensity systems ($P<0.05$). Strong co-movement among overhead inputs ($\rho>0.90$) and among variable-cost inputs ($\rho>0.80$), and a land-for-feed trade-off ($\rho \approx -0.35$) were quantified. The MM tool delivers transparent "what-if" scenario testing for herd and land planning without complex optimization, enabling data-driven feed-price hedging and stocking-rate adjustments.

Keywords: beef cattle, intensification, minimum module, Monte Carlo simulation, net present value, tropical grazing systems

1. Introduction

The global demand for sustainable beef production continues to rise, driving the need for grazing systems that balance economic viability, environmental health, and livestock productivity. In tropical regions such as Brazil, where extensive cattle farming underpins agribusiness, producers confront economic volatility, biophysical constraints, and technological uncertainty (Dickinson, 2001; Anderson, 2003; Moss, 2010; Stockton, 2022; Santos et al., 2024; Taylor et al., 2025).

Brazil's ruminant sector relies almost entirely on forage-based diets, with improved and native pastures covering approximately 180 million ha, of which about 30% are located in the Cerrado biome, making pasture management a cornerstone of national beef output (Barcellos et al., 2008; McManus et al., 2016; Parente et al., 2019; Sano et al., 2019; Cordeiro et al., 2023; Santos et al., 2024). Mato Grosso do Sul exemplifies this dynamic, hosting 18.9 million cattle over 14.6 million ha of grazing land, and the Campo Grande microregion alone supports 1.75 million head (9.2 percent of the state total) with strategic access to soybean and corn terminals and beef-processing plants (slaughter/packing facilities) (Moore et al., 1999; Tambara et al., 2021; Azevedo et al., 2023; Lapig, 2023).

Despite these assets, pasture-based beef systems face mounting pressures—deforestation, greenhouse-gas emissions, land-use conflicts, and financial risks—underscoring the need for integrated sustainability indicators in production models (Chapman et al., 2024; Lorencowicz et al., 2024). Sustainability frameworks operationalize economic, environmental, and social goals, guided by indicators that inform evidence-based management and align with the Sustainable Development Goals (SDGs) 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 15 (Life on Land) (Dumanski et al., 1998; Mukherjee, 1998; United Nations, 2015; Barry and Hoyne, 2021; Nadaraja et al., 2021).

Current economic and agronomic models often omit stochastic elements or have limited usability, limiting their adoption in commercial herds (Moss, 2010; Hardaker and Lien, 2010a,b; Gomes et al., 2015; Hardaker et al., 2015a,b; McManus et al., 2016; McKendree et al., 2021; Stockton, 2022; Tedeschi et al., 2024; Taylor et al., 2025). Moreover, most mathematical models remain confined to academic research, offering limited decision-support for producers and policymakers (Stygar and Makulska, 2010; Jones et al., 2017).

To bridge these gaps, Jorge (2019) developed the Minimum Module (MM), a modular deterministic–stochastic framework that links a rancher's target net income to endogenous adjustments in herd size and pasture area—defining the minimum viable scale as the point at which the removal of one breeding cow causes net present value (NPV) to fall below zero. This study applies the MM framework combined with Monte Carlo simulation to (i) quantify market-driven production risks, (ii) evaluate economic feasibility under low, medium, and high intensification strategies, and (iii) provide a practical decision-support tool for land-use and herd-scaling decisions in tropical grazing systems.

2. Material and methods

2.1. Study design

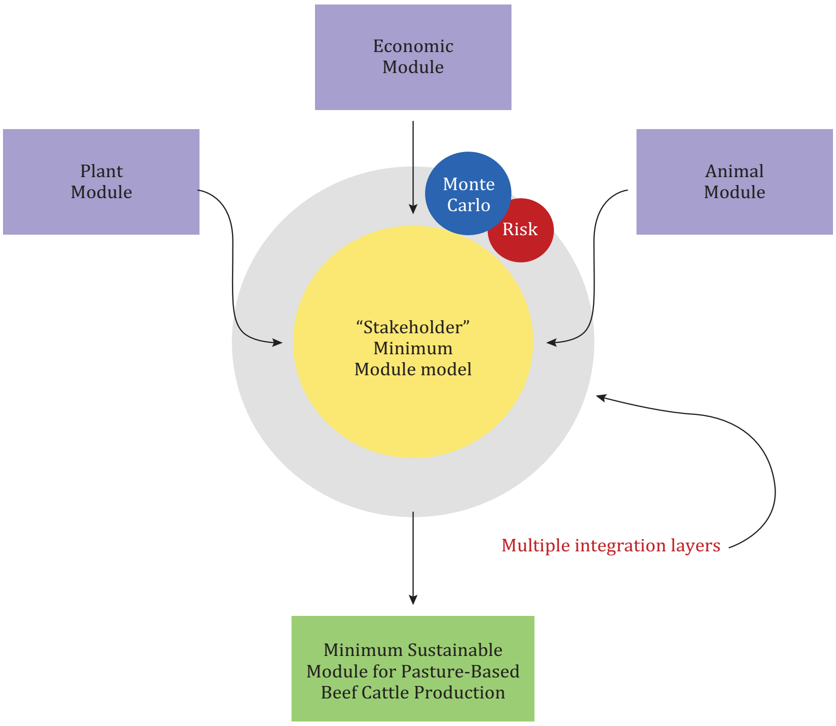
We applied the rule-based Minimum Module (MM) framework, a deterministic–stochastic simulation model, to determine the smallest viable herd size and pasture area capable of sustaining non-negative net present value (NPV ≥ 0) under three stocking-rate intensification levels: low (0.5 animal unit [AU] ha^{-1}), medium (1.0 AU ha^{-1}), and high (1.5 AU ha^{-1}). The MM overcomes the limitations of conventional economic models by embedding zootechnical and financial uncertainties within a single decision-support structure that mirrors on-farm management rules, rather than relying on mathematical optimization alone (Jorge, 2019; Lampert et al., 2020).

We conducted simulations for the Campo Grande microregion (20°26' S, 54°38' W) in Mato Grosso do Sul, Brazil—a representative pasture-based beef system characterized by *Urochloa brizantha* spp. pastures, annual rainfall of approximately 1,400 mm, and bimodal wet–dry seasons. We ran twelve scenarios combining three intensification levels and four production years (2017–2020), each spanning a 20-year horizon (20 annual cycles) to capture inter-annual climate variability and typical ranch investment amortization periods. For each scenario, we fixed an annual net-income requirement (Rr_1 = USD 70,725.93), informed by regional cost–return data (CEPEA, 2020), and identified the MM threshold by reducing herd size incrementally until the removal of one breeding cow caused NPV to drop below zero.

To quantify production risk, we reserved a detailed Monte Carlo simulation for section 2.9.

2.2. Modeling of the Minimum Module (MM)

We developed the Minimum Module (MM) as a modular, deterministic–stochastic simulation framework that quantitatively represents pasture-based beef production by linking three interconnected submodels: the Animal Production Module (Animal Module), the Plant Production Module (Plant Module), and the Economic Module (Pidd, 1997; Jorge, 2019) (Figure 1).



The flowchart illustrates how the three core submodels—Animal, Plant, and Economic—feed into the stakeholder-driven "Minimum Module" model. Monte Carlo risk analysis and DCF computations occur within the Economic Module before all streams converge in the central decision engine. Multiple integration layers (data-exchange files, open-source code libraries, among others) enable seamless interoperability and rapid "what-if" scenario testing. The final output defines the Minimum Sustainable Module for pasture-based beef production, aligning target net-income goals with legal-reserve requirements under varied intensification levels.

Figure 1 - Modular architecture and integration flow of the Minimum Module (MM).

Thus, we implemented all submodels and automated calculations in Microsoft Excel® 365 (build 2504, compilation 18730.20168) using a Microsoft Visual Basic 6.0 algorithm comprising eleven subroutines and totaling 3,867 lines of code, alongside the @Risk 8.0 (Palisade Corp., Ithaca, NY) add-in to generate correlated random variates, construct the risk-correlation matrix, and execute Monte Carlo simulations.

2.3. Animal Module

In the Animal Module, we tracked herd dynamics across 17 animal categories representing the full-cycle pasture-based beef system. These comprised 15 marketed production cohorts, one transitional birth class ("Animals born") used for herd-flow accounting, and one breeding-bull category used in the natural-mating subsystem. For the marketed cohorts, we defined average live weight (W_i, kg head^{-1}), carcass yield (R_i, kg carcass kg live weight^{-1}), and selection pressure (Ps_i, %) for under-threshold animals. The "Animals born" class was used only to register annual calf output before allocation into male and female cohorts and therefore had no direct market price. The breeding-bull category was retained in the biological and economic modules because bulls were required for the natural-mating system and also generated annual replacement and culling flows. We specified weight thresholds—180 kg for male weaners, 160 kg for female weaners, 195 kg for bull calves, 180 kg for female calves, 285 kg for 18-month-olds, and 360 kg for lean bulls—and directed animals failing to meet these thresholds into replacement markets (i.e., sold from one producer to another), while applying category-specific (Ps_i) rates to all others for slaughter (Table 1).

Furthermore, we standardized Animal Units at 450 kg live weight, imposed a bull-to-cow ratio of 1:25, set annual replacement rates at 20%, and targeted a calving rate of 70–90% (Table 2).

Table 1 - Animal module, biological performance, and fixed inputs

Item	Cohorts	Parameter	Symbol	Unit	Input
Animal cohort	Cows aged 37 to 48 months	Average weight of cull cow	W_1	kg hc^{-1}	410
		Carcass yield	R_1	kg kg^{-1}	0.50
		Market-driven selection pressure	Ps_1	%	0.65
	Weaning - male (7 to 8 months)	Average weight of live male	W_2	kg hc^{-1}	180
		Market-driven selection pressure (< 180 kg)	Ps_2	%	0.40
	Weaning - female (7 to 8 months)	Average weight of live female	W_3	kg hc^{-1}	160
		Market-driven selection pressure (< 160 kg)	Ps_3	%	0.40
	Bull calves (12 months)	Average weight of live	W_4	kg hc^{-1}	195
		Market-driven selection pressure (< 195 kg)	Ps_4	%	0.15
	Female calves (12 months)	Average weight of live	W_5	kg hc^{-1}	180
		Market-driven selection pressure (< 180 kg)	Ps_5	%	0.10
	Heifers from 18 to 20 months	Average weight of fat heifer	W_6	kg hc^{-1}	420
		Carcass yield	R_6	kg kg^{-1}	0.52
		Market-driven selection pressure	Ps_6	%	0.40
	Heifers from 21 to 28 months	Average weight of fat heifer	W_7	kg hc^{-1}	450
		Carcass yield	R_7	kg kg^{-1}	0.50
		Market-driven selection pressure	Ps_7	%	0.90
	Heifers from 29 to 36 months	Average weight of fat heifer	W_8	kg hc^{-1}	450
		Carcass yield	R_8	kg kg^{-1}	0.50
		Market-driven selection pressure	Ps_8	%	0.80
	18-month old bull	Average weight of 18-month old bull	W_9	kg hc^{-1}	285
		Market-driven selection pressure (< 285 kg)	Ps_9	%	0.15
	Lean bull (12 to 13 arrobas)	Average weight of lean bull	W_{10}	kg hc^{-1}	370
		Market-driven selection pressure (< 360 kg)	Ps_{10}	%	0.15
	Fat bull 18 to 20 months (milk-tooth - MT)	Average weight of fat bull	W_{11}	kg hc^{-1}	480
		Carcass yield	R_{11}	kg kg^{-1}	0.54
		Market-driven selection pressure	Ps_{11}	%	0.40
	Fat bull 21 to 28 months (up to 2 permanent teeth)	Average weight of fat bull	W_{12}	kg hc^{-1}	510
		Carcass yield	R_{12}	kg kg^{-1}	0.53
		Market-driven selection pressure	Ps_{12}	%	0.50
	Fat bull 29 to 36 months (up to 4 permanent teeth)	Average weight of fat bull	W_{13}	kg hc^{-1}	560
		Carcass yield	R_{13}	kg kg^{-1}	0.52
		Market-driven selection pressure	Ps_{13}	%	0.40
	Fat bull (37 to 48 months) (adult)	Average weight of fat bull	W_{14}	kg hc^{-1}	570
		Carcass yield	R_{14}	kg kg^{-1}	0.52
		Market-driven selection pressure	Ps_{14}	%	1.00
	Older fat bull "toruno"[1] 60 months	Average weight of fat bull	W_{15}	kg hc^{-1}	780
		Carcass yield	R_{15}	kg kg^{-1}	0.49
		Market-driven selection pressure	Ps_{15}	%	1.00

hc - head of cattle.
[1] "toruno" refers to mature bulls or improperly castrated males excluded from standard finishing categories, often culled due to age or reproductive behavior. This classification affects slaughter pricing and market placement.

Table 2 - Animal module, pasture-based production system, and fixed inputs

Item	Parameter	Description	Symbol	Unit	Input
Herd management	Bull-to-cow ratio	Number of bulls per cow	Rs_1	bulls cow^{-1}	1:25
	Cow replacement rate	Proportion of cows replaced annually	Rp_2	%	20
	Bull replacement rate	Proportion of bulls replaced annually	Rp_3	%	20
	Calving rate	Percentage of cows that give birth	Tn_4	%	70–90
Herd dynamics	Animal unit	Standardized live weight for one animal unit	AU	kg LW	450
	Cows aged 37 to 48 months	Average live weight	F_6	kg hc^{-1}	450
	Heifers from 29 to 36 months	Average live weight	F_5	kg hc^{-1}	400
	Heifers from 21 to 28 months	Average live weight	F_4	kg hc^{-1}	330
	Heifers from 18 to 20 months	Average live weight	F_3	kg hc^{-1}	290
	Female calves (12 months)	Average live weight	F_2	kg hc^{-1}	180
	Weaning - female (7 to 8 months)	Average live weight	F_1	kg hc^{-1}	160
	Weaning - male (7 to 8 months)	Average live weight	M_1	kg hc^{-1}	200
	Bull calves (12 months)	Average live weight	M_2	kg hc^{-1}	225
	18-month old bull	Average live weight	M_{3g}	kg hc^{-1}	285
	Lean bull (12 to 13 arrobas)	Average live weight	M_{3bm}	kg hc^{-1}	370
	Fat bull 18 to 20 months (milk-tooth - MT)	Average live weight	M_3	kg hc^{-1}	380
	Fat bull 21 to 28 months (up to 2 permanent teeth)	Average live weight	M_4	kg hc^{-1}	400
	Fat bull 29 to 36 months (up to 4 permanent teeth)	Average live weight	M_5	kg hc^{-1}	440
	Fat bull (37 to 48 months) (adult)	Average live weight	M_6	kg hc^{-1}	600
	Older fat bull “toruno” 60 months	Average live weight	M_{6bgt}	kg hc^{-1}	750
	Bulls	Average live weight	M_{6t}	kg hc^{-1}	800
Daily nutritional intake	Mineral salt	Salt consumed per animal per day	C_1	kg hc^{-1} d^{-1}	0.100
	Mineral salt for breeding cows	Salt consumed per 100 kg live weight	C_2	kg hc^{-1} d^{-1}	0.025
	Mineral protein supplement	Protein supplement per 100 kg live weight	C_3	kg hc^{-1} d^{-1}	0.200
	Mineral energy supplement	Energy supplement per 100 kg live weight	C_4	kg hc^{-1} d^{-1}	0.130
	Creep-feeding	Supplementary feeding for calves	C_5	kg hc^{-1} d^{-1}	1.400
	Creep-feeding intake limiter	Salt proportion in creep-feeding mix	C_6	%	0.80
	Semi-confinement pasture diet	Percentage of live weight intake	C_7	%	1
	Dry matter consumption at pasture	Percentage of live weight intake	Dm_1	%	2
	Average daily gain in semi-confinement diet	Weight gain per day in semi-confinement	Adg_1	kg hc^{-1} d^{-1}	1.300
Animal health	FMD vaccine	Doses applied per year	V_1	dose hc^{-1} yr^{-1}	1–2
	Blackleg vaccine	Doses applied per year	V_2	dose hc^{-1} yr^{-1}	1–2
	Brucellosis vaccine	Doses applied per year	V_3	dose hc^{-1} yr^{-1}	1
	Dewormer	Doses applied per year	V_4	dose hc^{-1} yr^{-1}	1–3
Production impacts	Pre-weaning mortality	Mortality before weaning	Mt_1	%	1.2
	Mortality rate (0–12 months)	Losses from weaning	Mt_2	%	1.0
	Mortality rate (12–20 months)	Losses from 12 to 20 months	Mt_3	%	1.0
	Mortality rate (21–28 months)	Losses from 21 to 28 months	Mt_4	%	1.0
	Mortality rate (29–36 months)	Losses from 29 to 36 months	Mt_5	%	0.5
	Mortality rate (37–48 months)	Losses from 37 to 48 months	Mt_6	%	0.5

hc - head of cattle.

Nutritional management incorporated daily mineral-salt and protein/energy supplementation, creep feeding, and semi-confinement diets yielding 1.3 kg day^{-1} gains, while health protocols included annual vaccinations for foot-and-mouth disease, blackleg, and brucellosis plus systematic deworming. We simulated replacement purchases of 170 cow-calf pairs and six breeding bulls per year, with younger replacements set to zero in core scenarios (Table 3).

Table 3 - Animal module, parameters for livestock acquisition in herd replacement, and fixed inputs

Item	Parameter	Description	Symbol	Unit	Live weight (kg)	Qty (head)
Replacement	Cow–calf pair	Unit price for lactating cow and calf	RC_1	USD pair^{-1}	–	170
	Bulls	Mature bulls used for reproduction	RC_2	USD hc^{-1}	380	6
	Weaning - female (7 to 8 months)	Price of young heifer calves	RC_3	USD kg^{-1}	175	0
	Weaning - male (7 to 8 months)	Price of young male calves	RC_4	USD kg^{-1}	200	0
	Heifers from 18 to 20 months	Price of prepubertal heifers	RC_5	USD kg^{-1}	235	0
	Heifers from 21 to 28 months	Price of heifers approaching reproductive age	RC_6	USD kg^{-1}	260	0

2.4. Plant Module

In the Plant Module, we modeled pasture over a ten-year lifespan, beginning with land preparation—stump removal (5 h ha^{-1}), disking (1 h ha^{-1}), plowing (1.5 h ha^{-1}), liming with 2 t ha^{-1} of dolomitic limestone, NPK fertilization at 300 kg ha^{-1}, and seeding at 18 kg ha^{-1}—and followed by uniform annual maintenance comprising lime spreading (1 h ha^{-1}), disking (1 h ha^{-1}), fertilizer application (0.35 h ha^{-1}), and selective herbicide use (4.4 L ha^{-1} of 2,4-D/Picloram) (Table 4).

In addition, we enforced a 20% legal reserve as required by Article 12 of the Brazilian Forest Code (Law 12,651/2012) (Brazil, 2012) and assumed a uniform 10% permanent preservation area per Article 4, recognizing that actual preservation percentages vary by property (1–25%, approximately), to maintain consistency across comparative intensification scenarios.

2.5. Economic Module

We integrated the Economic Module into the simulation to capture the financial dynamics of pasture-based beef production under varying environmental conditions. We incorporated both fixed and variable inputs, with variable inputs reflecting site-specific conditions to ensure a localized economic representation.

Fixed inputs, including operational costs such as labor, general expenses, rural inventory, tractor operators and ranch hands' monthly labor hours, internal transportation, technical assistance (veterinary, animal science, and agronomy consultations), accounting, electricity, machinery, equipment, and infrastructure costs and depreciation (e.g., seed/fertilizer spreaders, disc plows, leveling harrows) (Table 5), were incorporated into the simulation.

Variable inputs were presented in two parts. First, we outlined revenue sources—including local sale prices per unit for each cohort (cull cows, male and female weaned calves, bulls, and heifers at various growth stages) and early-slaughter bonuses to reflect market incentives (Table 6). We adjusted these prices for seasonal fluctuations, Rural Workers' Assistance Fund (Funrural) tax obligations, and the regional market context. Second, we detailed site-specific production costs—including labor, general expenses, pasture operations (stump removal, plowing, seeding/fertilizing, herbicide application, and

Table 4 - Plant module, pasture establishment, annual maintenance, and fixed inputs

Item	Parameter	Description	Symbol	Unit	Input
Soil preparation	Stump removal	Removal of tree stumps for land clearing	Ps_1	h ha^{-1}	5
	Topography	Land surface measurement and contouring	Ps_2	h ha^{-1}	0.5
	Terracing	Soil conservation practice to reduce erosion	Ps_3	h ha^{-1}	1
	Road adaptation	Improvement of access roads in pasture areas	Ps_4	h ha^{-1}	1
	Chemical destruction	Application of herbicides for vegetation control	Ps_5	h ha^{-1}	0
	Lime spreading	Distribution of lime for soil pH correction	Ps_6	h ha^{-1}	0.45
	Lime loading	Loading lime into machinery for field application	Ps_7	h ha^{-1}	0.15
Pasture establishment	Disking	Primary soil tillage operation to break compact layers	Fp_2	h ha^{-1}	1
	Plowing	Deep soil turning for seedbed preparation	Fp_3	h ha^{-1}	1.5
	Leveling	Smoothing of soil surface before planting	Fp_4	h ha^{-1}	0
	Seeding/fertilizing	Combined process of sowing pasture seeds and fertilizing	Fp_5	h ha^{-1}	1
	Herbicide application	Spraying herbicides to control weeds	Fp_6	h ha^{-1}	1
	Seed	Quantity of pasture seeds applied per hectare	Fp_7	kg ha^{-1}	18
	Dolomitic limestone	Calcium and magnesium carbonate for soil correction	Fp_8	t ha^{-1}	2
	Fertilizer 04-14-08	NPK fertilizer application for pasture establishment	Fp_9	kg ha^{-1}	300
	Herbicide 2,4-D and picloram	Selective herbicide for broadleaf weed control	Fp_{10}	L ha^{-1}	3
	Pasture lifespan (in years)	Expected duration of pasture productivity	Fp_{11}	yr	10
Annual pasture maintenance	Lime spreading	Annual soil pH correction with lime application	Mp_1	h ha^{-1}	1
	Disking	Maintenance tillage to prevent soil compaction	Mp_2	h ha^{-1}	1
	Fertilizer spreading	Annual nutrient replenishment in pastures	Mp_3	h ha^{-1}	0.35
	Herbicide application	Weed control in established pastures	Mp_4	h ha^{-1}	0.60
	Fertilizer 14-00-27	NPK fertilizer for annual pasture maintenance	Mp_5	kg ha^{-1}	150
	Lime	Quantity of lime applied annually per hectare	Mp_6	t ha^{-1}	1
	Herbicide 2,4-D and picloram	Annual herbicide application for pasture maintenance	Mp_7	L ha^{-1}	4.4

annual lime spreading), nutritional inputs (mineral salts, protein supplements, creep feeding), and animal health expenses (vaccinations, deworming) (Table 7)—to ensure that we captured both direct and indirect costs under the local conditions of the Campo Grande microregion.

By incorporating environment-dependent cost and price data, we enabled the Economic module to reflect specific regional market conditions, cost structures, and production strategies. This approach allowed us to simulate and accurately evaluate the economic performance of pasture-based beef systems across different intensification scenarios under real-world variability.

2.6. Simulation scenarios

We configured twelve scenarios by combining user-selected settings in the Simulation Panel with fixed biological, economic, and intensification parameters (Table 8). First, users specified their rancher profile (sole proprietor), land-ownership status (owned), annual net-income target (Rr_1), cohort prices (Pi) and cost components (Ci) for the chosen year (Sim_2: 2017–2020), stocking rate (Sr_2: 0.5, 1.0, or 1.5 AU ha^{-1}), land constraints (20% legal reserve, Ar_1, per Law 12,651/2012, Art. 12; 10% permanent preservation area, Ar_2, per Art. 4), geographic focus (Campo Grande microregion), and intensification level (Ni_3).

Table 5 - Economic module, general operating expenses, rural inventory, and fixed inputs

Item	Parameter	Description	Symbol	Unit	Input
Labor	Tractor operator	Number of operators per month	Mo_1	man-month^{-1}	1
	Ranch hand (cowboy)	Number of workers per month	Mo_2	man-month^{-1}	3
	Labor hours	Monthly total labor hours	Mo_3	h month^{-1}	220
General expenses	Internal transportation	Annual machinery hours	Dg_1	h yr^{-1}	150
	Technical assistance	Veterinary, animal science, or agronomy consulting	Dg_2	visits yr^{-1}	2
	Accounting expenses	Monthly payments per year	Dg_3	payments yr^{-1}	12
	Electricity	Total energy consumption	Dg_4	kWh yr^{-1}	15,000
Rural inventory	Seed/Fertilizer spreader	Mounted double-disc spreader for seed and fertilizer application	Ir_1	USD	2,663.47
	Lime spreader	Double-disc lime spreader with 5–7 ton capacity	Ir_2	USD	6,158.94
	Disc plow	Tillage implements with 20–28 discs, 26–28 inch diameter	Ir_3	USD	5,091.36
	Leveling harrow	Secondary tillage harrow with 40–44 discs, 20–22 inch diameter	Ir_4	USD	3,349.71
	Trailer	Four-wheel trailer with 4–6 ton load capacity	Ir_5	USD	1,371.71
	Hydraulic cattle grid	2.75-meter hydraulic cattle crossing gate	Ir_6	USD	2,161.10
	Front hydraulic unit	Front loader bucket, 1,500–1,800 kg capacity, mounted on tractor	Ir_7	USD	6,428.68
	Price per square meter	Unit cost for barn construction	Ir_8	USD m^{-2}	31.10
	Machinery salvage value	Residual value	Ir_9	%	20
	Implements salvage value	Residual value	Ir_{10a}	%	10
	Infrastructure salvage value	Residual value	Ir_{10b}	%	10
	Useful life of machinery	Depreciation period	Ir_{11}	yr	10
	Useful life of implements	Depreciation period	Ir_{12a}	yr	10
	Useful life of infrastructure	Depreciation period	Ir_{12b}	yr	20

After panel configuration, we applied the Animal Production assumptions. We set a November–January breeding season with first-exposure conception rates of 50–85% and subsequent annual rates of 75–92%, a 2–5% pregnancy loss rate, and an August–October calving window. Herd dynamics used a bull-to-cow ratio of 1:25, 20% annual replacement, a 70–90% calving rate, an Animal Unit of 450 kg, daily gains of 1.3 kg head^{-1}, and standard health and nutrition protocols (vaccinations, deworming, mineral and protein supplements, and creep feeding) (Table 9).

Next, we applied the Economic and Macroeconomic parameters. We used a federal income tax rate of 27.5%, a Rural Workers Assistance Fund (Funrural) tax rate of 1.5%, a minimum acceptable rate of return (MARR) and real discount rate of 6%, an annual inflation rate of 4.5%, a capital structure of 40% equity and 60% debt with a 10-year financing term and 2-year grace period, a nominal interest rate of 7%, and a bare-land value of USD 1,500 per hectare. These inputs drove fixed and variable cost calculations and revenue deflation (Table 10).

We then enforced the intensification-level parameters across all 20 annual cycles. We applied fertilizer at rates ranging from 40 kg ha^{-1} under low intensification to 180 kg ha^{-1} under high intensification; we varied pasture maintenance hours and lease rates; accordingly, and we fixed stocking rates at 0.5, 1.0, or 1.5 AU ha^{-1} (Table 11).

Table 6 - Economic module, revenue sources, and environment-dependent variable inputs

Item	Parameter	Description	Symbol	Unit
Animal category	Price per unit	Cull cow (with Funrural[1])	P_1	USD $@^{-1}$
	Price per unit	Weaning - male (7 to 8 months)	P_2	USD kg^{-1}
	Price per unit	Weaning - female (7 to 8 months)	P_3	USD kg^{-1}
	Price per unit	Bull calves (12 months)	P_4	USD kg^{-1}
	Price per unit	Female calves (12 months)	P_5	USD kg^{-1}
	Price per unit	Heifers from 18 to 20 months (with Funrural)	P_6	USD $@^{-1}$
	Early slaughter bonus	Bonus paid for early slaughter to encourage precocious cattle finishing	Pp_6	USD $@^{-1}$
	Price per unit	Heifers from 21 to 28 months (with Funrural)	P_7	USD $@^{-1}$
	Early slaughter bonus	Bonus paid for early slaughter to encourage precocious cattle finishing	Pp_7	USD $@^{-1}$
	Price per unit	Heifers from 29 to 36 months	P_8	USD $@^{-1}$
	Early slaughter bonus	Bonus paid for early slaughter to encourage precocious cattle finishing	Pp_8	USD $@^{-1}$
	Price per unit	18-month old bull	P_9	USD $@^{-1}$
	Price per unit	Lean bull (12 to 13 arrobas)	P_{10}	USD $@^{-1}$
	Price per unit	Fat bull 18 to 20 months (MT[2], with Funrural)	P_{11}	USD $@^{-1}$
	Early slaughter bonus	Bonus paid for early slaughter to encourage precocious cattle finishing	Pp_{11}	USD $@^{-1}$
	Price per unit	Fat bull 21 to 28 months (up to 2 permanent teeth, with Funrural)	P_{12}	USD $@^{-1}$
	Early slaughter bonus	Bonus paid for early slaughter to encourage precocious cattle finishing	Pp_{12}	USD $@^{-1}$
	Price per unit	Fat bull 29 to 36 months (up to 4 permanent teeth, with Funrural)	P_{13}	USD $@^{-1}$
	Early slaughter bonus	Bonus paid for early slaughter to encourage precocious cattle finishing	Pp_{13}	USD $@^{-1}$
	Price per unit	Fat bull (37 to 48 months, adult, with Funrural)	P_{14}	USD $@^{-1}$
	Price per unit	Older fat bull “toruno” (60 months, with Funrural)	P_{15}	USD $@^{-1}$

@ = 15 kg.
[1] Funrural - Brazilian rural social-security levy (rate defined in the economic assumptions of the manuscript).
[2] MT - milk-tooth (0 permanent incisors). Dentition class used as a proxy for age/precocity; other classes appear as “up to 2 permanent teeth” and “up to 4 permanent teeth".

With all inputs defined, the Minimum Module was determined for each scenario by reducing herd size and pasture area until the removal of one breeding cow caused net present value to fall below zero. The model then recorded fixed and variable costs, gross and net revenues, operating and net margins, total profit, and per-hectare profitability for each intensification level and year.

Hence, we structured the simulation workflow to maintain transparency and reproducibility and to allow us to isolate the effects of intensification level and production year on system resilience and land-use efficiency.

2.7. Data sources and parameterization

We sourced price and cost data from regional institutional databases and publicly accessible commercial sources and standardized values to December 2020 using the General Price Index – Internal Availability (Índice Geral de Preços – Disponibilidade Interna, IGP-DI; FGV IBRE, 2020). Beef-cattle production costs for the municipality of Campo Grande were obtained from the Center for Advanced Studies in Applied Economics (CEPEA) database (2020), and daily price series for 15 animal categories were downloaded from the Correa da Costa auction website (2021) covering January 2010 to December 2020. We provide the complete monthly aggregates and deflated time-series plots in Results (section 3.5). Annual price data were assembled for the 15 marketed cattle cohorts and used both for the historical price-series analysis and as the scenario price inputs for 2017–2020.

The breeding-bull category, however, did not have a standardized regional annual price series available for the study period; therefore, its annual average price was parameterized separately for the Campo Grande microregion based on consultation with local specialists. The transitional "Animals born" class was not assigned a direct market price because it functioned only as a biological herd-flow category. Lease rates for pastureland reflected prevailing local values.

Table 7 - Economic module, production costs, and environment-dependent variable inputs

Item	Parameter	Description	Symbol	Unit
Labor	Hourly wage	Tractor operator	Mo_1	USD h^{-1}
	Hourly wage	Ranch hand (cowboy)	Mo_2	USD h^{-1}
General expenses	Cost per hour	Internal transportation	$Dg_{1.1}$	USD h^{-1}
	Cost per visit	Technical assistance (veterinary, animal science, or agronomy)	$Dg_{2.1}$	USD $visit^{-1}$
	Cost per month	Accounting expenses	$Dg_{3.1}$	USD $month^{-1}$
	Cost per kilowatt	Electricity	$Dg_{4.1}$	USD kWh^{-1}
Soil preparation	Cost per hour	Stump removal	$Ps_{1.1}$	USD h^{-1}
	Cost per hour	Topography	$Ps_{2.1}$	USD h^{-1}
	Cost per hour	Terracing	$Ps_{3.1}$	USD h^{-1}
	Cost per hour	Road adaptation	$Ps_{4.1}$	USD h^{-1}
	Cost per hour	Chemical destruction	$Ps_{5.1}$	USD h^{-1}
	Cost per hour	Lime spreading	$Ps_{6.1}$	USD h^{-1}
	Cost per hour	Lime loading	$Ps_{7.1}$	USD h^{-1}
Pasture establishment	Cost per hour	Disking	$Fp_{2.1}$	USD h^{-1}
	Cost per hour	Plowing	$Fp_{3.1}$	USD h^{-1}
	Cost per hour	Leveling	$Fp_{4.1}$	USD h^{-1}
	Cost per hour	Seeding/fertilizing	$Fp_{5.1}$	USD h^{-1}
	Cost per hour	Herbicide application	$Fp_{6.1}$	USD h^{-1}
	Cost per kg	Seed	$Fp_{7.1}$	USD kg^{-1}
	Cost per metric ton	Dolomitic limestone	$Fp_{8.1}$	USD t^{-1}
	Cost per kg	Fertilizer 04-14-08	$Fp_{9.1}$	USD kg^{-1}
	Cost per liter	Herbicide 2,4-D and picloram	$Fp_{10.1}$	USD L^{-1}
Annual pasture maintenance	Cost per hour	Lime spreading	$Mp_{1.1}$	USD h^{-1}
	Cost per hour	Disking	$Mp_{2.1}$	USD h^{-1}
	Cost per hour	Fertilizer spreading	$Mp_{3.1}$	USD h^{-1}
	Cost per hour	Herbicide application	$Mp_{4.1}$	USD h^{-1}
	Cost per kg	Fertilizer 14-00-27	$Mp_{5.1}$	USD kg^{-1}
	Cost per metric ton	Lime	$Mp_{6.1}$	USD t^{-1}
	Cost per liter	Herbicide 2,4-D and picloram	$Mp_{7.1}$	USD L^{-1}
Nutrition	Cost per kg	Mineral salt	C_{p1}	USD kg^{-1}
	Cost per kg	Mineral salt for breeding cows	C_{p2}	USD kg^{-1}
	Cost per kg	Mineral protein supplement	C_{p3}	USD kg^{-1}
	Cost per kg	Mineral energy supplement	C_{p4}	USD kg^{-1}
	Cost per kg	Creep-feeding	C_{p5}	USD kg^{-1}
	Cost per kg	Corn grain	C_{p6}	USD kg^{-1}
	Cost per kg	Mineral nucleus for 85:15 semi-confinement diet	C_{p7}	USD kg^{-1}
Animal health	Cost per dose	FMD vaccine	V_{p1}	USD $dose^{-1}$
	Cost per dose	Blackleg vaccine	V_{p2}	USD $dose^{-1}$
	Cost per dose	Brucellosis vaccine	V_{p3}	USD $dose^{-1}$
	Cost per dose	Dewormer	V_{p4}	USD $dose^{-1}$

Table 8 - Minimum Module simulation panel

Item	Parameter	Description	Symbol	Unit	Input
Administration assumptions	Producer profile	The simulation assumes a beef cattle rancher operating as an individual (non-corporate farming unit)	Up_1	–	Individual (sole proprietor)
	Land ownership status	Production occurs on owned land (not leased)	Up_2	–	Owned property
Economic target	Minimum required remuneration by the rancher	Annual income target to ensure economic sustainability	Rr_1	USD yr^{-1}	70,725.93
Economic performance	Animal category price	Average price for each animal category (cull cows, weaned calves, etc.) for each year simulated (2017–2020)	Pi	USD	2017; 2018; 2019; 2020
Total costs	Production costs	Average price for each component of the costs (labor, nutrition, etc.) for each year simulated (2017–2020)	Ci	USD	2017; 2018; 2019; 2020
Grazing conditions	Pasture carrying capacity	Stocking rate based on pasture potential (low, medium, or high)	Sr_2	AU ha^{-1}	0.5; 1.0; 1.5
Land constraints	Legal reserve area	Legally protected area (20%) required by Brazilian Forest Code	Ar_1	%	20
	Environmental preservation area	Additional environmental reserve area (10%) assumed for the MM model	Ar_2	%	10
Production settings	Location of simulation	Geographic focus of the study	Sim_1	–	Campo Grande Microregion, Midwest Brazil
	Year of simulation	Years evaluated by the Minimum Module (MM) model	Sim_2	–	2017; 2018; 2019; 2020
	Production system intensification level	Management intensity level (low, medium, or high)	Ni_3	–	3; 2; 1
	Number of breeding cows	Initial number of breeding cows in the herd (decision variable)[1]	Nc	hc	≥ 1

hc - head of cattle.
Administrative assumptions, economic targets, grazing conditions, land constraints, and general simulation settings are defined in section 2.6.
[1] Nc is a decision variable. The Minimum Module is the smallest Nc ≥ 1 such that NPV(Nc) ≥ 0 and NPV(Nc − 1) < 0 (one-cow minimality test).

Table 9 - Animal production module, assumptions, Brazil

Item	Parameter	Description	Input
Animal production module	Animal breed	Nelore beef cattle breed	Nelore
	Infrastructure	Housing for labor (common workers and tractor operators)	1 complete setup
	Livestock handling facilities	Facilities for cattle management	1 complete setup
	Fencing	Boundary and pasture subdivision fences	1 set of fencing
	Water access and feed trough	Access to water and covered feed trough for supplementation	1 complete setup
	Natural breeding system	Natural breeding station	1 station
	Mating season	Breeding season (November to January)	November to January
	First exposure conception rate	Pregnancy rate after first bull exposure (50–85%)	50–85%
	Bull replacement	Bull replacement system for breeding	1 system
	Annual conception rate	Pregnancy rate after second bull exposure (75–92%)	75–92%
	Pregnancy diagnosis and weaning	Diagnosis and weaning (March to May)	March to May
	Pregnancy loss	2–5% loss of pregnancies	2–5%
	Birth period	Calving season (August to October)	August to October
	Open herd	Open herd system, including purchase of animals from previous phases	1 system
	Slaughter sales	Includes slaughter and replacement sales	1 system

Table 10 - Economic module, financial assumptions, macroeconomic parameters, and fixed inputs, Brazil

Item	Parameter	Description	Symbol	Unit	Input
Economic module	Income tax	Federal income tax rate	Ef_1	%	27.50
	Funrural (Rural Social Security Tax)	Contribution levied on gross revenue from cattle sales for slaughter	Ef_2	%	1.50
	MARR	Minimum acceptable rate of return	Ef_4	% yr^{-1}	6.00
	Real discount rate	Discount rate for present value calculation	Ef_5	% yr^{-1}	6.00
	Inflation rate	Annual inflation rate	Ef_7	% yr^{-1}	4.50
	Equity investment	Proportion of capital from own equity	Ef_8	%	40.00
	Third-party capital on herd value	Share of herd value financed with third-party capital	Ef_9	%	60.00
	Total number of installments	Repayment period for third-party financing	Ef_{10}	yr	10
	Grace period	Years before liability repayment begins	Ef_{11}	yr	2
	Annual interest rate	Nominal annual interest rate	Ef_{12}	% yr^{-1}	7.00
	Bare land value	Average municipal value of unimproved pastureland	Ef_{13}	USD ha^{-1}	1,500.00

Table 11 - Minimum Module pasture systems, fixed intensification parameters for LL (low level), ML (medium level), and HL (high level), 2017–2020

Parameter	Unit	LL	ML	HL
Pasture[1]	Cg-Rg	(Cg)	(Cg-Rg)	(Rg)
Stocking rate[2]	AU ha^{-1}	0.5	1.0	1.5
Pasture fertilization	kg ha^{-1}	40	120	180
Reproductive mineral salt	g hc^{-1} d^{-1}	25	25	25
Mineral supplement	g hc^{-1} d^{-1}	100	100	100
Protein supplement (7 to 8 months)	g hc^{-1} d^{-1}	0	200	200
Energy supplement (12 months)	g hc^{-1} d^{-1}	0	130	130
Creep feeding[3]	kg hc^{-1} d^{-1}	0	0	1.120
Diet (85:15)[4]	%	0	0	1.2
Pasture formation[5]	%	1	1	5
Pasture maintenance[5]	%	2	10	10
Lease rate[6]	%	10	12	15
Calving rate	%	70	82	90
Tractor	hp	120	140	180
Hydraulic terracing plow with 16 discs	Units	0	1	1
6m Mounted Boom Sprayer – 600L	Units	0	1	1
Barn	m^2	50	220	600

[1] Cg - continuous grazing; Rg - rotated grazing.
[2] Animal unit (AU) = 450 kg of live weight.
[3] Creep feeding - private supplementation.
[4] Diet (85:15) - semi-confined diet of 85% corn grain and 15% mineral core (% of live weight).
[5] Pasture formation/maintenance - percentages refer to the share of available grazing area (AgA) undergoing establishment and annual upkeep.
[6] Lease rate - percentage of the @ price of finished cattle; @ = 15 kg; La - leased area.
Values of 0 indicate that the corresponding input, feeding practice, or equipment was not adopted under that intensification level.

To capture biological and replacement uncertainty in the Animal Module, we parameterized each input variable by sampling from a uniform distribution bounded by minimum and maximum values reported in subtropical and tropical studies. We selected a uniform distribution to avoid bias where stronger empirical priors were unavailable. These ranges—drawn from Scarnecchia (1998); Euclides Filho et al. (2002); Abreu et al. (2003); Abreu and Lopes (2005); Costa et al. (2005); Pereira et al. (2005); Barioni et al. (2007); Fernandes et al. (2010); Allen et al. (2011); Porto et al. (2011); Pereira et al. (2014); Jorge (2019); Lampert et al. (2020); Moriel et al. (2020); and Dick et al. (2021)—ensured that simulated herd dynamics reflected full-cycle, pasture-based beef production conditions in the study region (Table 12).

Table 12 - Animal module, minimum and maximum values of input variables

Parameter	Unit	Amplitude
Stocking rate	AU ha^{-1}	0.3–2.0
Birth rate	%	50–90
Slaughter age for bulls	months	12–44
Average herd mortality rate	%	2–5
Annual culling rate for cows	% yr^{-1}	15–20
Annual culling rate for bulls	% yr^{-1}	15–25
Selection pressure for sale (females)	% yr^{-1}	15–70
Selection pressure for sale (males)	% yr^{-1}	15–100
Slaughter weight for culling cows	kg hc^{-1}	380–500
Slaughter weight for bulls	kg hc^{-1}	750–800
Slaughter weight for steers	kg hc^{-1}	380–480
Slaughter weight for heifers	kg hc^{-1}	360–420
Weight for weaned males (7–8 months)	kg hc^{-1}	170–300
Weight for 18–20 months steers (DL)	kg hc^{-1}	320–480
Weight for 21–28 months steers (up to 2 permanent teeth)	kg hc^{-1}	380–540
Weight for 29–36 months steers (up to 4 permanent teeth)	kg hc^{-1}	400–570
Weight for 37–48 months steers (adult)	kg hc^{-1}	405–650
Carcass yield (males)	%	52–58
Average daily gain (ADG) (male calf)	kg d^{-1}	0.150–0.950
ADG (male rearing)	kg d^{-1}	0.199–1.100
ADG (male finishing)	kg d^{-1}	0.350–1.500
Weight for weaned females (7–8 months)	kg hc^{-1}	120–180
Weight for 18–20 months heifers (DL)	kg hc^{-1}	160–360
Weight for 21–28 month heifers (up to 2 permanent teeth)	kg hc^{-1}	199–380
Weight for 29–36 month heifers (up to 4 permanent teeth)	kg hc^{-1}	260–395
Weight for 37–48 month cows (adult)	kg hc^{-1}	300–500
Carcass yield (females)	%	50–52
ADG (female calf)	kg d^{-1}	0.164–0.784
ADG (female rearing)	kg d^{-1}	0.164–0.950
ADG (female finishing)	kg d^{-1}	0.300–1.200
ADG (cow finishing)	kg d^{-1}	0.750–1.100
ADG (pasture without mineral supplementation)	kg d^{-1}	0.150–0.550
ADG (pasture with mineral supplementation)	kg d^{-1}	0.250–1.900
Carcass yield (cow)	%	48–50
Bull-to-cow ratio	cows bull^{-1}	15–25
Cow coefficient	AU	0.92–1.08
Culling cow coefficient	AU	0.74–0.92
18–20 months heifer (MT) coefficient	AU	0.35–0.8
21–28 months heifer (2 permanent teeth) coefficient	AU	0.40–0.8
29–36 months heifer (4 permanent teeth) coefficient	AU	0.56–0.87
37–48 months cow (adult) coefficient	AU	0.66–1.11
18–20 months steer (MT) coefficient	AU	0.71–1.06
21–28 months steer (2 permanent teeth) coefficient	AU	0.84–1.20
29–36 months steer (4 permanent teeth) coefficient	AU	0.88–1.26
37–48 months steer (adult) coefficient	AU	0.90–1.33
Bull coefficient	AU	1.44–1.88
Short-cycle diet consumption coefficient (kg per 100 kg body weight)	%	0.75–2
Grazing efficiency coefficient (dry and rainy season)	%	20–80
Daily forage dry matter consumption	kg AU^{-1} d^{-1}	7.5–12.5
Forage coefficient (kg crude protein per 100 kg dry matter)	%	4.2–13.4

Continues...

Table 12 (Continued)

Parameter	Unit	Amplitude
Mineral salt consumption	kg hc^{-1}	0.050–0.150
Mineral salt consumption for reproduction cows (kg per 100 kg body weight)	kg hc^{-1}	0.015–0.035
Mineral protein supplement consumption (kg per 100 kg body weight)	kg hc^{-1}	0.100–0.250
Mineral energy supplement consumption (kg per 100 kg body weight)	kg hc^{-1}	0.120–0.300
Creep feeding consumption	kg hc^{-1}	0.328–1.400

hc - head of cattle.

For the Plant Module, we parameterized machinery-hour requirements and input rates for land preparation and maintenance using data from Pacheco (2000) and Peres et al. (2013, 2014). These values informed simulated labor, fuel, and equipment needs across low-, medium-, and high-intensification scenarios in the MM. All deflation and data cleaning were performed in Microsoft Excel® 365, ensuring consistency with the simulation environment.

2.8. Mathematical formulation of the Minimum Module

2.8.1. Discounted cash flow components and economic metrics

We calculated annual economic outputs using the discounted cash-flow (DCF) component equations (Table 13). First, we computed total revenue (TR) as the sum across all animal categories of quantity sold, average live weight, carcass yield, selection pressure, and carcass price (Jorge, 2019, 2024). From TR, we derived net income (NI) by subtracting the Rural Workers Assistance Fund (Funrural) social security tax (α = 1.5%) (Damodaran, 2010, 2020).

Next, we calculated total operating cost (TOC) as the sum of fixed operating cost (FOC) and variable operating cost (VOC) streams (Matsunaga et al., 1976; Jorge, 2019). We estimated opportunity cost (OC_p) at Z% of potential beef production value, market arroba price multiplied by grazing area, annualized following Ross et al. (2013) and Jorge (2019, 2024). Summing TOC and OC_p yielded total cost (TC).

We defined earnings before interest, taxes, depreciation, and amortization (EBITDA) as NI minus TC (Damodaran, 2010, 2020). We calculated annual depreciation (Dep) on original asset costs using straight-line schedules with an 80% salvage value over 10 years for movable assets and 90% over 20 years for buildings (Damodaran, 2000, 2010; Kay et al., 2023; Jorge, 2019, 2024). Earnings before interest and taxes (EBIT) resulted from subtracting Dep from EBITDA.

We computed annual rural land tax (RLT) by multiplying the average bare-land value (VTN) by an 80% land-use coefficient (Jorge, 2019, 2024). We applied progressive income-tax rates up to 27.5% to each EBIT segment, using EBIT as a modeled proxy for taxable rural income, in accordance with the Brazilian Federal Revenue Service annual progressive income-tax table applicable to tax year 2019 (RFB, 2020), based on Law No. 11,482/2007 and Normative Instruction RFB No. 1,500/2014 (Brazil, 2007; RFB, 2014; Jorge, 2019). We aggregated annual reinvestment outlays (R) for livestock replacement, machinery, and infrastructure upgrades (Damodaran, 2000, 2010, 2020).

We determined free cash flow to equity (FCFE) as EBIT minus RLT, reinvestment, and debt service (principal plus interest) (Damodaran, 2000, 2010; Ross et al., 2013). We accumulated FCFE over the 20-year horizon, offsetting the initial investment (I_0) as an outflow, to obtain accumulated FCFE ($FCFE_a$) (Jensen, 1986; Damodaran, 2000, 2010, 2020). Finally, we expressed the annual economic result (ER) per hectare of grazing area by dividing FCFE by available grazing area (AgA) (Jorge, 2019, 2024).

2.8.2. Minimum Module outputs and indicator calculations

We generated annual performance indicators by applying the formulas summarized in Tables 14–17 to our discounted cash-flow projections and herd-dynamics outputs.

Table 13 - Economic module, components of the discounted cash flow (DCF)

Component	Equation	Description of the equation	Reference
Total revenue	$TR_{annual} = \sum_{i=1}^{n} Q_i \times (W_i \times R_i \times Ps_i) \times P_i$	Calculated as the sum of the products of quantity sold (Q_i), average live weight (W_i), carcass yield (R_i), market selection pressure (Ps_i), and market price in the corresponding commercial unit (P_i) across all animal categories (i).	Jorge (2019, 2024)
Net income	$Ni_{annual} = TR \times (1 - \alpha)$	Net income after deduction of the Funrural tax rate α.	Damodaran (2010, 2020)
Total operating cost	$TOC_{annual} = FOC_1 + FOC_2 + FOC_n + \cdots + VOC_1 + VOC_2 + VOC_n$	Sum of fixed operating costs (FOC) and variable operating costs (VOC).	Matsunaga et al. (1976); Jorge (2019)
Opportunity cost	$OC_p = Z \times P_a \times AgA \times 12$	Calculated as a percentage (Z) on the potential beef production value, using the market price per arroba (P_a) and the minimum grazing area AgA, adjusted to an annual basis.	Ross et al. (2013); Jorge (2019, 2024)
Total cost	$TC_{annual} = FOC + VOC + OC_p$	Sum of fixed, variable, and opportunity costs.	Matsunaga et al. (1976)
EBITDA	$EBITDA_{annual} = Ni - TC$	Earnings before interest, taxes, depreciation, and amortization.	Damodaran (2010, 2020)
Depreciation	$Dep_{annual} = \left(\sum_{i=1}^{n} \frac{0.80 \times M_i}{10}\right) + \left(\sum_{j=1}^{m} \frac{0.80 \times E_j}{10}\right) + \left(\sum_{k=1}^{o} \frac{0.90 \times I_k}{20}\right)$	Annual depreciation calculated separately for machinery, equipment, and infrastructure, considering salvage value.	Damodaran (2000, 2010); Kay et al. (2023); Jorge (2019, 2024)
EBIT	$EBIT_{annual} = EBITDA - Dep$	Earnings before interest and taxes.	Damodaran (2000, 2010)
Rural land tax	$RLT_{annual} = VTN \times GU$	Annual land tax calculated as the product of the average bare land value for pasture areas (VTN) and the land use coefficient (GU), set at 80% in this study.	Jorge (2019, 2024)
Income tax	$Itax_{annual} = \sum_{i=1}^{n} [(EBIT_i - L_{min,i}) \times T_i]$	Income tax calculated by applying progressive rates (T_i, 0%–27.5%) to each income segment ($EBIT_i - L_{min,i}$) across n tax brackets.	Jorge (2019); RFB (2020)
Re-investment	$R_{annual} = \sum_{i=1}^{n} R_i$	Total annual reinvestment, including livestock replacement, machinery, equipment, and infrastructure improvements.	Damodaran (2000, 2010, 2020)
Free cash flow to equity	$FCFE_{annual} = EBIT - RLT - R - (K_p + i)$	Cash flow available to shareholders after taxes, reinvestments, and debt service (principal (k) and interest (i)).	Damodaran (2000, 2010); Ross et al. (2013)
Accumulated free cash flow to equity	$FCFE_a = -I_0 + \sum_{i=1}^{T} FCFE_i$	Accumulated free cash flow to equity ($FCFE_a$), calculated as the sum of annual free cash flows to equity ($FCFE_i$) over the 20-year horizon, including the initial investment (I_0) as an outflow.	Jensen (1986); Damodaran (2000, 2010, 2020)
Economic result	$Er_{annual} = \frac{FCFE_i}{AgA}$	Economic results per hectare of grazing area (AgA).	Jorge (2019, 2024)

We first assessed financial viability metrics (Table 14). We calculated net present value (NPV; USD) by discounting each year's free cash flow (FCF_t) at the real discount rate, summing the present values, and subtracting the initial investment (K_0); we identified the minimum module when the removal of one breeding cow caused NPV to fall below zero (Damodaran, 2000, 2010, 2020; Ross et al., 2013; Jorge, 2019, 2024). We derived the modified internal rate of return (MIRR; %) by compounding positive cash flows at the reinvestment rate and discounting negative cash flows at the financing rate (Lin, 1976; Damodaran, 2000, 2010, 2020; Ross et al., 2013; Jorge, 2019, 2024). We determined the discounted payback period (years) as the smallest t for which cumulative discounted FCF_t met or exceeded K_0 (Ross et al., 2013).

Next, we calculated economic-performance and herd-value indicators (Table 15). We defined gross margin (GM; USD yr^{-1}) as total revenue minus variable operating costs (VOC) (Damodaran, 2000; Kay et al., 2023). We computed total profit (TP; USD yr^{-1}) as net income after tax minus total cost,

Table 14 - Minimum Module, financial indicators (final outputs)

Indicator	Equation	Description of the equation	Reference
Net present value (NPV)	$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+i)^t} - K_0$	Present value of net cash flows (CF_t) over the investment horizon (T = 20 years), discounted at rate (i), minus the initial investment (K_0). NPV ≥ 0 defines the minimum economic scale, where the removal of a single breeding cow results in a negative NPV, indicating the viability threshold.	Damodaran (2000, 2010, 2020); Ross et al. (2013); Jorge (2019, 2024)
MIRR	$MIRR = \left(\frac{\sum_{t=1}^{n} CF_t^{+} + (1+i_b)^{n-t}}{\sum_{t=1}^{n} \frac{CF_t^{-}}{(1+i_d)^t}} \right)^{\frac{1}{n}} - 1$	MIRR represents the return rate that equates the future value of positive cash flows (reinvested at i_b) with the present value of negative cash flows (discounted at i_d) over n periods. The Minimum Module (MM) is economically viable if MIRR>MARR; unviable if MIRR<MARR; and indifferent if MIRR=MARR.	Lin (1976); Damodaran (2000, 2010, 2020); Ross et al. (2013); Jorge (2019, 2024)
Discounted payback period	$\sum_{t=0}^{DP} \left(\frac{CF_t}{(1+i)^t} \right) \geq K_0$	Time (in years) required for the cumulative discounted cash flows to equal or exceed the initial investment (K_0). Reflects the time to recover the invested capital considering the time value of money.	Ross et al. (2013)

Table 15 - Minimum Module, economic performance and herd value indicators (final outputs)

Indicator	Equation	Description of the equation	Reference
Gross margin	$GM = TR - VOC$	Revenue minus variable operating costs (VOC); reflects gross profitability before fixed costs.	Damodaran (2000); Kay et al. (2023)
Total profit	$TP = Ni - TC$	Net income (after taxes) minus total cost, including fixed, variable, and opportunity costs.	Damodaran (2000, 2010); Kay et al. (2023)
Operational profitability	$Pr_{op} = \frac{TP}{AgA}$	Profit per hectare per year, calculated as total profit divided by the available grazing area (AgA).	Kay et al. (2023); Jorge (2019, 2024)
Final stock head	$SH_i = N_{i,initial} + B_i + Pu_i - Mt_i - S_i$	Final number of heads in each animal category (i) calculated by summing the initial stock and herd additions (births B_i), purchases (Pu_i) and subtracting mortalities (Mt_i) and sales (S_i).	Jorge (2019, 2024)
Total herd value	$HV = \sum_{i=1}^{n} (SH_i + W_i + P_i)$	Total market value of the herd at year-end, calculated as the product of final stock heads (SH_i), average live weight (W_i), and market price per kg (P_i).	Jorge (2019)

including fixed, variable, and opportunity costs (Damodaran, 2000, 2010; Kay et al., 2023). We expressed operational profitability (Prop; USD ha^{-1} yr^{-1}) by dividing TP by available grazing area (AgA; ha) (Kay et al., 2023; Jorge, 2019, 2024). We calculated final stock head (SH_i; head) by summing opening herd counts, births, and purchases, then subtracting mortalities and sales (Jorge, 2019, 2024). We determined total herd value (HV; USD) by summing SH_i × average live weight (W_i; kg) × carcass price (P_i; USD·kg^{-1}) across all categories (Jorge, 2019).

We then measured production-efficiency indicators (Table 16). We calculated beef productivity (Prod; arrobas ha^{-1} yr^{-1}) as total arrobas sold—summing each cohort's quantity sold (Q_i; head) multiplied by weight in arrobas ($@_i$)—divided by AgA (Jorge, 2019, 2024). We computed total animal units (TAU; AU) by summing all live weights (LW_i; kg) and dividing by 450 kg per animal unit (AU) (Jorge, 2019).

Thus, we derived sustainability indicators (Table 17). We calculated the minimum grazing area (AgA_i; ha) required to meet the user-defined annual income target (Rr_i; USD yr^{-1}) by dividing the simulated herd size (Hq_i; head) by the stocking rate (Sr_i; AU ha^{-1}) for each intensification level (Jorge, 2019). We then calculated total land area (TA_i) by inflating AgA_i to include the fixed legal reserve (LR_i = 20%) and a permanent preservation area (PP_i = 10%), the latter estimated in this study, as mandated by the Brazilian Forest Code (Table 17).

Table 16 - Minimum Module, production indicators (final outputs)

Indicator	Equation	Description of the equation	Reference
Productivity	$Prod = \frac{\sum_{i=1}^{n}(Q_i \times @_i)}{AgA}$	Total production of beef in arrobas (@), calculated as the sum of animals sold (Q_i) times the weight in arrobas ($@_i$), divided by the available grazing area (AgA).	Jorge (2019, 2024)
Total animal units	$TAU = \sum_{i=1}^{n}\frac{LW_i}{450}$	Sum of live weights of all animal categories (LW_i, in kg), divided by the standard live weight equivalent of 450 kg per animal unit.	Jorge (2019)

Table 17 - Minimum Module, sustainability indicators (final outputs)

Indicator	Equation	Description of the equation	Reference
Available grazing area	$AgA_i = \frac{Hq_i}{Sr_i}$	Minimum pasture area required to sustain the herd size (Hq_i) under the stocking rate (Sr_i) for each production intensification level (i). The herd size Hq_i is simulated based on the producer's required annual income (Rr_i), which is defined externally by the user and considered a fixed cost. The model computes the minimum viable configuration that satisfies the economic viability condition NPV ≥ 0, making AgA_i, an endogenous outcome driven by user-defined income expectations and system intensification.	Jorge (2019)
Total area	$TA_i = \frac{AgA_i}{\left(1 - \frac{LR_i}{100} - \frac{PP_i}{100}\right)}$	Total land area required to implement the Minimum Module (MM) under each production intensification level (i). It includes the minimum grazing area (AgA_i) plus the proportions of land allocated to the Legal Reserve (LR_i) and the Permanent Preservation Area (PP_i), both defined according to Brazilian environmental regulations. Since AgA_i is derived from the simulated herd size required to meet the producer's target income (Rr_i), the total area TA_i reflects both economic viability and land use compliance.	Jorge (2019, 2024); Brazil (2012)

2.9. Monte Carlo risk analysis

After establishing twelve Minimum Modules, one for each combination of stocking-rate intensification (low, medium, high) and simulation year (2017–2020), we quantified how uncertainty propagated through both economic and production submodels using Monte Carlo simulation. We performed 10,000 iterations per intensification level in @Risk 8.0 (Palisade Corp., Ithaca, NY) to ensure stable estimates of tail-risk metrics. Downside risk was measured as the empirical probability of loss, defined as the proportion of Monte Carlo iterations in which each target output fell below zero.

At each iteration, we sampled simultaneously from 51 probability distributions representing fixed-cost categories, pasture-establishment and maintenance parameters, daily nutrition and health inputs, service and labor costs (Table 18), and animal-related economic variables. These included observed prices and sale quantities for the 15 marketed cattle cohorts, together with the breeding-bull price parameter used for replacement and culling flows. The transitional "Animals born" class was excluded from direct price sampling because it functioned only as a biological herd-flow category. We selected

Table 18 - Minimum Module, cost, revenue, and profitability components for Monte Carlo risk analysis

Identification	Item	Data classification
A	Opportunity cost (land lease)	Input
B	Facilities and improvements	Input
C	Depreciation	Input
D	Machines and equipment	Input
E	Depreciation	Input
F	Producer's management fees	Input
$G = \sum(A \text{ to } F)$	Fixed cost (FC)	Output
H	Pasture formation	Input
I	Pasture maintenance	Input
J	Maintenance of facilities and improvements	Input
K	Maintenance of machinery and equipment	Input
L	Mineral supplement	Input
M	Protein/energy-raising/fattening supplement	Input
N	Creep-feeding weaning supplement	Input
O	Vaccines	Input
P	Dewormers	Input
Q	Other medicines	Input
R	Fuel and lubricants	Input
S	Salaries + employee charges	Input
T	General services and accountant	Input
U	Technical assistance	Input
V	Electricity, telephone, and transportation	Input
$W = \sum(H \text{ to } V)$	Variable cost (VC)	Output
$X = \sum(G \text{ and } W)$	Total cost (TC)	Output
Y	Average price	Input
Z	Productivity	Input
$\alpha = (Y \,.\, Z)$	Gross revenue	Output
$\beta = (\alpha \,.\, i)$	Tax and/or fee (Funrural[1])	Output
$\delta = (\alpha - \beta)$	Net income	Output
$\mu = (\alpha - W)$	Gross margin	Output
$\lambda = (\alpha - G)$	Operating profit (net margin)	Output
$\Omega = (\delta - X)$	Total profit	Output
$\Psi = (\Omega/AgA)$	Operating profitability (USD ha^{-1} year^{-1})	Output

AgA - available grazing area.
[1] i - Funrural rate of 1.5%.

distribution families—such as normal, lognormal, and triangular—by fitting candidate models using the Akaike Information Criterion (AIC) and truncated draws at zero to avoid nonphysical values (Kurata and Hamada, 2020). To preserve realistic co-movement among interdependent inputs, particularly price–quantity pairs and cost-category aggregates, we imposed a 51 × 51 correlation matrix.

The main simulation outputs, including histograms, percentile distributions, and downside-risk metrics, are reported in Results section 3.7.

3. Results

3.1. Minimum Module characterization

Table 19 summarizes the Minimum Module (MM) outputs—productivity (Prod, arrobas ha^{-1} yr^{-1}), breeding-cow count (Nc), available grazing area (AgA, ha), and total land area (TA, ha)—for the low- (LL, 0.5 AU ha^{-1}), medium- (ML, 1.0 AU ha^{-1}), and high-intensity (HL, 1.5 AU ha^{-1}) scenarios from 2017 to 2020. Within each intensification tier, Prod varied within narrow ranges: 3.30–3.38 (LL), 6.55–6.69 (ML), and 9.83–10.00 (HL). Over 2017–2020, Nc decreased from 1,011 to 406 (LL), from 1,131 to 444 (ML), and from 1,727 to 566 (HL). AgA contracted from 5,424 to 2,556 ha (LL), from 3,248 to 1,467 ha (ML), and from 3,367 to 1,245 ha (HL), and TA contracted from 7,748 to 3,651 ha (LL), from 4,640 to 2,095 ha (ML), and from 4,810 to 1,778 ha (HL).

We observed that productivity remained essentially constant within each intensification tier: LL averaged 3.38 arrobas ha^{-1} yr^{-1} in 2017–2018 and declined slightly to 3.30 arrobas ha^{-1} yr^{-1} in 2020; ML held at 6.69 arrobas ha^{-1} yr^{-1} before falling to 6.55 arrobas ha^{-1} yr^{-1}; and HL dropped from 10.00 arrobas ha^{-1} yr^{-1} to 9.83 arrobas ha^{-1} yr^{-1} over the same period.

Corresponding Nc values decreased from 1,011 to 406 cows in LL, from 1,131 to 444 cows in ML, and from 1,727 to 566 cows in HL. Available grazing area contracted from 5,424 ha to 2,556 ha in LL, from 3,248 ha to 1,467 ha in ML, and from 3,367 ha to 1,245 ha in HL. Total land area followed the same pattern, declining by 53% in LL, 55% in ML, and 63% in HL over the four years.

3.2. Herd evolution

We presented the annual herd composition for each intensification scenario (Table 20). We observed that total cow numbers declined modestly between 2017 and 2018—by 9% in both LL and ML and by 14% in HL—to begin aligning herd size with the NPV ≥ 0 threshold. A sharper adjustment occurred from 2019 to 2020, when cow counts fell by 27% under LL, 31% under ML, and 37% under HL.

We observed parallel declines across all age and sex cohorts. For example, fat bulls aged 21–28 months decreased from 100 head in 2017 to 68 head in LL (–32%), from 116 to 82 head in ML (–29%), and from 183 to 118 head in HL (–36%). Similar proportional reductions were observed across all other categories.

3.3. Cost structure

We summarized the annual fixed cost (FC) and variable cost (VC) for each intensification (Table 21). In 2020, we recorded that LL modules incurred USD 211,501 in FC (approximately 74% of total cost) and USD 72,776 in VC (approximately 26%). We found that ML modules allocated USD 223,757 to FC (67%) and USD 108,693 to VC (33%). Under HL, the cost composition shifted: FC amounted to USD 218,285 (48%) while VC rose to USD 239,454 (52%).

From 2017 to 2020, we observed total cost declines of 20% in LL (from USD 353,542 to USD 284,278), 26% in ML (from USD 447,077 to USD 332,451), and 41% in HL (from USD 774,376 to USD 457,739). These decreases reflected both herd-size adjustments and efficiency gains achieved through intensified management.

Table 19 - Minimum Module, outputs by intensification level (LL, ML, HL), 2017–2020 (final outputs)

Intensification level	LL				ML				HL			
PY	2017	2018	2019	2020	2017	2018	2019	2020	2017	2018	2019	2020
Prod	3.38	3.38	3.35	3.30	6.69	6.69	6.63	6.55	10.00	10.00	9.94	9.83
Nc	1,011	1,010	675	406	1,131	1,160	731	444	1,727	1,799	1,046	566
AgA	5,424	5,419	3,831	2,556	3,248	3,323	2,211	1,467	3,367	3,498	2,122	1,245
TA	7,748	7,741	5,473	3,651	4,640	4,748	3,159	2,095	4,810	4,998	3,032	1,778

Prod - productivity (@ ha^{-1} yr^{-1}); Nc - number of breeding cows (head); AgA - available grazing area (ha); TA - total area (ha); AU - animal unit (450 kg live weight); LL - low-level (0.5 AU ha^{-1}), ML - medium-level (1.0 AU ha^{-1}) and HL - high-level (1.5 AU ha^{-1}) production systems for the productive years (PY).

Table 20 - Minimum Module, annual herd evolution by intensification level (LL, ML, HL), 2017–2020 (final outputs)

Intensification level	LL				ML				HL			
Evolution of the herd	2017	2018	2019	2020	2017	2018	2019	2020	2017	2018	2019	2020
(Quantity)	Animals	Period change[9]	Animals	Period change	Animals	Period change	Animals	Period change	Animals	Period change	Animals	Period change
Cows (37 to 48 months)	1,111	1,012	935	682	1,131	1,027	1,049	724	1,727	1,479	1,534	963
Heifers 29 to 36 months	15	15	14	10	17	17	18	12	27	27	28	17
Heifers 21 to 28 months	149	149	138	101	173	173	177	121	271	271	282	175
Heifers 18 to 20 months	250	250	232	170	290	290	296	203	455	455	472	294
Female calves 12 months	281	281	260	190	325	325	332	228	511	511	530	329
Weaning - female[1]	474	474	439	321	549	549	561	385	862	862	895	556
Weaning - male[2]	474	474	439	321	549	549	561	385	862	862	895	556
Male calves (12 months)	281	281	260	190	325	325	332	228	511	511	530	329
18-month old bull	236	236	219	160	274	274	280	192	430	430	446	277
Lean bull[3]	200	200	185	135	231	231	236	162	363	363	377	234
Fat bull 18 to 20 months[4]	169	169	156	114	195	195	199	137	307	307	318	198
Fat bull 21 to 28 months[5]	100	100	93	68	116	116	119	82	183	183	190	118
Fat bull 29 to 36 months[6]	50	50	46	34	58	58	59	40	90	90	94	58
Fat bull (37 to 48 months)[7]	25	25	23	17	29	29	29	20	45	45	47	29
Older fat bull[8]	44	42	38	28	45	42	43	29	69	61	64	40

AU - animal unit (450 kg live weight); LL - low-level (0.5 AU ha^{-1}); ML - medium-level (1.0 AU ha^{-1}); HL - high-level (1.5 AU ha^{-1}).
[1] 7 to 8 months of age.
[2] 7 to 8 months of age.
[3] Between 12 and 13 arrobas of live weight.
[4] Milk-tooth animal category (MT).
[5] Up to 2 permanent teeth animal category.
[6] Up to 4 permanent teeth animal category.
[7] Adult.
[8] Over 60 months of age.
[9] Period-to-period transition in animal age class.
Table 20 reports the annual evolution of the main production cohorts. Breeding bulls were modeled separately in the reproductive subsystem and are not shown explicitly in this table.

Table 21 - Minimum Module, annual cost structure by intensification level (LL, ML, HL), 2017–2020 (final outputs)

ID	Intensification level	LL				ML				HL			
	Year	2017	2018	2019	2020	2017	2018	2019	2020	2017	2018	2019	2020
	Description	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}	USD yr^{-1}
	A - Fixed cost	253,536	252,991	227,535	211,501	257,623	267,546	234,880	223,757	258,772	271,755	236,325	218,285
1	Opportunity cost[1]	83,635	86,098	71,599	63,095	50,812	52,802	41,323	36,213	51,960	55,581	39,661	30,732
2	Facilities and improvements	6,825	6,916	6,962	6,543	18,614	18,862	18,987	17,844	18,614	18,862	18,987	17,844
3	Depreciation	341	346	348	327	931	943	949	892	931	943	949	892
4	Machines and equipment	66,390	68,050	62,434	64,424	88,692	100,147	85,156	89,217	88,692	101,447	87,981	89,225
5	Depreciation	6,639	6,805	6,243	6,442	8,869	10,015	8,516	8,922	8,869	10,145	8,798	8,922
6	Producer's management fees	89,706	84,776	79,949	70,670	89,706	84,776	79,949	70,670	89,706	84,776	79,949	70,670
	B - Variable cost	100,006	102,904	93,350	72,776	189,453	188,894	145,745	108,693	515,604	535,393	370,978	239,454
1	Pasture formation	16,533	17,323	11,894	6,962	11,554	12,126	7,905	4,996	64,865	69,754	42,096	23,666
2	Pasture maintenance	8,218	8,393	5,450	3,960	47,606	48,275	31,341	22,076	60,259	62,678	37,574	23,279
3	Maintenance of facilities and improvements	4,330	4,380	4,493	4,000	4,330	4,380	4,493	4,002	4,579	4,559	4,720	4,395
4	Maintenance of machines and equipment	4,209	4,629	4,552	4,214	4,209	4,629	4,552	4,234	4,956	4,794	5,441	4,823
5	Mineral supplement	39,137	39,232	30,746	18,801	17,027	16,819	12,009	6,461	25,625	26,095	17,186	8,236
6	Protein/energy-raising/ fattening supplement	-	-	-	-	75,724	72,264	48,110	30,869	193,536	202,779	132,023	77,037
7	Creep-feeding weaning supplement[2]	-	-	-	-	-	-	-	-	126,322	128,821	82,931	48,173
8	Vaccines	3,200	3,104	2,157	1,516	3,983	3,898	2,543	1,766	6,150	6,193	3,669	2,247
9	Deworming	2,704	2,643	2,366	1,432	3,346	3,301	2,777	1,662	5,159	5,236	4,003	2,115
10	Other medicines	92	131	125	129	92	131	125	131	142	236	193	171
11	Fuel and lubricants	4,452	4,418	4,471	6,308	4,452	4,418	4,471	6,313	4,950	4,651	4,696	6,470
12	Salaries + employee charges	13,654	14,836	22,425	20,309	13,654	14,836	22,425	20,497	13,654	15,295	30,019	30,850
13	General services and accountant	1,459	1,574	1,439	1,885	1,459	1,574	1,439	1,885	2,243	1,574	1,439	1,885
14	Technical services	343	377	533	785	343	377	533	785	1,030	377	1,599	2,748
15	Electricity, telephone, and transportation	1,675	1,865	2,698	2,473	1,675	1,865	3,021	3,016	2,133	2,352	3,390	3,359
	C - Total costs (A+B)	353,542	355,895	320,885	284,278	447,077	456,440	380,625	332,451	774,376	807,148	607,303	457,739

AU - animal unit (450 kg live weight); LL - low-level (0.5 AU ha^{-1}); ML - medium-level (1.0 AU ha^{-1}); HL - high-level (1.5 AU ha^{-1}).
[1] Land lease.
[2] Private feeding trough - creep-feeding.

3.4. Profitability metrics

We reported net income, total profit, and per-hectare profitability for each intensification level (Table 22). In 2020, we observed that LL modules generated USD 451,491 in net income and USD 167,213 in total profit, yielding USD 65 ha^{-1} yr^{-1}. We found that ML modules produced USD 516,578 in net income and USD 184,127 in total profit, yielding USD 125 ha^{-1} yr^{-1}. We noted that HL modules achieved the highest results—USD 657,646 in net income and USD 199,907 in total profit, yielding USD 161 ha^{-1} yr^{-1}.

We calculated gross margin ratios (gross margin/total revenue) across all scenarios and found that they remained high, ranging from 81.8 to 84.1% in LL, 72.5 to 79.2% in ML, and 51.0 to 64.0% in HL over the simulation period. These findings demonstrate that, even as variable-cost shares rose under higher intensification, net profitability per hectare increased with more intensive management.

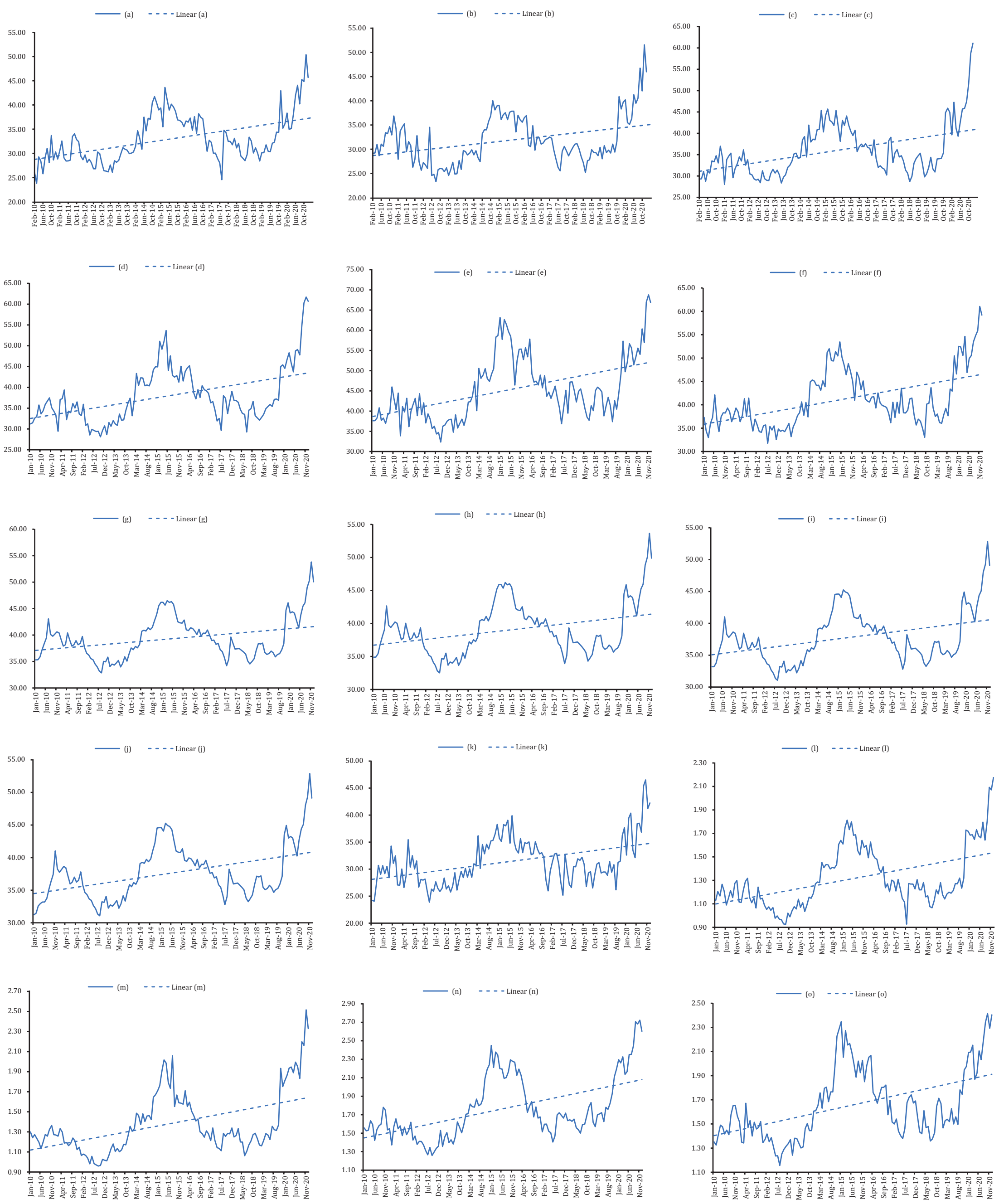
Table 22 - Minimum Module, annual profitability metrics by intensification level (LL, ML, HL), 2017–2020 (final outputs)

Intensification level	LL				ML				HL			
Year	2017	2018	2019	2020	2017	2018	2019	2020	2017	2018	2019	2020
Total revenue (USD yr^{-1})	568,461	566,594	512,939	456,601	688,693	692,789	589,693	522,369	1,055,519	1,092,971	848,644	665,021
Tax (Funrural)[1] (USD yr^{-1})	6,595	6,574	5,883	5,111	7,882	7,932	6,677	5,791	12,034	12,469	9,598	7,375
Net income (USD yr^{-1})	561,866	560,019	507,056	451,491	680,812	684,858	583,015	516,578	1,043,485	1,080,502	839,046	657,646
Fixed cost (USD yr^{-1})	253,536	252,991	227,535	211,501	257,623	267,546	234,880	223,757	258,772	271,755	236,325	218,285
Variable cost (USD yr^{-1})	100,006	102,904	93,350	72,776	189,453	188,894	145,745	108,693	515,604	535,393	370,978	239,454
Gross margin (USD yr^{-1})	468,455	463,690	419,589	383,825	499,240	503,895	443,948	413,676	539,915	557,578	477,666	425,567
Total cost (USD yr^{-1})	353,542	355,895	320,885	284,278	447,077	456,440	380,625	332,451	774,376	807,147	607,303	457,739
Net margin (USD yr^{-1})	314,925	313,603	285,404	245,100	431,070	425,243	354,813	298,612	796,748	821,217	612,318	446,736
Total profit (USD yr^{-1})	208,324	204,124	186,171	167,213	233,735	228,417	202,390	184,127	269,110	273,355	231,743	199,907
Profitability (USD ha^{-1} yr^{-1})	38	38	49	65	71	69	91	125	80	78	109	161
NPV (USD)	1,659	1,141	3,276	779	102	2,507	296	1,013	1,077	453	1,874	1,089

AU - animal unit (450 kg live weight); LL - low-level (0.5 AU ha^{-1}); ML - medium-level (1.0 AU ha^{-1}); HL - high-level (1.5 AU ha^{-1}).
[1] Brazilian rural social-security levy: 1.5% rate.

3.5. Price trends

We plotted monthly commercial price series for the 15 cattle cohorts from 2010 to 2020 (Figure 2). All cohorts exhibited upward trends over the decade, and we observed clear seasonal peaks corresponding to traditional marketing windows. We found that fat-bull categories (18–20 mo, 21–28 mo, 29–36 mo, 37–48 mo, and toruno > 60 mo) consistently commanded higher price levels and displayed greater volatility than replacement-heifer and weaner cohorts. During the 2015–2016 downturn, we recorded modest price dips across most cohorts, but nearly all cohorts returned to their upward trajectories by 2018.

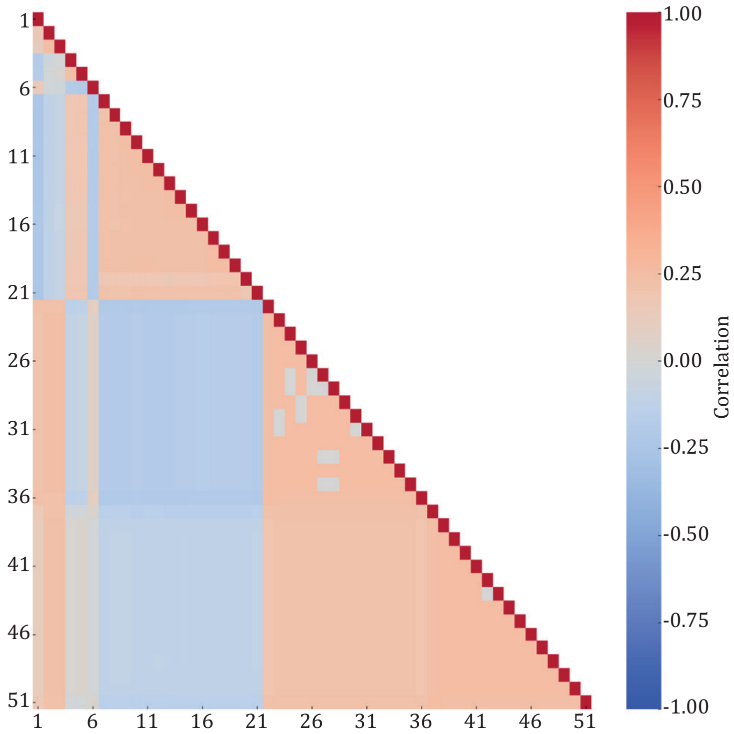


Monthly commercial prices (solid lines) and linear trends (dotted) for 15 cohorts: (a) cows 37–48 mo; (b) heifers 29–36 mo; (c) heifers 21–28 mo; (d) heifers 18–20 mo; (e) young bulls 18 mo; (f) lean bulls 12–13 @; (g) fat bulls 18–20 mo (milk-tooth); (h) fat bulls 21–28 mo (≤2 permanent teeth); (i) fat bulls 29–36 mo (≤4 permanent teeth); (j) fat bulls 37–48 mo (adult); (k) older fat bulls “toruno” (>60 mo); (l) bull calves 12 mo; (m) weaning males 7–8 mo; (n) weaning females 7–8 mo; (o) female calves 12 mo. Price units: arroba (@ = 15 kg carcass) for (a–k) and kg live weight for (l–o). Source: Correa da Costa (2021).

Figure 2 - Price trends, beef-cattle cohorts, 2010–2020, Campo Grande, MS.

3.6. Input correlation heatmap

We generated a 51 × 51 Spearman correlation heatmap for all Monte Carlo inputs, with correlation coefficients ranging from −1.0 to +1.0 (Figure 3). The heatmap reveals perfect self-correlations (ρ = 1.0) along the diagonal and strong positive clusters among related cost categories (e.g., fixed-service inputs). We also detected negative and near-zero correlations between certain price–quantity pairs and unrelated cost groups. We used this correlation matrix to drive our stochastic sampling and underpin the subsequent risk-analysis outputs.

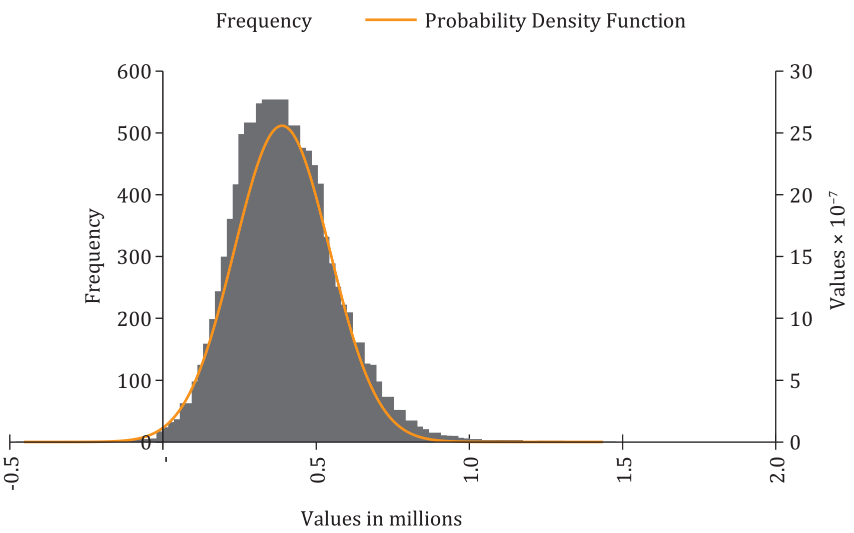


Groups: 1–5 cost categories; 6 available grazing area (ha); 7–21 cohort sale prices (arroba, @ = 15 kg carcass, or kg live weight); 22–36 cohort sale volumes (head); 37–51 simulated herd sizes (head). The heatmap shows the Spearman rank correlation coefficients (–1 to +1) used to drive stochastic sampling in the Minimum Module (MM). Warm colors indicate positive associations and cool colors negative ones, highlighting cost–revenue interdependencies and the land-for-feed trade-off.

Figure 3 - Spearman correlation matrix (51 × 51), Monte Carlo sampling, Minimum Module.

3.7. Risk distributions of gross margin and total profit

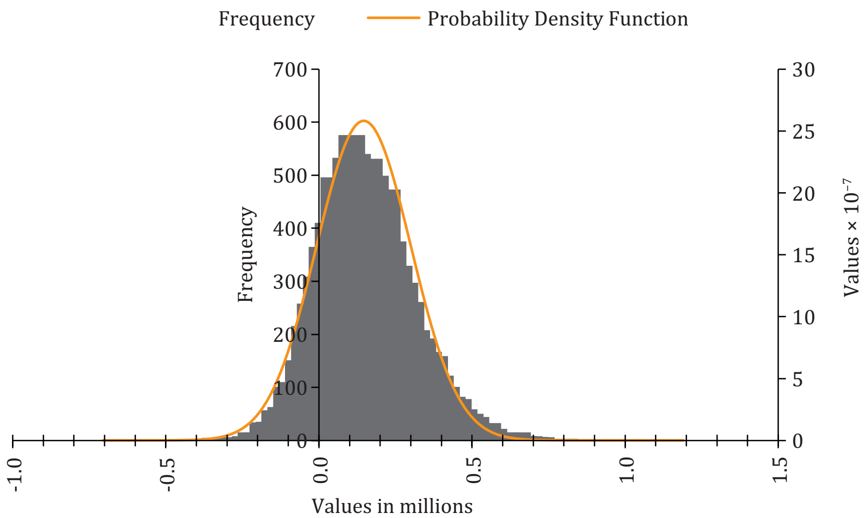
We plotted the Monte Carlo frequency distribution of gross margin across the twelve Minimum Module scenarios in Figure 4. The distribution was concentrated between approximately USD 300,000 and USD 500,000, and negative gross margin occurred in 0.25% of iterations



Histogram of simulated annual gross margin (USD million) with overlaid probability density function (PDF). Bars represent the frequency of outcomes; the orange curve shows the fitted PDF. Axes indicate frequency (left) and PDF values (right). The distribution summarizes central tendency, dispersion, and the probability of negative margins across intensification levels in full-cycle beef-cattle production.

Figure 4 - Annual gross-margin distribution, 12 Minimum Module scenarios, Campo Grande (MS), 2017–2020.

We then plotted the total profit distribution in Figure 5, which was centered near USD 150,000 and yielded negative outcomes in 15.55% of iterations. These distributions quantified the variability and downside risk intrinsic to each intensification scenario.



Histogram of simulated annual total profit (USD million) with overlaid probability density function (PDF). Bars represent simulation frequencies; the orange curve shows the fitted PDF. Axes indicate frequency (left) and PDF values (right). The distribution summarizes central tendency, variability, and the probability of negative profit across intensification levels in full-cycle beef-cattle production.

Figure 5 - Annual total-profit distribution, 12 Minimum Module scenarios, Campo Grande (MS), 2017–2020.

4. Discussion

4.1. Cost–structure trade-offs and scale effects

Low-intensity modules (LL) allocated most of their expenses to fixed costs, whereas high-intensity modules (HL) shifted the majority of expenditures to variable inputs, with medium-intensity systems (ML) falling between these extremes (Table 21). This distribution illustrates classic scale–risk dynamics: when fixed costs predominate, even a small decline in output—say, 1%—can erode profitability disproportionately because those costs cannot be reduced in the short term (Becker-Blease et al., 2010; Chen and Koebel, 2017). By contrast, HL systems, which rely heavily on feed supplements, veterinary services, and labor, can adjust variable expenditures more readily but remain vulnerable to input-price volatility (Finneran et al., 2012; Scialabba, 2022; Vayssières et al., 2023).

Our findings mirror those of Doole (2014) and Tedeschi et al. (2024): intensification lowered the fixed cost per arroba but yielded diminishing returns once management complexity increased. Specifically, LL modules maintained relatively stable gross margins (mean = USD 388,593 ± 155,968), while HL modules produced higher average profitability per hectare (USD 161 ha^{-1} yr^{-1}) yet displayed greater variability (SD = 154,435) and remained exposed to downside risk.

Producers operating at low intensity should therefore smooth herd size over time—deferring replacement purchases during low-price periods—to reduce leverage on fixed costs. Conversely, high-intensity operators might, for example, pre-purchase up to 30% of their annual feed and fuel requirements at forward prices to help limit variable-cost exposure. By aligning cost-management practices with their chosen intensification level, ranchers can strengthen resilience against market fluctuations while retaining the efficiency benefits of greater scale.

4.2. Market-risk implications from Monte Carlo simulations

Our Monte Carlo simulations characterized distinct risk profiles for the twelve Minimum-Module scenarios. For gross margin, we obtained a mean of USD 388,593 (SD = 155,968), a median of USD 375,742, a first quartile of USD 284,470, and a third quartile of USD 477,429. The distribution's moderate right skew (g_1 = 0.57) and excess kurtosis (g_2 = 1.33) reflect infrequent but large upside outcomes, while negative gross margin occurred in 0.25% of iterations. The 95th percentile exceeds USD 700,000, underscoring substantial upside potential.

Total profit exhibited a mean of USD 145,930 (SD = 154,435), a median of USD 133,949, a 25th percentile of USD 42,615, and a 75th percentile of USD 233,549 (g_1 = 0.56; g_2 = 1.37). Approximately 15.55% of iterations yielded negative total profit, indicating a higher downside risk for profit than for margin. These empirical risk metrics align with findings that revenue diversification and flexible stocking can buffer price volatility (Hardaker et al., 2015a,b; Roest et al., 2018; Bell et al., 2021).

To manage risk effectively, producers should align hedging and purchasing with system intensity: for high-intensity modules, forward-contracting, for example, up to 30% of annual feed needs—specifically concentrates and mineral supplements—may help limit exposure to short-term price spikes; for low-intensity modules, where fixed costs are proportionally higher, deferring discretionary replacement-stock purchases during price downturns helps stabilize cash flow. Extension agents and advisors can use the 5th and 95th percentiles of the simulated margin and profit distributions as benchmarks for stress-testing cash-flow projections and contingency planning (Hardaker and Lien, 2010a,b; Duane et al., 2014; Baudino et al., 2018).

4.3. Land-use efficiency gains

We observed that the Minimum Module reduced the required grazing area (AgA) by 53% in low-intensity (LL) systems and by 63% in high-intensity (HL) systems between 2017 and 2020 (Table 19).

These contractions exceeded the 30–50% land-sparing reported in commercial Cerrado operations following moderate intensification (Pellegrini and Fernández, 2018; Oliveira et al., 2023), highlighting the MM's capacity to release pasture for conservation or alternative production.

However, the model does not capture environmental-scale inputs—soil characteristics, water availability, or nutrient dynamics—and it does not simulate pasture biomass growth directly; instead, we parameterized pasture productivity via literature-derived stocking-rate relationships. Field studies in the Cerrado—including Mato Grosso do Sul—report increased fertilizer use under intensive grazing, with typical nitrogen applications of 80–200 kg N ha^{-1} yr^{-1} and up to approximately 240 kg N ha^{-1} yr^{-1} depending on sward targets (Monteiro, 2022; Martha Júnior et al., 2007; Vilela et al., 2020; Euclides et al., 2022), consistent with agronomic evidence on nitrogen utilization by Brachiaria grasses in Cerrado soils (Nakamura et al., 2005). These inputs can partially offset land-sparing gains through nutrient runoff or greater water withdrawals (Anache et al., 2019). To address these trade-offs, future versions of the MM should incorporate nutrient- and water-use modules and interpret economic gains alongside environmental externalities (Tedeschi et al., 2015; Dubeux et al., 2017; Jorge, 2024).

4.4. Integrating economic findings with farmer decision-making

Our contrasting cost–risk profiles for LL and HL systems suggest tailored management pathways. Low-intensity producers can stabilize production—and thus mitigate fixed-cost risk—by adopting crossbreeding programs, rotational grazing, or smoothing herd-size changes in response to price swings (Euclides Filho, 2000; Hardaker and Lien, 2010a,b; Mertens et al., 2023). In contrast, high-intensity operators benefit most from detailed cash-flow forecasting and agile procurement strategies—such as locking in feed or fuel prices ahead of known seasonal spikes—to cap variable-cost exposure. Smallholders in Mato Grosso do Sul adjust stocking rates seasonally based on credit access and market signals, a practice aligned with broader credit trends reported by the BNDES, which approved over R$ 885 million in rural financing under the 2024/2025 Plano Safra, indicating strong potential uptake for decision-support tools like the MM.

Nonetheless, our current MM framework does not account for key on-farm constraints—such as labor availability, animal welfare impacts at high stocking densities, or localized feed-grain market shocks—that critically influence management decisions. We recommend that future MM iterations incorporate stochastic labor-cost modules and dynamic feed-price risk models to better reflect real-world complexities and thereby enhance the tool's relevance for advisors and producers alike.

4.5. Price trends interpretation

4.5.1. Drivers of category-specific price paths

The sustained price increases in carcass-oriented cohorts likely reflected Brazil's expanding export markets and tightening domestic supplies following the onset of COVID-19-related disruptions. International demand, especially from China, coupled with intermittent droughts in the Pantanal and Cerrado biomes, likely contributed to higher adult cow and heifer prices (Costa et al., 2020; WTO, 2020; Viana et al., 2025). Lean and young bull categories (e–f) appear to have experienced even more pronounced gains, likely associated with favorable exchange-rate movements that increased export competitiveness after mid-2019 (Bussière et al., 2020; Paul and Dhiman, 2021). In contrast, live-weight cohorts (l–o) rose more gradually: modest year-over-year increases in bull-calf and weaner prices suggest that these segments were buffered by spot-market surpluses and established regional feeder-stock supply chains (Dill et al., 2020; Almadani et al., 2021). The relative price stability observed for female weaners and calves further suggests that these markets more closely tracked local input costs and seasonal placement patterns than global export signals.

Producers targeting high-value carcass classes should time their finishing and marketing to coincide with peak export windows and use forward contracts to lock in favorable prices when forecasts predict further Real depreciation. In contrast, operations focused on feeder-stock cohorts will likely benefit more from flexible purchase agreements tied to local cost indices, which can help smooth margin volatility. Accordingly, extension programs ought to tailor their risk-management guidance—offering export-oriented hedging strategies to carcass producers and local supply–chain contract advice to feeder-stock operators—to match each cohort's distinct market dynamics.

4.5.2. Managerial implications of trend dynamics

Our decadal price-trend analysis showed that carcass-oriented cohorts outpaced feeder-stock categories in both growth rate and volatility. To capitalize on these dynamics, producers finishing cattle for slaughter should schedule marketing to align with anticipated export peaks and secure feed through forward contracts when exchange-rate forecasts indicate further Real depreciation (Gopinath, 2019; Ahmed et al., 2015; USDA/FAS, 2020). In contrast, operations specializing in feeder calves and weaners, whose price growth proved more modest and locally driven, can stabilize margins by negotiating fixed-price feeder-stock agreements tied to regional cost indices.

The 2019 trade and health shocks highlighted that sudden market disruptions can widen price spreads across cohorts. In response, managers might, por example, reallocate 10–20% of herd capacity toward live-weight classes during export-downturn years to help buffer cash-flow swings. Extension services should therefore provide cohort-specific decision-support: delivering export-hedging tools and forward-pricing workshops to carcass finishers, while offering local feed-stock contracting guidance and margin-smoothing strategies to backgrounders.

4.5.3. Decadal trend insights

Our analysis of the 2010–2020 price series uncovered two consistent components across all 15 cattle cohorts. First, each cohort exhibited a steady upward drift reflecting long-term market tightening. In carcass-oriented categories (adult cows a–d; premium fat bulls g–k), we measured an average annual slope of +1.2 USD arroba per year—almost double the +0.6 USD arroba slope in feeder-stock cohorts (l–o), underscoring stronger incentives to expand finishing capacity rather than background only (Correa da Costa, 2021). Second, we observed cyclical troughs around mid-2012 and early-2016 that coincided with severe droughts in Mato Grosso do Sul and a lull in global export prices. During those downturns, carcass cohorts fell roughly 8 percent below trend, while feeder-stock prices dipped only 3 percent, suggesting that weaner and calf producers can serve as a natural cash-flow buffer when finished-beef margins compress.

The sharp price surge beginning in late 2019 across nearly all cohorts further highlighted the system's sensitivity to exogenous shocks—chiefly the onset of COVID-19 disruptions and adjacent trade-policy shifts. We recorded carcass-price spikes exceeding 15 percent above trend, whereas live-weight cohorts climbed 5–7 percent. These patterns point to the value of cohort-specific hedging horizons: finishing operations may benefit from, for example, locking in forward sales about 6–9 months before expected export peaks, whereas feeder-stock producers may favor shorter hedging windows, for example around 2–3 months. Incorporating these long-run slopes and shock-amplitude metrics into decision-support tools will enable ranchers, advisors, and investors to anticipate market inflection points and tailor risk-management strategies to each segment's distinct dynamics.

4.6. Clusters and anticorrelations: What they tell us

Our 51 × 51 input–correlation matrix (Figure 3) revealed distinct clusters with clear implications for planning and real-time risk management. Within the fixed-cost core (inputs 1–10), we found near-perfect co-movement (ρ>0.90) among land-lease rates, infrastructure depreciation, and equipment upkeep—mirroring the "overhead inertia" documented by Dillon and Hardaker (1980) and Martin (2016) in Australian sheep enterprises and later confirmed in Brazilian cattle systems (Raineri et al., 2015; Arantes et al., 2018; Telles et al., 2024). This tight coupling implies that attempts to trim one fixed-cost item in isolation will likely yield negligible savings.

In the variable-cost cluster (inputs 11–20), mineral and protein supplements (inputs 11–12) correlated strongly (ρ>0.80) with creep-feeding and pasture-maintenance herbicide/fertilizer costs (inputs 13–15). Consistent with Costa et al. (2005); Pereira et al. (2014); Raineri et al. (2015), and Gonçalves et al. (2017), these findings underscore that feed-intensity protocols drive a "rising tide" of associated expenses: when feed prices spike, managers must anticipate near-synchronous increases across these line items.

We also identified two subgroups within the revenue-price block (inputs 21–40). Young animal categories (calves and yearlings, inputs 21–30) co-moved at ρ ≈ 0.75–0.85, reflecting sensitivity to domestic feeder markets, whereas mature cohorts (fattening bulls and cull cows, inputs 31–40) correlated more modestly (ρ ≈ 0.60–0.70), likely due to divergent export versus domestic consumption dynamics (Belasco et al., 2009; Li et al., 2019). These subgroupings suggest that a one-size-fits-all price-forecast model may misstate risk unless it differentiates by cohort type.

Finally, we observed a pronounced anticorrelation (ρ ≈ –0.35) between pasture-area variables (inputs 16–18) and feed-intensity inputs (11–13), quantifying the land-for-feed trade-off: reductions in grazing area tended to be associated with higher purchased supplement costs, in line with evidence from the Cerrado biome (de Oliveira Silva et al., 2017; de Girão Rodrigues Mello et al., 2025). We also detected weaker negative linkages (ρ ≈ –0.20 to –0.25) between adult-cattle prices and upstream feed costs, indicating countercyclical behavior during drought-driven input shocks (Countryman et al., 2016).

Together, these correlation structures suggest three tactical priorities: (1) managers should budget overheads holistically, avoiding narrow cuts in fixed costs without re-optimizing land and asset use (Li et al., 2019); (2) they may reduce volatility across major variable-cost components by adopting coordinated feed-input hedging strategies, an approach supported by evidence from corn-fed beef systems (Hardaker and Lien, 2010a,b); and (3) they can unlock economies of scope by using the same or complementary inputs across multiple production lines—such as mixed-species grazing or niche, value-added beef products—to reduce average costs and spread risk (Roest et al., 2018; Bell et al., 2021).

By aligning budgeting, hedging, and diversification strategies to these clusters and anticorrelations, producers can strengthen both their day-to-day management and long-term resilience under market and environmental uncertainty.

4.7. Model flexibility and "what-if" scenario utility

Pasture-based beef production has long faced an important strategic knowledge gap in understanding pasture conditions and resilience—information that is relevant for directing limited research and policy investments toward sustainable financial and environmental outcomes (Chapman et al., 2024). The modular Minimum Module (MM) framework directly addressed this gap by combining zootechnical, agronomic, and economic dimensions into a single, user-driven simulation environment. Rather than prescribing a fixed herd size, the MM allowed producers and advisors to define a target annual net income and then adjusted herd composition and pasture area to maintain a non-negative net present value (NPV ≥ 0) (Jorge et al., 2019; Jorge, 2024).

The MM's "what-if" scenario engine empowered stakeholders—from smallholders to agribusiness investors—to explore alternative strategies in seconds. Users simulated increased dry-season supplementation, expanded legal-reserve allocations, or deferred capital investments and immediately assessed impacts on profitability, land requirements, and cash-flow risk (Moss, 2010; Hardaker et al., 2015a,b; McKendree et al., 2021). This real-time responsiveness supported proactive risk management: producers could implement feed-grain hedging strategies ahead of price spikes.

Our findings also enabled producers and advisors to link income targets directly to herd-composition and land-allocation decisions, explore feed-price hedging and herd-size smoothing strategies, and design forward-pricing arrangements aimed at limiting downside exposure. By integrating economic viability with environmental compliance, the MM offered a practical decision-support platform that public agencies and private consultants could deploy to prioritize research, guide extension programs, and inform policy on pasture restoration and conservation.

Although the implemented MM omitted explicit nutrient-use dynamics, mechanistic pasture-growth simulations, water-availability constraints, and animal-welfare metrics, it delivered robust benchmarks for profitability and risk under real-world variability. Future MM iterations would couple process-based pasture and nutrient modules, integrate welfare and ecosystem-service valuations, and embed spatially explicit land-use data to further close the knowledge gap on pasture resilience and ensure that integrated, multidisciplinary insights translated seamlessly into on-the-ground actions.

5. Conclusions

This study demonstrates the value of the Minimum Module (MM) as a transparent, user-driven decision-support tool that integrates zootechnical, agronomic, and economic submodels with Monte Carlo risk analysis. The MM identifies the minimum herd size and pasture area needed to keep net present value nonnegative across low, medium, and high intensification and shows that intensification increases per-hectare productivity from 3.3 to 9.8 arrobas ha^{-1} yr^{-1} while reducing required grazing area by >50%. Risk remains contained, with negative gross margin occurring in only 0.25% of iterations and negative total profit in 15.55% of iterations. The cost structure shifts from approximately 72% fixed at low intensity to approximately 52% variable at high intensity.

Data availability

All essential data generated or analyzed during this study are included in this published article. The Microsoft Excel spreadsheets and code for data analysis are available from the corresponding author and will be provided upon request after publication.

Author contributions

Conceptualization: Jorge, M. A.; Dourado Neto, D. and Sainz, R. D. **Data curation:** Jorge, M. A.; Dourado Neto, D.; Sainz, R. D.; Alves, L. R. A.; Da Silva, S. C. and Zen, S. **Formal analysis:** Jorge, M. A.; Dourado Neto, D.; Sainz, R. D.; Alves, L. R. A.; Da Silva, S. C. and Zen, S. **Funding acquisition:** Dourado Neto, D. and Zen, S. **Investigation:** Jorge, M. A.; Dourado Neto, D.; Sainz, R. D.; Alves, L. R. A.; Da Silva, S. C. and Zen, S. **Methodology:** Jorge, M. A.; Dourado Neto, D.; Sainz, R. D.; Da Silva, S. C. and Zen, S. **Project administration:** Dourado Neto, D. and Reichardt, K. **Software:** Jorge, M. A. **Supervision:** Dourado Neto, D. **Validation:** Jorge, M. A.; Dourado Neto, D.; Sainz, R. D.; Alves, L. R. A.; Da Silva, S. C. and Zen, S. **Visualization:** Jorge, M. A.; Dourado Neto, D.; Sainz, R. D.; Alves, L. R. A.; Da Silva, S. C.; Zen, S. and Reichardt, K. **Writing – original draft:** Jorge, M. A. **Writing – review & editing:** Jorge, M. A. and Reichardt, K.

Conflict of interest

The authors declare no conflict of interest.

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