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A decision frontier in throughput, feed conversion and price for shrimp farm investment: application to oligohaline Penaeus vannamei in Northeast Brazil

Onivaldo da Rocha Mendes Filho
Universidade Federal Rural de Pernambuco
Manoel Xavier Pedroza Filho
manoel.pedroza@embrapa.br
Embrapa Pesca e Aquicultura
Roberto Manolio Valladão Flores
Embrapa Pesca e Aquicultura
Luis Otavio Brito
Universidade Federal Rural de Pernambuco

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Abstract

This study estimates the decision frontier of a new investment in a commercial *Penaeus vannamei* farm in oligohaline water in Northeast Brazil and measures whether the farm's record establishes its position relative to that frontier. Seventy-five cycles from 14 ponds (7.42 ha) and monthly prices for shrimp, feed and postlarvae were propagated through 5,000 ten-year Monte Carlo paths. At an 8% real hurdle rate, mean net present value (NPV) was USD 3,129 ha^{-1} and P(NPV < 0) 12.1%. At a feed conversion ratio of 1.67 and the historical median base price of USD 3.67/kg, 6.03 t ha^{-1} yr^{-1} is required for 75% of paths to break even, against 6.29 simulated; at that throughput the required base price is USD 3.57/kg. These margins, 4.3% and 2.8%, remain positive at every criterion from 50% to 95% only because the median price removes price risk; with each path's own prices the throughput margin is 1.3% and turns negative from the 90% criterion. A nested bootstrap over the farm's cycles and market record gives 95% intervals of − 7.8% to 19.8% and − 5.1% to 12.9% for the two margins, wider still on the negative side once corrected for bootstrap bias, and the most recent second-quarter cycles yielded 16% less than earlier ones. The farm operates at the frontier, and its record does not establish on which side. The procedure, including its uncertainty layer, transfers to any operation with cycle-level records; the thresholds do not.

Clinical trial number: not applicable.

1 Introduction

Penaeus vannamei farming is capital-intensive and simultaneously exposed to factors such as production variability, price dynamics, feed costs and health risks. The expansion of culture into inland regions using low-salinity water has widened the alternatives for production growth in Northeast Brazil and created commercial systems with environmental and operational conditions that differ from those of coastal farms (Roy et al. 2010; Pimentel et al. 2023; FAO 2024). For investors, producers and lenders, this expansion increases the need to assess not only yield per cycle, but the annual capacity utilisation of the asset and the safety margin available to absorb production, market and capital shocks.

The aquaculture economics literature uses net present value (NPV), payback and stochastic models to appraise investments. In this study, uncertainty is incorporated into NPV through Monte Carlo simulation, repeating the cash flow across thousands of plausible futures to estimate the distribution of returns and the frequency of negative NPV (Engle 2010; Valderrama and Engle 2001; Sanchez-Zazueta and Martinez-Cordero 2009; Rego et al. 2017; Moor et al. 2022; Liu and Asche 2026). The aim is not to estimate a technical efficiency frontier but to propagate production and market variability through to the capital decision; production risk and technical inefficiency therefore remain distinct concepts (Long 2024; Hernández-Llamas et al. 2025).

A binary classification of an investment as viable or unviable offers limited managerial guidance, because it conveys neither the distance to the point at which the decision would change nor how much safety margin remains once the project crosses that point. The distinction is operationally relevant because a farm can generate a positive operating margin and still fail to remunerate the capital invested, a recurring

finding in economic appraisals of small and medium-sized aquaculture enterprises (Engle 2010; França et al. 2025; Petrolia and Caffey 2024). The more useful question for management is which minimum combination of output per unit of area and time, feed efficiency and price received allows capital to be remunerated with a defined probability.

In this study, throughput denotes the biomass marketed per hectare and per year. The term is taken from operations management, where it designates the rate at which a system converts inputs into output effectively sold per unit of time, rather than the volume produced in an isolated cycle (Goldratt 1990); it is applied here in physical units because the binding resource of the farm is pond area over time. The bioeconomic decision frontier is the set of combinations of throughput, feed conversion ratio (FCR) and price that places NPV at break-even; crossing the frontier means moving into the region in which the target proportion of simulated paths shows non-negative NPV. The link between biology and market is particularly relevant because the commercial rule sets a base quotation for 10 g shrimp and moves the price by BRL 1.00/kg per gram of difference from that weight: values above 10 g receive an increment and values below 10 g receive a reduction. Growth and final weight therefore affect biomass and unit price simultaneously, while lengthening the cycle can reduce rotation and raise costs and risk exposure. Risk and optimisation studies in shrimp show that price, harvest size, density, scale and rotation interact in the economic decision (González-Romero et al. 2014; Ruiz-Velazco et al. 2021; Bhargavi et al. 2025).

The central contribution is to convert risk into a measurable investment rule and to state how precisely that rule can be estimated from the record of a single farm. Instead of ending at the sign of NPV, the frontier quantifies the distance to break-even; an uncertainty layer then asks whether that distance is distinguishable from zero, given the finite production and market history from which the simulation is built. The question of this article is therefore twofold: which combinations of throughput, FCR and price remunerate capital with a defined probability, and whether a farm's own record is sufficient to establish on which side of that frontier the operation stands. The first objective is methodological: to set out a procedure that turns a stochastic appraisal into a decision frontier, with safety margins and their uncertainty intervals, and to state what a grow-out operation needs in order to re-estimate it for itself. The second is empirical: to apply the procedure to a commercial *P. vannamei* farm in oligohaline water and to translate the result into decision references for producers, investors and lenders. The thresholds reported here belong to that farm; the procedure does not. The taxonomy of Walker et al. (2003) is used to organise the sensitivities of market, production, finance and commercial rule, and to separate Monte Carlo, parameter and model uncertainty.

2 Materials and methods

2.1 Commercial farm and longitudinal design

The study used records from an anonymized commercial P. vannamei grow-out farm located in Salgado de São Félix, Paraíba, Northeast Brazil (Fig. 1). The enterprise operates inland and uses oligohaline water, with salinity of approximately 2 g L^{-1}. Fourteen earthen ponds were monitored, totalling 7.42 ha of water surface, with individual areas between approximately 0.17 and 0.89 ha. The design is observational and

longitudinal: the same ponds contributed repeated cycles over time. The oligohaline condition defines the production context of the case study; because salinity was neither experimentally manipulated nor used as a cycle-level covariate, the study does not estimate a causal effect of salinity.

The production series was kept at the area effectively observed. Revenue, expenses and NPV are presented per hectare to facilitate economic interpretation. Initial investment, land, replacement and annual fixed costs, however, are not treated as observed historical outlays of the property: they are reference economic intensities per hectare derived from the technical budget that forms part of the economic documentation of the project. NPV therefore represents the attractiveness of a new investment reproducing the observed longitudinal performance under those capital and cost intensities, and not the retrospective accounting profitability of the farm. The organisation of economic categories follows established approaches to cost and investment analysis in aquaculture (Matsunaga et al. 1976; Pedroza Filho et al. 2017; Mendes Filho et al. 2024).

2.2 Production database, quality control and throughput

The analytical database contained 75 valid cycles. Two source records with computed survival above 100% were excluded because the result is incompatible with the biological definition of the variable. The valid cycles were distributed across the 14 ponds between November 2021 and September 2023. Each cycle recorded area, stocking and harvest dates, initial population, density, duration, final weight, biomass, survival, feed quantity, FCR, yield and costs. Biologically plausible extreme values supported by the original records were retained; no exclusion was based solely on distance from the mean or on statistical convenience. The raw and quality-controlled records, the quality-control rules and the field-by-field data dictionary are available in the deposited dataset (Mendes Filho et al. 2026).

Throughput summarises asset utilisation because it integrates, in a single indicator, cycle yield, culture duration and the time a pond remains idle until the following stocking. Two systems with identical yield per cycle can therefore differ in annual capacity if they differ in cycle length or in the interval between cycles. Bioeconomic models of shrimp production have shown that stocking and harvesting schedules, duration of cultivation and rotation time alter economic performance as much as stocking density does (Estrada-Pérez et al. 2015; Hernández-Llamas et al. 2025); throughput expresses that joint effect as a single decision variable.

The interval between cycles was defined as the period between harvest and the subsequent stocking of the same pond. This interval was directly observed in 61 of the 75 valid cycles. For the last available cycle of each pond, with no subsequent stocking in the series, the median of the observed intervals of that pond was used; 14 intervals were thus imputed by a pre-specified rule. The annualised throughput of each cycle was computed as yield × 365.25/(duration + interval)/1,000, in t ha^{-1} yr^{-1}. In the simulation, cycles were organised sequentially by pond and the model resampled complete vectors from the same pond and, where available, from the same starting quarter, jointly preserving duration, biomass, weight, feed, FCR and operational interval. One sensitivity introduced a farm-wide production shock to represent situations in which several ponds are affected simultaneously.

Table 1
Characteristics of the valid production cycles and observed scale of the commercial oligohaline farm

Indicator	Oligohaline farm
Total water surface (ha)	7.42
Cycles recorded in the raw database	77
Excluded source records: computed survival > 100%	2
Intervals between cycles: observed / imputed	61 / 14
Valid cycles	75
Ponds	14
Stocking density (shrimp m^{-2})	44.75 ± 10.52
Cycle duration (days)	92.64 ± 24.39
Survival (%)	43.10 ± 15.12
Final weight (g)	10.95 ± 2.15
Yield (kg ha^{-1} $cycle^{-1}$)	1,996.01 ± 651.79
Annualised cycle throughput (t ha^{-1} yr^{-1})	6.81 ± 2.71
FCR	1.67 ± 0.59
Interval between cycles (days)	21.00 ± 26.80
Cycles with weight < 10 g	20 (26.7%)
Biomass from cycles < 10 g	28.0%

Note: values are mean ± standard deviation unless otherwise indicated. Cycle-level annualised throughput is a descriptive indicator obtained as a mean of ratios. In the sequential ten-year simulation, which reconstructs the pond calendar path by path, mean throughput converges to 6.29 t ha^{-1} yr^{-1}. FCR = feed conversion ratio.

2.3 Price series and the joint monthly panel

A total of 1,335 dated shrimp quotations, 77 feed price records and 59 postlarvae records were retrieved. Nominal BRL values were deflated by the general IPCA index (IBGE/SNIPC), obtained from Ipeadata, and expressed in constant August 2024 currency (Ipea 2026). The shrimp series covers May 2020 to August 2024, totalling 52 months and 41 twelve-month moving averages. The joint shrimp-feed-postlarvae panel used in the market simulation contains 31 monthly states over the common period from October 2021 to April 2024.

A monthly state gathers, for the same month, the shrimp quotation, the feed price index and the postlarvae price. This avoids treating multiple monthly quotations as independent periods and allows each cycle to be exposed to the prices of the months it spans. Internal gaps were interpolated between observed monthly

medians. April 2024 is an edge month without a shrimp price; it was retained in the audited panel as missing but excluded only from the complete-state bootstrap, with no value imputed or carried forward. One sensitivity used only the 19 complete monthly states with independent draws.

Feed prices included formulations with 35%, 38% and 40% crude protein. The counts n = 13, n = 25 and n = 39 correspond to price observations and not to the share of each formulation in consumption. To separate differences between products from temporal variation, each price was normalised by the median of its protein class and incorporated into a relative monthly index applied to the truncated base feed cost of the farm (USD 0.85/kg), corresponding to a median per-cycle real unit cost of USD 0.858/kg (USD 0.86/kg rounded). Because the database records total feed quantity and expenditure per cycle, but not the share of each protein content consumed in each phase, no nutritional sequence was imposed by the model.

The base scenario used a multivariate moving-block bootstrap with six-month blocks, resampling observed sequences of consecutive months to preserve part of the temporal persistence and of the common movement among shrimp, feed and postlarvae (Künsch 1989; Davison and Hinkley 1997). The 31-state joint panel contributed 30 eligible bootstrap states because the April 2024 edge state had no shrimp price. Robustness was tested with 3-month and 12-month blocks and with complete independent months.

Two qualifications follow from the size and the construction of the panel. The observed market window is short relative to the ten-year horizon simulated, so the simulation extends well beyond the period from which its market states were drawn. And the moving-block bootstrap assumes that observed patterns carry useful information about plausible futures: it resamples the sampled domain and does not constitute a structural forecast outside it.

Monetary results are presented in United States dollars using the closing PTAX rate of 30 August 2024, BRL 5.6145 per USD 1 (Banco Central do Brasil 2024a). PTAX is a reference exchange rate published by the Central Bank of Brazil; here it was used only to convert the presentation unit. Because all cash flows were converted at the same rate, this linear transformation alters neither the sign of NPV nor the simulated probabilities.

Table 2
Price structure and reference economic intensities of the base scenario

Item	Value / basis	Treatment in the model
Feed 35% CP	n = 13; median USD 0.86/kg	Relative index by formulation
Feed 38% CP	n = 25; median USD 1.13/kg	Relative index by formulation
Feed 40% CP	n = 39; median USD 1.20/kg	Relative index by formulation
Base feed cost	USD 0.86/kg (median 0.858; model 0.85 truncated)	Reference unit cost of the farm
Observed area	7.42 ha	Production series kept at the observed scale
Postlarvae	n = 59; median USD 2.04/1,000 PL	Monthly price at stocking
Other inputs per cycle	Values observed in each cycle	Resampled with the production vector
Initial investment intensity	USD 27,162/ha	Per-hectare benchmark; ±20% sensitivity
Land value intensity	USD 2,315/ha	Recovered in the terminal year of the base scenario
Initial working capital	Median USD 5,764/ha	Approximately one cycle of OPEX; recovered at the terminal year
Equipment replacement	USD 4,773/ha	Replacement within the ten-year horizon
Annual administrative costs	USD 607/ha/yr	Annual reference intensity
Annual energy	USD 2,891/ha/yr	Annual reference intensity
Annual labour	USD 1,742/ha/yr	Annual reference intensity
Annual owner's compensation	USD 855/ha/yr	Annual reference intensity
Other operating costs	5% of direct operating costs	Convention of the audited database
Required real return	8% per year	Base scenario; 6% and 10% in sensitivity

Note: capital and fixed costs are reference economic intensities, separate from the raw production data, and do not assert that the property disbursed those amounts. All monetary values are equivalents of real August 2024 values. August 2024 coincides with the last month of the longest shrimp price series; re-expressing the same cash flows in later currency would change only the unit, without adding market observations. CP = crude protein; OPEX = operating expenditure.

2.4 Commercial size-price rule

The observed quotation represents the farm-gate price for 10 g shrimp. The commercial rule provided was implemented linearly and symmetrically around that weight:

$P(w,t) = P10,t + (w - 10)\Delta$, for all w

where P10,t is the base quotation of month t and Δ = BRL 1.00/kg per gram, equivalent to approximately USD 0.18 kg^{-1} per gram at the presentation PTAX. Thus, if P10,t = BRL 20.00/kg, a lot at 9 g receives BRL 19.00/kg and a lot at 11 g receives BRL 21.00/kg. Robustness includes two commercial counterfactuals: absence of any size adjustment, and absence of the penalty below 10 g.

The symmetric application is material because 26.7% of the valid cycles, equivalent to 28.0% of the observed biomass, ended below 10 g. In the base scenario these cycles receive the reduction corresponding to their mean harvest weight, while cycles above 10 g receive the increment under the same linear rule. The rule is modelled as a strictly linear relationship of ± BRL 1.00/kg per gram around 10 g. Where actual transactions apply price floors, grading bands, additional discounts or buyer-specific conditions, the frontier has to be recalibrated for that schedule before its thresholds are used.

2.5 Cash flow, required rate and Monte Carlo simulation

The model computed pre-tax, unlevered NPV. Unlevered means that the economic performance of the asset was assessed independently of loans, interest, amortisation or the proportion between debt and equity. OPEX gathers the outlays required to operate the farm: postlarvae, feed, other inputs per cycle, administration, energy, labour, owner's compensation and an additional 5% on direct operating costs. At time zero, initial investment and working capital equivalent to approximately one operating cycle were considered. Equipment with an approximate five-year service life was replaced within the horizon and, in the base scenario, land was the only fixed asset recovered at real value in the terminal year, alongside the working capital released in the same period. Capital and fixed costs enter the model as reference economic intensities rather than as the historical capital expenditure disbursed by the property, and no claim is made that the operation disbursed those amounts.

The main horizon was ten years and the required real rate of return was 8% per year, used as a hurdle rate to judge whether the project remunerates capital. It does not represent a specific weighted average cost of capital (WACC), since the model defines no debt and equity structure. In August 2024, the pre-fixed interest component Jm of the Brazilian Long-Term Rate (TLP), a public benchmark derived from the real yield of inflation-linked Treasury bonds, was 6.28% per year; for August 2026 it was published at 8.21% per year (Banco Central do Brasil 2024b, 2026). Accordingly, 8% is retained as the central reference tied to the base date of the study, while 6% and 10% test sensitivity to the real opportunity cost of capital (Ruiz Campo and Zuniga-Jara 2018).

A total of 5,000 Monte Carlo paths were simulated in Python 3.13.5 and NumPy 2.3.5. Each path represents a possible ten-year future formed by resampling the production cycles and the monthly market states. The base scenario used seed 20260851. April 2024 remained in the audited panel as a missing state; it was not treated as an observed value, repeated or interpolated, and therefore did not enter the

eligible complete-state bootstrap set. NPV was the primary criterion; IRR was not central because replacements and terminal value can generate multiple sign changes in the cash flow. The original script that generated the first version of the results was not recovered. All results were regenerated with a documented reconstructed implementation under the recorded seeds, and executing it against the deposited workbook reproduces every reported output exactly. This is computational reproducibility: it shows that the reported numbers follow from the deposited data and code, not that the model represents the farm correctly, which is the purpose of the checks in Section 2.7. The analyses added in this revision import the deposited implementation without modification. Generative artificial intelligence tools were used in the development and review of the computational code and in language editing; their use is described in the Statements and Declarations. The implementation, the documented seeds, all simulated paths and the audited outputs of every scenario and every revision analysis are available in the deposited dataset (Mendes Filho et al. 2026).

2.6 The throughput-FCR-price frontier and decision criteria

To convert risk into managerial targets, the NPV of each simulated path *i* was written as a function of three multipliers applied to that path's own cash flows (the derivation, term by term, is given in Appendix A):

$$\mathrm{NPV}_i(m, f, d) = A_i + m(R_i + dB_i - fF_i) \quad (1)$$

Each term is a present value at the 8% real hurdle rate, computed from the same monthly cash flows that generate the simulated NPV. R_i is discounted revenue under the simulated price regime and the size-price rule; B_i is discounted marketed biomass (kg ha^{-1}), so that dB_i is the revenue change caused by a uniform shift of d USD/kg in the 10 g base quotation; F_i is the discounted feed bill at the observed FCR, including the 5% surcharge that the model applies to every direct operating cost. A_i gathers every flow that does not change when harvested biomass changes: initial investment and working capital, fixed direct costs (administration, energy and labour) with their surcharge, owner's compensation, the year-5 equipment replacement, the terminal recovery of land and working capital, and the stocking-related variable costs (postlarvae and other per-cycle inputs) with their surcharge. The multiplier m scales the biomass harvested in every cycle of the path, f scales the feed used per kilogram harvested (f = FCR/1.67) and d shifts the base quotation. Every component of the cash flow is linear in harvested biomass, feed quantity and base price, so Eq. (1) is exact rather than an approximation; at $m = f = 1$ and $d = 0$ it reproduced the simulated NPV of all 5,000 paths with a largest absolute discrepancy of 6.5×10^{-11} USD ha^{-1}.

Throughput is $T = mT_{\mathrm{obs}}$, where T_{obs} = 6.29 t ha^{-1} yr^{-1} is the mean simulated throughput of the farm. Because the pond calendar is held fixed, m changes the biomass of each harvest and not the number of harvests, and the thresholds refer to the farm's expected throughput rather than to the throughput realised on a particular path. Placing feed inside the bracket and stocking costs in A_i corresponds to a survival mechanism: more shrimp reach harvest from the same number of postlarvae, at the same harvest weight and the same FCR, so the feed bill rises in proportion to biomass while the postlarvae bill does not. Two alternative mechanisms were also evaluated (Section 2.7): a density mechanism, in which the number of postlarvae stocked rises with biomass at constant survival, and a calendar mechanism, in which the idle

interval between cycles is shortened, which changes the number of harvests and is therefore solved by re-simulation rather than by Eq. (1).

With price rebased to the historical median, the throughput at which path *i* breaks even follows from setting Eq. (1) to zero:

$$T_i^* = T_{obs}\,(-A_i)/(R_i^{med} - fF_i),\ R_i^{med} = R_i + (P_{hist} - a_i)B_i \quad (2)$$

where a_i is the base quotation simulated on the path (discounted revenue valued at the unadjusted 10 g quotation, divided by B_i) and P_{hist} = USD 3.67/kg is the median of the 41 twelve-month moving averages of the shrimp series. The base quotation at which path *i* breaks even at the simulated throughput T_{obs} and the observed FCR is

$$P_i^* = a_i - \mathrm{NPV}_i/B_i \quad (3)$$

The rebasing in Eq. (2) is needed because the simulated price regime averages USD 3.62/kg at the 10 g base weight rather than P_{hist}; without it the throughput thresholds would refer to a price level that is not reported. Neither threshold depends on the level of the simulated shrimp price: in Eq. (3) the level enters a_i and NPV_i/B_i equally and cancels, and in Eq. (2) it is replaced by P_{hist}. Both thresholds are solved in closed form, path by path, without numerical root search. Eq. (2) has a positive finite solution only if $A_i < 0$ and the throughput-scaled margin $R_i^{med} - fF_i$ is positive. A path with a non-positive margin cannot reach a non-negative NPV at any throughput, and its threshold was set to $+\infty$; a path with $A_i \geq 0$ is non-negative at any throughput, and its threshold was set to zero. Quantiles were taken over all paths under these conventions, so a robust threshold remains finite while fewer than 25% of paths are infeasible. Neither case occurred in the base run: A_i was below − USD 98,870 ha^{-1} on every path and the scaled margin above USD 100,217 ha^{-1} on every path.

The central threshold T_{50} is the median of T_i^* across paths, the throughput at which half the paths have non-negative NPV; the robust threshold T_{75} is the 75th percentile, at which three quarters do; P_{50} and P_{75} are defined in the same way from P_i^*. The 75% level is a decision convention and not an estimate: it states how much downside the investor or lender accepts, a one-in-four chance that the hurdle is not met, in the same way that a confidence level does in a value-at-risk measure. It was retained as the reference level of the original analysis, but no single level can be derived from the data, so thresholds and margins are reported for every criterion from 50% to 95% (Section 3.3) and a reader with a different risk tolerance can read the corresponding value directly. The throughput safety margin was defined as $M_T = T_{obs}/T_{75} - 1$ and the price safety margin as $M_P = P_{hist}/P_{75} - 1$. Both are safety margins in the investment-appraisal sense, the proportional distance between the farm's simulated performance and the level at which the decision would change, and are distinct from the operating margin of the enterprise, which compares revenue with operating expenditure within a single period. The two margins change sign together: both are negative

exactly when fewer than 75% of paths reach a non-negative NPV at T_{obs} and P_{hist}, so they are one test expressed on two scales.

Stating the frontier at P_{hist} conditions it on a price level. Rebasing removes the path-to-path variation in the level of the shrimp price, which is the main source of the 12.1% probability of loss, and leaves production and cost risk: at P_{hist} and T_{obs}, 99.98% of paths break even, against 87.9% when each path keeps its own simulated prices. The frontier was therefore also solved with price risk retained, replacing R_i^{med} by R_i in Eq. (2) and measuring the price margin against the mean simulated base quotation rather than P_{hist}. Both versions are reported; the first answers what throughput is needed if prices hold at their historical median, the second what throughput is needed when the price level is itself uncertain.

2.7 Uncertainty of the thresholds and checks of the model

Three sources of uncertainty were separated. Monte Carlo error arises because 5,000 paths are a finite sample from the simulation model; it was measured by bootstrapping the 5,000 paths (2,000 resamples) and by repeating the simulation with independent seeds. Parameter uncertainty arises because the simulation model is itself estimated from a finite record, 75 cycles, 30 eligible monthly market states and 52 months of shrimp quotations, and another record of the same length from the same farm would have produced a different model. Model uncertainty arises from structural choices that the data do not settle: the resampling unit, the block length, quarterly stratification and the mechanism behind a change in throughput.

Parameter uncertainty was estimated by a nested bootstrap (Davison and Hinkley 1997). In each outer replicate the inputs of the model were resampled from the observed record: the cycles of each pond were drawn with replacement from that pond's own cycles, keeping the number of cycles per pond; the joint monthly panel was resampled in circular moving blocks of six months; and the 52-month shrimp series was resampled in the same way, its twelve-month moving averages recomputed and their median taken as the replicate's P_{hist}. Circular blocks were used so that the first and last months, which in the shrimp series are the lowest-priced, are drawn as often as the others. Because neither threshold depends on the level of the simulated shrimp price, the panel affects the margins only through its feed and postlarvae prices, and the shrimp price enters only through P_{hist}; panel and price series were therefore resampled independently. The simulation (1,000 paths), the frontier and both margins were then recomputed for each replicate, so that T_{obs}, T_{75}, P_{hist} and P_{75} vary together. 400 outer replicates were run. The 2.5th and 97.5th percentiles across replicates give a 95% percentile interval for each margin; because the bootstrap distribution can be biased relative to the fixed-record estimate θ, the basic (reflected) interval, 2θ minus the same percentiles, is reported beside it, with θ recomputed on 5,000 paths under each specification. The share of replicates with negative margins indicates how often a record of the same size from the same farm would have placed the operation below the frontier. Three further runs (150 replicates of 500 paths each) resampled only the production cycles, only the market inputs, or cycles and panel with P_{hist} held at its observed value, and a run without resampling (100 replicates of 1,000 paths), in which replicates differ only in the seed, isolates the Monte Carlo component.

Two features of the record make these intervals lower bounds rather than complete measures. Cycles are resampled independently within each pond, so shocks shared by several ponds in the same calendar period are not reproduced by the resampling; and 11 of the 30 eligible monthly states contain interpolated components (19 are fully observed), which smooths the market series that is resampled. Both understate downside uncertainty.

Model uncertainty was assessed by repeating the nested bootstrap (150 replicates of 500 paths each) under four alternative specifications: cycles drawn from the whole farm rather than from the same pond, with per-hectare performance rescaled to the area of the receiving pond; three-month and twelve-month blocks for both market series; and no quarterly stratification of cycle draws. The mechanism behind a change in throughput was assessed separately: by Eq. (2) with postlarvae moved into the scaled bracket (density mechanism at constant survival and harvest weight); by the density mechanism re-solved numerically with the response observed across cycles, in which yield rises with density with the estimated elasticity and harvest weight, and with it the size-adjusted price, falls with the estimated slope; and by re-simulation with the idle interval between cycles reduced to 75%, 50%, 25% and 0% of its observed value (calendar mechanism).

Equation (2) gives an accounting frontier: the throughput the cash flow requires, whatever its biological source. Whether that throughput is attainable is a separate question, which the records can answer only within the range they cover. A biologically attainable frontier proper would require a production function linking survival, growth and the calendar to density and management, estimated on assigned rather than chosen stocking densities, which the farm's records do not support. Three empirical references were therefore set beside it: the throughput of each pond, simulated alone over the same ten-year calendar so that it is on the same scale as T_{obs}; the throughput simulated when the idle interval is removed altogether; and the cross-cycle relations of survival, harvest weight and yield with stocking density, estimated by ordinary least squares with bootstrap intervals (4,000 resamples) and by Spearman correlation. Shortening the grow-out period was not evaluated, because it would also lower harvest weight, and with it the size-adjusted price, through a growth curve that the records do not allow to be estimated.

Two checks address whether the model, and not only the code, behaves as described. First, the closed form was tested against the cash-flow loop itself: the biomass and feed of every cycle record (and, for the density mechanism, the population stocked) were multiplied by $m \in \{0.85, 0.90, 0.95, 1.00, 1.05\}$, the full simulation was rerun on 500 paths with the same seed, and the resulting NPVs and break-even multipliers were compared with Eqs. (1) and (2). Because the random draws do not depend on the values of the records, the rescaled and the original runs share every draw. Second, an out-of-sample check was run on the most recent cycle of each pond. These 14 cycles are also those whose interval had to be imputed; the model was re-estimated on the remaining 61 cycles, whose intervals are all observed, and each held-out cycle was located through the probability integral transform (PIT). The model itself draws from the same pond and quarter, but that pool holds a median of one training cycle, too few for a test, so two broader references bracket it: training cycles of the same quarter from the whole farm, and earlier cycles of the same pond. PIT values were computed from ranks with ties broken at random; under a calibrated model

they are uniform on (0, 1). Departure was measured by the Kolmogorov-Smirnov distance, with the 5% critical value Bonferroni-adjusted for the four variables tested (0.43 at $n = 14$).

3 Results

3.1 Production performance

The farm showed mean stocking density of 44.75 shrimp m⁻², survival of 43.10%, final weight of 10.95 g, yield of 1,996 kg ha⁻¹ cycle⁻¹ and FCR of 1.67. Annualised throughput computed directly on the cycles was 6.81 ± 2.71 t ha⁻¹ yr⁻¹. In the sequential farm simulation, which reconstructs the pond calendar and operational intervals over ten years, mean throughput was 6.29 t ha⁻¹ yr⁻¹, equivalent to approximately 46.7 t/yr on the observed area of 7.42 ha and to 3.20 cycles per pond-year.

3.2 NPV distribution in the base scenario

Under the reference economic intensities and the symmetric size-price rule, mean NPV was USD 3,129 ha⁻¹ and the median approximately USD 3,142 ha⁻¹. The simulated probability of negative NPV was 12.08% (95% Wilson interval: 11.21–13.01%), with P5 of approximately USD − 1,174 ha⁻¹ and P95 of USD 7,466 ha⁻¹. The Wilson interval expresses the precision associated with the finite number of simulated paths; it is not a confidence interval on the biology of the farm (Wilson 1927).

Table 3
Base scenario results per hectare

Indicator	Result
Mean NPV	USD 3,129/ha
Median NPV	USD 3,142/ha
NPV P5	USD − 1,174/ha
NPV P95	USD 7,466/ha
P(NPV < 0)	12.08% (95% Wilson interval: 11.21–13.01%)
Mean annual throughput	6.29 t ha⁻¹ yr⁻¹
Approximate annual output on the observed area	46.7 t/yr
Mean annual revenue	USD 23,716/ha/yr
Mean annual OPEX	USD 18,447/ha/yr
Cycles per pond-year	3.20

Note: 5,000 paths; 10-year horizon; required real return of 8%; terminal recovery of land value plus working capital; 30 monthly states were eligible for bootstrap because the April 2024 edge state remained missing in the audited panel. Throughput in t ha⁻¹ yr⁻¹; revenue, OPEX and NPV in real August 2024 USD per hectare.

3.3 Thresholds of throughput, feed efficiency and price

Because the decomposition holds two dimensions fixed and solves the third, the frontier answers the central operational question one decision variable at a time. At FCR 1.67 and the historical median price of USD 3.67/kg, the throughput required for 75% of paths to show non-negative NPV is 6.03 t ha⁻¹ yr⁻¹, against 6.29 t ha⁻¹ yr⁻¹ simulated. Holding simulated throughput and FCR, the base price required under the same criterion is USD 3.57/kg. At the central threshold, the corresponding values are 5.96 t ha⁻¹ yr⁻¹ and USD 3.55/kg. If FCR falls to 1.40 and price remains at USD 3.67/kg, the required robust throughput drops to 5.51 t ha⁻¹ yr⁻¹. Throughput, FCR and price therefore act as compensating levers of the same decision (Fig. 2; Table 4).

Under reference conditions, simulated throughput lies 4.3% above the robust threshold and the historical median price 2.8% above the required price. With price held at P_{hist}, the margins decline as the criterion becomes more demanding but remain positive at every level from 50% to 95%, from 5.5% to 2.6% in throughput and from 3.6% to 1.7% in price (Table 5). That robustness is close to automatic, because at P_{hist} 99.98% of paths break even at the simulated throughput. When each path keeps its own simulated price level, the throughput margin falls to 1.3% at the 75% criterion and becomes negative from the 90% criterion upwards (Table 5); the price margin, measured against the mean simulated quotation, falls to 1.2%. The choice of criterion therefore matters once price risk is retained: at the more demanding levels the point estimate lies below the frontier even with every input fixed at the observed record. With respect to Monte Carlo error the margins are precise: the standard error of either margin is at most 0.063 percentage points at every criterion. Whether they are also precise with respect to the record from which the model was estimated is examined in Section 3.6.

Table 4
Bioeconomic decision frontiers for the oligohaline farm

Fixed condition	Central threshold (50%)	Robust threshold (75%)	Variable solved
Throughput 6.29 t ha⁻¹ yr⁻¹; FCR 1.67	USD 3.55/kg	USD 3.57/kg	Base quotation
P10 = USD 3.67/kg; FCR 1.67	5.96 t ha⁻¹ yr⁻¹	6.03 t ha⁻¹ yr⁻¹	Throughput
P10 = USD 3.67/kg; FCR 1.40	5.45 t ha⁻¹ yr⁻¹	5.51 t ha⁻¹ yr⁻¹	Throughput

Note: each row holds two dimensions fixed and solves the third required to reach break-even. P10 = base quotation for 10 g shrimp. The values are economic thresholds of the project under the modelled assumptions, not automatic management recommendations.

Table 5
Thresholds and safety margins under alternative probability criteria, with the model inputs fixed at the observed record

Criterion (share of paths with NPV ≥ 0)	Throughput threshold at P_{hist} (t ha^{-1} yr^{-1})	M_T, % (MC s.e.)	Price threshold (USD/kg)	M_P, % (MC s.e.)	Throughput threshold, simulated prices	M_T, simulated prices, %	Throughput threshold at P_{hist}, FCR 1.40
50%	5.96	5.5 (0.03)	3.547	3.6 (0.02)	6.10	3.1	5.45
60%	5.99	5.1 (0.03)	3.557	3.3 (0.02)	6.14	2.5	5.47
70%	6.01	4.6 (0.04)	3.568	3.0 (0.02)	6.18	1.7	5.50
75%	6.03	4.3 (0.04)	3.574	2.8 (0.02)	6.21	1.3	5.51
80%	6.05	4.0 (0.04)	3.582	2.6 (0.03)	6.24	0.9	5.53
90%	6.09	3.3 (0.04)	3.598	2.1 (0.03)	6.31	−0.3	5.56
95%	6.13	2.6 (0.06)	3.613	1.7 (0.04)	6.37	−1.2	5.60

Note: survival mechanism, FCR 1.67 and P_{hist} *= USD 3.67/kg unless stated; 5,000 paths, seed 20260851.* $M_T = T_{obs}/T_q - 1$ *and* $M_P = P_{hist}/P_q - 1$*, with* T_q *and* P_q *the thresholds at criterion* q*. Simulated prices: each path keeps its own simulated price level (*R_i *in place of* R_i^{med} *in Eq. 2). MC s.e. is the Monte Carlo standard error in percentage points, from 2,000 bootstrap resamples of the paths; it does not include parameter uncertainty (*Table 6*). The 75% row reproduces* Table 4.

3.4 Price history and position of the frontier

The 41 twelve-month moving averages of the full shrimp series ranged from USD 3.50 to 3.92/kg, with a median of USD 3.67/kg. Under the symmetric rule, the central price threshold is USD 3.55/kg and the robust 75% threshold is USD 3.57/kg; both remain within the historical range and below the median. The historical median price is 2.8% above the price required under the robust criterion. Eleven of the 41 windows nevertheless fall below the robust threshold, including the seven most recent ones, from February to August 2024, so the safety margin measured against the median is not the safety margin that prevailed at the end of the series. The comparison uses moving averages rather than the 1,335 point quotations because the frontier represents a persistent price regime over the life of the investment (Fig. 3).

3.5 Mechanism and attainability of the throughput threshold

The mechanism through which throughput changes alters the threshold. Under the survival mechanism of Eq. (2) the robust threshold is 6.03 t ha^{-1} yr^{-1}. If the same biomass were obtained by stocking more postlarvae with survival and harvest weight unchanged, the postlarvae bill would rise with output and the threshold would fall to 5.96 t ha^{-1} yr^{-1} (margin 5.6%), because postlarvae and other per-cycle stocking inputs account for about 28% of the present value of variable costs and the survival mechanism keeps that cost when output falls. For downside risk the survival frontier is therefore the conservative one: mortality destroys revenue but not the postlarvae already paid for. The density figure assumes constant survival and harvest weight, which the farm's own records contradict. Re-solved with the response observed across cycles (yield elasticity 0.48, harvest weight and the size-adjusted price falling with density), the robust threshold falls further, to 5.52 t ha^{-1} yr^{-1} (margin 13.9%): because yield rises less than proportionally with density, a fall in throughput obtained by stocking fewer postlarvae saves proportionally more postlarvae than it loses biomass. A separate result concerns higher density: the margin on each added kilogram still exceeds the cost of the added postlarvae and of the smaller harvest weight for a while, so NPV on the median path rises with density up to about 18% more throughput than simulated. Both results are sensitive to the elasticity: at the ends of its 95% interval (0.14 and 0.78) the robust threshold is 4.20 and 5.83 t ha^{-1} yr^{-1}, and the NPV-maximising density lies below the observed one at the lower end and above it at the upper end, so the records cannot say in which direction stocking should move. Use of the calendar acts through the number of harvests rather than their size. Reducing the idle interval between cycles to 75% of its observed value raised simulated throughput to 6.57 t ha^{-1} yr^{-1} and lowered P(NPV < 0) to 0.4%; removing it altogether gave 7.58 t ha^{-1} yr^{-1}, the upper bound attainable with the observed cycles and no time for pond preparation.

The robust threshold lies within the range of the farm's own ponds. Simulated alone over the ten-year calendar, and therefore on the same scale as T_{obs}, the 14 ponds ranged from 2.95 to 9.54 t ha^{-1} yr^{-1} (area-weighted mean 6.29), and 6 of them, holding 39% of the water area, reached the threshold or more. The threshold is therefore not an extrapolation beyond observed performance; what the record does not show is the farm as a whole performing at the level of its better ponds. Across cycles, higher stocking density was associated with lower survival (− 0.46 percentage points per shrimp m^{-2}; 95% bootstrap interval − 0.82 to − 0.10) and lower harvest weight (− 0.042 g per shrimp m^{-2}; −0.100 to − 0.002), but with higher yield (21.3 kg ha^{-1} $cycle^{-1}$ per shrimp m^{-2}; 6.2 to 34.7), an elasticity of about 0.48 at the mean. Yield thus rose less than proportionally with density. These are associations across cycles; they do not identify the response of a given pond to a change in density, and the re-solved density frontier inherits that limitation.

3.6 Uncertainty of the safety margins

Monte Carlo error does not limit the conclusion; the length of the record does. Replicates that differed only in the seed, at 1,000 paths each, produced margins with a standard deviation of 0.08 percentage points in throughput and 0.05 in price. When the inputs were resampled from the farm's own record, the robust throughput margin had a median of 5.9%, a 95% percentile interval from − 7.8% to 19.8% and a basic interval from − 11.1% to 16.5%; for the price margin the corresponding values were 3.9%, − 5.1% to 12.9% and − 7.3% to 10.7% (Table 6; Fig. 4). Both margins, which change sign together, were negative in 22% of

replicates. The mean of the bootstrap distribution exceeds the fixed-record estimate by 1.6 percentage points in throughput and 1.1 in price; the percentile interval and the share of negative replicates carry that bias and are therefore the more favourable reading, while the basic interval corrects for it and extends further on the negative side; corrected in the same way, the share of replicates below the frontier rises to 37%. Holding P_{hist} at its observed value gave a throughput margin of 6.3% [− 4.3, 16.7], so the result does not depend on resampling the price series separately from the panel. With price risk retained, the throughput margin had a median of 4.6% against a fixed-record estimate of 1.3%, a percentile interval from − 7.5% to 16.3% and a basic interval from − 13.7% to 10.1%, and was negative in 24% of replicates.

Both parts of the record contribute, in similar measure. The standard deviation of the throughput margin was 5.2 percentage points when only the cycles were resampled, 4.7 when only the market inputs were, and 7.0 when both were, close to the 7.0 expected if the two sources add. Resampling only the production cycles, with the market record held at its observed values, gave 5.2% [− 4.0, 14.6] (median and 95% percentile interval), and resampling only the market inputs gave 3.6% [− 4.1, 13.3]: each part of the record is, on its own, wide enough to place the frontier on either side of the farm. The alternative specifications changed the width of the intervals but not their position across zero: 5.0% [− 9.0, 21.5] with cycles pooled across the farm, 6.1% [− 4.8, 19.5] with three-month blocks, 6.1% [− 6.7, 18.6] with twelve-month blocks and 4.2% [− 9.2, 18.9] without quarterly stratification. In none of the 1,550 replicates was any path infeasible in the sense of Section 2.6. The probability of negative NPV under the simulated price regime, 12.1% in the base run, ranged from 0% to 99.9% across the central 95% of replicates (median 0.5%), because the price level of a resampled 30-month panel moves a mean NPV that is small; the margins, which do not depend on that level, are the steadier summary. The Wilson interval of Section 3.2 measures only Monte Carlo error.

Table 6
Uncertainty of the robust (75%) safety margins by source and specification

Source of uncertainty	Replicates × paths	M_T median, %	M_T 95% interval, %: percentile; basic	M_P median, %	M_P 95% interval, %: percentile; basic	Below the frontier, % of replicates	P(NPV < 0), %: median [95% interval]
Monte Carlo only (seed)	100 × 1,000	4.3	[4.2, 4.5]; [4.2, 4.5]	2.8	[2.7, 2.9]; [2.7, 2.9]	0	11.7 [10.1, 13.4]
Parameter: production cycles only	150 × 500	5.2	[− 4.0, 14.6]; [− 5.9, 12.6]	3.5	[− 2.6, 9.4]; [− 3.7, 8.2]	17	6.2 [0.0, 97.7]
Parameter: market inputs only	150 × 500	3.6	[− 4.1, 13.3]; [− 4.6, 12.8]	2.4	[− 2.7, 8.7]; [− 3.1, 8.3]	17	5.1 [0.0, 97.8]
Parameter: cycles and panel, P_{hist} fixed	150 × 500	6.3	[− 4.3, 16.7]; [− 8.0, 13.0]	4.1	[− 2.8, 11.0]; [− 5.4, 8.4]	11	0.6 [0.0, 99.6]
Parameter: all sources (reference)	400 × 1,000	5.9	[− 7.8, 19.8]; [− 11.1, 16.5]	3.9	[− 5.1, 12.9]; [− 7.3, 10.7]	22	0.5 [0.0, 99.9]
Model: cycles pooled across the farm	150 × 500	5.0	[− 9.0, 21.5]; [− 12.9, 17.7]	3.2	[− 5.9, 13.9]; [− 8.2, 11.5]	25	0.9 [0.0, 100.0]
Model: three-month blocks	150 × 500	6.1	[− 4.8, 19.5]; [− 9.9, 14.4]	4.0	[− 3.1, 12.9]; [− 6.6, 9.4]	17	0.9 [0.0, 99.6]
Model: twelve-month blocks	150 × 500	6.1	[− 6.7, 18.6]; [− 11.8, 13.6]	4.0	[− 4.3, 11.9]; [− 7.5, 8.8]	21	0.1 [0.0, 95.5]
Model: no quarterly stratification	150 × 500	4.2	[− 9.2, 18.9]; [− 10.3, 17.7]	2.8	[− 5.9, 12.0]; [− 6.4, 11.5]	28	5.7 [0.0, 99.9]

Note: nested bootstrap. Each replicate resamples the indicated inputs from the observed record (cycles within pond with replacement; joint monthly panel and 52-month shrimp series in circular moving blocks), re-simulates the farm and recomputes T_{obs}, T_{75}, P_{hist}, P_{75} *and both margins. Percentile intervals are the 2.5th and 97.5th percentiles across replicates; basic intervals are 2θ minus those percentiles, with θ the fixed-record margin under the same specification. The two margins are below zero in the same replicates (*Section 2.6*). P(NPV < 0) is evaluated under the simulated price regime. Fixed-record values, reference specification*: M_T *= 4.3%*, M_P *= 2.8%, P(NPV < 0) = 12.1%. Seeds are derived from 20260851 and recorded with every replicate in the deposit.*

3.7 Out-of-sample check on the most recent cycles

The held-out cycles were not well predicted by the earlier record. Relative to training cycles of the same quarter, their yield had a mean PIT of 0.30, with 14% below the 10th percentile and none above the 90th; its Kolmogorov-Smirnov distance, 0.46, exceeds the Bonferroni-adjusted critical value of 0.43 (exact p = 0.004, against an adjusted level of 0.0125). Survival, FCR and harvest weight did not depart at that level (distances 0.24, 0.21 and 0.23). Against earlier cycles of the same pond the shortfall in yield was larger (mean PIT 0.22; distance 0.53). On average the held-out cycles yielded 1,521 kg ha^{-1} against 2,105 in training, with survival of 34.6% against 45.1% and FCR of 2.01 against 1.59. They were not truncated or emergency harvests: they lasted 97 days on average against 92 and ended at 11.8 g against 10.8 g. Of the 14, 11 were second-quarter cycles, the weakest quarter in training as well, but the comparison restricted to the second quarter still gave 1,549 against 1,842 kg ha^{-1}.

Estimated on the 61 training cycles alone, the model gives a throughput of 6.56 t ha^{-1} yr^{-1} and robust margins of 9.1% and 5.9%, about twice those of the full record. The margin is therefore sensitive to which cycles enter the record, and the most recent ones pull it down. With a single recent cycle per pond the record cannot tell a poor season in 2023 from a trend. It is, however, the direction that matters for the decision: if every cycle yielded 16% less with unchanged feed, throughput would fall to 5.29 t ha^{-1} yr^{-1}, against a robust threshold of 6.03, and every path would have negative NPV even at P_{hist}.

3.8 Robustness of the decision

The sensitivities tested four sources of decision risk: persistence and composition of prices, production dependence across ponds, financial assumptions, and commercial specification. Blocks of 3 and 12 months, complete independent months, removal of quarterly stratification, a farm-wide production shock, zero land value at exit, real rates of 6% and 10%, a ± 20% variation in initial investment and two size-price counterfactuals were evaluated. The zero-land-value scenario removes the land recovery only, because working capital is a timing item released whatever the exit route. All stochastic scenarios used 5,000 paths; in the base scenario, with P(NPV < 0) = 12.08%, the Monte Carlo standard error is approximately 0.46 percentage points, and it does not exceed 0.71 percentage points at any probability reported here.

Table 7
Methodological and economic sensitivities; mean NPV in USD ha⁻¹

Sensitivity	Uncertainty type	Mean NPV	P(NPV < 0)
Reference: 6-month blocks	Reference	3,129	12.08%
3-month price blocks	Random / market	3,865	6.46%
12-month price blocks	Random / market	3,132	5.16%
Complete months; independent draws	Structural / market	2,434	13.08%
No quarterly stratification	Structural / production	3,467	11.78%
Farm-wide production shock	Structural / production	-971	64.02%
Zero land value at exit	Structural / financial	2,053	22.44%
Required real return 6%	Structural / financial	6,970	0.50%
Required real return 10%	Structural / financial	-153	52.38%
Initial investment − 20%†	Structural / capital	8,562	not re-estimated
Initial investment + 20%†	Structural / capital	-2,303	not re-estimated
No size adjustment	Structural / commercial	-3,552	89.72%
No penalty below 10 g	Structural / commercial	5,204	2.26%

Note: mean NPV in real August 2024 USD ha⁻¹. The reference uses the commercial rule applied symmetrically around 10 g. †The ± 20% variation in initial investment intensity is an algebraic shift in the time-zero flow; the probability distribution was therefore not re-estimated in those two scenarios. The row "No penalty below 10 g" retains the increment above 10 g but does not reduce the price of sub-10 g lots.

The results identify which assumptions materially alter the decision under the symmetric rule (Table 7). Changing the length of the price blocks did not change the sign of mean NPV, but it moved P(NPV < 0) between 5.2% and 12.1%. Production dependence across ponds mattered more: the common shock raised P(NPV < 0) to approximately 64.0%. The commercial specification also remained decisive: removing every size adjustment turned mean NPV negative (USD − 3,552 ha^{-1}; P(NPV < 0) = 89.72%), whereas removing only the penalty below 10 g raised mean NPV to USD 5,204 ha^{-1} and reduced P(NPV < 0) to 2.26%.

The opportunity cost of capital and investment intensity complete the diagnostic. At 10% real, mean NPV is below break-even (approximately USD − 153 ha⁻¹) and P(NPV < 0) is 52.38%; at 6%, mean NPV rises to approximately USD 6,970 ha⁻¹. Because the variation in initial investment is a time-zero shift, + 20% of CAPEX directly reduces mean NPV to about USD − 2,303 ha⁻¹, while − 20% raises it to approximately USD 8,562 ha⁻¹.

3.9 Scale of the result and the investment decision panel

The frontier indicates whether the project crosses break-even; the ratio of NPV to the present value of operating expenditure indicates how much room remains afterwards. The mean NPV of USD 3.1 thousand ha^{-1} is equivalent to approximately 2.42% of the present value of OPEX and 1.90% of discounted revenue. The positive result is therefore small relative to the flows that generate it and can be consumed by moderate changes in cost, price or performance. The ratio is used only as a descriptive measure of that room, not as a structural elasticity.

Table 8
Investment decision panel based on the robust 75% frontier

Decision indicator	Result
Simulated throughput	6.29 t ha^{-1} yr^{-1}
Required throughput (75%; P10 = USD 3.67/kg)	6.03 t ha^{-1} yr^{-1}
Throughput safety margin over the robust threshold	+ 4.3% (95% percentile interval − 7.8% to 19.8%, basic − 11.1% to 16.5%; negative in 22% of replicates); +1.3% with price risk retained
Historical median price (12 months)	USD 3.67/kg
Required price (75%; simulated throughput and FCR)	USD 3.57/kg
Price safety margin over the required price	+ 2.8% (95% percentile interval − 5.1% to 12.9%, basic − 7.3% to 10.7%; negative in the same replicates)
P(NPV < 0), base scenario	12.08% at fixed inputs; 0% to 99.9% under parameter uncertainty (central 95% of replicates)
P(NPV < 0), farm-wide production shock	≈ 64.0%
NPV / PV(OPEX)	+ 2.42%
Required real return of 10%	Mean NPV ≈ USD − 153/ha; P(NPV < 0) ≈ 52.38%
Initial investment + 20%	Mean NPV ≈ USD − 2,303/ha
No commercial size adjustment	Mean NPV USD − 3,552/ha; P(NPV < 0) = 89.72%
Reading for new capital	At the frontier: positive point margins that the record does not distinguish from zero; recent cycles below the earlier record; material exposure to the size-price rule, common shocks and CAPEX discipline
Robust reference combination (75%)	FCR 1.67 + throughput ≥ 6.03 t ha^{-1} yr^{-1} at P10 = USD 3.67/kg; or throughput 6.29 t ha^{-1} yr^{-1} + P10 ≥ USD 3.57/kg
Most recent cycle of each pond (out of sample)	Yield 1,549 vs 1,842 kg ha^{-1} in second-quarter training cycles; margins of the training record alone about twice those of the full record

Note: throughput safety margin = $T_{obs}/T_{75} - 1$*; price safety margin =* $P_{hist}/P_{75} - 1$*. Intervals are 95% percentile and basic intervals from the nested bootstrap (*Table 6*). The sensitivities are individual and do not constitute a joint adverse scenario, which would require a specific re-run.*

For the new-capital decision the reading is narrower than the point estimates suggest. The point estimates exceed both thresholds under the commercial rule as reported, by 4.3% and 2.8%; the uncertainty that comes from a record of 75 cycles and 30 market months is wider than those margins, and the most recent

cycles performed below the earlier record. The robust reference combination remains FCR 1.67 with throughput of at least 6.03 t ha^{-1} yr^{-1} at the median price of USD 3.67/kg, or a base price of at least USD 3.57/kg at 6.29 t ha^{-1} yr^{-1}; what the data do not establish is that the farm sustains either condition (Table 8). A common production shock, a 10% real return and a 20% increase in capital expenditure (CAPEX) each move the point estimate below the frontier on their own.

4 Discussion

4.1 From the bioeconomic frontier to the investment decision

For a new investment the frontier reduces to two equivalent operating conditions: at FCR 1.67, a throughput of at least 6.03 t ha^{-1} yr^{-1} when the base price is USD 3.67/kg; at a throughput of 6.29 t ha^{-1} yr^{-1}, a base price of at least USD 3.57/kg. The point estimates of the farm's performance cross both conditions, by 4.3% and 2.8% at the historical median price and by 1.3% in throughput when price risk is retained, and the most recent twelve-month price windows already sit below the required price. The uncertainty analysis changes how that result should be read. The margins are robust to Monte Carlo error, and to the probability criterion only while the price is held at its historical median; they are not robust to the finiteness of the record: bootstrap replicates that mimic another record of the same length from the same farm placed the operation below the frontier in about 22% of cases, and the most recent cycles moved in that direction. The defensible statement is that the farm operates at the frontier and that its record does not establish on which side. This is itself the main managerial information of the study: a project whose expected margin is smaller than the uncertainty of its own performance record has no established safety margin, whatever the sign of the point estimate. The width of that uncertainty also says what would change the reading. With the present record, an interval of this width would exclude zero only for a throughput margin of about 14%, a throughput near 6.9 t ha^{-1} yr^{-1}; at the present margin the record would have to be roughly 10 times longer, since the width falls with the square root of its length. Raising the margin is therefore the practical route, rather than waiting for the record to lengthen.

This reading is more useful than the label "viable". A positive mean NPV and a P(NPV < 0) of 12.1% describe the simulation conditional on its inputs; the interval of 0% to 99.9% for the same probability under parameter uncertainty describes how much those inputs are worth. Reporting the first without the second would present a precision that belongs to the model as if it were knowledge of the farm. A common production shock, higher CAPEX and a higher opportunity cost of capital show, in addition, that the operation has little capacity to absorb structural change.

Earlier studies show that price, disease, intensity, scale and costs affect the economic risk of shrimp farming (Sanchez-Zazueta and Martinez-Cordero 2009; Rego et al. 2017; Asche et al. 2021; Ruiz-Velazco et al. 2021; Bhargavi et al. 2025). Clark et al. (2010) also simulated the NPV of a shrimp investment. The advance here is twofold: to complement the probability of loss with a frontier that reports how much throughput, FCR or price would have to change for the decision to change, and to add to the simulation the

uncertainty of its own input distributions, which in a single-farm record of this length exceeds the Monte Carlo error by nearly two orders of magnitude.

4.2 Throughput, survival and feed efficiency

On the farm studied, mean survival of 43.1% at a density of 44.75 shrimp m^{-2} indicates that survival losses reduce the biomass obtained with infrastructure and capital already committed. The robust threshold lies within the farm's own range: 6 of its 14 ponds, with 39% of the water area, reach it when simulated on their own records. Securing the margin is therefore a matter of making the performance of the better ponds typical rather than of reaching a performance the farm has never recorded. The cross-cycle associations show that density cuts both ways: yield rose less than proportionally with density, while survival and harvest weight fell, and with weight the size-adjusted price. Re-solved with that response, the density frontier lies below the survival frontier, because a fall in throughput through lower stocking saves proportionally more postlarvae than it loses biomass; separately, NPV rises with density up to about 18% more throughput, because the added biomass more than pays for the added postlarvae over that range (Section 3.5). Because density was not assigned across cycles and the elasticity is imprecise, to the point that across its interval the NPV-maximising density falls on either side of the observed one, this is a hypothesis for a stocking trial rather than a recommendation. Gains in survival, if attainable without a disproportionate increase in cost or risk, act through the conservative mechanism of Eq. (2) and raise throughput without adding postlarvae cost; the records, however, do not identify the cause of mortality, which would require water quality, disease and management variables at cycle level. The calendar offers a third route: an idle interval 25% shorter raised simulated throughput by about 4.5%, of the same order as the throughput margin itself, although the interval also serves drying, liming and pond preparation, whose effect on the following cycle the records do not measure. In low-salinity culture, carrying capacity, water quality, mineral nutrition, biosecurity and management can limit the response to intensification (Roy et al. 2010; Pimentel et al. 2023).

The frontier also allows FCR to be interpreted without turning it into an isolated objective. Reducing FCR from 1.67 to 1.40, holding the price regime constant, lowers the required robust throughput from 6.03 to 5.51 t ha^{-1} yr^{-1}. Efficiency gains widen the safety margin; even so, the economic decision remains dependent on the interaction between annual biomass, price and capital. The usefulness of the model is to quantify the size of that trade-off, not to assert that a single husbandry indicator should be maximised.

4.3 Price, harvest weight and market risk

Size-based remuneration is a central bioeconomic link and works in both directions. Each gram above 10 g adds BRL 1.00/kg to the base quotation and each gram below reduces the price by the same magnitude. Because 26.7% of the valid cycles, equivalent to 28.0% of the observed biomass, ended below 10 g, the penalty is not marginal in this dataset. At the same time, higher weight is not automatically the optimal economic decision, because longer cycles can reduce rotation and increase feeding and health risk (Bhargavi et al. 2025; Ruiz-Velazco et al. 2021).

The commercial counterfactuals show how much the form of this rule matters. If the penalty below 10 g is removed while the increment above 10 g is retained, mean NPV rises to USD 5,204 ha⁻¹ and P(NPV < 0) falls to 2.26%. If every size adjustment is removed, mean NPV becomes negative (USD − 3,552 ha⁻¹) and P(NPV < 0) rises to 89.72%. Both the gain from growth and the loss from harvesting below 10 g therefore need to be represented correctly. In future applications, sales invoices recording mean weight, grading and the price actually received would allow verification of whether the reported linear relationship is applied without floors, size bands or additional discounts.

Monthly modelling avoids confusing 1,335 raw quotations with 1,335 independent periods. By summarising the data into monthly states and resampling consecutive blocks, the moving-block bootstrap preserves part of the autocorrelation and of the dependence between output and inputs, an aspect relevant in aquaculture markets (Asche et al. 2015). The block length changed P(NPV < 0) between 5.2% and 12.1% at fixed inputs (Table 7) and changed the width of the uncertainty intervals of the margins, but in no case moved those intervals clear of zero (Table 6).

4.4 Systemic risk and shared events

Using repeated cycles within the same pond improves the representation of temporal variability relative to an analysis based on a mean cycle. Even so, temperature, water quality, energy, management and disease can affect several ponds simultaneously. Under the symmetric rule, the farm-wide production shock raised P(NPV < 0) from 12.08% to approximately 64.0%, showing that assuming partial independence across ponds may overstate the diversification benefit. This result does not demonstrate technical inefficiency; it shows that a shared event displaces several production components in the same direction and materially alters investment risk.

The magnitude of this effect runs against a common management intuition. Operating several ponds suggests diversification, but the benefit depends on performances being partially independent. When a shared event displaces all of them in the same direction, the dispersion of the aggregate result ceases to be attenuated by the number of units. For the investor and the lender, the implication is that effective protection depends on measures that reduce common exposure, such as energy and aeration redundancy, biosecurity and staggered stocking. The result also helps explain why shrimp farmers adjust density and strategy according to risk perception, and not only according to expected return (Joffre et al. 2018).

Shrimp diseases can cause severe losses and alter the economics of the system (Silva et al. 2010; Estrada-Pérez et al. 2020; Asche et al. 2021; Andrade et al. 2022). Because the available database does not support estimation of a causal and stable epidemiological frequency, the study assigns no artificial probabilities to specific outbreaks. The common-shock sensitivity generically represents the loss of diversification under shared events; epidemiological analyses would require dedicated data.

4.5 Cost of capital, credit and the safety margin

Sensitivity to the opportunity cost of capital reinforces the reading in terms of safety margin. At a required real return of 10%, mean NPV is practically zero and P(NPV < 0) approaches 50%; with initial investment 20% higher, mean NPV falls to approximately USD − 2,303 ha⁻¹. The conclusion therefore depends on

budget discipline and on the rate required by the investor. The Jm component of the TLP is used only as a macro-financial reference and not as the effective cost of a specific loan.

Sensitivity to capital and to the commercial rule also defines the financing problem of the enterprise. A safety margin that the record cannot distinguish from zero means the project has little demonstrated capacity to absorb implementation cost overrun and price deterioration at the same time, which constrains the level of leverage compatible with debt service. Credit analyses in semi-intensive shrimp farming show that the source of funds, its rate and its disbursement schedule alter the viability of the operation, and not only its liquidity (Sanchez-Zazueta et al. 2013); efficiency studies also identify access to formal credit as a determinant of the economic performance of shrimp farms (Long et al. 2020; Long 2022). Where subsidised or long-term bank credit is available, a lower financial cost and a longer amortisation period change the equity cash flow without changing the economics of the asset; in Northeast Brazil that role is played by the FNE Aquipesca rural credit programme (Banco do Nordeste do Brasil 2026). The present model, however, computes unlevered project NPV. Favourable financing may improve the investor's capacity to pay, but it creates neither throughput nor operating revenue; a debt analysis is therefore complementary and does not replace the bioeconomic frontier. For a lending institution, the frontier can support credit analysis by making explicit which performance the project must sustain before any debt structure, and how far the record is from establishing that the project sustains it.

The NPV/PV(OPEX) ratio of approximately 2.42% helps interpret the accuracy required of economic records. Because NPV is a small difference between large gross flows, modest changes in costs, price or performance can consume the positive NPV, and the same arithmetic explains why a record of 75 cycles cannot fix the sign of the margin. In investment terms, the result is better described as a project at the frontier, whose safety margin is not established by the available record, than as viable.

4.6 Managerial implications for producers, investors and lenders

The managerial application can be summarised in three indicators: annual throughput per hectare, FCR and the mean price received. For this configuration, the robust 75% criterion corresponds to throughput ≥ 6.03 t ha^{-1} yr^{-1} at FCR 1.67 and P_{10} = USD 3.67/kg, or, at a throughput of 6.29 t ha^{-1} yr^{-1} and FCR 1.67, to P_{10} ≈ USD 3.57/kg or above. A lower FCR shifts the frontier favourably. Each indicator should be read against its threshold together with the interval of the margin: a margin whose interval includes zero, as here, calls for a higher margin or a lower-risk configuration before new capital is committed, rather than for a decision based on the sign of the point estimate.

The panel in Table 8 should be recalculated when costs, technology, the commercial schedule or the price regime change. Between those revisions, management can track the trend in throughput, FCR and price received and check whether the operation is moving towards or away from the economic thresholds.

The results point to three practical priorities: realising and documenting the commercial size-price rule in both directions; controlling CAPEX, since + 20% in initial investment turns mean NPV negative; and

reducing exposure to shocks shared across ponds, which raise P(NPV < 0) to about 64.0%. These priorities are directly observable in the production flow and in the capital decision, although choosing the least-cost technical intervention requires local diagnosis.

For the producer, the frontier works as a minimum performance reference; for the lender, as a verifiable operating condition before structuring debt. The value of the method lies in making the safety margin explicit and in testing whether a proposed improvement is large enough to widen it.

The threshold throughput can be reached through survival, density or better use of the calendar, and the frontier differs between them (Section 3.5). Survival gains leave the postlarvae bill unchanged and are evaluated by the conservative frontier; higher density adds postlarvae cost and, in the farm's records, lowers harvest weight, so the frontier must be recalculated with the observed response; calendar gains add harvests and are evaluated by re-simulation.

The frontier therefore neither replaces technical diagnosis nor prescribes management. It provides the economic criterion for comparing alternatives in production, marketing or investment under the same assumptions.

4.7 Transferring the frontier to other operations

The unit of inference in this study is a single enterprise. Longitudinal repetition across 14 ponds and 75 valid cycles improves the temporal representation of performance, but it does not make this farm an average of oligohaline shrimp farming in Northeast Brazil, and the design identifies no causal effect of salinity. The numerical thresholds in Table 4, such as 6.03 t ha^{-1} yr^{-1} and USD 3.57/kg, are specific to this configuration, cost structure and price regime, and do not constitute a sector benchmark. What transfers is the procedure, not the numbers. Re-estimating the frontier for another grow-out operation requires four inputs, all of which a commercial farm either already records or can obtain from public sources. The first is a cycle-level production history: stocking and harvest dates, pond area, biomass harvested and feed used, for enough cycles to cover the seasonal cycle at least twice. This is what converts yield per cycle into annual throughput, because the interval between cycles is as decisive as the yield itself. The second is a dated price series for the output and for the two dominant inputs, feed and postlarvae, long enough to be deflated and resampled; where the farm sells by size category, the commercial schedule linking weight to price is needed as well, because it determines how much of the biomass is paid at the base quotation. The third is a cost structure that separates the intensities scaling with area from those scaling with biomass, together with an initial investment per hectare. The fourth is a required real rate of return, which is a decision of the investor or the lender rather than a property of the farm.

Given those inputs, the steps are those described in Section 2: build the joint monthly panel, resample it by moving blocks so that the common movement among series is preserved, propagate each path through the cash flow, and solve, path by path, for the minimum throughput, the maximum FCR and the minimum base price consistent with a non-negative NPV. The safety margins follow as the ratio between observed performance and the threshold at the chosen probability. The uncertainty layer belongs to the procedure: resampling the operation's own cycles and market months around the simulation shows whether the

margin exceeds the uncertainty of the record, and the width of that interval narrows only as the record lengthens. Nothing in the procedure is specific to oligohaline water, to shrimp or to Brazil. What changes between operations is the cost structure, the price regime and the length of the production calendar, and those are the quantities from which the frontier is estimated.

One caution applies to the data requirement. The binding constraint in practice is rarely the economic parameters, which can be reconstructed from a technical budget, but the cycle-level history. An operation that records only annual aggregates cannot separate yield from use of the calendar, and the throughput term, where most of the decision sensitivity sits, becomes unidentifiable. Where that history is short, the margin should be reported with its interval, and the robust criterion treated as indicative until the interval excludes zero.

4.8 Limits of inference

Five limits bound what the study establishes. First, the unit of inference is one farm, whose 75 cycles cover 23 months; parameter uncertainty is estimated by resampling that record, which cannot represent conditions the farm did not experience, such as a disease outbreak of a kind absent from the period. Second, the market model resamples 30 monthly states to project ten years; it assumes that future price regimes resemble the observed window and is not a forecast. Third, the frontier is an accounting construct: it states what the cash flow requires, and its link to biology rests on the assumptions of the mechanism used, constant FCR and harvest weight under the survival mechanism, postlarvae proportional to output under the density mechanism and unchanged cycle performance under the calendar mechanism, none of which was tested experimentally; energy, for instance, is held fixed although aeration demand rises with biomass. Within the first two limits, the resampling reproduces neither shocks shared by ponds in the same period nor the full variability of the 11 interpolated market states, so its intervals are lower bounds on downside uncertainty.

Fourth, the reconstructed implementation reproduces the reported results, and the checks of Section 2.7 confirm that its algebra matches its cash flow and expose its predictive limits; neither constitutes validation against the realised outcome of an investment, which would require following one or more farms over the horizon simulated. Fifth, the capital and fixed-cost intensities are reference values from a technical budget rather than observed outlays, and their uncertainty is not part of the bootstrap, although a 20% increase in initial investment alone moves the point estimate below the frontier; the size-price rule is the one reported by the farm, not one verified on sales invoices. The thresholds are conditional on all five.

5 Conclusions

For the oligohaline farm analysed, the robust decision rule is a throughput of at least 6.03 t ha^{-1} yr^{-1} at FCR 1.67 and a base price of USD 3.67/kg or, at a throughput of 6.29 t ha^{-1} yr^{-1}, a base price of at least USD 3.57/kg. The farm’s point estimates exceed both by 4.3% and 2.8% at the historical median price, and by only 1.3% in throughput when price risk is retained; the uncertainty of its record is larger than those

margins, and its most recent cycles fell short of the earlier ones. The farm operates at the frontier, and the record does not establish on which side.

Even setting parameter uncertainty aside, a common production shock, a 10% required real return, 20% higher CAPEX and the removal of the commercial size adjustment each move the point estimate below the frontier. For new capital, the result calls for gains in survival or in use of the calendar large enough to exceed the uncertainty of the margin, a throughput near 6.9 t ha^{-1} yr^{-1} at the present record length, before the investment is committed.

Beyond this farm, the transferable result is the procedure: a frontier in throughput, FCR and price, solved path by path in closed form, together with an uncertainty layer that compares the safety margin with the uncertainty of the record from which it was estimated. Any grow-out operation holding a cycle-level production history, dated price series for output and main inputs, a cost structure separated into area-based and biomass-based intensities, and a required rate of return can estimate its own frontier and learn whether its record is long enough to read its own margin.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose. The organisations that provided access to records and technical support had no role in study design, data analysis, interpretation of results, writing of the manuscript or the decision to submit it for publication.

Ethics approval

No approval of a research ethics committee was required to accomplish the goals of this study. The work uses technical and economic records of routine commercial production. No animal experimentation was conducted and no personal data on workers, consumers or other human participants were collected or analysed.

Consent to participate

Not applicable. The study involved no human participants.

Consent for publication

Not applicable. The study contains no individual personal data.

Clinical trial number

not applicable.

Use of generative artificial intelligence

The authors used generative artificial intelligence tools to support language editing, translation, text organisation, development and review of computational code, and consistency checks of the stochastic bioeconomic analysis. These tools were not used as a data source and are not authors. All assumptions, quality control criteria, analytical decisions, numerical results, references, interpretations and conclusions were reviewed and validated by the authors, who take full responsibility for the accuracy, originality and integrity of the work.

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Author Contribution

O.R.M.F. and M.X.P.F. conceived the study. O.R.M.F., M.X.P.F. and R.M.V.F. designed the methodology. O.R.M.F. assembled and curated the production and market databases, wrote the simulation and revision analysis code and prepared Figures 1-4. O.R.M.F. and R.M.V.F. carried out the formal analysis of the Monte Carlo results and of the decision frontier. M.X.P.F., R.M.V.F. and L.O.B. validated the assumptions, the economic parameters and the reported values. L.O.B. provided resources and acquired funding. M.X.P.F. and L.O.B. supervised the work. O.R.M.F. wrote the main manuscript text. All authors reviewed and approved the manuscript.

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Data Availability

The data, code and simulation outputs supporting this article are openly available in Zenodo at https://doi.org/10.5281/zenodo.23601691 (version 1.1.0) under a CC BY 4.0 licence for data and documentation and an MIT licence for code, and are cited in the manuscript as Mendes Filho et al. (2026). The deposit contains the raw and quality-controlled production records, the market series, the economic assumptions, the deterministic Monte Carlo implementation, all simulated paths, the revision analyses

with every replicate and its seed, a data dictionary and a provenance table with the checksum of every file. The farm is identified only by the label OPB, and ponds and postlarvae suppliers are pseudonymised.

Code availability

The deterministic Monte Carlo implementation, the revision analysis script (revision_analysis.py, which imports the implementation unchanged), the figure-generating scripts and the de-identification script are included in the deposit cited above, under an MIT licence.

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Figures

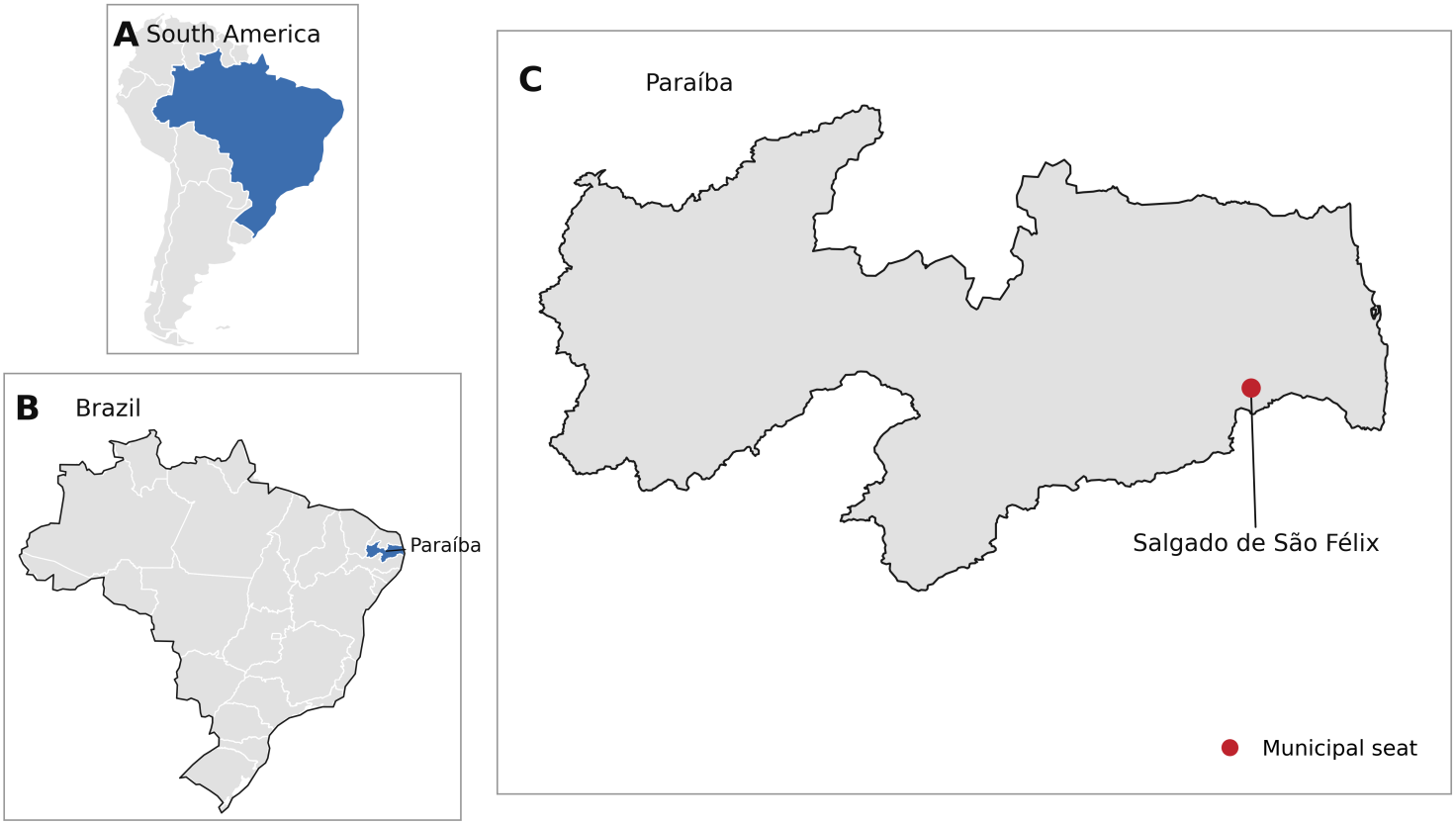

Figure 1

Location of the study area. (A) South America with Brazil highlighted; (B) Brazil with the state of Paraíba highlighted; (C) Paraíba with the municipal seat of Salgado de São Félix indicated. The point represents the municipal seat and not the exact coordinates of the farm

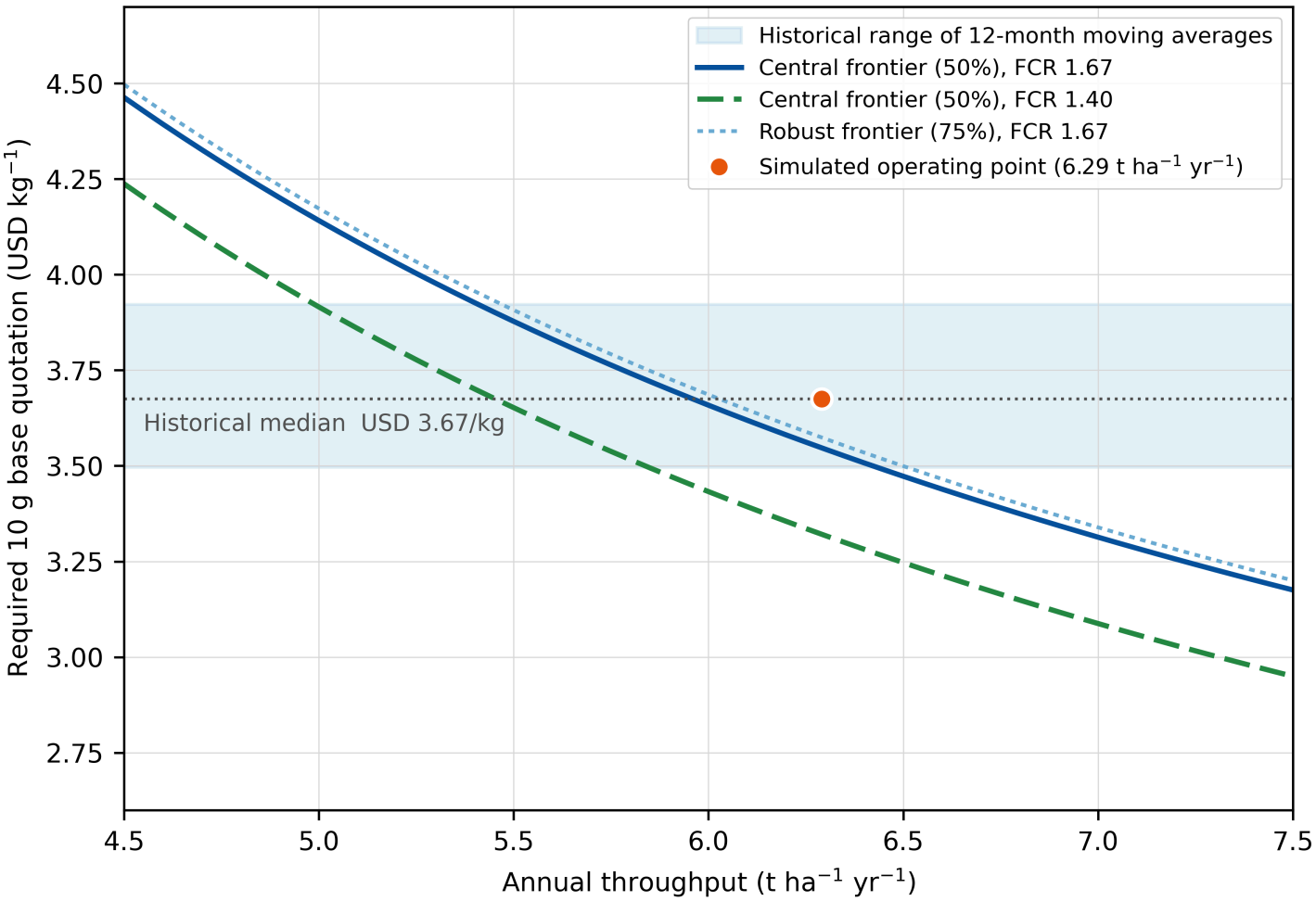

Figure 2

Central decision frontier linking annual throughput, FCR and the 10 g shrimp base quotation. The curves represent the central criterion (median NPV = 0); the shaded band shows the historical range of 12-month moving averages and the dotted horizontal line the historical median. The marker indicates the simulated throughput of the farm. Thresholds under the robust 75% criterion are reported in Table 4

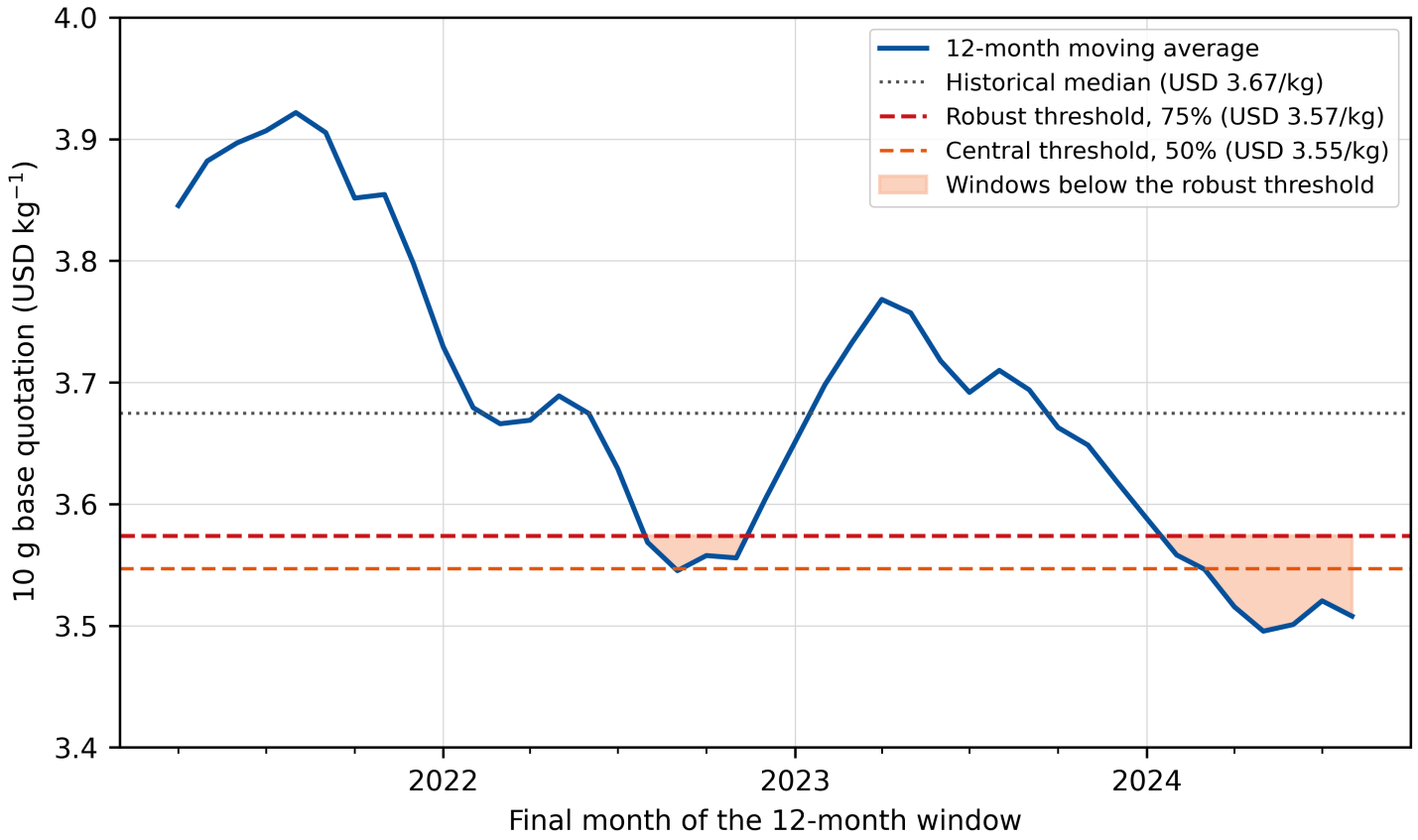

Figure 3

Twelve-month moving averages of the 10 g base quotation and break-even thresholds of the oligohaline farm. The shrimp series covers May 2020 to August 2024; the 41 moving windows begin after the first 12 months

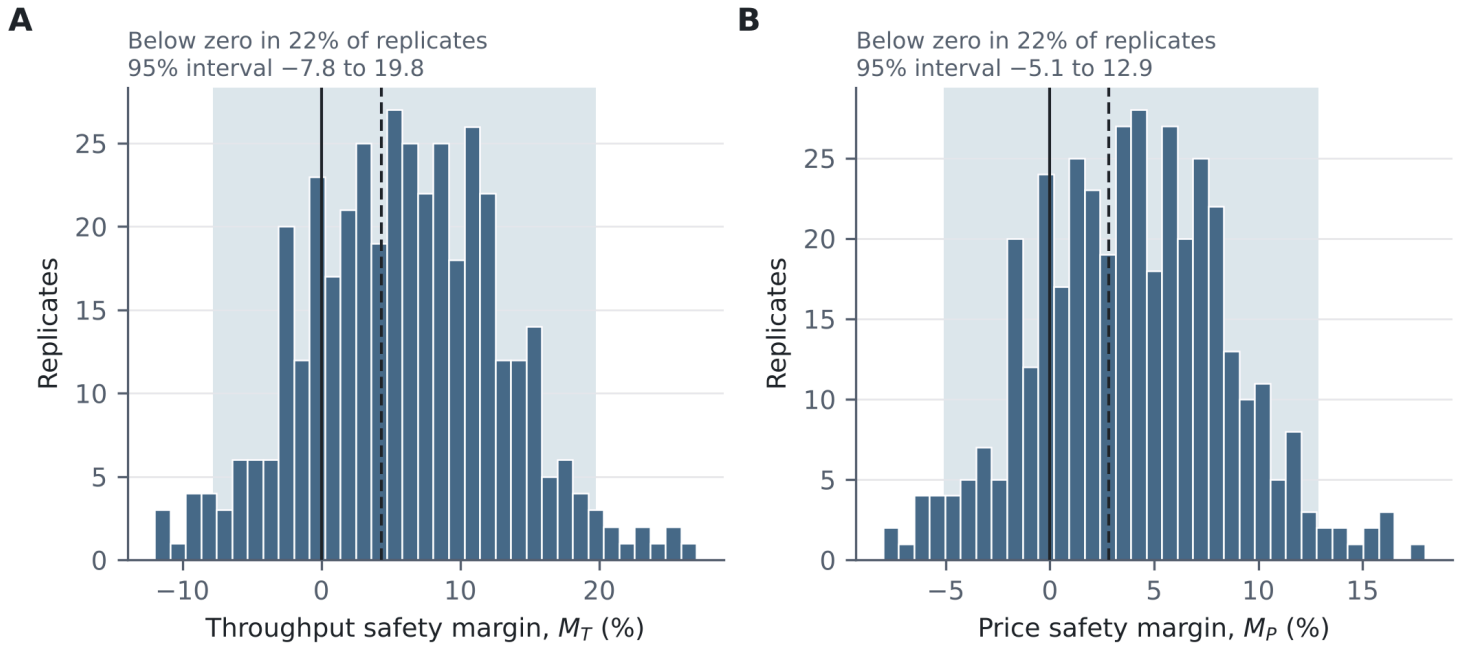

Figure 4

Distribution of the robust (75%) safety margins across 400 nested-bootstrap replicates. (A) Throughput margin M_T; (B) price margin M_P. Each replicate resamples the production cycles, the monthly market panel and the shrimp price series from the observed record and re-solves the frontier. The solid line marks zero, the dashed line the fixed-record estimate and the shaded band the 95% percentile interval

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendix.docx