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Research Article

Keywords: Lobster aquaculture, bioeconomic modeling, system dynamics, sustainability, environmental feedback, Indonesia

Posted Date: May 4th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9406841/v1

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Additional Declarations: No competing interests reported.

Integrating Bioeconomic and System Dynamics Modeling to Evaluate Sustainability Trade-offs in Indonesian Lobster Aquaculture

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Abstract

Sustainable lobster aquaculture in Indonesia is shaped by complex interactions among biological productivity, economic incentives, environmental capacity, and regulatory constraints, yet integrated analytical approaches capturing these dynamics remain limited. This study develops a field-parameterised bioeconomic system dynamics model to evaluate sustainability trade-offs in lobster aquaculture systems. Empirical data collected from major production regions (Java, Lombok, and Sulawesi) during 2022–2025 were used to parameterise biological, economic, and environmental subsystems within a unified feedback-based framework implemented in Vensim®. The model simulates system behaviour over a 10-year horizon under two scenarios: baseline production practices and a sustainability-oriented management strategy. Results indicate that baseline practices generate high short-term profitability but progressively degrade environmental quality, leading to reduced system resilience and stabilization of biomass and profit levels over time. In contrast, the sustainability scenario—characterised by moderated stocking intensity, improved survival performance, and enhanced environmental recovery—produces more stable biomass trajectories, higher long-term profitability, and significantly improved environmental conditions. These findings highlight the critical role of environmental feedbacks in shaping long-term aquaculture performance and demonstrate that sustainability-oriented management can mitigate trade-offs between economic returns and ecological integrity. The study contributes a novel empirical bioeconomic-system dynamics framework to support evidence-based aquaculture policy and sustainable development in Indonesia and comparable tropical aquaculture systems.

Keywords Lobster aquaculture; bioeconomic modeling; system dynamics; sustainability; environmental feedback; Indonesia

1. Introduction

Lobster aquaculture has emerged as one of the highest-value sectors in global aquaculture, driven by strong international demand and premium market prices (FAO 2022; Engle 2010). Indonesia is recognized as a major producer of spiny lobster (*Panulirus* spp.), with substantial potential to enhance value creation through grow-out aquaculture rather than continued reliance on capture-based supply chains (FAO 2022; Wahyudin et al. 2020). Consequently, lobster aquaculture has become increasingly important in national development strategies, particularly in supporting coastal livelihoods and export-oriented aquaculture expansion (KKP RI 2021; Bailey et al. 2016).

Despite this potential, achieving sustainability in lobster aquaculture remains a critical challenge. Intensive production practices can generate substantial short-term economic returns, yet they often impose increasing pressure on environmental capacity and biological performance over time (Boyd et al. 2020; Tlusty et al. 2019). These challenges arise from dynamic interactions among biological growth processes, economic incentives, environmental constraints, and regulatory interventions, which evolve simultaneously rather than independently (Clark 2010; Sterman 2000). Failure to account for these interactions may lead to unstable production systems, environmental degradation, and reduced long-term economic performance (Costanza et al. 1998; Barbier 2011).

Bioeconomic modeling provides a well-established theoretical framework for analysing renewable resource systems by linking biological dynamics with economic behaviour and resource use decisions (Clark 2010; Conrad and Clark 1987). Classical bioeconomic models have been widely applied in fisheries and aquaculture to examine optimal harvesting strategies and economic efficiency (Knowler 2002; Engle 2010). However, many conventional bioeconomic approaches rely on static equilibrium assumptions or short-term optimization frameworks, which may not adequately capture feedback mechanisms, time delays, and capital accumulation processes inherent in aquaculture systems (Martin et al. 2018; Filgueira et al. 2021).

System dynamics modeling offers a complementary approach capable of representing feedback loops, non-linear relationships, and long-term system behaviour in complex socio-ecological systems (Forrester 1961; Sterman 2000; Meadows 2008). In aquaculture research, system dynamics has been increasingly applied to analyse sustainability challenges, including resource constraints, production risks, and environmental impacts (Nguyen et al. 2018; Zhang et al. 2020). When integrated with bioeconomic principles, this approach enables simultaneous evaluation of biological production, economic performance, and environmental feedbacks within a unified analytical framework (Filgueira et al. 2021).

Despite these advances, the integrated application of bioeconomic and system dynamics approaches to lobster aquaculture remains limited, particularly in empirical contexts. Existing studies on lobster aquaculture in Indonesia have primarily focused on technical performance, site suitability, or economic feasibility at the farm level (Priyambodo 2018; Syahrir et al. 2024; Setyanto et al. 2021). Few studies explicitly model lobster aquaculture as a feedback-driven system that links production intensity, environmental dynamics, and economic outcomes over time. This limitation constrains the ability of existing analyses to evaluate sustainability trade-offs and to inform policy interventions in rapidly developing aquaculture systems.

To address this gap, this study develops a field-parameterised bioeconomic system dynamics model of lobster aquaculture in Indonesia using multi-regional empirical data collected between 2022 and 2025. The model integrates biological production, economic performance, environmental quality, and regulatory controls within a unified feedback-based framework. Rather than focusing on optimization, the model is designed to explore system behaviour and sustainability trade-offs under alternative management scenarios, consistent with policy-oriented modeling approaches in complex aquaculture systems (Sterman 2000; Filgueira et al. 2021).

The objectives of this study are to (1) analyse the dynamic behaviour of lobster aquaculture systems under current production practices, (2) evaluate the effects of sustainability-oriented management strategies, and (3) identify trade-offs between short-term economic gains and long-term ecological resilience. By explicitly incorporating environmental feedbacks and empirical production parameters, this study contributes a policy-relevant modeling framework to support sustainable aquaculture development in Indonesia and comparable tropical aquaculture systems.

To our knowledge, this is among the first studies to integrate field-derived empirical parameters with a bioeconomic system dynamics framework for lobster aquaculture at a multi-regional scale.

2. Materials and Methods

2.1 Study Area and Field Data Collection

This study was based on empirical field data collected from lobster aquaculture operations in Indonesia between 2022 and 2025 (Figure 1). Data were obtained from major lobster farming regions, including Java, Lombok, and Sulawesi, which represent diverse environmental conditions, farming systems, and institutional settings relevant to lobster aquaculture development in Indonesia (Priyambodo, 2018; Syahrir, 2024).

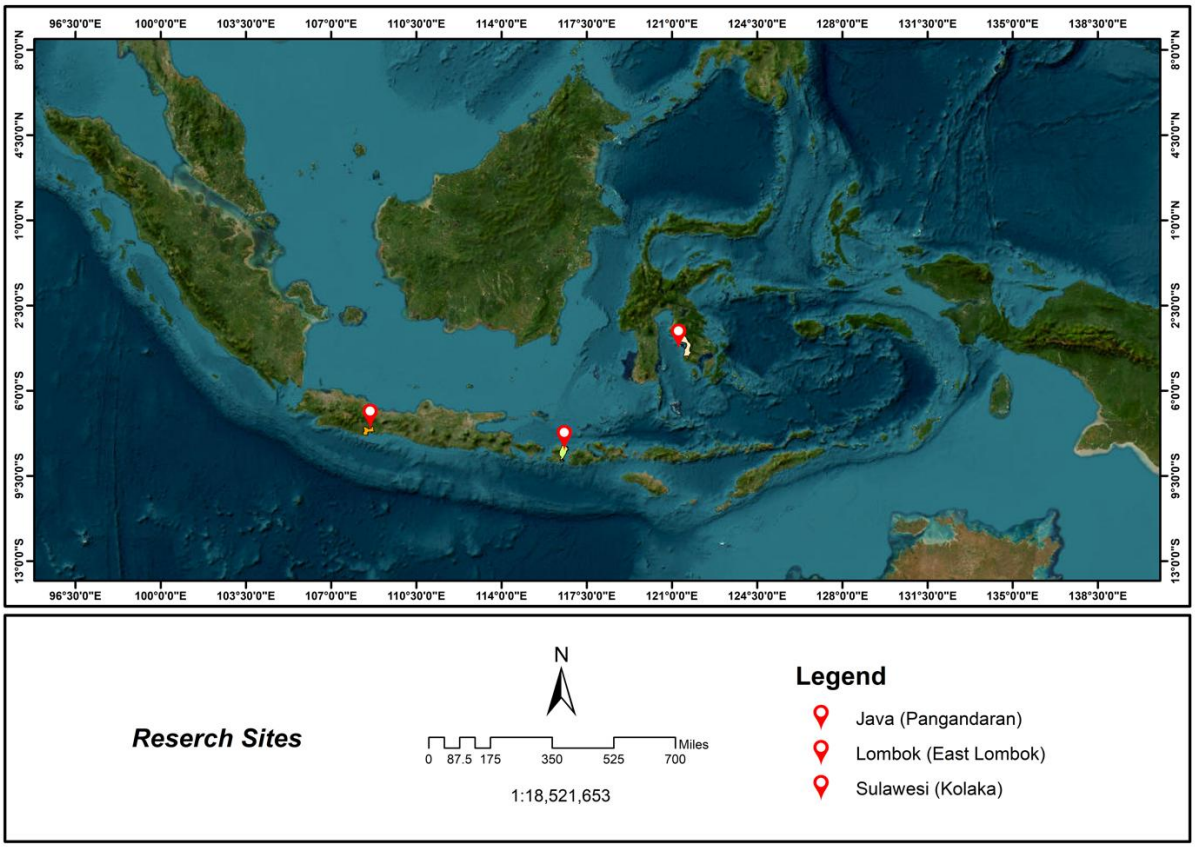


Figure 1. Map of study locations showing major lobster aquaculture regions in Indonesia, including Java, Lombok, and Sulawesi, where field data were collected between 2022 and 2025.

Field data collection was conducted through direct engagement with lobster farmers and local production units. The dataset comprises four main categories of variables. Biological data include stocking density, initial and harvest biomass, production cycle duration, survival rate, and mortality. Economic data cover seed cost, feed cost, labor expenditure, operational expenses, investment value, depreciation, and farm-level profit. Environmental data consist of water temperature, salinity, dissolved oxygen concentration, and qualitative indicators of environmental condition. Institutional and policy-related information includes access to lobster seed, minimum harvest size regulations, and spatial restrictions governing aquaculture activities.

All variables were standardized on a per-production-cycle basis to ensure comparability across farming systems and locations. Subsequently, the data were aggregated to represent average national conditions for modeling purposes. This aggregation approach is commonly applied in bioeconomic and system dynamics studies aimed at

supporting policy-oriented analysis, where the objective is to capture generalized system behavior rather than site-specific variability (Clark, 2010; Hilborn and Walters, 1992).

2.2 Data Standardization, Aggregation, and Quality Control

The unit of analysis in this study was the production cycle at the farm level. Field observations were obtained from multiple lobster farming operations across Lombok, Sulawesi, and Java between 2022 and 2025, encompassing several production cycles under different farming systems. Each observation represented a complete grow-out cycle, allowing consistent comparison of biological performance, cost structure, and production outcomes.

To ensure comparability, all biological and economic variables were standardized to a per-cycle basis. Production inputs and outputs were further normalized to reflect equivalent operational scales (e.g., per 1,000 juveniles stocked or per kilogram of harvested biomass) when necessary. Because the data were collected within a relatively short and recent time horizon characterized by stable macroeconomic conditions, monetary values were expressed in nominal Indonesian Rupiah without inflation adjustment, a practice commonly adopted in farm-level bioeconomic studies when interannual price variability is limited (Engle, 2010).

National-level parameters were derived using a structured aggregation procedure. First, farm-level observations were screened for completeness and internal consistency. Second, extreme values were evaluated against field notes and production logic; observations reflecting atypical operational failure rather than normal production variability were excluded to avoid biasing parameter estimates. Finally, arithmetic means were used to represent baseline national conditions, consistent with modeling approaches that aim to capture general system behavior rather than site-specific performance (Sterman, 2000; Martin et al., 2018).

Data quality assurance was implemented through iterative verification with farmers and cross-checking among biological, production, and financial records whenever available. Missing values were handled conservatively by relying only on validated observations, while parameters exhibiting moderate variability were represented in the simulation through sensitivity-aware baseline estimates rather than extreme bounds. This procedure enhances model transparency and supports reproducibility in policy-oriented system dynamics research (Forrester, 1961; Sterman, 2000).

Table 1 presents the standardized parameters used to initialize and calibrate the bioeconomic system dynamics model. Parameter values were derived from multi-regional lobster aquaculture field observations in Indonesia collected between 2022 and 2025 and subsequently standardized into consistent units for simulation.

Table 1. Standardized model parameters derived from multi-regional lobster aquaculture field data in Indonesia (2022–2025).

Parameter	Symbol	Unit (model)	Standardized value (baseline)	Used in model equation(s)	Role in Model	Source
Production cycle duration	T_cycle	year/cycle	0.33–0.42 (≈4–5 mo) or 0.83–1.0 (≈10–12 mo)	scenario timing	Defines production turnover and harvest timing	Primary field survey
Stocking input	I	individuals·year^{-1}	annualized from 70–300 individuals/cage/cycle*	dN/dt	Controls population inflow	Primary field survey
Initial individual weight	w_0	kg·individual^{-1}	0.015–0.030	B(t)=N(t)·ω(t) (initialization)	Defines starting biomass state	Primary field survey

Harvest individual weight (target)	w_h	kg·individual^{-1}	0.20–0.30 (sand lobster) ; >1.00 (ornate/pearl)	B(t)=N(t)·ω(t); H conversion	Determines harvestable biomass and harvest conversion	Primary field survey
Average individual weight used for conversion	ω	kg·individual^{-1}	0.25 (baseline conversion weight)**	dN/dt; B(t)	Converts biomass harvest to harvested individuals; links N→B	Field-derived (this study)
Survival rate	SR	– (fraction)	0.80–0.90	affects M and/or effective harvest	Determines effective production performance	Primary field survey
Mortality rate	m	– (fraction)	0.10–0.20	M term in dN/dt	Represents biological loss	Primary field survey
Harvest (biomass)	H	kg·year^{-1}	annualized from ≈200 kg/cycle*	dN/dt; π	Production output flow (biomass)	Field-derived (this study)
Market price	P	IDR·kg^{-1}	450,000	π = P·H − C	Revenue calculation	Primary field survey
Seed cost (BBL)	C_seed	IDR·individual^{-1}	8,500	C aggregation	Variable cost component	Policy document (Kepmen KP No. 24/2024)
Feed cost	C_feed	IDR·year^{-1}	annualized from 15,000,000 IDR/cycle*	C aggregation	Major operational cost driver	Primary field survey
Labor cost	C_lab	IDR·year^{-1}	30,000,000 (≈2,500,000/ month × 12)	C aggregation	Operating expenditure	Primary field survey
Health & maintenance cost	C_hm	IDR·year^{-1}	annualized from 3,000,000 IDR/cycle*	C aggregation	Supports survival and performance	Primary field survey
Other operational cost	C_ops	IDR·year^{-1}	annualized from 5,000,000 IDR/cycle*	C aggregation	Non-feed operating cost	Primary field survey
Total production cost	C	IDR·year^{-1}	annualized from ≈51,500,000 IDR/cycle*	π = P·H − C	Determines profit dynamics	Author synthesis (this study)
Revenue	R	IDR·year^{-1}	R = P·H (annualized)*	reporting	Gross economic return	Model-derived (this study)
Profit	π	IDR·year^{-1}	π = R − C (annualized)*	π = P·H − C	Economic performance indicator	Model-derived (this study)
Initial capital stock	K_0	IDR	20,000,000–80,000,000	K(t) initialization	Initializes capital stock	Primary field survey
Depreciation rate	δ	year^{-1}	0.20–0.33 (≈1/L, L=3–5 years)	$dK/dt = I_k - \delta K$	Capital outflow rate	Field-derived (this study)

Environmental quality (index)	E	– (0–E_max)	initialized at 1 (normalized)	dE/dt	Environmental state variable	Author-defined scaling
Max environmental quality	E_max	–	1 (normalized)	dE/dt = r(E_max−E) −αB	Upper bound of E	Author-defined scaling
Environmental recovery rate	r	$year^{-1}$	(to be calibrated / sensitivity)	dE/dt	Natural recovery process	Model assumption; sensitivity-tested
Environmental pressure coefficient	α	$index \cdot kg^{-1} \cdot year^{-1}$	(to be calibrated / sensitivity)	dE/dt	Environmental loading from biomass	Model assumption; sensitivity-tested

Footnote:
* Cycle-based values were annualized using:
X_year = X_cycle × (12 / T_cycle_months).
Where multiple cycle durations occur (4–5 vs 10–12 months), the conversion used the scenario-specific cycle length.
**ω was set to the baseline conversion weight (0.25 $kg \cdot individual^{-1}$) to translate biomass harvest into harvested individuals; scenario tests may vary ω within the observed harvest-weight range.
Species note**.** Values represent aggregated ranges across dominant cultured *Panulirus* spp. in Indonesia (including *P. homarus* and *P. ornatus*), reflecting multi-regional farming diversity.

Table 1 ensures traceability between field-derived evidence and the mathematical formulation by explicitly linking each standardized parameter to the corresponding model equations. To maintain dimensional consistency across subsystems, all flow variables were expressed on an annual basis prior to simulation, while cycle-level observations were converted using the observed production-cycle duration.

2.3 Modeling Framework

A bioeconomic system dynamics modeling approach was employed to analyze the sustainable lobster aquaculture business ecosystem. Bioeconomic modeling integrates biological processes with economic decision-making to assess renewable resource systems and management outcomes (Clark, 2010). System dynamics modeling complements this framework by explicitly representing stocks, flows, feedback loops, and time delays that govern system behavior over time (Forrester, 1961; Sterman, 2000).

In this study, system dynamics was used to capture the dynamic interactions among lobster population dynamics, harvestable biomass, economic performance, environmental quality, and regulatory intervention. The modeling process followed a two-stage structure: conceptualization using causal loop diagrams to identify feedback mechanisms, followed by formalization into a stock–flow structure suitable for simulation and scenario analysis (Sterman, 2000).

2.4 Model Structure

The system dynamics model was structured as an integrated bioeconomic–environmental stock–flow framework representing the lobster grow-out aquaculture system under baseline conditions (S0). The model consists of three tightly coupled subsystems: (1) biological production dynamics, (2) economic capital accumulation, and (3) environmental feedback regulation.

- ***Biological Subsystem***

The biological core of the model is represented by the stock N (lobster abundance), which accumulates through stocking inflow and decreases through harvest and mortality outflows.

Stocking is governed by an exogenous stocking rate reflecting field-based farming practices. Harvest is determined as a function of survival-adjusted biomass and grow-out duration, while mortality depends on the mortality rate derived from survival and grow-out time.

Survival is endogenously influenced by environmental quality, forming a feedback loop between ecological conditions and biological performance. Biomass production (Harvest Biomass) is calculated as a function of harvested individuals and average harvest weight, linking biological dynamics to economic revenue generation.

This structure captures delayed growth processes and density-independent mortality consistent with grow-out aquaculture systems (Clark, 2010; Engle, 2010).

- ***Economic Subsystem***

The economic subsystem is represented by the stock Capital, which accumulates through profit inflow. Profit is calculated as: Revenue − Operating Costs − Seed Cost.

Revenue is generated from harvested biomass multiplied by market price, while seed cost depends on stocking intensity and seed price per unit. Operating costs are treated as annualized expenditures per production unit.

Capital accumulation creates a reinforcing feedback loop: increased capital enables sustained production, influencing stocking decisions and overall system scale under baseline conditions.

- ***Environmental Subsystem***

The environmental subsystem is represented by the stock Environmental Quality (EQ), modeled as a dynamic balance between degradation and recovery processes.

Environmental degradation is driven by production pressure, which is a function of lobster abundance (N) relative to reference carrying conditions. Degradation occurs at rate α, while recovery occurs at rate r.

Environmental quality directly influences biological survival through a survival effectiveness parameter, creating a balancing ecological feedback loop. As production pressure increases, environmental quality declines, reducing survival and indirectly constraining harvest and capital growth.

These interactions are embedded within reinforcing and balancing feedback loops that jointly determine system behavior over time, as commonly represented in system dynamics models (Forrester, 1961; Sterman, 2000). The complete stock–flow representation of the model is shown in Figure 2.

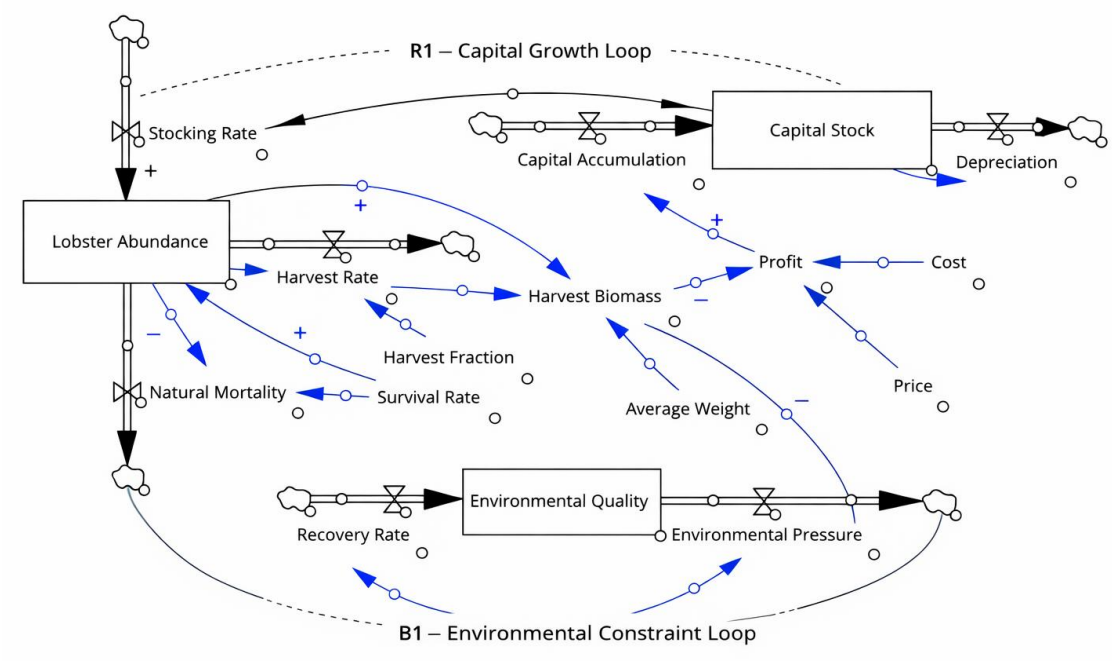


Figure 2. Stock–flow diagram of the bioeconomic system dynamics model of lobster aquaculture. The model integrates biological production (lobster stock and biomass), economic processes (revenue, cost, and capital accumulation), and environmental dynamics (environmental quality, degradation, and recovery) within a unified feedback structure. Reinforcing and balancing feedback loops regulate system behavior, while arrows indicate causal relationships and flow variables represent rates of change between stock variables.

Following this structural representation, the model is mathematically formalized using a system of differential equations to enable dynamic simulation and scenario analysis.

2.5 Mathematical Formulation

The five subsystems described in Section 2.4 are formalized mathematically using a set of ordinary differential equations (ODEs). This formulation enables dynamic simulation of lobster aquaculture system behavior under alternative management and policy scenarios, consistent with bioeconomic and system dynamics theory (Clark, 2010; Sterman, 2000).

The model is formulated in continuous time, where t denotes time measured in years. State variables include lobster abundance (N, individuals), harvestable biomass (B, kg), capital stock (K, IDR), and environmental quality (E, dimensionless index). Flow variables represent biological and economic processes such as stocking (I, individuals·year^{-1}), harvest (H, kg·year^{-1}), mortality (M, individuals·year^{-1}), and investment (I_k, IDR·year^{-1}). Economic parameters include market price (P, IDR·kg^{-1}) and total production cost (C, IDR·year^{-1}). The parameter ω denotes average individual weight (kg·individual^{-1}), δ represents the depreciation rate (year^{-1}), r is the environmental recovery rate (year^{-1}), E_max indicates the maximum attainable environmental quality, and α measures environmental pressure per unit biomass.

The governing equations of the model are summarized as follows:

- ***Biological Subsystem***

Lobster abundance (N) changes over time as a function of stocking input (I), harvest (H), and mortality (M):

$$\frac{dN}{dt} = I - \frac{H}{\omega} - mN \qquad (1)$$

The parameter ω was initialized using field-derived harvest weights and treated as a scenario-sensitive variable to capture differences in production strategies targeting either smaller, faster-growing lobsters or larger, high-value individuals. This equation represents the core population balance governing lobster availability in the production system, consistent with classical renewable resource modeling frameworks (Clark, 2010).

- ***Production Subsystem***

Harvestable biomass (B) is modeled as a function of lobster abundance and average individual weight (ω):

$$B(t) = N(t) \times \omega(t) \qquad (2)$$

This formulation links biological stock dynamics to production output, enabling translation of population changes into harvestable yield. Harvest flows are expressed in biomass units (kg·year^{-1}) to ensure consistency with economic revenue calculations.

- ***Economic Subsystem***

Economic profit (π) is defined as total revenue minus total production costs:

$$\pi = P \times H - C \qquad (3)$$

where P denotes the market price of lobster and C represents total production costs, including seed, feed, labor, operational expenses, and depreciation. This profit formulation is standard in bioeconomic analysis of aquaculture and fisheries systems (Clark, 2010).

Capital stock (K) evolves over time as a function of investment (I_k) and depreciation (δ):

$$\frac{dK}{dt} = I_k - \delta K \quad (4)$$

This equation captures capital accumulation dynamics and links economic performance to future production capacity, reflecting long-term investment behavior in aquaculture enterprises (Sterman, 2000).

- ***Environmental Subsystem***

Environmental quality (E) is modeled as a dynamic state variable influenced negatively by production intensity and positively by natural recovery processes:

$$\frac{dE}{dt} = r(E_{max} - E) - \alpha B \qquad (5)$$

where r represents the environmental recovery rate, E_{max} denotes the maximum attainable environmental quality, and α represents the environmental pressure exerted by biomass production. This formulation represents environmental quality as a dynamic balance between ecological recovery processes and biomass-induced environmental pressure, reflecting the limited assimilative capacity of coastal farming environments (Sterman, 2000; Barbier, 2011).

Environmental index anchoring and calibration. Environmental quality E was modeled as a normalized latent suitability index (0–1) representing farm-scale environmental conditions relevant to lobster growth and survival. The index was anchored to the observed field ranges of key water-quality indicators (temperature 29–31 °C, salinity 32–36 ppt, and dissolved oxygen 4.27–7.12 mg·L^{-1}), such that $E(t_0) = 1$ represents conditions within the empirically observed suitable ranges. Because the field dataset provides cycle-level observations rather than continuous time-series environmental monitoring, the recovery rate r and biomass-loading coefficient α were treated as calibrated/sensitivity-tested parameters. Baseline values were selected to reproduce plausible gradual environmental decline under intensified production, while the sustainability scenario assumes improved practices that increase effective recovery (higher r) and reduce per-biomass environmental loading (lower α), consistent with policy-exploratory system dynamics applications (Forrester, 1961; Sterman, 2000; Filgueira et al., 2021).

- ***Policy Subsystem***

Policy intervention is incorporated through regulatory parameters that influence stocking rates, harvest intensity, and allowable production levels. These parameters affect the biological and production subsystems indirectly by constraining decision variables rather than introducing additional state variables, consistent with policy-oriented system dynamics modeling practices (Sterman, 2000). Policy variables enter the model parametrically by modifying stocking and harvest rates.

2.6 Simulation and Scenario Design

The system dynamics model was implemented and simulated using Vensim® DSS software (Ventana Systems Inc.), a widely adopted platform for dynamic policy analysis and feedback-based modeling (Sterman, 2000). Simulations were conducted over a 10-year time horizon, which is sufficient to capture long-term capital accumulation, environmental feedbacks, and delayed policy effects typical of aquaculture systems.

The model was simulated in continuous time using a time step (Δt) of 0.125 years (1.5 months), selected to balance numerical stability and computational efficiency while preserving sensitivity to intra-annual production dynamics. Numerical integration was performed using the default fourth-order Runge–Kutta (RK4) method available in Vensim, which provides higher accuracy than first-order Euler approaches for nonlinear dynamic systems (Sterman, 2000).

Two primary scenarios were evaluated to explore policy trade-offs between economic performance and environmental sustainability:

1) Baseline scenario, representing current farming practices derived from aggregated field observations (2022–2025); and
2) Sustainability-oriented scenario, representing improved management through moderated stocking density, enhanced survival rates, and adaptive harvest controls.

Scenario outcomes were compared in terms of biomass stability, profit trajectories, capital growth, and environmental quality to identify potential leverage points for sustainable aquaculture policy.

Table 2. Numerical scenario assumptions used in system dynamics simulations (baseline: *P. homarus*, 4–5-month cycle).

Parameter	Symbol	Unit	Baseline (S0)	Sustainability (S1)	Implementation note
A. Core biological–production controls					
Cycle duration	T_{cycle}	months/cycle	4.5	4.5	Fixed to represent *P. homarus* grow-out
Survival rate	SR	fraction	0.80	0.90	Improved husbandry/ feed management
Stocked juveniles	I_{cycle}	individuals/cage/cycle	250	180	Moderated intensity within observed range

Stocking inflow (annualized)	I	individuals·year^{-1}	667	480	$I = I_{cycle} \times (\frac{12}{T_{cycle}})$
Harvest biomass	H_{cycle}	kg/cycle	200	180	Regulated harvest intensity (cap)
Harvest flow (annualized)	H	kg·year^{-1}	533	480	$H = H_{cycle} \times (\frac{12}{T_{cycle}})$
Mean harvest weight for conversion	ω	kg·individual^{-1}	0.25	0.25	Used in H/ω conversion (kept constant here)
Harvest cap (biomass)	H_{cap}	kg/cycle	200	180	Policy lever: harvest cannot exceed cap
B. Economic levers (cycle-based + annualized for reporting)					
Market price	P	IDR·kg^{-1}	450,000	450,000	Held constant (exogenous)
Feed cost	$C_{feed,cycle}$	IDR/cycle	15,000,000	12,000,000	Efficiency improvement (technology/learning)
Feed cost (annualized)	C_{feed}	IDR·year^{-1}	40,000,000	32,000,000	$C_{feed} = C_{feed,cycle} \times (12/T_{cycle})$
Seed (BBL) unit cost	C_{seed}	IDR·individual^{-1}	8,500	8,500	Kepmen KP No. 24/2024
Seed cost per cycle	$C_{seed,cycle}$	IDR/cycle	2,125,000	1,530,000	$C_{seed,cycle} = C_{seed} \times I_{cycle}$
Other operating costs*	$C_{other,cycle}$	IDR/cycle	11,000,000	10,000,000	Slight efficiency gain (ops/health/energy)
**Other operating costs aggregate non-feed variable costs (health/maintenance + other operational components). Labor is treated as annual and held constant unless you want it scenario-dependent.*					
C. Environmental subsystem parameters (explicit, reproducible, sensitivity-tested)					
Environmental quality (initial)	$E(t_0)$	index (0–1)	1.00	1.00	Normalized initial condition
Maximum environmental quality	E_{max}	index	1.00	1.00	Normalized upper bound
Recovery rate	r	year^{-1}	0.60	0.80	Faster recovery under better practices
Pressure coefficient	α	index·kg^{-1}·year^{-1}	0.0012	0.0008	Lower loading per biomass in sustainability

All cycle-based quantities were annualized using $X_{year} = X_{cycle} \times (\frac{12}{T_{cycle}})$, with $T_{cycle} = 4.5$ months for the baseline (*P. homarus*) representation. Scenario S1 modifies only the parameters listed in Table 2; all other parameters are held constant at baseline calibration values.

2.7 Model Validation

Model validation was conducted following established system dynamics protocols, including structural verification, dimensional consistency testing, behavioral validation, and sensitivity analysis (Forrester, 1961; Sterman, 2000). Structural validation involved evaluating the causal logic and feedback structure to ensure consistency with bioeconomic theory and empirical aquaculture processes. Dimensional consistency was verified using the automated units-check function in Vensim, with all equations passing the dimensional balance test. Behavioral validation was performed by comparing simulated trajectories of lobster abundance, harvest biomass, and profit with observed production ranges from field data collected between 2022 and 2025. The model

successfully reproduced realistic growth patterns and economic magnitudes without generating implausible oscillations or system collapse under baseline conditions.

Sensitivity analysis was conducted on key leverage parameters, including survival rate, market price, and feed cost, to evaluate model robustness under uncertainty. Simulation results remained directionally consistent across plausible parameter ranges, indicating that the model structure is stable and suitable for policy exploration rather than point prediction. Together, these validation procedures enhance confidence that the model captures the essential dynamics of the lobster aquaculture business ecosystem while maintaining analytical reliability for scenario analysis. The model is therefore intended as an exploratory decision-support tool rather than a deterministic forecasting instrument.

3. Results

3.1 Empirical System Characteristics of Lobster Aquaculture in Indonesia

Field data collected across major lobster-producing regions in Indonesia (Figure 1) between 2022 and 2025 reveal a production system characterized by strong economic potential alongside emerging biological and environmental constraints. Standardized parameters derived from multi-regional observations (Table 1) indicate that lobster aquaculture operates within a relatively high-survival production regime, with survival rates ranging from 80–90% per cycle. These survival rates indicate that improvements in husbandry practices and feed management have contributed to relatively stable biological performance in Indonesian lobster farming systems (Boyd et al. 2020; FAO 2022; Effendi et al. 2025).

Production cycles vary depending on species and target harvest size. Sand lobster (*Panulirus homarus*) typically reaches marketable size within 4–5 months, whereas spiny lobster such as *Panulirus ornatus* may require 10–12 months to achieve premium export weight. This difference has important implications for capital turnover and production risk across production strategies (Engle, 2010; Clark, 2010). Shorter production cycles enable faster capital turnover, whereas longer cycles offer higher per-unit market value.

From an economic perspective, lobster aquaculture demonstrates strong profitability under current market conditions. Average production yields of approximately 200 kg per cycle generate revenues near IDR 90 million, resulting in estimated profits of about IDR 38.5 million per production cycle. Feed costs constitute the largest operational expenditure, highlighting their critical role as a leverage point in farm-level profitability. This finding is consistent with cost structures commonly reported for high-value aquaculture enterprises (Engle 2010; Filgueira et al. 2021).

Capital investment requirements remain moderate relative to other high-value aquaculture sectors. Initial infrastructure investments range between IDR 20–80 million, with technical lifespans of 3–5 years. These cost structures suggest that lobster farming remains accessible to small and medium-scale producers, reinforcing its importance for coastal livelihood development.

Environmental observations indicate generally favorable farming conditions across study locations. Water temperatures between 29–31 °C, salinity levels of 32–36 ppt, and dissolved oxygen concentrations exceeding 4 mg/L fall within biologically suitable ranges for tropical spiny lobster cultivation. However, the model parameters also incorporate environmental pressure generated by biomass accumulation, reflecting the limited assimilative capacity of coastal ecosystems.

Institutional factors further shape system dynamics. Access to lobster seed remains regulated, minimum harvest size rules are enforced, and spatial controls govern aquaculture expansion. These regulatory mechanisms function as external constraints that indirectly influence stocking and harvest decisions, thereby moderating production intensity. This reflects the role of governance in shaping aquaculture expansion and compliance incentives (Bailey et al. 2016; FAO 2022).

Taken together, these empirical characteristics depict Indonesian lobster aquaculture as a profit-driven yet regulation-dependent system operating within identifiable ecological limits. Such conditions underscore the importance of adopting an integrated modeling framework capable of capturing feedback interactions among biological growth, capital accumulation, environmental pressure, and policy intervention. Accordingly, the standardized field parameters summarized in Table 1 form the empirical foundation for the dynamic simulations presented in the following sections.

3.2 Baseline System Dynamics (S0)

The baseline scenario (S0) represents current lobster aquaculture practices under a typical 4–5-month production cycle (Panulirus homarus), using parameter values derived from field observations (Table 1) and standardized simulation assumptions (Table 2).

Simulation results reveal a characteristic bioeconomic adjustment process driven by interactions among biological growth, economic incentives, and environmental feedbacks.

At the beginning of the simulation period, harvest biomass increases rapidly due to high stocking input and favorable initial environmental conditions. This early growth phase reflects production expansion under relatively low ecological constraints. As biomass accumulates, production pressure on the environment intensifies through increased resource use and ecological disturbance.

Consequently, environmental quality declines progressively from its initial optimal condition ($E \approx 1$) and stabilizes at a lower equilibrium level. This decline reflects the cumulative effect of production pressure exceeding natural recovery capacity, although not leading to system collapse under baseline conditions.

The reduction in environmental quality introduces a feedback mechanism that moderates system performance. Survival rates decline slightly as environmental conditions deteriorate, increasing effective mortality and limiting further expansion of biomass. As a result, harvest biomass gradually stabilizes at a steady-state level, indicating that the system reaches its ecological carrying capacity under current practices.

Economic dynamics follow a similar adjustment pattern. Profit increases rapidly during the initial phase as biomass production expands and revenue rises. However, as environmental quality declines and biological performance becomes constrained, profit growth slows and eventually stabilizes. This indicates diminishing marginal returns under environmental limitations.

Capital accumulation reflects the long-term economic trajectory of the system. As profit is partially reinvested, capital stock increases over time, supporting continued production capacity. However, the stabilization of profit under environmental constraints also leads to a gradual leveling of capital growth, indicating that long-term expansion is limited by ecological feedbacks rather than financial constraints alone.

Overall, the baseline simulation demonstrates a self-regulating system in which biological growth, economic incentives, and environmental feedbacks interact to produce a dynamic equilibrium. While current practices remain economically viable, the observed decline in environmental quality indicates underlying sustainability risks if production intensity increases beyond current levels.

These dynamic patterns are illustrated in Figure 3, which shows the temporal trajectories of harvest biomass, profit, and environmental quality under baseline conditions.

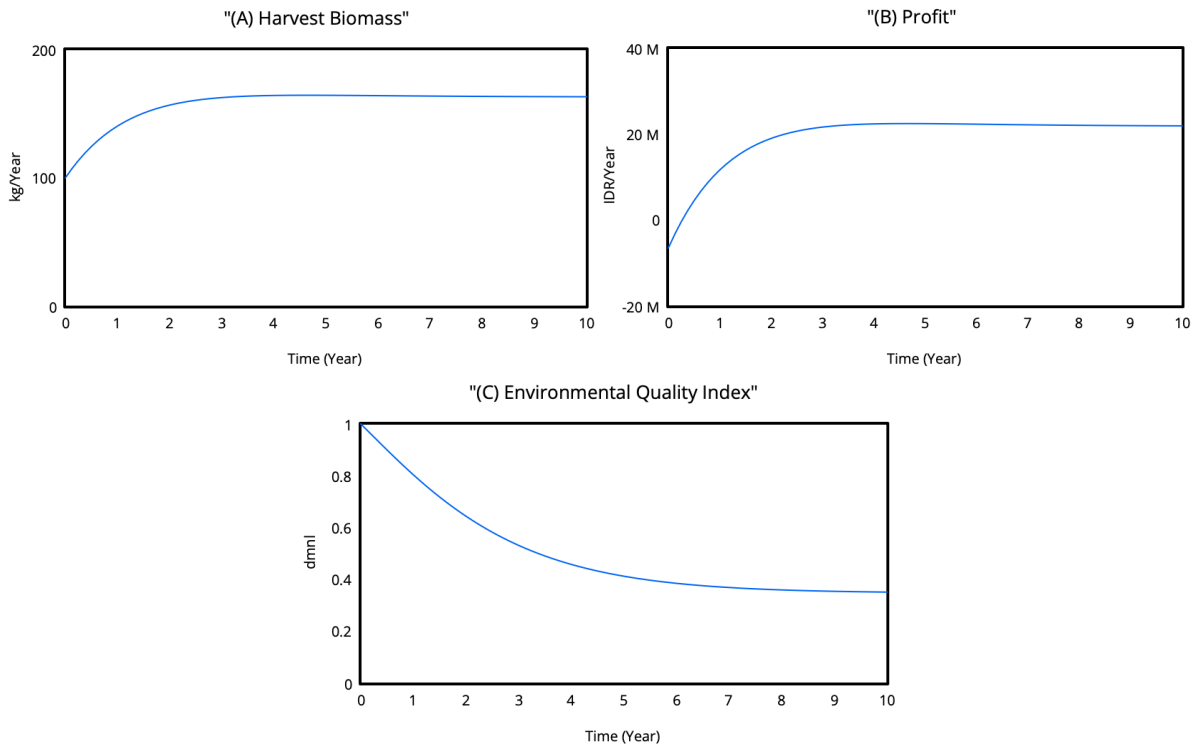


Figure 3. Simulated trajectories of harvest biomass, profit, and environmental quality under baseline production conditions (S0) over a 10-year simulation period.

These baseline dynamics provide a reference point for evaluating the impact of sustainability-oriented management interventions, which are explored in the following section.

3.3 Sustainability-Oriented Scenario (S1)

The sustainability-oriented scenario (S1) represents an improved management strategy designed to balance economic performance with environmental conservation. This scenario incorporates moderated stocking intensity, enhanced survival rates, reduced environmental pressure, and improved environmental recovery capacity, as specified in Table 2.

Simulation results indicate that the sustainability scenario produces a more balanced system trajectory compared to the baseline. Harvest biomass initially increases at a slower rate than in the baseline scenario due to reduced stocking intensity and controlled harvest levels. However, biomass stabilizes at a relatively high and stable level over time, indicating improved system resilience under moderated production pressure.

Environmental dynamics show a substantial improvement relative to the baseline scenario. Environmental quality declines more gradually and stabilizes at a significantly higher equilibrium level. This reflects the combined effect of reduced environmental loading per unit biomass (lower α) and enhanced recovery capacity (higher r), which together strengthen the system's ecological resilience.

Economic performance under the sustainability scenario follows a slightly different trajectory. Profit growth is slower during the initial phase due to reduced production intensity and lower short-term output. However, as environmental conditions remain more favorable, biological performance is sustained over time, resulting in stable and competitive long-term profitability. This demonstrates that sustainability-oriented management can mitigate the trade-off between economic returns and environmental conservation.

Capital accumulation under this scenario reflects steady and sustainable growth. Although initial capital expansion is slower compared to the baseline, the long-term trajectory is more stable due to reduced environmental constraints and consistent profitability.

Overall, the sustainability scenario demonstrates that improved environmental management and moderated production intensity can enhance long-term system stability without significantly compromising economic performance. These results highlight the importance of balancing reinforcing economic growth with ecological feedback mechanisms to achieve sustainable aquaculture development.

A direct comparison between baseline and sustainability scenarios is presented in Figure 4 to highlight differences in system trajectories and trade-offs between economic performance and environmental sustainability.

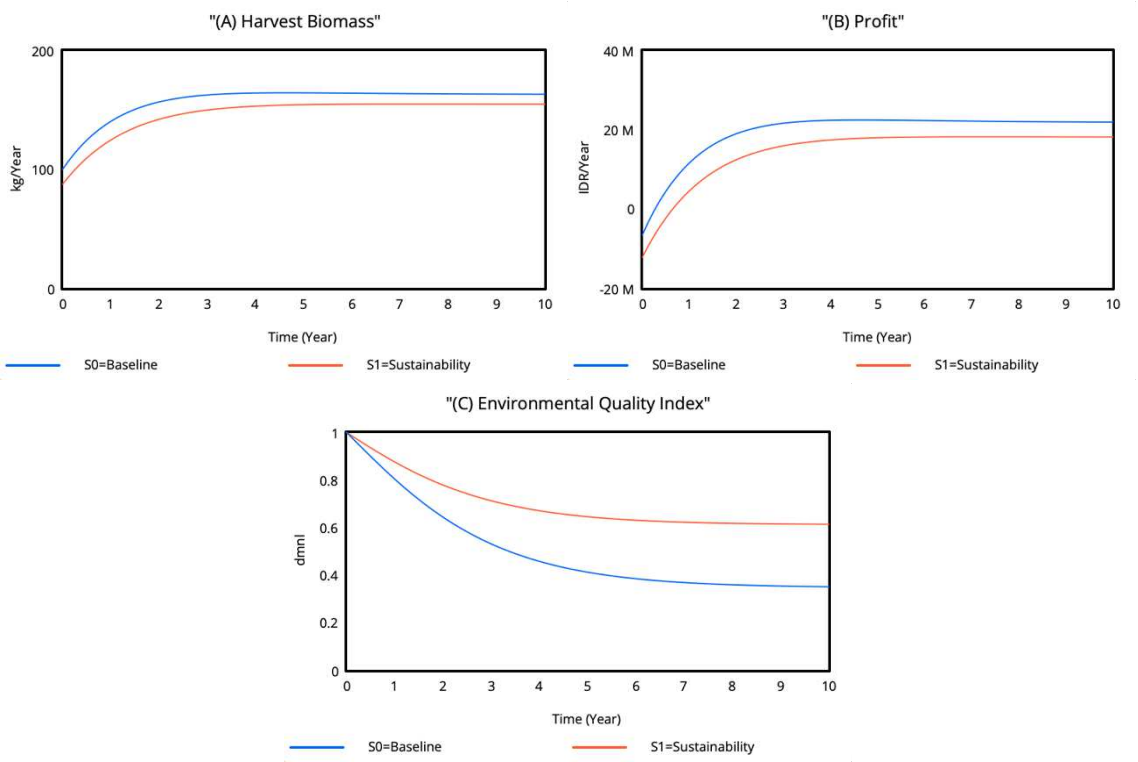
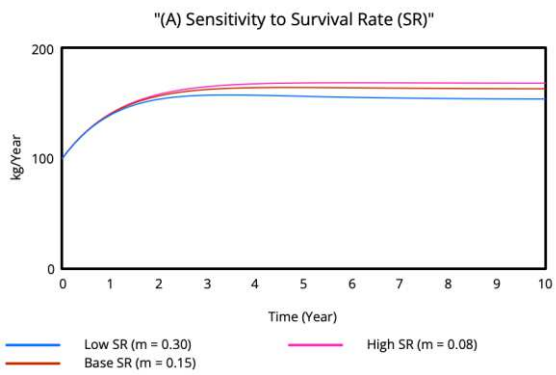


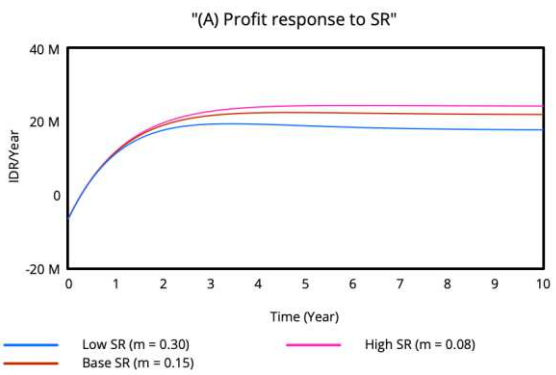
Figure 4. Comparison of system dynamics under baseline (S0) and sustainability-oriented (S1) scenarios over a 10-year simulation period. The sustainability scenario produces more stable environmental conditions and long-term system performance, although with slightly lower short-term biomass and profit compared to the baseline.

Figure 4 clearly illustrates the divergence between economic performance and environmental outcomes under alternative management strategies. These findings reinforce the importance of integrating economic incentives with ecological constraints in aquaculture management strategies.

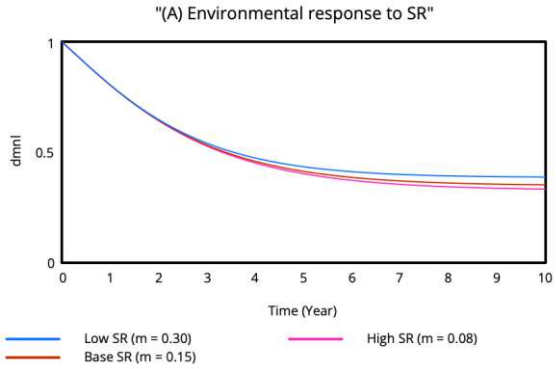
3.4 Sensitivity Analysis

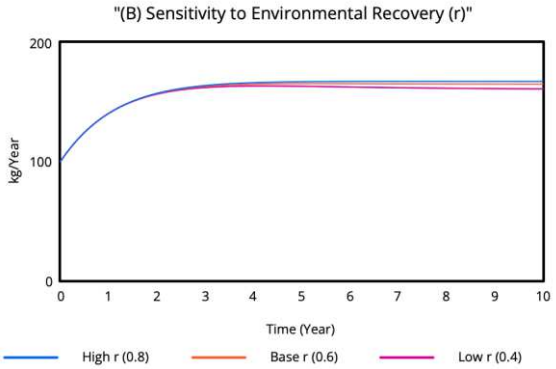
Sensitivity analysis was conducted to evaluate the robustness of the model under uncertainty in key leverage parameters, namely survival rate (SR), environmental recovery rate (r), and environmental pressure coefficient (α). These parameters were selected due to their central role in linking biological performance, environmental feedback, and production intensity within the bioeconomic system. The results of the sensitivity analysis are presented in Figure 5.


"(A) Sensitivity to Survival Rate (SR)"
kg/Year
200
100
0
0 1 2 3 4 5 6 7 8 9 10
Time (Year)
Low SR (m = 0.30)
Base SR (m = 0.15)
High SR (m = 0.08)

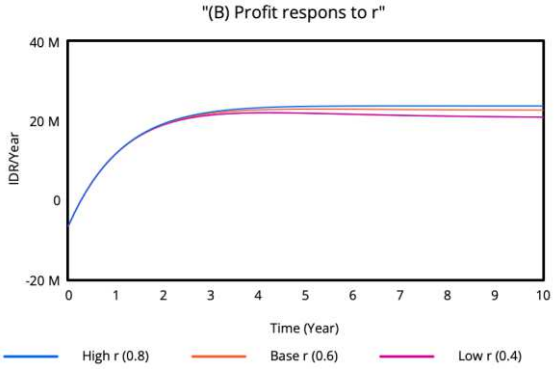

"(A) Profit response to SR"
IDR/Year
40 M
20 M
0
-20 M
0 1 2 3 4 5 6 7 8 9 10
Time (Year)
Low SR (m = 0.30)
Base SR (m = 0.15)
High SR (m = 0.08)

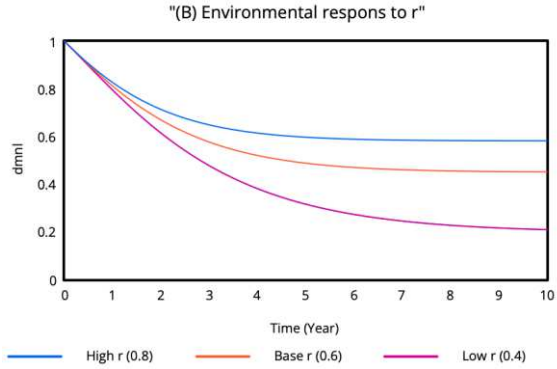
423


"(A) Environmental response to SR"
dmnl
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10
Time (Year)
Low SR (m = 0.30)
Base SR (m = 0.15)
High SR (m = 0.08)


"(B) Sensitivity to Environmental Recovery (r)"
kg/Year
200
100
0
0 1 2 3 4 5 6 7 8 9 10
Time (Year)
High r (0.8)
Base r (0.6)
Low r (0.4)

424


"(B) Profit respons to r"
IDR/Year
40 M
20 M
0
-20 M
0 1 2 3 4 5 6 7 8 9 10
Time (Year)
High r (0.8)
Base r (0.6)
Low r (0.4)


"(B) Environmental respons to r"
dmnl
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
Time (Year)
High r (0.8)
Base r (0.6)
Low r (0.4)

425

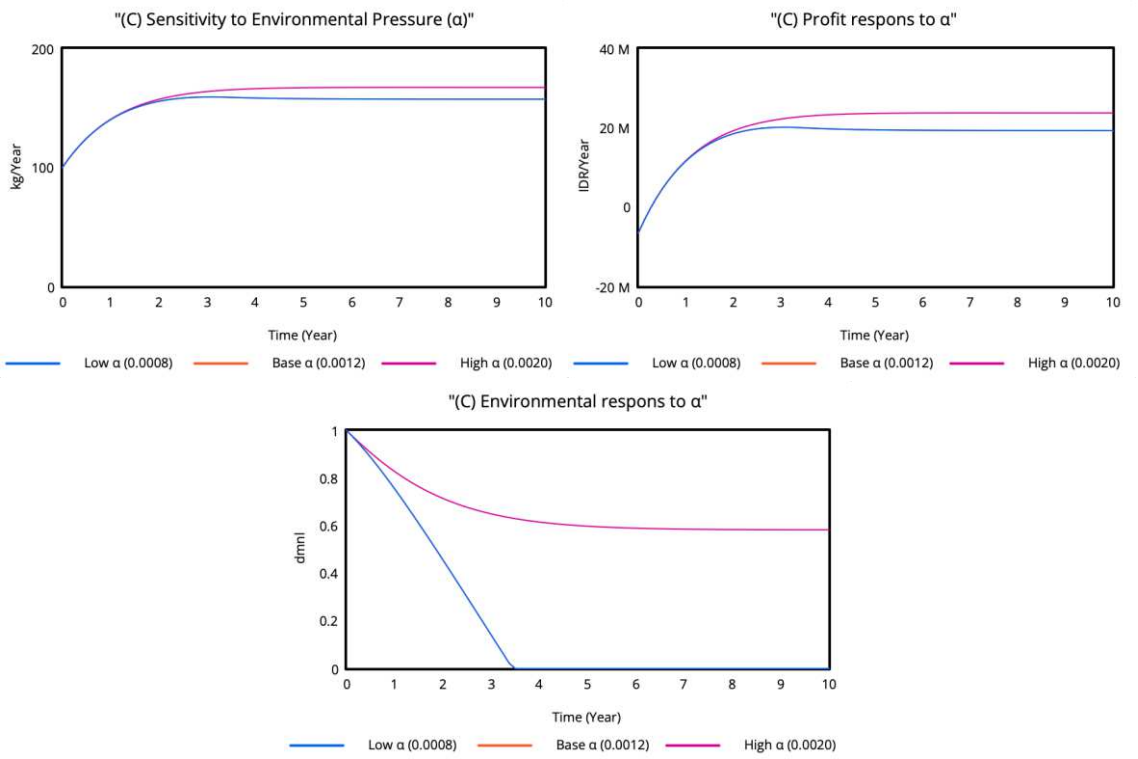


Figure 5. Sensitivity analysis of key model parameters illustrating system response to variations in (A) survival rate (SR), (B) environmental recovery rate (r), and (C) environmental pressure coefficient (α). The results demonstrate consistent system behavior and confirm the robustness of the model structure under parameter uncertainty.

As shown in Figure 5A, variations in survival performance (SR) primarily influence biomass accumulation and economic outcomes. Higher survival rates lead to increased harvest biomass and higher profit trajectories due to improved biological efficiency. In contrast, lower survival rates reduce production output and slow capital accumulation, indicating the strong dependence of system productivity on biological performance.

Figure 5B demonstrates the dominant role of the environmental recovery rate (r) in shaping long-term environmental dynamics. Higher recovery rates significantly improve environmental quality and allow the system to maintain a higher equilibrium level over time. This enhanced environmental condition also supports more stable biomass and profit trajectories. Conversely, lower recovery rates accelerate environmental degradation and constrain long-term system sustainability.

Figure 5C highlights the critical influence of the environmental pressure coefficient (α) on the trade-off between production intensity and environmental sustainability. Higher α values intensify environmental degradation as biomass increases, resulting in a lower equilibrium environmental quality and indirectly limiting long-term production performance. In contrast, lower α values reduce environmental loading per unit biomass, enabling the system to sustain higher environmental quality and more stable overall dynamics.

Overall, the sensitivity analysis confirms that while parameter variations affect the magnitude of system outcomes, the fundamental system behavior and policy-relevant trade-offs remain consistent. This indicates that the model is structurally robust and suitable for exploratory policy analysis rather than deterministic prediction, consistent with established system dynamics principles (Sterman, 2000). All results are presented under baseline scenario conditions unless otherwise specified.

4. Discussion

This study demonstrates that lobster aquaculture systems in Indonesia are governed by tightly coupled interactions among biological production, economic incentives, and environmental feedbacks, resulting in dynamic trade-offs between short-term profitability and long-term sustainability. The simulation results highlight that while baseline production practices can sustain relatively high economic returns in the short term, they also generate cumulative environmental pressures that gradually constrain biological performance and system stability over time.

These findings are consistent with previous studies emphasizing that aquaculture intensification often leads to declining environmental quality and increased ecological risks if not properly managed (Boyd et al. 2020; Tlusty et al. 2019). Similar dynamics have been reported in broader aquaculture systems, where increased production intensity can exceed local environmental carrying capacity, leading to reduced survival rates and diminished long-term productivity (Filgueira et al. 2021). The results of this study extend these insights by explicitly demonstrating how such environmental constraints emerge endogenously through feedback mechanisms linking biomass accumulation and environmental quality.

From a bioeconomic perspective, the results highlight the importance of incorporating environmental feedbacks into the evaluation of aquaculture performance. Classical bioeconomic models typically emphasize optimal harvesting and economic efficiency under simplified ecological assumptions (Clark 2010; Conrad and Clark 1987). However, the present findings suggest that ignoring environmental dynamics may lead to overestimation of long-term economic benefits. By integrating environmental quality as a dynamic state variable, this study shows that economic performance is not only a function of production intensity but also of the system's ecological resilience. This reinforces the argument that sustainable aquaculture management requires moving beyond static optimization toward dynamic, feedback-aware analytical frameworks (Martin et al. 2018; Filgueira et al. 2021).

The sustainability-oriented scenario further demonstrates that moderating production intensity and improving environmental recovery processes can significantly enhance long-term system performance. Although this strategy results in slightly lower short-term production and profit, it produces more stable biomass trajectories, higher environmental quality, and sustained economic returns over time. This finding aligns with the concept of ecological–economic trade-offs in renewable resource systems, where maximizing short-term output may compromise long-term system viability (Costanza et al. 1998; Barbier 2011). In this context, the results provide empirical support for management strategies that prioritize system resilience over immediate economic gains.

Importantly, the model results suggest that relatively modest adjustments in key management parameters—such as stocking density, survival performance, and environmental recovery capacity—can generate substantial improvements in system outcomes. This highlights the role of management efficiency and adaptive practices in enhancing sustainability without requiring drastic reductions in production. Similar findings have been reported in aquaculture systems where improved husbandry, feed efficiency, and environmental management practices contribute to both economic and ecological performance (Engle 2010; Nguyen et al. 2018).

From a policy perspective, the findings underscore the critical role of regulatory frameworks in shaping sustainable aquaculture development. In Indonesia, policies governing lobster seed utilization, harvest size limits, and spatial planning play an important role in moderating production intensity and preventing overexploitation (KKP RI 2020; Bailey et al. 2016). The model demonstrates that such regulatory mechanisms can be interpreted as leverage points within the system, influencing both biological and economic dynamics indirectly. Strengthening these regulatory instruments, combined with incentives for environmentally responsible farming practices, could enhance long-term sustainability outcomes.

This study contributes to the aquaculture literature by providing an integrated bioeconomic system dynamics framework that explicitly captures feedback-driven interactions among production, environment, and economic performance. Unlike conventional bioeconomic models that focus on optimal control solutions, the present approach emphasizes system behaviour and policy-relevant trade-offs under realistic production conditions. This makes the model particularly suitable as a decision-support tool for exploring alternative management scenarios in data-constrained and complex aquaculture systems.

Nevertheless, several limitations should be acknowledged. First, the model relies on aggregated field data, which may mask site-specific variability in environmental conditions and farming practices. Second, economic

behaviour is represented through scenario-based parameters rather than explicit optimization or decision-making functions. While this approach is appropriate for policy exploration, future research could extend the model by incorporating endogenous decision-making and market dynamics. Third, environmental processes are represented through a simplified index-based formulation, which, although suitable for capturing general system behaviour, may not fully reflect detailed biophysical processes.

Future research should focus on integrating spatial heterogeneity, market dynamics, and farmer decision behaviour into bioeconomic system dynamics models to further enhance their analytical power and policy relevance. Additionally, empirical validation using long-term time-series data would strengthen model robustness and improve its applicability for operational decision-making.

5. Conclusions

This study develops a field-parameterised bioeconomic system dynamics model to evaluate sustainability dynamics in lobster aquaculture systems in Indonesia. By integrating biological production, economic performance, and environmental feedbacks within a unified framework, the model provides a comprehensive representation of aquaculture systems as dynamic socio-ecological processes.

The results demonstrate that current production practices can generate substantial short-term economic benefits but are associated with gradual environmental degradation that constrains long-term system performance. In contrast, sustainability-oriented management strategies—characterised by moderated stocking intensity, improved survival performance, and enhanced environmental recovery—can produce more stable biomass trajectories, maintain higher environmental quality, and support sustained economic returns over time. These findings highlight the critical role of environmental feedbacks in shaping long-term aquaculture outcomes and underscore the importance of balancing production intensity with ecological capacity.

From a practical perspective, the study shows that relatively moderate adjustments in key management parameters can yield significant improvements in both economic and environmental performance. This suggests that sustainable lobster aquaculture does not necessarily require reduced profitability but rather improved management efficiency and adaptive production strategies.

From a policy standpoint, the results emphasize the importance of regulatory frameworks that control stocking intensity, enforce harvest standards, and support environmentally responsible aquaculture practices. Strengthening these policy instruments, alongside farmer-level adoption of improved management practices, is essential for ensuring the long-term sustainability of lobster aquaculture in Indonesia.

Methodologically, this study contributes an integrated bioeconomic system dynamics approach that complements conventional optimization-based bioeconomic models by explicitly capturing feedback mechanisms and long-term system behaviour. As such, the model provides a useful decision-support tool for exploring sustainability trade-offs in complex and data-constrained aquaculture systems.

Overall, this study highlights that achieving sustainable lobster aquaculture requires a systemic approach that simultaneously considers ecological resilience, economic viability, and governance mechanisms. The framework developed in this study offers a foundation for future research and policy development aimed at supporting sustainable aquaculture in Indonesia and other tropical regions.

Acknowledgements

This research was supported by the Higher Education Financing and Assessment Services Center (PPAPT), the Indonesian Education Endowment Fund (LPDP Indonesia) through the Indonesian Education Scholarship (BPI) program of the Ministry of Higher Education, Science, and Technology (Kemdiktisaintek RI). The authors also acknowledge the support of the Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, PT. Kolaka Lobster Indonesia (PT. KOLSTERA), and Universitas Sembilanbelas November Kolaka in facilitating this research.

Declarations

- Funding

This research was supported by the Indonesian Education Endowment Fund (LPDP Indonesia) and the Higher Education Financing and Assessment Services Center (PPAPT) through the Indonesian Education Scholarship (BPI) program.

- Conflict of interest

The authors declare no conflict of interest.

- Author contributions

Conceptualization: Syahrir; Methodology: Syahrir et al.; Analysis: Syahrir; Writing: Syahrir; Review & editing: All authors.

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