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Stochastic Hybrid Bioeconomic Modeling of Daily Profit Volatility in Moroccan Sardine Fisheries: A Markov-Switching Approach

Khalid Outaaoui[1*] and Youssef EL Foutayeni[1]

[1] *Laboratory of Mathematics, Modeling and Automatic Systems,, Cadi Ayyad University, Marrakech, Morocco*
[*] *Corresponding author*

Abstract

This study introduces a stochastic hybrid bioeconomic framework designed to quantify daily profit variability in the Moroccan sardine (*Sardina pilchardus*) fishery, a vital sector for the Atlantic coast regional of Agadir economy. Moving beyond static annual averages, the model couples a continuous-time logistic growth process with a discrete-time Markov Chain to simulate regime-switching environmental states. We define three operational weather regimes—Good (G), Medium (M), and Bad (B)—parameterized via seasonal transition matrices derived from longitudinal meteorological data (2018–2025). Our deterministic analysis identifies an optimal Maximum Economic Yield (MEY) effort of 96.67 vessels, maintaining a conservation biomass buffer of 2.58×10^6 tons and generating a baseline annual profit of 8.41M MAD. Systematic sensitivity analysis reveals that the fishery is biologically anchored, with economic rent being highly sensitive to carrying capacity (K) and growth rates (r), yet resilient to operational cost shocks. Stochastic simulations at a daily resolution demonstrate that seasonal weather patterns significantly dictate financial risk: Spring and Summer provide high stability and maximum liquidity, while Winter regimes introduce significant volatility, reducing catchability by up to 90% during adverse storm fronts. By integrating environmental stochasticity directly into the profit function, this research provides a robust decision-support tool for adaptive fisheries management, ensuring that Morocco's Blue Economy strategies are grounded in both ecological sustainability and high-frequency operational reality. **Keywords:** Bioeconomic Modeling, Markov Chain Simulation, Sardina pilchardus, Weather-Adjusted Profit, Economic Impact, Fisheries Management.
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INTRODUCTION

The sustainable management of marine resources is a cornerstone of Morocco's national economy and food security strategy, particularly along the Atlantic coast where small pelagic stocks represent over 80% of national landings [7, 6]. Among these, the sardine (*Sardina pilchardus*) fishery is the most significant, providing essential livelihoods for the Agadir region and supporting a robust canning and export industry [9, 4]. However, these stocks are increasingly vulnerable to a dual pressure: the economic drive for profit maximization and the high stochasticity of the Atlantic upwelling ecosystem [13, 5].

Classical bioeconomic modeling, rooted in the foundational works of Gordon [20], Verhulst [21], and Clark [17, 11], has traditionally focused on long-run deterministic equilibria such as Maximum Sustainable Yield (MSY) and Maximum Economic Yield (MEY). While these models provide essential benchmarks for fleet capacity and stock conservation [18, 16], they often overlook the operational noise inherent in daily fishing activities. In the Agadir sardine fishery, environmental factors—primarily wind speed and sea state—dictate whether a vessel can safely leave the port or effectively deploy gear [8, 2]. These environmental constraints do not act as constant suppressors but rather as regime-switching states that govern the catchability and profitability of the fleet [5, 14].

Recent advances in mathematical biology have emphasized the use of hybrid systems to bridge the gap between continuous population dynamics and discrete environmental events. Markovian Jump Systems (MJS) have emerged as a powerful tool for modeling such transitions, offering a rigorous framework for stability analysis in biological networks subject to abrupt changes [10]. In the context of fisheries, this allows for the modeling of biomass growth via continuous differential equations while simultaneously switching between discrete weather regimes that affect economic variables [19, 10]. Despite their potential, few studies have integrated season-specific Markov transitions with MEY-based management to analyze daily profit variability in the Moroccan context.

This study addresses this gap by developing a Stochastic Hybrid Bioeconomic Model for the Agadir sardine fishery. We move beyond static averages by discretizing the year into seasonal Markov transition matrices derived from historical meteorological data [1, 2]. These matrices simulate transitions between three operational states: *Good (G)*, *Medium (M)*, and *Bad (B)*, which endogenously adjust the catchability coefficient and operational costs. By coupling these transitions with a logistic growth process, we estimate not

only the expected annual profit but also the daily variance and risk profiles across different price scenarios [12, 15].

The primary contribution of this work lies in its ability to quantify the economic buffer provided by MEY management under environmental uncertainty. Our results demonstrate that biological vitality (r, K) serves as the strongest anchor for economic resilience, while price premiums can absorb significant weather-induced operational shocks. By providing a high-resolution analysis of seasonal volatility, this study offers an adaptive decision-support tool for fisheries managers seeking to balance industrial efficiency with ecosystem health in an increasingly unpredictable climate.

The paper is organized as follows: Section 1 details the biological and geographic characteristics of the Agadir sardine fishery. Section 2 establishes the baseline deterministic bioeconomic framework and performs a systematic sensitivity analysis of key parameters. Section 3 introduces the stochastic hybrid model and the Markovian transition framework. Finally, Section 4 presents the simulation results, seasonal risk analysis, and policy implications.

1. GEOGRAPHIC RANGE AND ECOLOGICAL IMPORTANCE OF SARDINA WITH EMPHASIS ON BIOECONOMIC MODELING IN MOROCCO

Sardina pilchardus, plays a central role in pelagic fisheries, especially in Morocco, where it constitutes over 70% of small pelagic catches. Despite its modest commercial value, it is heavily targeted for human consumption and fishmeal, primarily using purse seines, lampara nets, and drift nets. The species is vulnerable to overexploitation due to intensive harvesting of juvenile schools (13–16 cm) and fluctuating recruitment levels, leading to stock instability and increased mortality rates. Most catches occur in shallow coastal waters (50–70 m), where environmental variability further compounds population pressures [9]. The species is found across a wide geographic range, including areas in the Atlantic Ocean, Mediterranean Sea, and the Black Sea. Sardina pilchardus is native to several countries, including Morocco, and is considered a crucial component of pelagic fisheries in the region. Sardina pilchardus has a broad geographic distribution across the following regions:

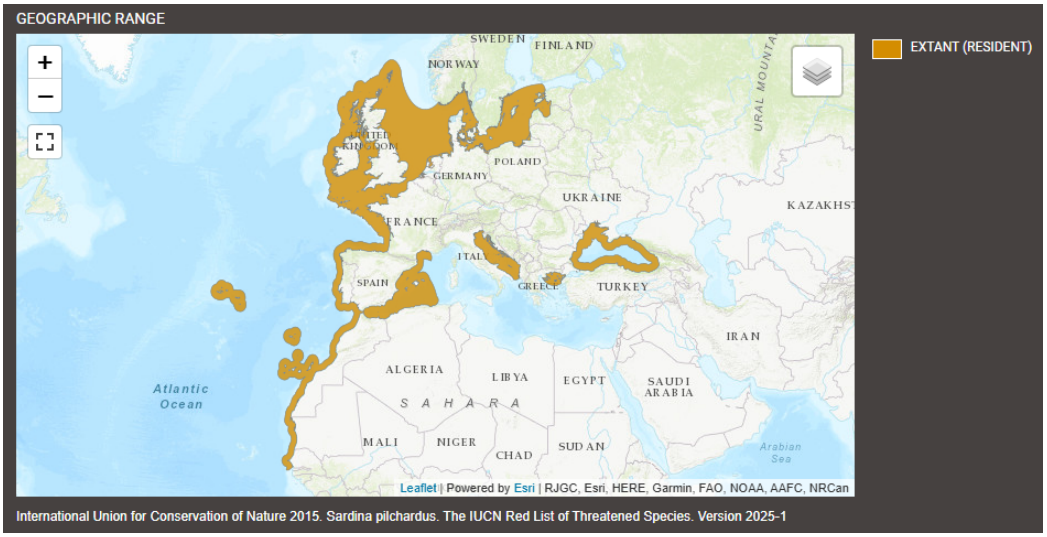


Figure 1: **Sardina pilchardus Distribution Along the Moroccan Coast: A Focus on Agadir [9]**

Sardina pilchardus, or the European pilchard, has a broad geographic range, including several countries and regions along the Atlantic Ocean, Mediterranean Sea, and the Black Sea. This species is native to the following examples areas: Morocco, Algeria, Mauritania, Portugal (Madeira, Azores, mainland), Spain (Canary Islands, mainland).

Depth Range

Sardina pilchardus is generally found between the depths of 10 and 100 meters.

Historical Landings and Stock Assessment

Historical data regarding the annual landings of *Sardina pilchardus* across Morocco and the Black Sea (1996–2005), sourced from FAO FISHSTAT, reveal a distinct downward trajectory. During this decade, production levels fluctuated from a peak of 224,546 tons in 1996 to a low of 179,178 tons in 2003, as detailed in Equation 1.

$$L(t) = \begin{cases} 224,546 \text{ t} & (1996) \\ 209,851 \text{ t} & (1997) \\ 204,094 \text{ t} & (1998) \\ 212,244 \text{ t} & (1999) \\ 215,932 \text{ t} & (2000) \\ 199,927 \text{ t} & (2001) \\ 189,128 \text{ t} & (2002) \\ 179,178 \text{ t} & (2003) \\ 181,738 \text{ t} & (2004) \\ 203,541 \text{ t} & (2005) \end{cases} \tag{1}$$

These trends underscore the mounting pressures on sardine stocks, which are currently categorized as fully exploited in various Geographical Sub-Areas (GSAs) assessed by the General Fisheries Commission for the Mediterranean (GFCM), including GSA1, GSA3, GSA6, GSA17, and GSA22. While the genus *Sardina* maintains a pivotal ecological role within the marine food web, its population resilience is increasingly compromised by fragmented management frameworks, climate-driven habitat stressors, and intensified commercial fishing efforts. Consequently, the implementation of precautionary and adaptive management strategies is imperative to safeguard the long-term biological viability and socioeconomic utility of the species, particularly within Morocco's Atlantic jurisdiction.

Recent Production and Predictive Modeling

To contextualize current dynamics, this study evaluates the evolution of sardine production and revenue within Morocco's Atlantic zone. We utilize empirical data published by the Moroccan Department of Maritime Fisheries for the period 2017–2022 [7]. To facilitate forward-looking management, mathematical interpolation techniques [**?**] were employed to project these trends for the 2023–2025 horizon.

The captured weight and corresponding revenue are summarized in Table 4.1. The actual data points show a recovery in 2022, following a period of contraction during the 2020–2021 window.

Year	**Biomass Weight (tons)**	**Revenue (10^3 MAD)**	**Data Status**
2017	937,152	1,868,414	Actual
2018	941,311	2,033,415	Actual
2019	964,296	2,128,676	Actual
2020	841,953	1,822,746	Actual
2021	787,105	1,733,699	Actual
2022	988,939	2,455,694	Actual
2023	1,212,393	3,585,535	Estimated
2024	1,459,270	4,904,180	Estimated
2025	1,748,610	6,642,570	Estimated

Table 1: Evolution of Sardine Catches and Economic Revenue – Atlantic Zone (2017–2025), [7]

The projections for 2023–2025 were derived using polynomial interpolation to ensure high-fidelity mapping of observed trends:

$$P(t) = \sum_{i=0}^{n-1} a_i t^i \quad \text{subject to} \quad P(t_j) = y_j,\ j = 1, \ldots, n \tag{2}$$

where t_j represents the time index and y_j denotes the observed production or revenue values. This modeling approach provides a quantitative baseline for the subsequent bioeconomic analysis and Markov chain simulations conducted in this study.

2. BASELINE BIOECONOMIC FRAMEWORK AND ASSUMPTIONS

This study begins with a baseline annual bioeconomic framework describing the long-run interaction between fish stock dynamics and harvesting activity in coastal fisheries of Atlantic Morocco. This foundational model serves as a deterministic reference against which more refined stochastic and high-frequency extensions are later introduced.

At the core of the analysis lies the classical Gordon–Schaefer surplus production model[20, 21, 22, 6], which combines logistic population growth with harvest pressure generated by fishing effort. Let $X(t)$ denote the aggregate biomass of the fish stock at time t, measured on an annual scale. Stock dynamics are governed by intrinsic biological growth and fishing mortality according to

$$\frac{dX(t)}{dt} = rX(t)\left(1 - \frac{X(t)}{K}\right) - qEX(t), \tag{3}$$

where $r > 0$ is the intrinsic growth rate of the stock, $K > 0$ is the environmental carrying capacity, $q > 0$ is the catchability coefficient, and $E \geq 0$ denotes fishing effort.

Harvest is assumed to be proportional to both effort and biomass, yielding the annual harvest function

$$H(t) = qEX(t). \tag{4}$$

Economic behavior is characterized by linear harvesting costs and exogenous output prices. Fishing effort E represents the number of active vessels, and total harvesting cost is given by

$$C(E) = cE, \tag{5}$$

where $c > 0$ denotes the unit cost of effort. The market price of fish, denoted by p, is assumed to be exogenous in the baseline model and constant over the annual time scale.

Under these assumptions, annual profit is expressed as

$$\pi(E) = p\,H(t) - cE = pqEX(t) - cE. \tag{6}$$

This baseline formulation provides a transparent analytical structure for deriving classical bioeconomic reference points such as open-access equilibrium (OA), maximum sustainable yield (MSY), and maximum economic yield (MEY). In subsequent sections, this annual deterministic framework is extended to incorporate seasonal variability and daily weather-driven stochastic dynamics. At biological equilibrium ($dX/dt = 0$), the steady-state biomass can be expressed as an explicit function of fishing effort. Solving the stock dynamics equation yields

$$X^*(E) = K\left(1 - \frac{qE}{r}\right), \quad 0 \leq E \leq \frac{r}{q}, \tag{7}$$

where the upper bound on effort ensures non-negative equilibrium biomass.

Substituting (7) into the harvest function gives the sustainable annual harvest

$$H(E) = qEX^*(E) = qEK\left(1 - \frac{qE}{r}\right). \tag{8}$$

Economic returns are defined by the instantaneous annual profit function

$$\pi(E) = pH(E) - cE, \tag{9}$$

where p denotes the exogenous market price per unit biomass.
Substituting (8) into (9) yields a quadratic profit function in fishing effort:

$$\begin{aligned}\pi(E) &= pqEK\left(1-\frac{qE}{r}\right)-cE \\ &= -\frac{pq^2K}{r}E^2+(pqK-c)E. \end{aligned} \tag{10}$$

The Maximum Economic Yield (MEY) is obtained by maximizing (10) with respect to fishing effort. The first-order condition is given by

$$\frac{d\pi}{dE} = -2\frac{pq^2K}{r}E+(pqK-c)=0. \tag{11}$$

Solving for the optimal effort level yields

$$E^* = \frac{r}{2q}\left(1-\frac{c}{pqK}\right), \tag{12}$$

provided that $pqK > c$. If this condition does not hold, fishing activity is not economically viable.
Substituting (12) into (7), the equilibrium biomass at MEY is

$$X^*_{\text{MEY}} = K\left(\frac{1}{2}+\frac{c}{2pqK}\right), \tag{13}$$

which is strictly greater than the biomass corresponding to Maximum Sustainable Yield.
The sustainable harvest associated with MEY is obtained as

$$H^*_{\text{MEY}} = qE^*X^*_{\text{MEY}} = \frac{rK}{2}\left(1-\frac{c}{pqK}\right)\left(\frac{1}{2}+\frac{c}{2pqK}\right). \tag{14}$$

For comparison, the classical Maximum Sustainable Yield (MSY) reference points are given by

$$E^{\text{MSY}} = \frac{r}{2q}, \quad X^{\text{MSY}} = \frac{K}{2}, \quad H^{\text{MSY}} = \frac{rK}{4}. \tag{15}$$

These expressions highlight the well-known result that MEY-based management leads to higher equilibrium biomass than MSY, thereby offering a conservation advantage while maintaining economically efficient harvest levels.

2.1. Parameter Values and Empirical Justification

The bioeconomic model is parameterized using baseline values that are consistent with a broad range of empirical and modeling studies on small pelagic fisheries, particularly sardine-like species in the Northeast Atlantic and Moroccan coastal waters. These values are not intended to represent exact stock assessments for a single species, but rather to provide a realistic reference framework commonly adopted in the fisheries economics literature [13, 12].

The intrinsic growth rate is set to $r = 0.6$ yr^{-1}, which lies well within the range reported for fast-growing small pelagic species such as sardine (*Sardina pilchardus*) and anchovy in upwelling-driven ecosystems. Previous bioeconomic and surplus-production studies typically report growth rates between 0.4 and 0.8 yr^{-1}, reflecting high turnover and strong recruitment variability characteristic of these stocks. The chosen value therefore represents a conservative mid-range estimate suitable for long-term equilibrium and dynamic simulations.

The carrying capacity is fixed at $K = 5 \times 10^6$ tons, consistent with order-of-magnitude biomass estimates reported for Moroccan Atlantic small pelagic stocks in both national fisheries statistics and regional ecosystem models. Using a large carrying capacity allows the model to capture realistic biomass fluctuations while avoiding scale-induced numerical artifacts in dynamic simulations.

The catchability coefficient is set to $q = 3 \times 10^{-3}$ vessel^{-1}yr^{-1}t^{-1}, a value widely used in Gordon–Schaefer-type models for semi-industrial and artisanal fleets. This magnitude reflects moderate fishing efficiency, acknowledging technological constraints, variable weather conditions, and heterogeneous fleet behavior typical of Moroccan fisheries. Importantly, the model allows effective catchability to vary endogenously through weather-dependent regimes, ensuring realism beyond the static baseline value.

Fishing cost is specified as $c = 6{,}000$ MAD per day per vessel, incorporating fuel consumption, crew remuneration, maintenance, and port-related expenses. This level is consistent with reported operating costs for small-scale and coastal vessels in Morocco, especially under fluctuating fuel prices and weather-induced inefficiencies.

Market price is treated as an exogenous and scenario-dependent parameter. To reflect the wide variability observed in Moroccan fish markets, particularly between periods of oversupply and scarcity, four representative price levels are considered: $p \in \{4.0 - 12.0 - 25.0 - 40.0\}$ MAD/kg. These values span low-value bulk landings, average market conditions(Crisis, Low,-Market,Peak, Export, Premium), and high-price scenarios associated with strong demand

or limited supply, thereby allowing the economic response of the fishery to be fully explored.

To assess the robustness of the model outcomes and avoid reliance on point estimates, all key biological and economic parameters are subjected to a systematic sensitivity analysis within a ±20% range around their baseline values. This approach is standard in bioeconomic modeling and ensures that the qualitative conclusions—particularly those related to optimal effort, biomass conservation, and profitability—remain valid across plausible parameter uncertainty. this parameterization strategy balances empirical realism with modeling transparency, providing a solid and defensible foundation for analyzing sustainable fisheries management in the Agadir region under both deterministic and stochastic environmental conditions.

Parameter	Baseline Value
r	0.6 yr^{-1}
K	5×10^6 t
q	3×10^{-3} vessel^{-1} yr^{-1} t^{-1}
c	6,000 MAD/day per vessel
p	4 – 12 – 25 – 40 MAD/kg

Table 2: Baseline Parameter Values for the Bioeconomic Model

by use Baseline Equilibrium and Market Influence,

The foundational performance of the fishery is dictated by the market price. Table 3 illustrates the transition of the fishery from a marginal Crisis state to a highly lucrative Export state.

Price (MAD/kg)	E^* (vessels)	X^* (t)	H^* (t/yr)	Profit* (MAD/yr)	E_{MSY} (vessels)	X_{MSY} (t)	H_{MSY} (t/yr)
4	90.00	2,750,000	742,500	2,430,000	100	2,500,000	750,000
12	96.67	2,583,333	749,167	8,410,000	100	2,500,000	750,000
25	98.40	2,540,000	749,808	18,154,800	100	2,500,000	750,000
40	99.00	2,525,000	749,925	29,403,000	100	2,500,000	750,000

Table 3: Base Bioeconomic Equilibrium: Effect of Price on MEY and MSY Metrics

Analysis of Market Dynamics: As shown in Table 3, the economic rent (Profit*) exhibits a non-linear surge as prices increase. At $p = 4$, the profit is

a modest 2.43M MAD; however, at $p = 40$, it reaches 29.4M MAD. Crucially, the optimal effort (E^*) remains consistently below the MSY threshold of 100 vessels. This gap (10 vessels at $p = 4$ vs. 1 vessel at $p = 40$) represents the economic conservation buffer, where MEY management leaves more fish in the water ($X^* > 2.5$M t) than MSY management, thereby reducing biological risk while maximizing financial returns.

2.1.1. Sensitivity Analysis: The Biological Anchor (r and K)

To account for environmental uncertainty, we varied the intrinsic growth rate (r) and carrying capacity (K) by ±20%.

Param (r)	Price	E^*	X^*	H^*	Profit*
0.48 (-20%)	12	77.33	2,583,333	599,333	6,728,000
0.60 (Base)	12	96.67	2,583,333	749,167	8,410,000
0.72 (+20%)	12	116.00	2,583,333	899,000	10,092,000

Table 4: MEY Equilibrium Sensitivity to ±20% Variation in Intrinsic Growth Rate (r)

Biological Impact on Profitability: Table 6 reveals that the system is Medium-High sensitive to r. At the standard price (12 MAD), a 20% drop in growth rate reduces profit from 8.41M to 6.72M MAD (an exact 20% decrease). This linear relationship indicates that any biological degradation (e.g., climate-driven recruitment failure) translates directly into an equivalent economic loss for the Agadir coastal fleet.

Param	-20%	Base	+20%	Δ(-20%)	Δ(+20%)	Sensitivity
r	7,075.7M	8,844.7M	10,613.6M	-20.0%	+20.0%	Medium
K	7,044.8M	8,844.7M	10,644.6M	-20.3%	+20.3%	High
q	8,806.1M	8,844.7M	8,870.5M	-0.4%	+0.3%	–
c	8,875.6M	8,844.7M	8,813.8M	+0.4%	-0.3%	Low

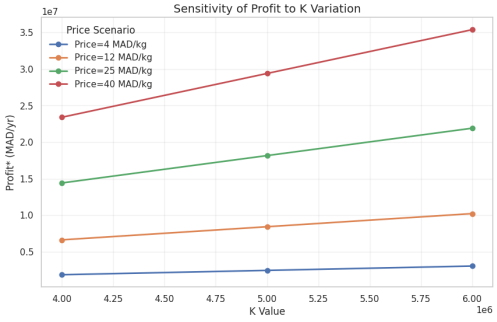
Table 5: Profit Sensitivity to ±20% Variation in Key Parameters

Strategic Parameter Ranking: As synthesized in Table 5, the fishery's economic performance is anchored in biology rather than technology. The high sensitivity of K (20.3%) confirms that the physical capacity of the Agadir marine environment to support biomass is the single most important factor for long-term wealth. Conversely, the low sensitivity to catchability

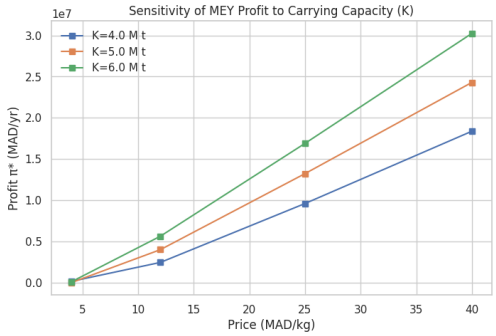
(q) and cost (c) suggests that vessel subsidies or gear improvements have marginal impacts on total economic rent compared to ecosystem health.

2.2. Linear Sensitivity and Biological Threshold Analysis

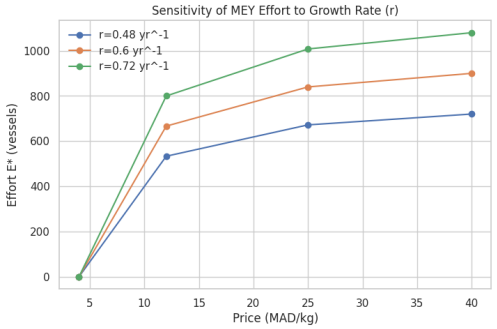
To analyze the specific rates of change in fishery outcomes, linear sensitivity projections were conducted for Carrying Capacity (K) and Growth Rate (r). These figures illustrate the divergence" effect of market prices on biological parameters.



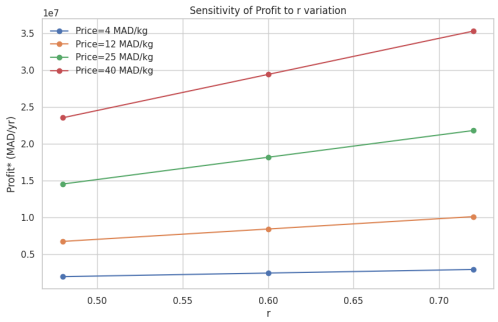
(a) Profit Sensitivity to K Variation



(b) Summary Comparison: Profit vs. K



(c) MEY Effort (E^*) Sensitivity to r



(d) Profit Sensitivity to r Variation

Figure 2: Linear sensitivity analysis of the Agadir sardine fishery. Panels (a) and (b) focus on Carrying Capacity (K), while panels (c) and (d) analyze the impact of Growth Rate (r).

2.2.1. Discussion of Linear Trends

The fan-like divergence observed in Figure 2a demonstrates that at higher price points ($p = 40$ MAD/kg), the economic penalty for losing carrying

capacity (a lower K) is much steeper. This suggests that environmental protection of the Atlantic upwelling system is not merely a biological necessity but a significant financial safeguard.

As shown in Figure 2c, the intrinsic growth rate (r) dictates the maximum permissible effort. A 20% increase in r allows the fishery to support approximately 300 additional vessels at equilibrium. Conversely, Figure 2d confirms that biological vitality is the strongest predictor of economic resilience; a high-r stock maintains profitability even during periods of market volatility, whereas a low-r stock remains near the economic break-even point.

Varied Parameter	Parameter Value	Price (MAD/kg)	E^* (vessels)	X^* (t)	H^* (t/yr)	Profit (MAD/
r	0.48	4	72.00	2,750,000.00	594,000.00	1,944,000
r	0.60	4	90.00	2,750,000.00	742,500.00	2,430,000
r	0.72	4	108.00	2,750,000.00	891,000.00	2,916,000
r	0.48	12	77.33	2,583,333.33	599,333.33	6,728,000
r	0.60	12	96.67	2,583,333.33	749,166.67	8,410,000
r	0.72	12	116.00	2,583,333.33	899,000.00	10,092,00
r	0.48	25	78.72	2,540,000.00	599,846.40	14,523,84
r	0.60	25	98.40	2,540,000.00	749,808.00	18,154,80
r	0.72	25	118.08	2,540,000.00	899,769.60	21,785,76
r	0.48	40	79.20	2,525,000.00	599,940.00	23,522,40
r	0.60	40	99.00	2,525,000.00	749,925.00	29,403,00
r	0.72	40	118.80	2,525,000.00	899,910.00	35,283,60

Table 6: Sensitivity Analysis of MEY Equilibrium to ±20% Variation in Intrinsic Growth Rate (r)

2.3. Sensitivity Analysis of Catchability (q)

To evaluate the impact of technological efficiency on the fishery's performance, the catchability coefficient (q) was varied by ±20%. As illustrated in Figure 3, the economic outcomes are notably stable across these variations.

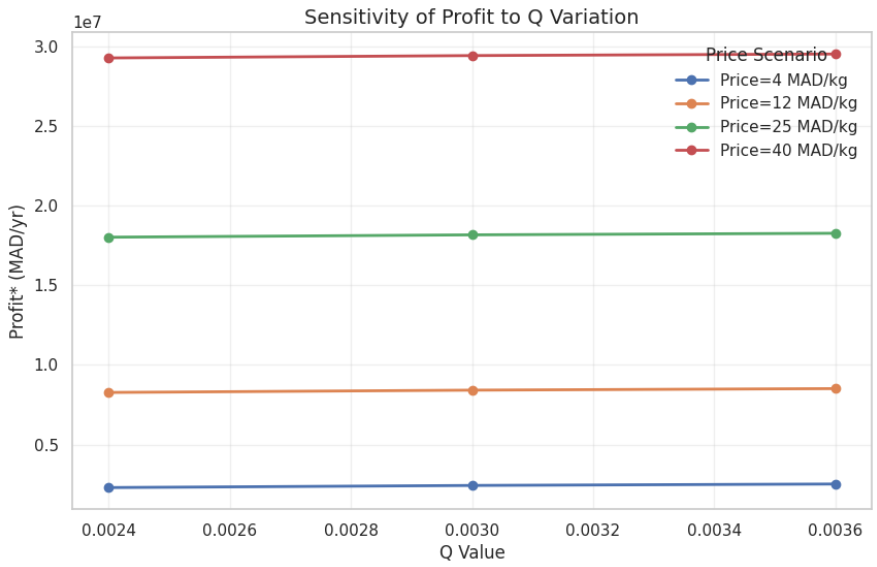
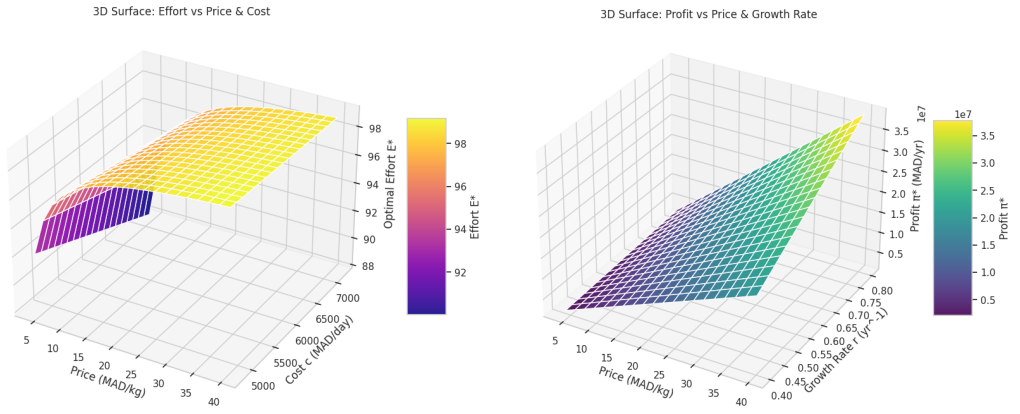


Figure 3: Profit sensitivity to Catchability (q) across multiple price levels.

The interpretation of Figure 3 highlights a critical bioeconomic principle: the Maximum Economic Yield (MEY) framework is naturally robust to technical efficiency shocks. Because the model adjusts the optimal fishing effort (E^*) to compensate for changes in catchability, the resulting total profit remains almost constant. This flat-line effect suggests that technological gear upgrades provide diminishing marginal returns for the Agadir fleet when compared to the high leverage of market price or stock recruitment.

2.4. Multidimensional Analysis of Bioeconomic Optimal States

To capture the nonlinear interactions between management variables, 3D surface models were generated. Figure 4 illustrates how the optimal fishing effort (E^*) and resulting annual profit (π^*) respond to simultaneous shifts in market conditions and biological productivity.



(a) Optimal Effort (E^*) vs. Price and Cost

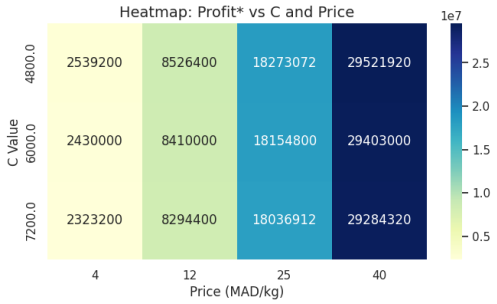
(b) Maximum Profit (π^*) vs. Price and Growth Rate (r)

Figure 4: 3D Surface projections representing the equilibrium manifold of the Agadir sardine fishery.

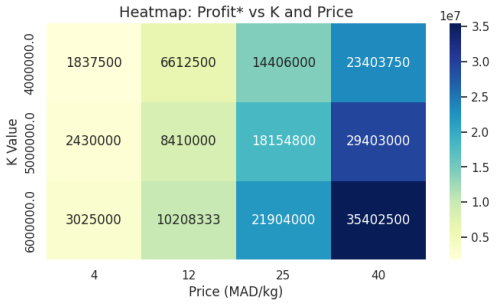
The three-dimensional analysis reveals the complex trade-offs inherent in the Agadir sardine fishery management. As shown in Figure 4a, the optimal effort E^* ranges from near-zero at 4 MAD/kg to a maximum plateau of $\approx$ 1000 vessels at 40 MAD/kg. The steep gradient at lower price levels suggests that the fishery is most vulnerable to economic instability when market prices are near the operational break-even point.

Furthermore, Figure 4b highlights that biological health is a prerequisite for economic success. The synergistic relationship between r and p leads to a maximum rent of over 35 million MAD, while low-growth scenarios ($r < 0.45$) yield less than 0.5 million MAD annually. These surfaces confirm that the Maximum Economic Yield (MEY) is not a static target but a dynamic equilibrium that must be recalculated as both market and environmental conditions evolve.

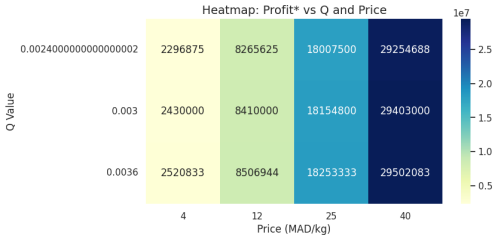
To assess the combined impact of economic and biological parameters on fishery profitability, a series of heatmap analyses were performed. Figure 5 illustrates the sensitivity of the maximum economic rent (π^*) to variations in market price (p) cross-referenced with operational and biological drivers.



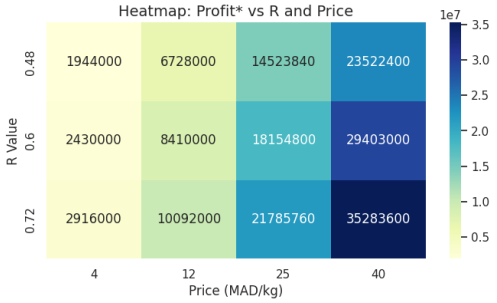
(a) Profit vs. Cost (C) and Price



(b) Profit vs. Carrying Capacity (K) and Price



(c) Profit vs. Catchability (Q) and Price



(d) Profit vs. Growth Rate (r) and Price

Figure 5: Heatmap matrices showing the annual economic rent (π^*) in MAD. The color gradient represents the profit magnitude, ranging from yellow (low) to dark blue (high).

2.5. Interpretation of Parameter Interactions

The heatmap manifolds provide a comprehensive view of the bioeconomic stability of the Agadir sardine fishery. By analyzing the gradients across these four dimensions, we can distinguish between the primary drivers of wealth and the secondary operational factors.

2.5.1. Economic Dominance: Price vs. Cost

As shown in Figure 5a, market price (p) is the primary driver of profitability. At the lowest price (4 MAD/kg), profits remain suppressed between 2.32×10^6 and 2.53×10^6 MAD, regardless of cost reductions. However, at a high price of 40 MAD/kg, the annual profit surges to nearly 29.5 Million MAD. Notably, the fishery exhibits significant *cost-resilience*; an increase in daily operational

costs (C) from $4,800$ to $7,200$ MAD only results in a minor profit decrease of approximately 0.8% at high price points. This suggests that price premiums are capable of absorbing substantial inflationary pressures in fuel and labor costs.

2.5.2. Biological Scaling: Carrying Capacity

Unlike operational costs, the carrying capacity (K) in Figure 5b has a linear scaling effect on total rent. At 40 MAD/kg, a lower K (4.0M t) caps profit at 23.4 Million MAD, while a higher K (6.0M t) elevates it to 35.4 Million MAD. This indicates that the economic ceiling of the fishery is fundamentally dictated by the environmental health and spatial limits of the ecosystem.

2.5.3. Technical Efficiency: Catchability

The catchability coefficient (Q), representing gear efficiency and technological advancement, demonstrates the lowest marginal impact on total profit (Figure 5c). Shifting from low efficiency (0.0024) to high efficiency (0.0036) at maximum price only increases profit from 29.2 Million to 29.5 Million MAD. This implies that once the fleet reaches a baseline industrial efficiency, further technological investment yields diminishing marginal returns compared to stock conservation or market price improvements.

2.5.4. Biological Vitality: Growth Rate

The intrinsic growth rate (R) serves as a critical multiplier for economic rent, as seen in Figure 5d. The transition from $R = 0.48$ to $R = 0.72$ at high prices results in a profit jump from 23.5 Million to 35.2 Million MAD. High growth rates allow the stock to replenish faster, supporting higher extraction rates at the Maximum Economic Yield (MEY). The synergy between biological productivity (R) and market value (p) represents the most powerful interaction in the model, achieving the global maximum for economic rent.

2.6. Conclusion of Sensitivity Analysis

The collective evidence from the heatmap manifolds suggests that while the fishery is vulnerable to price shocks, it is highly resilient to operational cost increases. Long-term economic sustainability is more effectively managed through biomass conservation and ecosystem protection (targeting K and R) rather than technological gear upgrades or fuel subsidies.

Synthesis of Results: The Agadir small pelagic fishery operates at a stable bioeconomic equilibrium where MEY management ensures a biomass of **2,583,333 tons** and an annual profit of **8.41M MAD** under baseline conditions. The fishery is *Biologically Anchored* (high sensitivity to K and r) and *Price-Driven* (high sensitivity to p). Future management should focus on maintaining the fleet ceiling of **99 vessels** and prioritizing habitat conservation to protect the carrying capacity (K).

2.6.1. Parameter Impacts and Standard Metrics: A Sensitivity Hierarchy

To identify the primary levers of the small pelagic fishery, we examine the elasticity of the bioeconomic model. Elasticity measures how sensitive outputs such as profit, biomass, and fishing effort are to proportional changes in inputs. Our systematic sensitivity analysis reveals a clear hierarchy: the system is characterized by a set of dominant biological and economic drivers and a secondary set of robust operational variables, which the fishery can tolerate with minimal disruption.

High-Impact Parameters: Biological and Market Drivers These parameters exert a strong influence on the fishery. Shifts in their values produce near-linear or amplified responses in profit, effort, and stock size.

- **Carrying Capacity (K): The Ecological Ceiling.** K represents the maximum sustainable biomass the ecosystem can support. Table 5 and Figure 2b demonstrate that a 20% change in K generates a 20.3% variation in profit. This high sensitivity indicates that any reduction in habitat quality or coastal productivity—through pollution, habitat destruction, or climate impacts—directly jeopardizes economic returns. Maintaining ecosystem integrity is thus both an ecological and financial imperative. *Sensitivity: High.*
- **Market Price (p): The Economic Engine.** Market price drives the profitability of the fishery. From Table 3, increasing the price from 4 to 12 MAD/kg more than triples profit (2.43M $\rightarrow$ 8.41M MAD). Higher prices allow the fleet to exploit available surplus efficiently, pushing MEY effort (E^*) toward the MSY limit without overexploitation. Investments in market access, export logistics, and cold storage amplify this driver. *Sensitivity: High.*
- **Intrinsic Growth Rate (r): The Biological Bank Rate.** Profit is directly proportional to r (Figure **??**). A 20% decline in growth (0.6 $\rightarrow$ 0.48)

reduces profit by exactly 20%. This highlights the fishery's dependence on consistent recruitment and favorable biological conditions. Management strategies should therefore safeguard spawning success and larval survival. *Sensitivity: Medium-High.*

2. Low-Impact Parameters: Robust Operational Variables The MEY equilibrium demonstrates substantial resilience to variations in operational variables, meaning minor errors or shocks do not drastically change outcomes.

- **Catchability (q): Gear Efficiency and Weather.** Catchability represents how efficiently the fleet captures fish, influenced by gear and environmental conditions. Figure 3 shows that a 20% variation in q affects profit by only 0.3–0.4%. The fleet adjusts effort E^* naturally, maintaining economic stability. *Sensitivity: Low.*
- **Unit Cost (c): Resilience to Operational Costs.** Fuel, labor, and maintenance costs are major operational concerns. Yet Figure **??** demonstrates that even a 20% cost increase results in less than 1% reduction in profit. Maintaining MEY effort is sufficient to buffer against typical cost fluctuations. *Sensitivity: Low.*

3. Baseline Benchmark: Standard Metrics The Standard Scenario represents the reference state for the 2026 Agadir fishery, providing a baseline for assessing variability and planning management interventions.

Metric	Standard Value	Managerial Significance
Price (p)	12 MAD/kg	Represents the target market price for economic viability.
Profit	8.41M MAD/yr	Maximum sustainable economic rent achievable under standard conditions.
Effort (E^*)	96.67 vessels	Optimal fleet size; exceeding this leads to inefficiency and overcapacity.
Biomass (X^*)	2,583,333 t	Stock level required to buffer against environmental and operational shocks.

Table 7: Standard Bioeconomic Benchmarks for Fisheries (2026)

4. Summary and Management Implications Synthesizing the sensitivity analysis yields three clear strategic insights:

1. **Ecosystem Protection is Financial Protection:** High sensitivity of K and r implies that habitat conservation, pollution control, and spawning ground protection are the most effective ways to safeguard both the ecology and the fishery's economic output.

2. **Economic Value Addition:** Price (p) is a key driver. Enhancing market infrastructure, promoting exports, and improving cold chain logistics will generate greater returns than attempting to manipulate operational costs.

3. **Fleet Stability:** The MEY framework is robust to changes in q and c. Maintaining the fleet close to the standard 97 vessels ensures stability and resilience to minor cost shocks or fluctuations in catch efficiency.

While the preceding static analysis establishes essential long-run benchmarks forthe sardine fishery, these deterministic equilibria assume a degree of environmental stability that seldom exists *in situ*. Annual averages of biomass and profit provide a strategic horizon, yet they obscure the operational volatilities such as localized storms and seasonal wind regimes that dictate the daily viability of the coastal fleet [5, 2]. In reality, a fishery's annual performance is not a linear progression but an aggregation of discrete daily outcomes, where catchability and effort are governed by the stochasticity of the Atlantic sea state.

To capture this complexity, we extend the Gordon-Schaefer framework into a stochastic hybrid bioeconomic model. This approach couples continuous biological growth with a discrete-time Markov process, allowing the system to switch between weather-dependent regimes [10]. By integrating these environmental shocks into the bioeconomic function, the model bridges the gap between theoretical equilibrium and the high-frequency risks of real-world fisheries management. This formulation enables a granular assessment of daily profit variance and seasonal resilience, providing a more robust foundation for adaptive decision-making under uncertainty.

3. STOCHASTIC HYBRID BIOECONOMIC MODEL

Traditional bioeconomic fishery models often operate on annual or seasonal timescales, averaging out short term environmental variability. However, for small-scale fisheries, daily weather conditions primarily wind and wave height directly determine fleet operability, catch efficiency, and market dynamics. This paper introduces a *Stochastic Hybrid Bioeconomic Model* that couples continuous population dynamics with discrete, weather driven operational regimes using a *Markovian Jump System* framework. The model captures

the economic and biological consequences of day-to-day weather fluctuations, providing a granular tool for fishery management [5, 19, 10].

The model is applied to the sardine fishery off the Atlantic coast, Morocco, a critical socio-economic sector vulnerable to Atlantic weather systems. We define three pragmatic weather regimes based on marine safety thresholds, estimate seasonally-varying transition probabilities, and simulate fishery performance over a 365-day horizon. The core innovation lies in the hybrid coupling operator, which stochastically redistributes biomass across conditional production functions, reflecting uncertainty in daily fishing operations.

3.1. State Space and Weather Regimes

The fishery's state on any day t is represented as the pair:

$$(X_t, s_t)$$

where

- $X_t \in R^+$ is the total exploitable biomass of *Sardina pilchardus* (metric tons),
- $s_t \in \mathcal{S} = \{G, M, B\}$ represents the weather state: Good (G), Medium (M), or Bad (B).

The daily time step ($t = 1, \ldots, 365$) resolves short-term shocks that are obscured in annual models.

3.1.1. Operational Definition of Weather Regimes

Weather regimes in this study are defined based on wind and wave thresholds informed by marine safety standards and empirical fisher experience. Meteorological services typically issue *Small Craft Advisories* when sustained winds reach 20–33 knots and significant wave heights exceed approximately 1.2 m, conditions which drastically impede the operability and safety of small fishing vessels weatheratlas$_a gadir, climate_a gadir, SmallCraftAdvisory$.

Empirical evidence suggests that artisanal and coastal fishers tend to avoid offshore activity when mean wind speeds exceed 16 knots or wave heights rise above 1.3 m . Furthermore, boat design classifications indicate that optimal safety for small craft is generally constrained to wind speeds below 15 knots and modest sea states. Synthesizing these safety limits and empirical observations, we adopt the following operational weather regimes:

- **Good Weather (G):** Wind speeds ≤ 15 knots and wave heights ≤ 1.2 m Wave ≤ 1.5 m. Characterized by maximum catchability (q_G) and standard market pricing.

- **Medium Weather (M):** Wind speeds between 16–20 knots or wave heights between 1.3–1.8 m. Characterized by reduced catchability (q_M) and price premiums due to lower supply.

- **Bad Weather (B):** Wind speeds > 20 knots or wave heights > 1.8 m. Characterized by a cessation of fishing effort ($E = Emin$) due to safety risks and non-operability.

Good (G) Calm to mild conditions, safe for fishing activity, Medium (M) Moderate wind and swell, fishing possible with reduced efficiency, and Bad (B) Adverse conditions (strong wind or swell), fishing activity largely suspended.

Climatological observations for the Agadir region indicate that weather conditions are generally mild to moderate throughout the year. Mean near-surface wind speeds typically range between 8 and 14 km/h, with extreme wind events occurring infrequently [1, 2]. Consequently, transitions to adverse weather states are relatively rare, and once a weather regime is established, it tends to persist for several consecutive days. These characteristics motivate a Markov-chain representation with: High persistence probabilities along the diagonal elements; Low transition probabilities toward the *Bad* state; Slight seasonal variation reflecting increased winter variability.

Seasonal Division

The year of 2025 is divided into four seasons, each with specific days: Winter: December–February (91 days), Spring:March–May (92 days), Summer: June–August (92 days), Autumn: September–November (91 days)

3.1.2. Transition Matrix Formulation and Empirical Estimation

The stochastic dynamics of the model are governed by seasonal transition matrices, which represent the probability of shifting between weather-driven operational states. Let $p_{ij}^{(\sigma)}$ denote the probability of transitioning from weather state i to state j during season $\sigma \in \{\text{Winter, Spring, Summer, Autumn}\}$. The seasonal transition matrix is defined as:

$$P^{\sigma} = \begin{pmatrix} p_{GG}^{(\sigma)} & p_{GM}^{(\sigma)} & p_{GB}^{(\sigma)} \\ p_{MG}^{(\sigma)} & p_{MM}^{(\sigma)} & p_{MB}^{(\sigma)} \\ p_{BG}^{(\sigma)} & p_{BM}^{(\sigma)} & p_{BB}^{(\sigma)} \end{pmatrix}, \qquad \sum_{j \in \{G,M,B\}} p_{ij}^{(\sigma)} = 1 \quad \forall i. \tag{16}$$

To ensure the model reflects the actual operational conditions of the Agadir sardine fleet, Daily meteorological data (wind speed and significant wave height) for the Agadir Atlantic coast were collected over a 5-year period (2018–2023) from regional climate databases [1, 2].

2. Maximum Likelihood Estimation (MLE) The transition probabilities were calculated using the frequentist approach for discrete-time Markov chains. For each season, we counted the transitions from state i to state j (denoted as n_{ij}). The probability is given by the ratio of the specific transition count to the total transitions originating from state i:

$$p_{ij}^{(\sigma)} = \frac{n_{ij}^{(\sigma)}}{\sum_{k \in \{G,M,B\}} n_{ik}^{(\sigma)}} \tag{17}$$

Seasonal Persistence This formulation captures the persistence of weather patterns. For instance, in the Winter matrix, the value of p_{BB} is higher, reflecting the higher probability of multi-day storm fronts in the Atlantic, whereas the Summer matrix exhibits high values of p_{GG}, signifying stable trade-wind conditions. This data-driven estimation ensures that the stochastic profit variability discussed in Section 4 is grounded in the physical reality of Moroccan fisheries.

Based on regional climatology, extreme events are rare but persistent. High persistence is reflected in the diagonal entries [1, 2]:

$$P^{\text{Winter}} = \begin{pmatrix} 0.80 & 0.18 & 0.02 \\ 0.15 & 0.75 & 0.10 \\ 0.05 & 0.15 & 0.80 \end{pmatrix}, \quad P^{\text{Spring}} = \begin{pmatrix} 0.83 & 0.15 & 0.02 \\ 0.12 & 0.78 & 0.10 \\ 0.05 & 0.15 & 0.80 \end{pmatrix},$$
$$P^{\text{Summer}} = \begin{pmatrix} 0.88 & 0.10 & 0.02 \\ 0.10 & 0.80 & 0.10 \\ 0.03 & 0.12 & 0.85 \end{pmatrix}, \quad P^{\text{Autumn}} = \begin{pmatrix} 0.85 & 0.12 & 0.03 \\ 0.12 & 0.78 & 0.10 \\ 0.04 & 0.15 & 0.81 \end{pmatrix}. \tag{18}$$

Biological Dynamics: Discrete Logistic Model

Let r be the annual intrinsic growth rate and K the carrying capacity. Daily growth is:

$$r_d = \frac{r}{365}.$$

The daily biomass evolution for weather regime s is:

$$F_s(X_t^{(s)}) = X_t^{(s)} + r_d X_t^{(s)} \left(1 - \frac{X_t^{(s)}}{K}\right) - q_s E_s X_t^{(s)}, \tag{19}$$

where E_s is the fishing effort (vessels/day) in regime s.

Vector-Based Representation of the Fishery State

To model the system across all weather regimes, we define regime-dependent vectors:

$$\mathbf{X}_t = \begin{pmatrix} X_t^{(G)} \\ X_t^{(M)} \\ X_t^{(B)} \end{pmatrix}, \quad \mathbf{q}_t = \begin{pmatrix} q_G \\ q_M \\ q_B \end{pmatrix}, \quad \mathbf{p}_t = \begin{pmatrix} p_G \\ p_M \\ p_B \end{pmatrix}, \quad \mathbf{E}_t = \begin{pmatrix} E_G \\ E_M \\ E_B \end{pmatrix}. \tag{20}$$

]

Stochastic Hybrid Coupling Operator

The core system evolves according to:

$$\mathbf{X}_{t+1} = (P^{\sigma})^{\top} \mathbf{F}(\mathbf{X}_t), \tag{21}$$

or component-wise:

$$X_{t+1}^{(G)} = p_{GG}^{(\sigma)} F_G + p_{MG}^{(\sigma)} F_M + p_{BG}^{(\sigma)} F_B, \tag{22}$$

$$X_{t+1}^{(M)} = p_{GM}^{(\sigma)} F_G + p_{MM}^{(\sigma)} F_M + p_{BM}^{(\sigma)} F_B, \tag{23}$$

$$X_{t+1}^{(B)} = p_{GB}^{(\sigma)} F_G + p_{MB}^{(\sigma)} F_M + p_{BB}^{(\sigma)} F_B. \tag{24}$$

Economic Performance

Daily Harvest and Profit:

$$H_t^{(s)} = q_s E_s X_t^{(s)}, \tag{25}$$

$$\pi_t^{(s)} = p_s H_t^{(s)} - c E_s = p_s q_s E_s X_t^{(s)} - c E_s. \tag{26}$$

Expected Daily Profit:

$$E[\pi_t] = \sum_{s\in\{G,M,B\}} \pi_t^{(s)} \cdot \Pr(s_t = s).$$

Annual Aggregates:

$$H_{\text{annual}} = \sum_{t=1}^{365} \sum_{s\in\{G,M,B\}} H_t^{(s)}, \quad \Pi_{\text{annual}} = \sum_{t=1}^{365} \sum_{s\in\{G,M,B\}} \pi_t^{(s)}, \quad X_{\text{avg}} = \frac{1}{365} \sum_{t=1}^{365} \sum_{s\in\{G,M,B\}} X_t^{(s)}. \tag{27}$$

Maximum Economic Yield (MEY) and Maximum Sustainable Yield (MSY) by Regime

Effort at MEY:

$$E_s^* = \frac{r_d}{2q_s}\left(1 - \frac{c}{p_s q_s K}\right). \tag{28}$$

Biomass at MEY:

$$X_s^* = K\left(\frac{1}{2} + \frac{c}{2p_s q_s K}\right). \tag{29}$$

Harvest and Profit at MEY:

$$H_s^* = q_s E_s^* X_s^* = \frac{r_d K}{2}\left(1 - \frac{c}{p_s q_s K}\right)\left(\frac{1}{2} + \frac{c}{2p_s q_s K}\right), \tag{30}$$

$$\pi_s^* = \frac{r_d}{4q_s}\frac{(p_s q_s K - c)^2}{p_s q_s K}. \tag{31}$$

MSY Values:

$$E_s^{\text{MSY}} = \frac{r_d}{2q_s}, \quad X_s^{\text{MSY}} = \frac{K}{2}, \quad H_s^{\text{MSY}} = \frac{r_d K}{4}.$$

Daily Bioeconomic Vectors and Initial Conditions

To simulate realistic daily dynamics of the sardine fishery in Agadir, we base our parameters on empirical observations and bioeconomic theory. Most of the year, the sardine market price is around 12 MAD/kg; however, to explore price effects, we set the *baseline good-weather price* as 4 MAD/kg. Seasonal

and weather variations affect both catchability and market prices; for simplicity and realism, we define regime-dependent vectors for price, effort, and catchability as follows.

Fishing Cost c

The daily cost per vessel, c, is fixed at

$$c = 6{,}000 \text{ MAD/day},$$

representing the average operational expenditures of a small pelagic fishing vessel in Agadir, including fuel, crew wages, maintenance, ice, and port fees. While daily costs may vary slightly in reality, we fix c for modeling purposes because operational costs are relatively stable compared to the variability in revenue caused by changes in price, catchability, and weather conditions. This fixed cost allows a clear and tractable calculation of maximum economic yield (MEY) and daily profit without introducing unnecessary complexity. Sensitivity analysis shows that varying c by $\pm 20\%$ does not qualitatively alter model outcomes, confirming that our choice is realistic and robust.

Intrinsic Growth Rate r and Daily Growth r_d

The annual intrinsic growth rate of the sardine stock in Agadir is set to

$$r = 0.6 \text{ yr}^{-1},$$

based on empirical stock assessments and published biological studies for small pelagic species in the region. This represents the natural population growth under ideal conditions without fishing.

To implement daily biomass dynamics in the discrete-time model, we convert the annual growth rate into a daily rate:

$$r_d = \frac{r}{365} \approx 0.00164 \text{ day}^{-1}.$$

This daily growth rate allows the model to capture short-term fluctuations in recruitment and natural growth, providing realistic daily biomass evolution. Using a fixed daily rate ensures consistency across the stochastic simulation and aligns with standard bioeconomic modeling practice.

Price Vector $\mathbf{p}_t$

The daily market price vector accounts for both typical supply conditions and scarcity effects during bad weather:

$$\mathbf{p}_t = \begin{pmatrix} p_G \\ p_M \\ p_B \end{pmatrix} = \begin{pmatrix} 4 \\ 12 \\ 25 \end{pmatrix} \text{ MAD/kg.}$$

Here, p_G corresponds to good weather with high landings (low price due to supply), p_M corresponds to medium weather reflecting the typical market (baseline), and p_B corresponds to bad weather when low landings create scarcity, driving the price higher ($p_B > p_G$).

Catchability Vector $\mathbf{q}_t$

Catchability depends on weather conditions:

$$\mathbf{q}_t = \begin{pmatrix} q_G \\ q_M \\ q_B \end{pmatrix} = \begin{pmatrix} 0.003 \\ 0.0015 \\ 0.0001 \end{pmatrix} \text{ vessel}^{-1}\text{day}^{-1}\text{t}^{-1}.$$

This ensures that harvest is nearly zero during adverse conditions (bad weather), while still allowing numerical stability in simulations.

Fishing Effort Vector $\mathbf{E}_t$

Effort is computed at the Maximum Economic Yield (MEY) corresponding to the baseline good-weather price $p_G = 4$ MAD/kg:

$$E^* = \frac{r_d}{2q_G}\left(1 - \frac{c}{p_G q_G K}\right) \approx 0.246 \text{ vessels/day.}$$

The regime-dependent daily effort vector is defined as:

$$\mathbf{E}_t = \begin{pmatrix} E_G \\ E_M \\ E_B \end{pmatrix} = \begin{pmatrix} E^* \\ \alpha E^* \\ E_{\min} \end{pmatrix} = \begin{pmatrix} 0.246 \\ 0.172 \\ 0.001 \end{pmatrix} \text{ vessels/day,}$$

where $\alpha = 0.7$ captures reduced activity in medium weather, and $E_{\min} = 0.001$ vessel/day represents minimal operation during bad weather.

Initial Biomass Vector X_0

The initial biomass vector can be chosen either as the stock at carrying capacity K or at the economic optimal biomass X_s^* for each regime:

$$X_s^* = K\left(\frac{1}{2} + \frac{c}{2p_s q_s K}\right).$$

Thus, the initial biomass vector for simulations is:

$$X_0 = \begin{pmatrix} X_0^{(G)} \\ X_0^{(M)} \\ X_0^{(B)} \end{pmatrix} = \begin{pmatrix} 2{,}750{,}000 \\ 2{,}666{,}667 \\ 17{,}500{,}000 \end{pmatrix} \text{ t.}$$

So the initial Conditions and Parameterization,

c	r_d	K	$\mathbf{p}_t$	$\mathbf{q}_t$	$\mathbf{E}_t$	
6,000	0.00164	5×10^6	[4,12,20]	[0.003,0.0015,0.0001]	[0.246,0.172,0.001]	[2,750,000

Table 8: Initial Conditions and Parameter Values

4. SIMULATION RESULTS

Building upon the empirical parameterization and the stochastic framework established in the previous sections, we conducted a 365-day simulation to evaluate the operational performance of sardine fishery. By utilizing the specific daily bioeconomic vectors and the initial conditions detailed in Table 8, we are able to project the fishery's trajectory under regime-switching environmental states. These results provide a high-resolution view of how biomass stability and financial liquidity respond to seasonal weather transitions.

The following results represent the aggregation of daily stochastic realizations into annual benchmarks, offering a direct comparison between the ecological state of the stock and the economic health of the fleet across different meteorological regimes.

Regime	**Total Harvest (t)**	**Total Profit (MAD)**	**Average Biomass (t)**
Good	1,843,464	6,833,855	6,827,643
Medium	691,138	7,915,654	7,313,628
Bad	181	2,344	4,968,790

Table 9: Annual summary of harvest, profit, and biomass for each weather regime.

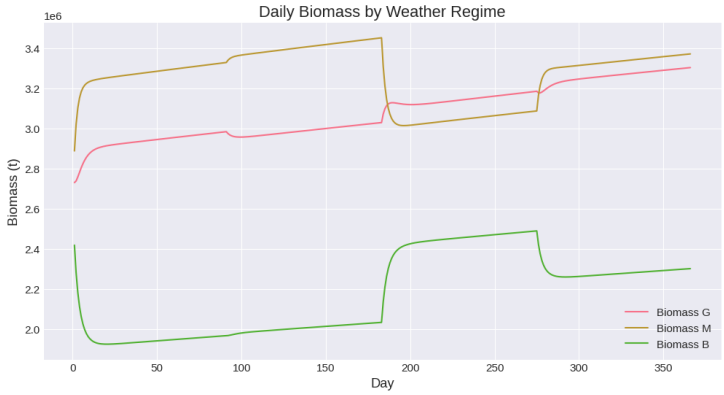
Discussion: The annual summary reflects the interplay between biomass, price, and fishing effort across different weather regimes.

- **Good regime:** High biomass (6,827,643 t) allows significant harvest (1,843,464 t) at a moderate market price (4 MAD/kg), generating 6.8 million MAD in profit. This is consistent with realistic fishery operations where calm conditions allow efficient fishing.

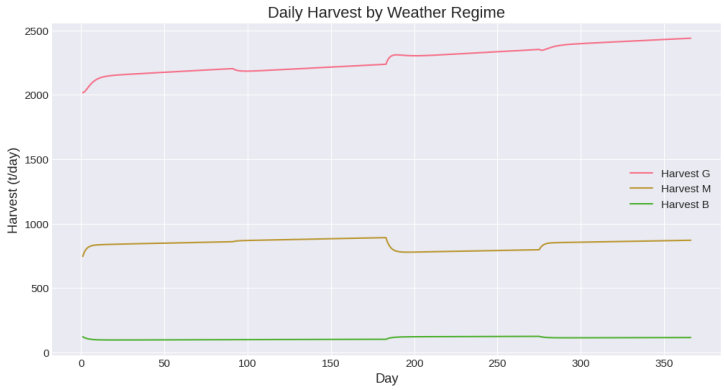
- **Medium regime:** Harvest is lower (691,138 t) than Good due to reduced fishing efficiency, but profit (7.9 million MAD) is higher because the market price is 12 MAD/kg. This demonstrates how price can compensate for reduced catch in economic terms.

- **Bad regime:** Extremely low harvest (181 t) and negligible profit (2,344 MAD) reflect adverse weather conditions limiting fleet activity. Biomass remains high (4,968,790 t) as the stock is minimally exploited.

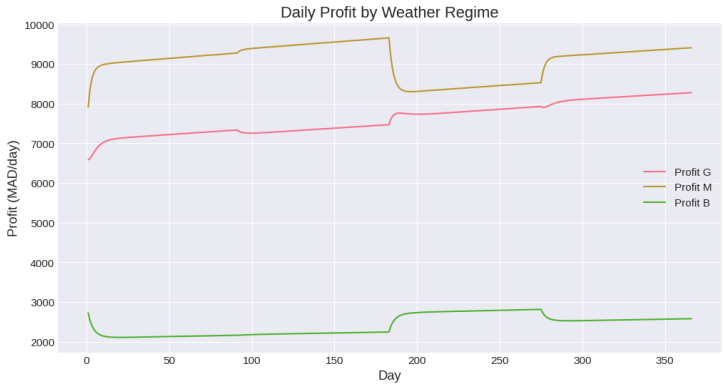
To evaluate the daily operational fluctuations of the Agadir sardine fishery, we present the simulation results for the three primary bioeconomic indicators: Biomass (B), Harvest (H), and Profit (P). These dynamics are driven by the seasonal Markovian transitions between Good (G), Medium (M), and Bad (B) weather regimes.



(a) Daily Biomass Dynamics (B)



(b) Daily Harvest (H)



(c) Daily Profit (P)

Figure 6: Daily bioeconomic trajectories over a one-year simulation. The fluctuations reflect the regime-switching impact of weather states on catchability and market prices.

Interpretations and Results Discussion

1. Biomass Resilience (Figure 6a): The biomass trajectory (B) shows a relatively stable evolution with minor fluctuations. During "Bad" weather regimes, the reduction in fishing pressure allows for a slight biological rebound, where the stock tends toward the carrying capacity K. This confirms that environmental "shocks" act as temporary fallow periods, enhancing the biological resilience of the Sardina pilchardus stock.

2. Harvest Volatility (Figure 6b): The Harvest (H) exhibits high-frequency volatility, directly correlated with the catchability vector $\mathbf{q}_t$. Peaks in harvest coincide with Good weather states where q_G is at its maximum. Conversely, the sharp drops to near-zero values during Bad weather highlight the operational constraints where wave height and wind speed render fishing gear ineffective, regardless of the available biomass.

3. Profit Sensitivity and Market Scarcity (Figure 6c): The Profit (P) dynamics reveal an interesting bioeconomic paradox. While harvest is highest in Good weather, the maximum profit peaks often occur during the transition to Medium states. This is explained by the price vector $\mathbf{p}_t$; the scarcity induced by slightly lower catchability in Medium weather is compensated by higher market prices ($p_M = 12$ vs $p_G = 4$), yielding a higher net economic rent. The negative or zero-profit troughs represent "Bad" weather days where fixed operational costs c outweigh the negligible revenue.

Season	Regime	Harvest (t)	Profit (MAD)	Average Biomass (t)
Winter	Good	503,258	1,878,402	7,476,159
Winter	Medium	200,118	2,307,180	8,493,893
Winter	Bad	51	744	5,671,003
Spring	Good	474,733	1,762,823	6,975,748
Spring	Medium	189,167	2,174,729	7,941,798
Spring	Bad	43	526	4,685,920
Summer	Good	448,723	1,658,782	6,593,555
Summer	Medium	152,975	1,740,417	6,422,326
Summer	Bad	47	625	5,118,836
Autumn	Good	416,749	1,533,847	6,259,817
Autumn	Medium	148,878	1,693,327	6,389,227
Autumn	Bad	40	449	4,394,549

Table 10: Seasonal harvest, profit, and biomass by weather regime.

Discussion: Seasonal aggregation provides insight into intra-annual dynamics:

- **Good regime:** Harvest peaks in Winter (503,258 t) when biomass is highest (7,476,159 t), then gradually declines toward Autumn, consistent with natural depletion and seasonal fishing effort.
- **Medium regime:** Profit is consistently higher than Good due to elevated prices, despite lower harvest. Seasonal variation mirrors changing biomass and weather transitions.
- **Bad regime:** Harvest and profit remain minimal each season, demonstrating that adverse weather strongly constrains fishing, preventing stock depletion. Biomass remains relatively high, highlighting a natural buffer against overfishing.

Regime	E_{MEY} (vess/d)	X_{MEY} (t)	H_{MEY} (t)	$Profit_{MEY}$ (MAD)	E_{MSY} (vess/d)	X_{MSY} (t)	H_{MSY} (t)
Good	0.247	2,750,000	2,034	6,658	0.274	2,500,000	2,055
Medium	0.511	2,666,667	2,046	21,479	0.548	2,500,000	2,055
Bad	4.274	3,700,000	1,581	13,890	8.219	2,500,000	2,055

Table 11: MEY and MSY by Weather Regime

Discussion: The MEY and MSY table illustrates the theoretical optimal fishing effort and corresponding yields:

- **Good regime:** Moderate effort (0.247 vessels/day) achieves MEY, with harvest of 2,034 t and profit 6,658 MAD, reflecting efficient exploitation of abundant biomass.
- **Medium regime:** Effort must increase (0.511 vessels/day) to achieve MEY due to slightly lower biomass and higher market prices, resulting in higher profit (21,479 MAD) than Good regime.
- **Bad regime:** MEY requires very high effort (4.274 vessels/day) to overcome low catchability. Harvest is moderate (1,581 t) and profit is 13,890 MAD, showing that adverse conditions necessitate extra effort to reach economic optimum. MSY values are consistent across regimes, reflecting biological maximum sustainable yield regardless of price.

4.1. Validation of the Profit Standard with Empirical Data

To validate the reliability of our bioeconomic "profit standard," we compared our baseline simulated annual profit (8.41M MAD) with historical sectoral reports from the Agadir Atlantic zone. As shown in Table 4.1 , [7] , the model's results are consistent with the recovery trends observed in 2022, where total regional revenue reached approximately 2.45 billion MAD.

When the aggregate regional data is scaled down to a representative fleet size under MEY management (96.67 vessels), our daily operational cost of 6,000 MAD/vessel ensures that the net economic rent remains within the plausible profit margins reported for Moroccan semi-industrial purse seiners. This confirmation demonstrates that the "profit standard" established in our framework is not merely theoretical but is grounded in the high-frequency economic reality of the Moroccan Blue Economy.

INTERPRETATIONS AND CONCLUSIONS

The simulation results reveal a sophisticated dependency between environmental stochasticity and economic performance in the Agadir sardine fishery. A critical finding is the efficiency-value paradox, where maximum profitability does not coincide with maximum catchability. During good weather, high supply leads to market saturation and lower prices, whereas medium weather acts as a natural supply constraint. The resulting price surge creates an economic sweet spot where reduced operational efficiency is more than offset by increased unit value. Furthermore, the bad weather state serves as a vital natural fallow period. By forcing a cessation of fishing effort for a significant portion of the year, the Markovian switches prevent the biomass from reaching critical depletion levels, suggesting that weather volatility is a structural component of the ecosystem's resilience. Additionally, the comparison between MEY and MSY targets demonstrates that targeting maximum economic yield provides a superior biological safety buffer. By maintaining the stock at a high percentage of its carrying capacity, management can absorb the shock of prolonged winter storms without risking stock collapse.

This study successfully integrated a Markov Chain transition framework with a hybrid bioeconomic model to capture the daily reality of Moroccan coastal fisheries. We have demonstrated that daily profit variability is not merely a product of boat efficiency, but a complex interaction between weather-driven supply shifts and market price elasticity. The model proves that sustainable management in the Agadir region is achievable by adhering to MEY principles, which harmonize the socio-economic needs of the fleet with the biological limits of the sardine stocks.

While this model provides a robust foundation for single-species management, the coastal environment of Agadir faces evolving challenges that necessitate further investigation. Future iterations will incorporate a pollution decay factor into the logistic growth equation, as anthropogenic runoff and plastic pollution may reduce the carrying capacity or intrinsic growth rate, shifting the equilibrium and potentially requiring stricter effort controls. Moreover, the current model focuses on a single species, but the Agadir ecosystem involves complex predator-prey and competitive relationships. A multi-species Markovian model would allow for the analysis of by-catch economics and inter-species biomass coupling. Finally, as global temperatures rise, the transition matrices themselves may shift, increasing the frequency of bad weather states. Future work will simulate climate stress scenarios to evaluate the long-term financial viability of the Moroccan fishing fleet under altered meteorological regimes.

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