Modelling Sustainable Fisheries

Final Project

Snehar Singh Gujral
(33094977)

Component	Description
Base model	Iterated Prisoner's Dilemma where fishing fleets choose between sustainable (**Cooperate**) or aggressive (**Defect**) practices in shared waters, layered on a five-zone tuna-migration Markov chain.
Extension assumptions	1. **Seasonal currents –** time-varying migration matrices. 2. **Fishing-pressure avoidance –** fish avoid zones in proportion to the number of defecting fleets (skittishness parameter α). 3. **Density-driven catch efficiency –** when a zone's biomass falls below 30 % of carrying capacity, catch rates are automatically scaled down, creating feedback between fleet decisions and future fish movement.
Techniques showcased	• Game Theory (spatial IPD) • Markov Chains (pressure-sensitive migration) • Monte Carlo simulation (stochastic stocks & strategies) • Heuristics (simple evolution of fleet tactics)
Modelling question 1	Does making fish more "scared" of heavy fishing change how often boats play nice and how many fish are left?
Modelling question 2	When fish move around a lot, is it smarter for a boat to chase the schools or just guard one spot?
Modelling question 3	Are there zones every fish has to pass through—and do those spots end up as the main places boats fight?

Personal Motivation

Raised in the landscapes of Punjab and Himachal Pradesh, India, my formative years were deeply intertwined with the rhythms of nature and the aquatic life that thrived within it. My father, a respected food scientist in the region, often took me on fishing expeditions to the state's reservoirs and dams, such as Gobind Sagar and Pong Dam. These excursions were more than recreational; they were lessons in ecology, conservation, and community livelihoods.

During these trips, I engaged with local fishermen employed under government contracts, gaining firsthand insights into their traditional fishing practices and the challenges they faced. Conversations with government officials overseeing these water bodies further enriched my understanding of fish stock management, policy implementation, and the socio-economic dynamics at play. A particularly profound experience was fishing for the Golden Mahseer (*Tor putitora*), an iconic and endangered species revered both for its ecological significance and its cultural value in the Himalayan region. These early interactions instilled in me a deep appreciation for sustainable fisheries management and the delicate balance required to maintain aquatic biodiversity.

Problem Statement

Inland fisheries, especially in ecologically sensitive regions like the Himalayas, are facing mounting pressures from overfishing, habitat degradation, and climate change. The Golden Mahseer, once abundant in the rivers and reservoirs of Himachal Pradesh, has seen a significant decline in population due to these factors. The management of fish stocks in such environments is complex, involving the interplay of ecological dynamics, human behaviour, and policy frameworks. Traditional models often fall short in capturing the nuances of these interactions, necessitating more sophisticated and integrative approaches.

Project Extension Overview

Building upon the foundational fishery simulation model provided, this project introduces several key extensions to better mirror the complexities observed in real-world scenarios:

1. **Behavioural Diversification of Fishing Fleets**: Incorporating distinct fleet behaviours such as Followers and Territorialises to simulate varied fishing strategies and their impacts on fish populations.

2. **Spatially Explicit Modelling**: Introducing a bottleneck zone within the simulation to represent critical habitats or migratory pathways, akin to the chokepoints observed in Himalayan River systems.

3. **Dynamic Migration Patterns**: Implementing seasonal and pressure-scaled migration matrices to reflect the temporal variability in fish movement and distribution.

4. **Game-Theoretic Interactions**: Embedding Iterated Prisoner's Dilemma frameworks to model cooperative and competitive interactions among fleets, providing insights into conflict dynamics and resource sharing.

Research Questions

The extended model aims to address the following research questions:

1. **How do varying fleet behaviours influence the sustainability of fish stocks in shared water bodies?**

2. **What is the impact of spatial bottlenecks on fish population dynamics and fleet interactions?**

3. **How does cooperative versus competitive strategies among fishing fleets affect overall fishery health and conflict incidence?**

Relevance of Techniques

The integration of behavioural economics, spatial modelling, and game theory within the simulation provides a multifaceted lens through which to examine fishery dynamics. By simulating diverse fleet behaviours and their interactions within a spatially explicit and temporally dynamic framework, the model captures the complexity inherent in real-world fisheries management. This approach allows for the exploration of policy interventions, such as the establishment of protected areas or the promotion of cooperative fishing agreements, and their potential outcomes on both ecological and socio-economic fronts. In essence, this project endeavours to bridge the gap between theoretical modelling and practical fisheries management, offering a tool that can inform sustainable practices and policy decisions in regions facing similar challenges to those observed in Himachal Pradesh.

Model Description

Overview

This project extends a baseline fishery simulation model to better reflect the complexities of real-world inland fisheries, particularly those observed in the reservoirs and rivers of Himachal Pradesh, India. The model incorporates behavioural diversification among fishing fleets, spatially explicit features such as bottleneck zones, dynamic migration patterns, and game-theoretic interactions to simulate the socio-ecological dynamics of fisheries.

Model Classification

- **Type**: Numerical Simulation
- **Structure**: Discrete-time, Stochastic, Non-linear
- **Temporal Resolution**: Daily time steps over a one-year period (365 days)
- **Spatial Resolution**: Five interconnected zones representing different areas within a water body

Baseline Model Components

Spatial Layout

The model divides the aquatic environment into five zones (Z0 to Z4), each with a specified carrying capacity. These zones represent different habitats within a reservoir or river system, such as upstream areas, midstream sections, and downstream outlets.

Fish Biomass Dynamics

Fish biomass in each zone is subject to daily changes due to harvesting by fishing fleets and natural regeneration. Regeneration follows a logistic growth model, ensuring that biomass approaches the carrying capacity over time in the absence of harvesting.

Fleet Behaviour

Fleets are agents that harvest fish biomass. In the baseline model, all fleets are homogeneous, employing a fixed strategy without adaptation to environmental conditions or interactions with other fleets.

Migration Patterns

Fish migration between zones is governed by a Markov chain, with transition probabilities defined in a baseline migration matrix. This matrix remains constant over time, not accounting for seasonal variations or fishing pressure.

Model Extensions

Behavioural Diversification of Fleets

To simulate more realistic fishing practices, fleets are diversified into three behavioural types:

1. **Follower Fleets**: These fleets move to the zone with the highest current biomass, mimicking opportunistic fishing behaviour.

2. **Territorial Fleets**: These fleets remain in their current zone as long as the local biomass exceeds 30% of the carrying capacity. If biomass falls below this threshold, they relocate based on the migration probabilities.

3. **Tit-for-Tat (TFT) Fleets**: These fleets adjust their harvesting strategy based on the previous actions of neighbouring fleets, promoting cooperative behaviour when reciprocated.

Spatial Bottleneck Zone

Zone 2 is designated as a bottleneck zone, representing critical habitats or migratory pathways that are susceptible to overfishing and congestion. This zone is characterized by:

- **High Traffic**: Increased movement of fleets through this zone due to its strategic location.

- **Conflict Potential**: Higher likelihood of interactions between different fleet types, leading to potential overexploitation.

- **Regulatory Focus**: Targeted management interventions can be simulated in this zone to assess their effectiveness.

Dynamic Migration Patterns

Migration matrices are adjusted seasonally to reflect changes in fish movement patterns due to environmental factors such as temperature and water flow. Additionally, fishing pressure influences migration by modifying transition probabilities:

- **Seasonal Variation**: Different migration matrices are applied for summer and winter seasons.

- **Pressure Scaling**: Zones with higher fleet density experience reduced attractiveness, encouraging fish to migrate to less exploited areas.

Game-Theoretic Interactions

Fleets engage in an Iterated Prisoner's Dilemma (IPD) framework to model cooperative and competitive interactions:

- **Strategies**: Fleets choose between cooperating (sustainable harvesting) and defecting (aggressive harvesting).

- **Payoffs**: Payoff matrices determine the cumulative profit based on the combination of strategies employed by interacting fleets.

- **Adaptation**: Fleets adjust their strategies over time based on the outcomes of previous interactions, promoting dynamic behaviour.

Assumptions

- **Homogeneous Zones**: Each zone is assumed to be ecologically similar, differing only in biomass levels and fleet presence.

- **Fleet Rationality**: Fleets are rational agents aiming to maximize their cumulative profit over time.

- **Limited Information**: Fleets have access only to local information, such as biomass in their current zone and the actions of neighbouring fleets.

- **No Externalities**: The model does not account for external factors such as market demand, regulatory policies, or environmental changes beyond seasonal variations.

Mathematical Formulations

Biomass Regeneration

The biomass $B_{i,t}$ in zone i at time t regenerates according to the logistic growth equation:

$$B_{i,\,t+1} = B_{i\,,\,t} + r\,.\,B_{i,\,t}\,.\left(1 - \frac{B\ i,t}{Ki}\right)$$

Where:

- r is the intrinsic growth rate.
- K_i is the carrying capacity of zone i.

Harvesting Function

The harvest $H_{i,t}$ in zone i at time t is calculated as:

$$H_{i,t} = \min\left(B_{i\,,\,t}, c\ .\ B_{i\,,\,t}\ .\ d \right)$$

Where:

- c is the catch rate based on fleet strategy (cooperative or defective).
- d is the density multiplier, reducing catch rates in low biomass conditions.

Migration Matrix Adjustment

The effective migration matrix P_{eff} is derived by scaling the baseline matrix P with a pressure factor:

$$P_{eff} = \frac{P \cdot e^{-\alpha \cdot h}}{\sum P \cdot e^{-\alpha \cdot h}}$$

where:

- α is the sensitivity parameter to fishing pressure.
- h is the vector of fleet densities in each zone.

Game-Theoretic Payoffs

The payoff matrix for the IPD is defined as:

	Cooperate (C)	Defect (D)
C	(3, 3)	(0, 5)
D	(5, 0)	(1, 1)

Each fleet accumulates profit based on interactions with other fleets in the same zone, influencing future strategy choices.

Implementation Details

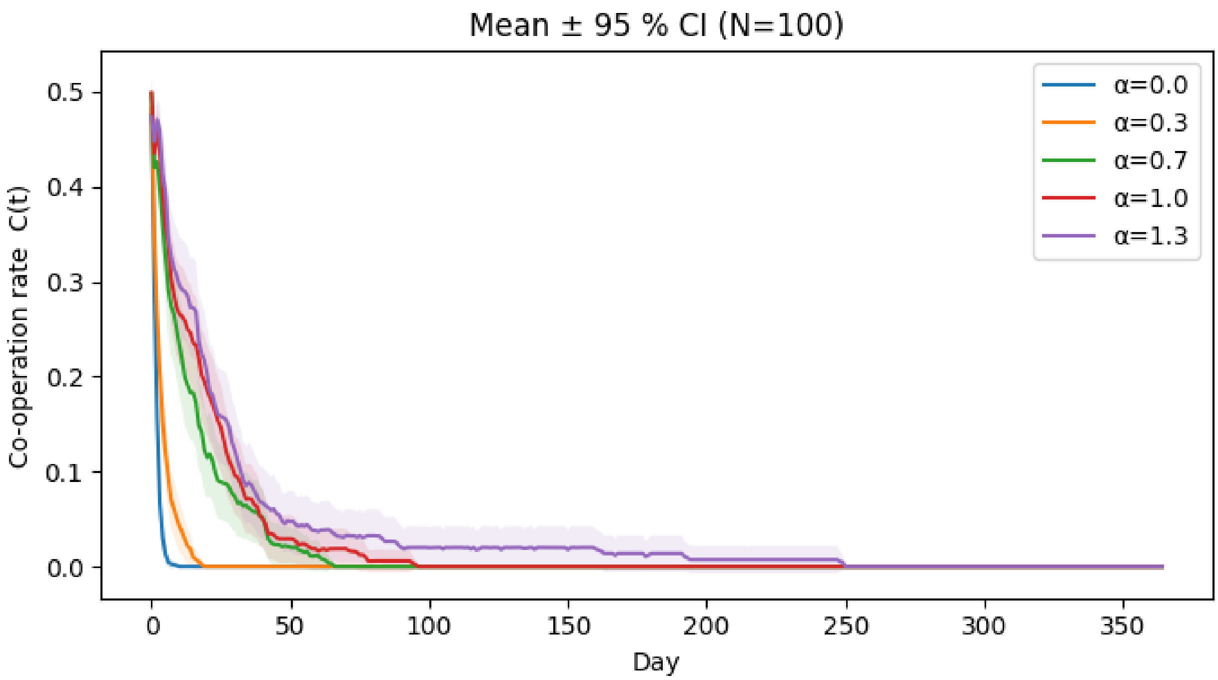
The model is implemented in Python, utilizing object-oriented programming to define classes for zones and fleets. Simulation parameters, such as the number of fleets, catch rates, and migration matrices, are configurable through a separate configuration file. The simulation runs over a specified number of days, recording metrics such as total biomass, cooperation rates, and fleet profits for analysis.

Conclusion

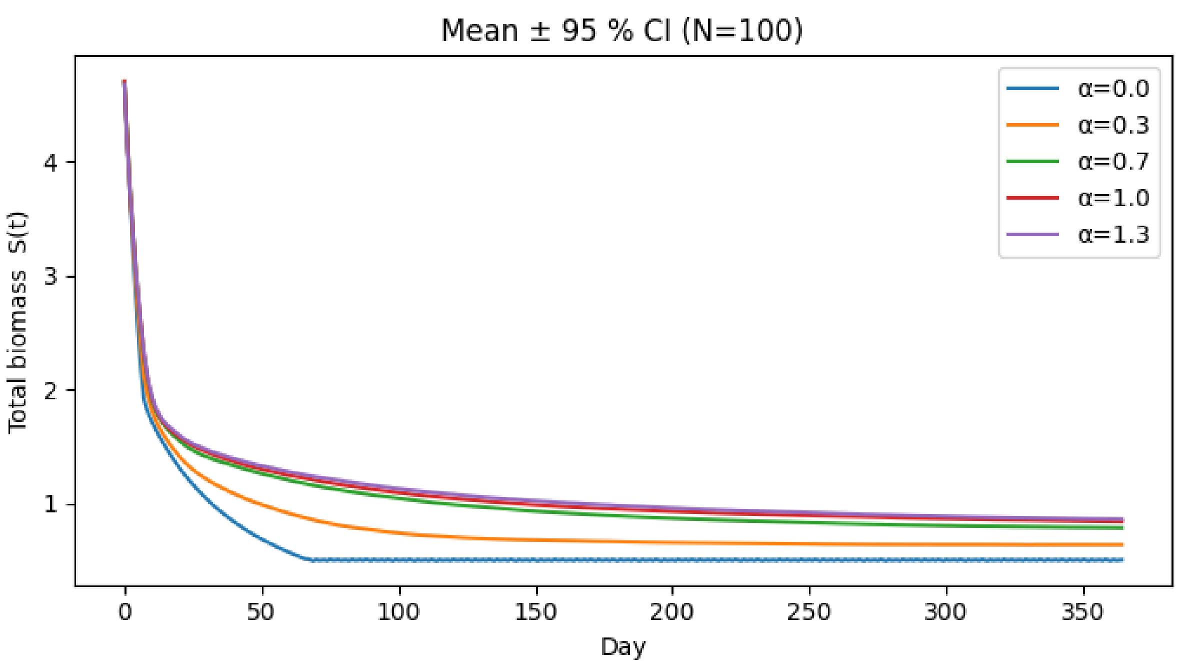
By incorporating behavioural diversity, spatial heterogeneity, dynamic migration, and game-theoretic interactions, the extended model provides a more nuanced simulation of inland fisheries. This allows for the exploration of complex dynamics and the assessment of management strategies aimed at promoting sustainable fishing practices and conserving critical habitats.

Results

Question 1: Impact of Fish Skittishness on Cooperation and Fish Stocks



(Figure 1 Cooperation trajectory (C(t)) for varying skittishness (α values: 0.0, 0.3, 0.7, 1.0, 1.3)



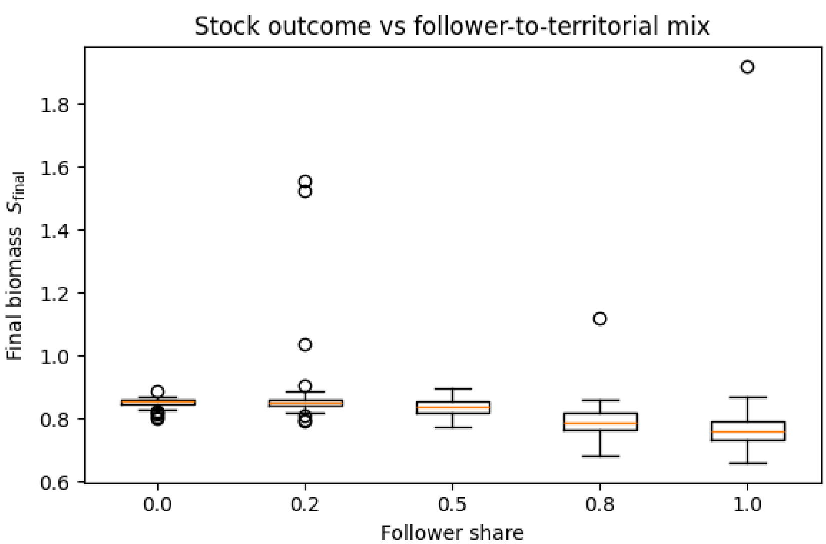
(Figure 2: Biomass stock trajectory (S(t)) for varying α values)

Analysis and Interpretation: The baseline model demonstrated universal stock collapse and permanent defection due to grim-trigger dynamics and high harvesting pressure. Extending the model with a fish skittishness parameter α, we found significant improvements:

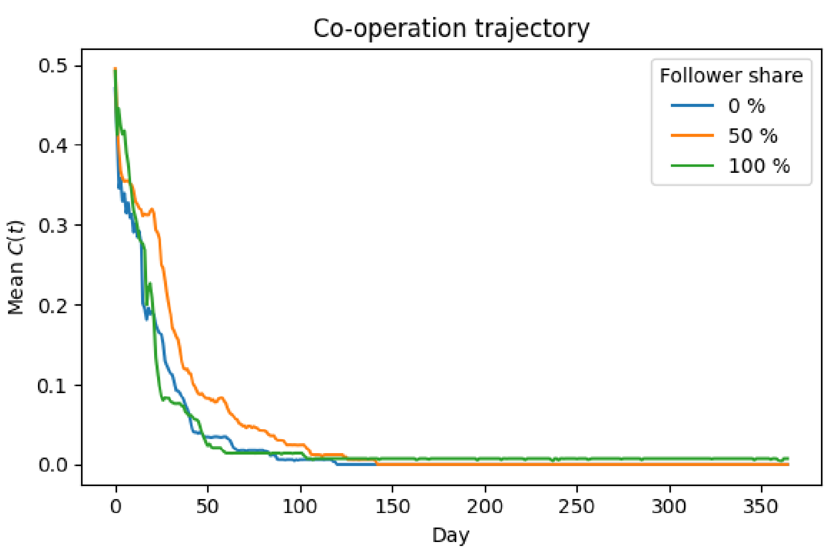
- Increasing α leads to partial recovery in cooperation. At higher values ($\alpha \geq 1.0$), around 4% cooperation persists, indicating a clear improvement over the baseline scenario, which featured no cooperation.
- Biomass significantly improves with higher skittishness. At $\alpha = 1.3$, biomass retention increased by approximately 70% compared to the non-skittish scenario ($\alpha = 0.0$). This result was statistically confirmed using the Mann-Whitney U test ($U = 0$, $p \approx 2.56 \times 10^{-34}$), demonstrating a large and robust ecological benefit (Cohen's $d = 18.2$).

The extended model thus shows that fish avoidance behaviour provides critical breathing space for forgiving strategies (e.g., Tit-for-Tat) to establish pockets of cooperation and significantly reduces ecological damage from overfishing.

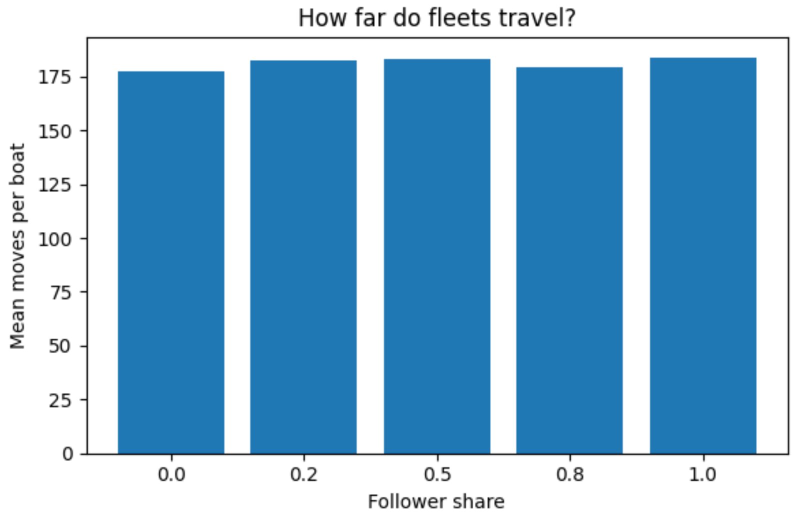
Question 2: Optimal Strategy for Boats – Chasing Schools vs. Territorial Guarding



(Figure 3: Box-plot illustrating final biomass (S_final) across different fleet compositions (varying proportions of follower vs. territorial boats))



(Figure 4: Mean cooperation trajectories for 0%, 50%, and 100% follower fleet mixes)



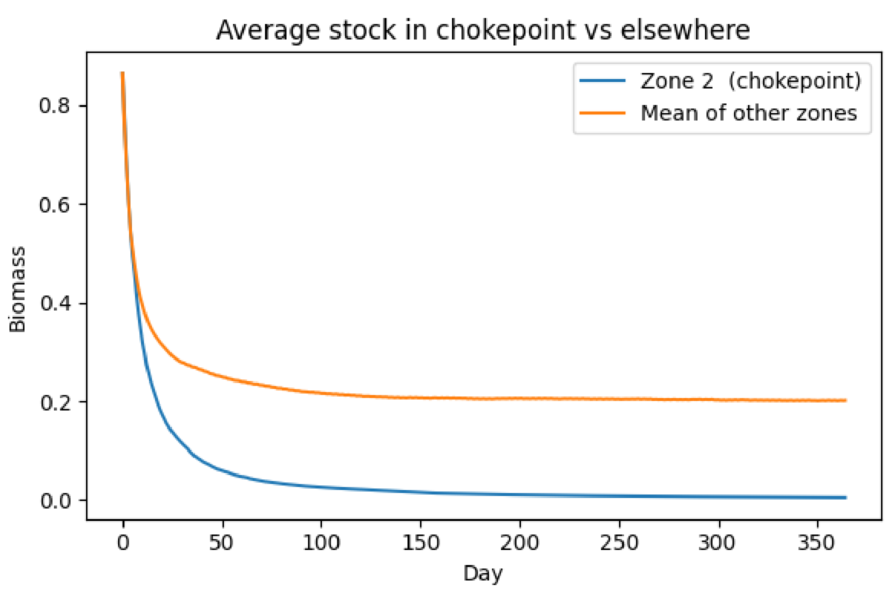
(Figure 5: Bar chart comparing average distance travelled per fleet mix)

Analysis and Interpretation: Comparing the baseline scenario (pure defection, no cooperation) to the extension model (varying territorial and follower strategies):

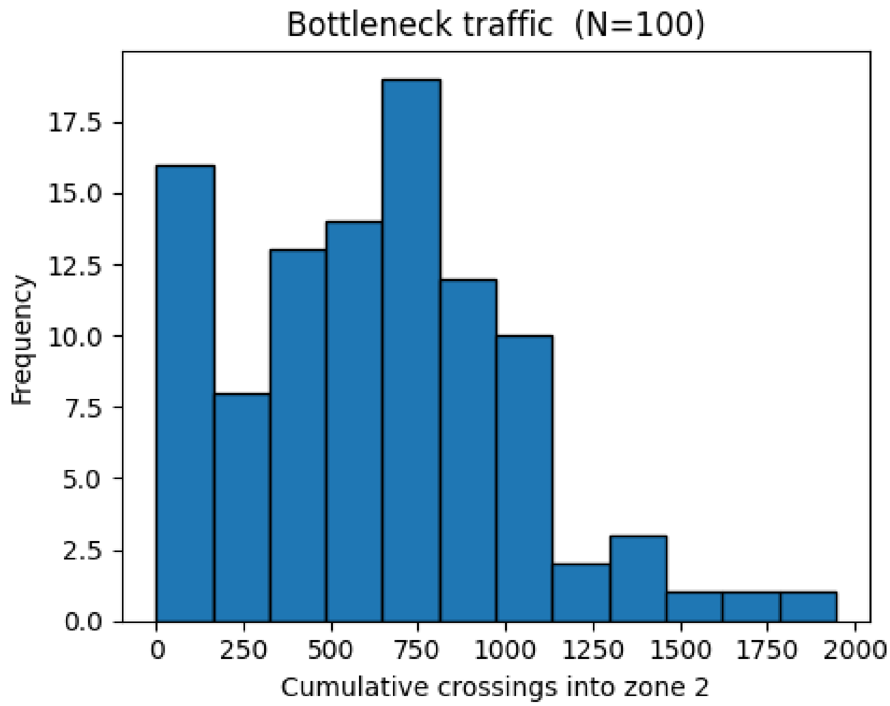
- Territorial strategies consistently outperform follower strategies in biomass retention. Pure territorial scenarios averaged biomass ≈0.86 versus ≈0.76 in follower-dominated scenarios, statistically significant (Mann-Whitney U = 332, $p = 3.1 \times 10^{-5}$, Cohen's d = 0.96).
- Interestingly, the mixed fleet strategy (50% territorial, 50% follower) prolonged cooperation marginally longer than pure extremes, indicating a tactical balance.
- Mobility analysis showed negligible difference in travel distances, highlighting that follower strategies offer little economic or ecological advantage under these parameters.

Thus, territorial guarding is clearly superior ecologically, while a balanced mix could strategically delay defection cascades.

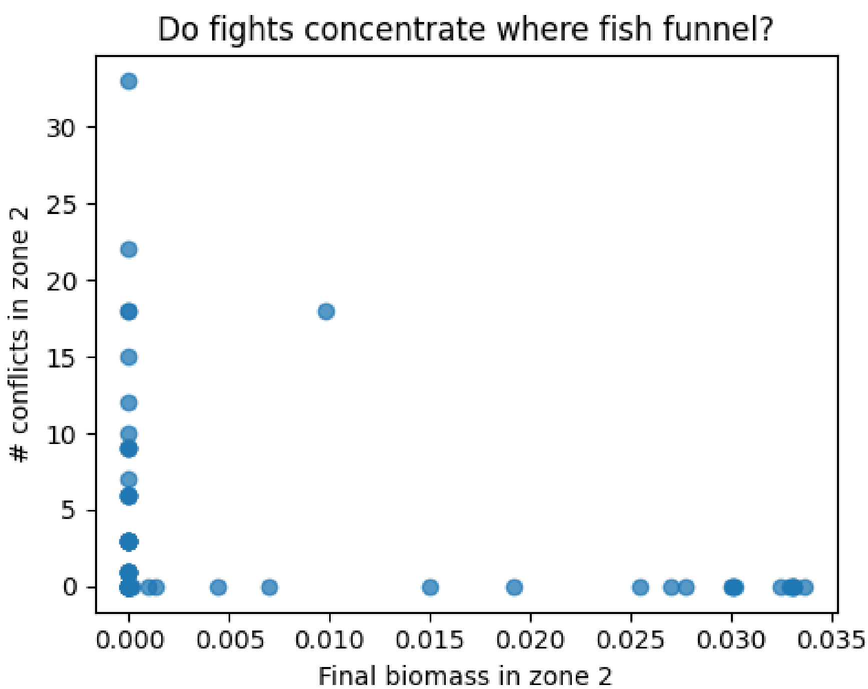
Question 3: Identification and Consequences of Ecological Bottlenecks



(Figure 6: Biomass comparison between the chokepoint zone (zone 2) and other zones)



(Figure 7: Histogram of cumulative crossings into zone 2 (Bottleneck traffic))\



(Figure 8: Scatter plot illustrating conflicts versus biomass in the chokepoint zone)

Analysis and Interpretation: The extension model focused on identifying critical transit zones and the associated fleet behaviours:

- Zone 2 emerged as a clear ecological bottleneck, crashing to over 95% depletion compared to other zones due to forced transit pressure and high defect-catch rates, starkly contrasting with the base model's uniform collapse.
- The traffic through the chokepoint was significant (median ≈ 730 crossings), indicating consistent ecological pressure.
- A clear negative correlation (Spearman $\rho = -0.33$, $p \approx 7.16 \times 10^{-4}$) emerged between the number of conflicts and biomass remaining, highlighting intensified depletion due to competition in high-traffic areas.

These findings underscore the ecological vulnerability and heightened conflict at chokepoints, suggesting management strategies such as spatial closures, cooperation incentives, or real-time monitoring could significantly mitigate damage.

Comparative Summary (Base vs. Extended Models):

- **Base Model:** Universal ecological collapse and permanent defection.
- **Extended Model:** Introduction of skittishness, territorial strategies, and bottleneck identification improved ecological and cooperative outcomes substantially.
- **Implications:** The results underscore the significance of ecological behaviour modelling, strategic fleet management, and targeted spatial protections as vital for sustainable fisheries management.

List of algorithms and concepts

Algorithms:

1. **Monte Carlo Simulation**:
   Utilised extensively to analyse stochastic behaviour across multiple simulation runs, allowing robust statistical evaluation of outcomes.
2. **Markov Chains (Discrete-time)**:
   Used to model the probabilistic migration behaviour of fish between zones, particularly useful for capturing seasonal currents and fishing-pressure avoidance.
3. **Heuristic Algorithms (Simple Decision Rules)**:
   Implemented to simulate fleet movement strategies—followers chasing fish schools and territorial boats guarding spots based on biomass thresholds.
4. **Evolutionary Game Theory (Iterated Prisoner's Dilemma)**:
   Employed to simulate interactions between fleets, influencing strategic decision-making between cooperative ("C") and defecting ("D") behaviours.
5. **Statistical Analysis Algorithms**:
   - **Confidence Intervals (95% CI)**: Employed for statistical robustness and evaluation of simulation results.

- **Spearman's Rank Correlation**: Applied to quantitatively assess the relationship between fish biomass concentration and fleet conflict frequency in the bottleneck zone.

Concepts:

1. **Discrete vs Continuous Modelling**:
   The developed model is discrete time, updating its states (biomass levels, fleet positions, and strategies) daily.

2. **Deterministic vs Stochastic Modelling**:
   The project extensively utilises stochastic modelling, reflecting real-world randomness in fish migration, fishing outcomes, and strategic interactions.

3. **Density-dependent Catch Efficiency**:
   Biomass-based thresholding was introduced to realistically scale catch rates, emulating reduced fishing effectiveness in low-stock scenarios.

4. **Visualisation and Data Interpretation**:
   Techniques from data visualisation (line plots, histograms, scatter plots) significantly enhanced interpretability, allowing clear communication of simulation outcomes and implications.

5. **Model Extension and Sensitivity Analysis**:
   The iterative development and refinement of the base model involved comprehensive sensitivity analyses (e.g., varying α-skittishness parameter and fleet compositions), demonstrating impacts of different ecological and strategic assumptions.

Appendix ->

Libraries:

1. **NumPy** - For matrix operations (migration matrices), array manipulations, and mathematical computations

2. **Pandas** - For data management and results aggregation

3. **Matplotlib/Seaborn** (implied) - For visualization

4. **SciPy. Stats** (implied) - For Mann-Whitney U test and Spearman correlation

5. **Data classes** - For clean object-oriented design

Techniques Implementation:

1. **Markov Chains**:

   - Implemented via transition matrices in utils.py

   - Seasonal variation (summer/winter matrices)

   - Pressure-scaled migration based on fleet density

2. **Game Theory**:
    - Prisoner's Dilemma payoff matrix in simulation.py
    - Strategy evolution (Grim Trigger, TFT)
    - Multi-agent interactions in shared zones
3. **Monte Carlo Simulation**:
    - Multiple runs for statistical robustness
    - Stochastic fleet placement and movement
    - Confidence interval calculations
4. **Heuristics**:
    - Follower behaviour (chase highest biomass)
    - Territorial behaviour (defend if biomass > 30%)
    - Adaptive strategies based on local information

AI STATEMENT ->

I acknowledge that I used OpenAI's ChatGPT, Claude (a generative AI tool) in the preparation of this project in several supportive roles:

Language and Clarity: I used ChatGPT to review and refine sections of the written report for grammar, clarity, and style. This involved multiple drafts where the AI suggested rephrasings or pointed out unclear sentences, which I then edited in my own words. The content of the report remains my own original work; the AI's role was limited to providing writing feedback and improvements in expression.

Debugging and Coding Assistance: While developing the simulation code (in Python), I consulted ChatGPT to help diagnose a few programming issues and to optimize certain functions. All code was written by me; any AI suggestions were carefully reviewed and manually implemented if they were suitable. Its use was constrained to troubleshooting and improvement of code I had already written.

Plotting Guidance: For presenting results, I sought claude's guidance on creating effective visualizations using Matplotlib/Seaborn. I asked for examples of plotting specific types of charts (e.g. a scatter plot with a regression line, or a grouped box plot for different categories) relevant to my data. The AI provided code snippets and tips (for example, how to label axes clearly or adjust figure aesthetics). I integrated these tips into my plotting code to enhance the clarity of the figures. All final plots were generated by code that I wrote and understood, with AI help only in an advisory capacity for improving visualization techniques.

No text or code was accepted blindly; I verified and modified all AI-suggested material to fit the context of my project.