Modelling Fisheries: A Multi Agent Approach to Modelling Trophic Cascades

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Abstract

We propose a novel, multi agent model for the modelling of fisheries and fishery policy. We describe each of the model's four types of agent and present a process by witch its parameters may be tuned to reflect real-world conditions. Finally, we present the findings of one of the experiments used to validate our model, where it is successfully used to reproduce a top-down trophic cascade based on the one observed in the Aleutian archipelago from 1986 to 2000. Our model consistently reproduces the desired effect, albeit in a reduced capacity.

Introduction & Background

In recent years, agent-based models (ABMs) have gained considerable traction in various academic fields, a newfound prominence attributed to the ongoing collaboration between social, ecological, and computer scientists [3]. Techniques such as ABM can play a key role in filling knowledge gaps and serving as 'virtual laboratories' for exploring causal hypotheses. This is especially relevant in the study of ecology, as real-life experimentation with ecosystem management is often infeasible or unethical [4]. Rather than attempting to reproduce the behaviour of one intelligent agent, ABMs focus on simulating many heterogeneous agents, the aggregate of which models a complex system, and often rely on theories from physics, the science of complexity and the social sciences [3].

Fisheries are complex coupled natural-human systems. The impact of fisheries on the ecosystem can be directly determined using the quantitative indicators of how much fishing occurs (the number of vessels, their size, and frequency with which they fish); however, the most crucial impact comes from fishery management systems [4]. These regulations commonly represent any factor that may impede or increase access to a resource. Their goal is to control the exploitation of fishery resources to achieve outcomes such as profit maximisation and sustainable usage [5].

Models (particularly ABMs) of fisheries are important tools for informing these regulations. They allow researchers and policymakers to make predictions about the response of industry and fish populations to the complex interactions of natural and social systems. Advances in computation have enabled the construction of ABMs capable of modelling fisheries in great detail. These models are based on explicitly describing individual agents' behaviour to understand and predict their aggregate behaviours. ABMs allow us to understand examples of high complexity such as ecosystem [4]. The authors of Fisheries ABM Review [4] have described three directions for research on ABMs of fisheries, one of which we successfully used in our model. We drew on their work extensively when tackling joint development and application challenges that arise in applying ABMs to study human participation in fisheries.

Related Work

The authors of [8] provide one of the best examples of how ABM driven fishery study can impact real-world policy and ecosystem dynamics. The U.S. West Coast groundfish fishery was declared an economic disaster in 2000. Over the last two decades, researchers managed to significantly reduce over-fishing and move towards a sustainable rate of exploitation. Furthermore, the study also observed the successful rebuilding of certain over-fished species, despite being exceedingly complex and costly [8].

In [4], researchers used an exemplary model, called POSEIDON, to demonstrate how salient strategic advances with this model could lead the way to increased tactical usage of ABMs in fishery management settings. Using [4] as a reference, our model has a similar basis to that of POSEIDON but differs in both scope and focus. Compared to agent-based models of comparable scope, our model focuses more heavily on the fisheries ecosystem, abstracting away many of the complexities present in the economic aspect of fishery policy. To the best of our knowledge, our model is the only model of comparable complexity that represents an entire vertical slice of the ecosystem while maintaining a high degree of generality.

Methodology

The principal aim of our project was to implement a model capable of faithfully recreating behaviours exhibited by marine ecosystems under sustained human exploitation. The simple two species ABM created by Hiroaki Sayama [1] served as a baseline, to which additional agents, smart agent behaviour and additional tunable parameters were added. We also implemented a substantial testing harness for experimental validation. The model itself and the code used for testing and analysis are available in the project repository [2].

MODEL DESIGN

In line with other ecological ABM's, our model is relatively high level, with numerous simplifying assumptions. The fishery is represented as a constrained 2D plane populated with four classes of agent. These are autotrophic producers, mesoconsumers, apex predators, and fishing trawlers (named after their trophic roles). Each population of agents (with the exception of fishing trawlers) has its growth bounded logistically. This is done to represent factors other than food that are likely to affect its behaviour. The behaviours of our model emerge from the properties of these agents and their interaction which are as follows:

- **Autotrophic Producers:** These agents do not require food to reproduce and spawn uniformly throughout the model universe.
- **Mesoconsumers:** These agents must eat autotrophic producers to survive and are in turn prayed upon by the apex predators. They reproduce through mitosis.
- **Apex Predators:** Behave similarly to mesoconsumers, but have no natural predators.
- **Fishing Trawlers:** Move at an even rate through the model universe, catching a percentage of each species they pass over. The exact percentage caught can be adjusted on a per species basis.

In addition to this, mesoconsumers and apex predators can be set to exhibit optional 'smart' behaviour. If this feature is enabled each will move towards prey or away from predators withing a certain range representing their sight.

MODEL PARAMETERS

Due to the general nature of our model, a large list of parameters were made available for tuning. The full list of these is omitted for brevity but can be found in Appendix A along with descriptions of their function. Initial behavioural parameters used for our experiments were determined through a search process based on the principles of pattern-oriented modelling (POM) [6]. POM is a common modelling practice in ecology, where model parameters are determined based on observed behaviours in real-world agent counterparts. This stands in contrast to traditional approaches, where parameters are fit to measured values and circumvents the issue of faithfully representing time-spans common to ABM. In our case, this took the form of behaviours such as slow reproduction rates and high endurance of predators. The search process aimed to fulfil the following constraints:

1. All three agent populations should remain stable after 500 generations (no species rendered extinct).
2. Population levels should stabilise substantially below their respective logistic growth caps (to avoid constraining potential dynamic changes).
3. Agents' behaviours should resemble the patterns of their real-world counterparts to the greatest degree possible.

Initial parameters used for our experiments can be found in Appendix A.

TROPHIC CASCADES

We will now present the results of one the experiments used to validate our model. In it we attempted to reproduce a three species trophic cascade, where the sustained over-exploitation of an apex predator species indirectly lead to a sharp rise in the population density of a species lower down the food chain (in the literature, this phenomenon is known as 'top-down forcing' [11]). Specifically, we attempted to emulate the trophic cascade observed in the Aleutian Archipelago between the years 1986 and 2000 [10]. In this scenario, a declining population of sea otters (due to human exploitation) had a radical effect on the population of sea urchins (their typical food source) and indirectly affected the population density of kelp in the area (the primary food source of the urchins). Although the study considers an additional trophic role, that of rock greenlings, several compelling factors make it an appropriate choice for our purposes. Firstly, the rock greenlings were affected indirectly, as their only interaction with the other species is as a consumer of kelp. Secondly, the archipelago's biodiversity is relatively low (the total biomass of different fish species is only a fraction of that of the rock greenling), meaning the data is likely to contain far less noise than would typically be present. Finally, this ecosystems has been well documented over the years, acting as a 'drosophila' of sorts in the study of trophic cascades and ecosystem dynamics [9]. As a result, we were able to draw on ample sources of additional data for parameter tuning.

EXPERIMENTAL DESIGN

The logistic caps for the populations of kelp (autotrophic producers), and sea urchins (mesoconsumers) were set to the ratio of the number of individuals per square meter in the vicinity of the Attu islands. Although the final population of apex predator agents was considerably higher than that of sea otters on the archipelago [7], this was deemed acceptable due to their high mobility of otters compared to the other species (many individuals are likely entering and leaving a specific area at any one time). Additional behavioural parameters were determined according to the method set out in the previous section and are available in Appendix A.

The resulting parameters, were tested on a batch of 30 runs and were found to be stable $86.\overline{66}\%$ of the time. Notably, the ratio of stable populations of model agents (producers to mesoconsumers) was greater than that of their respective caps, and closely resembled that found on the Amchitka islands in 1986 [10].

Species	**p-value**
Sea Otters	$2.15 * 10^{-10}$
Sea Urchins	$1.25 * 10^{-7}$
Kelp	$3.07 * 10^{-15}$

Table 1: Results of paired student t-test to determine equality of means for species' populations before and after cascade.

To simulate increased exploitation of otters, the apex predator throwback rate (probability of surviving an encounter with a fishing trawler) was decreased from 100% to 80% mid simulation. A constant unsustainable rate of exploitation was expected to produce an approximately linear decline in the average population of otters (reflective of that observed in the case study). Although possible, higher exploitation rates were found to have a significant detrimental impact to the stability of the simulation. An example of such a simulation can be seen in Figure 1 (the beginning of exploitation is denoted by the dashed line). Populations are plotted as a moving average of 150 time steps to reduce noise and highlight general trends. The effects of the trophic cascade are clearly visible as increases in the average population of urchins and decreases in that of otters and kelp (in the latter, these are somewhat harder to see). A relatively long simulation was chosen to showcase large fluctuations in population size typical of our model (on of these can be seen around time-step 700 in Figure 1).

Due to the large quantity of such noise, a further experiment was conducted at these parameters to determine the cascade's typical scope and prove the effect can be reproduced. A sample of 30 simulations of 600 time-steps in length with trophic cascades induced at the 300^{th} time-step was conducted. Of these, two resulted in the collapse of the ecosystem and were subsequently discarded. Six measurements were taken from each of the remaining 28 samples corresponding to the stable population sizes before and after the cascade (calculated as the mean population of the first and last 300 simulations, respectively). The measured changes in stable population rates are displayed in Figure 2. Notably, all three populations settled at stable rates significantly below their respective caps. The stable population rate of otters was found to have decreased by an average of 29.6%, of urchins to have increased by 11.3% and of kelp to have decreased by 2.5%. A student t-test was conducted on each pair of samples to confirm the significance of these results (Table 1).

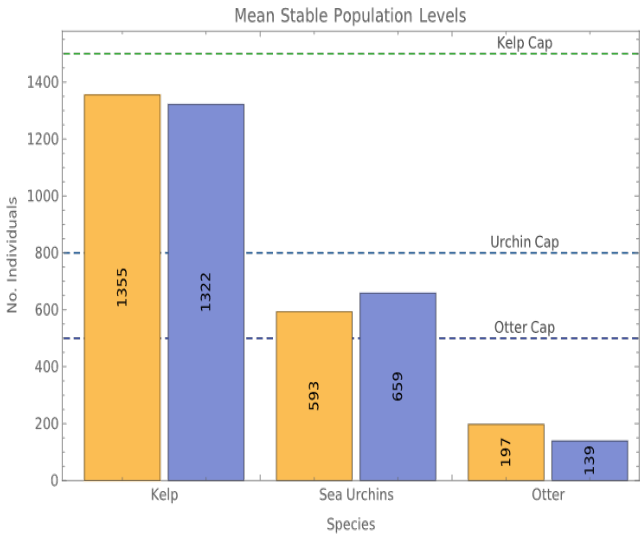

Figure 2: Visualisation of the average observed effect over an ensemble size of 30

CONCLUSION

The scope of the effect reproduced in our model differs greatly from that presented in the selected study (where kelp populations decreased by as much as 10 times). Upon closer observation of our model's behaviour, it appears that the perturbations to stable population levels diminish as they move down the food chain. A likely cause for this is the logistic growth limit of our model's agents, which appears to keep populations at the extremes. Regrettably, attempts to correct this issue (by, for example, moving to a linear growth rate) proved largely unsuccessful. In light of this, our model's numerous assumptions and the unavoidable discrepancies between model and real-world parameters, it would appear our model has low predictive value when it comes to specific ratios of populations. Although the discrepancies observed in this regard were larger than initially expected, this is un-

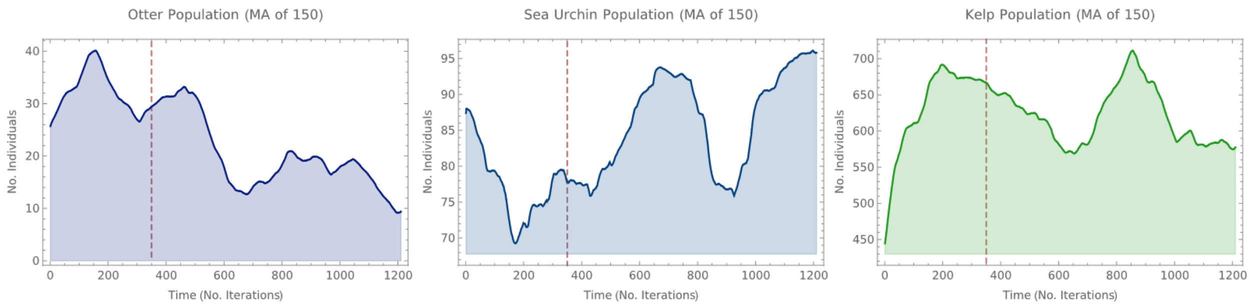

Figure 1: Example of a trophic cascade induced in our model. The dotted line indicates the beginning of sea otter exploitation.

surprising for models of this sort [4]. In contrast to our model's low tactical value, it has been shown to be capable of producing predictable and consistent results on a more abstract level. This points towards its potential strategic value for modelling trophic relationships and predicting general trends. In this regard, the validation process has proved successful.

Future Work

In addition to the experiments presented here, research was conducted into the model's ability to simulate the effects of bycatch and overfishing. Although these explorations yielded some initial success, it is omitted in the interest of brevity. Future work could seek to expand the repertoire of agents, allowing it to model a more comprehensive section of the food web. Additionally, not all large scale fishing is done through trawling and other methods such as the use of pots and cages could increase the power of our model for representing those circumstances. Finally, during experimentation, our model was found to be computationally expensive. Further research would therefore greatly benefit from parrelelisation, such as is provided by gridMathematica.

References

[1] A copy of this project has been made available by the Wolfram foundation at: `http://demonstrations.wolfram.com/` Accessed: 05/05/2021.

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Appendix A: Model Parameters for Trophic Cascades

The following table contains the model parameters originally elicited for Section 1. Note that algae, sardines and sharks are nicknames given to producers, mesoconsumers and predators used during development. All spatial parameters are provided as a fraction of the width of the simulation universe.

Parameter Name	**Description**	**Value**
maxAlgae	Logistic growth cap for producers.	1500
maxSardines	—"—	800
maxSharks	—"—	500
algaeGrowthRate	Producer growth rate.	0.725
sardineGrowthRate	—"—	0.455
sharkGrowthRate	—"—	0.15
sardineMobility	Maximum mesoconsumer movement per generation.	0.06
sharkMobility	—"—	0.068
sardineEndurance	Number of generations mesoconsumer can survive without food.	10
sharkEndurance	—"—	15
tSpawnRate	Average number of generations between trawler spawns.	5
tSpeed	Trawler movement per time-step.	0.1
tSize	Trawler size (long diagonal)	1
targetAlgae	Probability of producer caught (passed over) by trawler being killed. This parameter represents trawler efficiency.	0.99
targetSardines	—"—	0.99
targetSharks	—"—	0.5
smartSharks	Enable smart hunting behaviour for apex predators.	True
smartSardines	Enable smart evasion for mesoconsumers.	True