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Impact of Gear Choice on Open Access Fisheries: A Study on Fishery Regimes

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Impact of Gear Choice on Open Access Fisheries: A Study on Fishery Regimes *

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Abstract

The regulation of gears constitutes a fisheries management strategy primarily aimed at preserving immature fish. This approach circumvents the politically sensitive and difficult-to-enforce direct restrictions on entry and catches that characterize many developing contexts. However, existing recommendations often oversimplify socioeconomic dimensions and assume complete government control over gear selection. This oversimplification overlooks crucial effects resulting from the fishers' agency. To address this gap, our study highlights the implications of fishing gear selection in the outcomes of a fishery. We propose that the choice of fishing gear, i.e., the ability of fishers to select for different fish sizes, has significant direct implications for management due to the distinct fishery regimes it leads to. A swift transition between two states characterizes these regimes: one with high output value and a significant proportion of fishers targeting large fish, and the other with low output value and a predominant number of fishers aiming for small fish. These regimes emerge in response to contextual variables such as prices and economic activity and are not a product of government intervention. Policy management operates on top of these regimes, taking advantage of or hampered by them depending on the context. Our findings are derived from an agent-based model replicating the general conditions on the Nile Perch Fishery in Lake Victoria and accurately simulating its age-structured fish stock. This allows for dynamic shifts driven by gear choices that target different fish sizes.

Keywords: Gear Selectivity; Gear Choice; Agent Based Modeling; Nile Perch Fishery, Lake Victoria.

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1 Introduction

Designing better management policies for a Fishery is a complex endeavor. This is particularly true in developing contexts in which the states' weak policy enforcement capacity impedes the implementation of traditional fisheries management instruments, such as those combining entry restrictions and quota settings (Ostrom, 2008; Costanza et al., 2014). In this paper, we take the case of Lake Victoria, in East Africa, as an illustrative example. Lake Victoria management institutions have focused on gear restrictions (LVFO, 2016; Njiru et al., 2008, 2018). Focusing on gear restrictions facilitates the government's effort to enforce regulations, as it is easier to check than quantities extracted, particularly in a Lake characterized by a wide dispersion of landing sites over the 7 142 Km shore length of the Lake (Hamilton, 2018).

While there is an open discussion about the extent to which current measures have been successful Nunan (2020); Cepić and Nunan (2017); Obiero et al. (2015), the debate still focuses on the type of mechanism that could help improve these gear regulations more than on changing the paradigm to one based on entry restrictions and quotas (Aura et al., 2020; Mpomwenda et al., 2022; Diekert et al., 2022). This paper takes it as a given that governments focus on regulating gears. In particular, we analyze how the fishers' agency in choosing their gear affects the potential of gear regulating policies.

One of the most used tools to aid policy decisions is modeling approaches that aim to capture the most fundamental relations in a fishery. Most modeling approaches in Lake Victoria are based on providing a high resolution of the below water activity (Kammerer et al., 2022; Nyamweya et al., 2016) and a straightforward take on the way fishing effort happens. In particular, L.V. models share the assumption that the level of effort is an exogenous variable that can be changed to any desired level by an appropriate policy. Recent results suggest shifting the fishery to target larger sizes will improve the fishery outcomes, bringing a higher value with a more sustainable fish stock (Kammerer et al., 2022; LVFO, 2016). This approach has led to an increase in regulation enforcement, with a high point reached when the Uganda army patrolled their waters.

This paper improves on previous modeling approaches that use an exogenous setting of the fishing effort by providing an endogenous fish effort choice in two dimensions. The first dimension refers to an entry and exit decision, i.e., fishers freely decide whether or not to implement a fishing trip. The second dimension refers to gear choice, i.e., fishers freely decide which gear they use in their fishing trips. By modeling these two dimensions, we can uncover dynamics not present in previous models of L.V. fisheries. Consequently, this improved approach allows us to think about gear policies not as a fully enforceable regulation but, in a general way, as a change in the incentives fishers have to make their choices (Becker, 1968; Nøstbakken, 2008). This is done by developing an agent-based model that runs on top of size/age-structured fish stock dynamics.

This paper starts by providing an overview of the components of the model and its structure. It continues by showing its outcomes, particularly the emerging nonlinear dynamics it produces. A simple and general approach to gear regulation is implemented using this as a background. This allows us to understand how the inherent dynamics of the coupled socio-ecological system respond to gear policy. This exercise shows the inherent limits present in the system that can help or deter a gear policy from reaching its objectives.

2 The Model

We built a model based on two components: an ecological and a socioeconomic one. The ecological component essentially discretizes and simplifies the continuous age structure model developed in Johannes (Kammerer et al., 2022). The socioeconomic component is composed of a set of individual boats. Each period each one decides between either fishing or not and, conditional on fishing, choose between two different available gears.

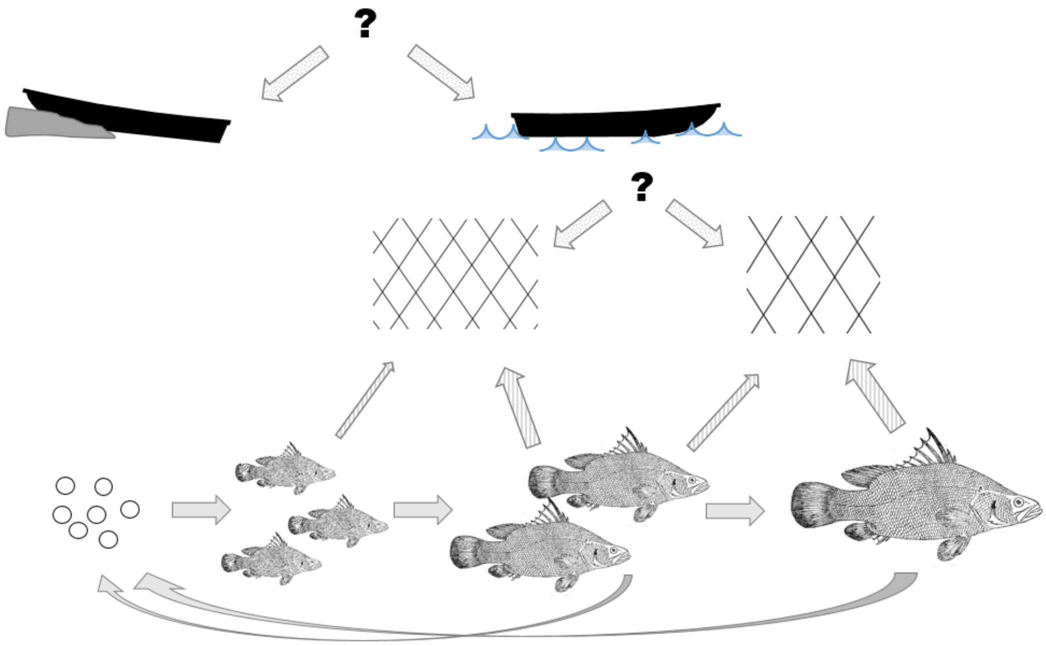

Figure 1: Model's Basic structure. Fish hatch from eggs; they grow between periods, and as they do, some individuals are lost either due to fishing or natural death. Once fish reach a minimum size, they begin laying eggs that replenish the population. Each agent in the model represents a boat. They decide whether to stay on land or go fishing during each period. If they go fishing, they must decide to use either a small-sized net, targeting small fish, or a larger net, targeting large fish.

Choosing a different gear implies targeting a different fish size spectrum. Importantly, there is a partial overlap between the available gears. The ecological and socioeconomic components are linked through the extraction produced by fishing boats in each period.

2.1 Building Blocks

The model is based on discrete periods, each representing a tenth of a year (36 days). At the start of each period, there is a given stock and a number of boats that will target this stock. Each boat can use two different gear types that target larger or smaller fish, respectively. Fishing activities are governed by a stochastic process determining the outcome for each boat. Fish are caught independently by each boat from the population at each size. Fish, at each possible size/age, are more likely to be caught if there are more individuals and if there is a higher efficiency of the gear used for that particular size. Boat sell their fish and pay for their inputs. The average profit boats made with each gear is public information. Each boat/agent uses their outcomes and the average catch information to decide whether to fish and what gear to use in the next period. After the fish population is updated by subtracting those captured by the boats, some fish die from natural causes, and the surviving ones grow for one period. Eggs are spawned by fish that reach reproductive age. From eggs, fingerlings are hatched, replenishing the fish, starting at the smaller size/age category in the next period. These last processes set the stage for the next period by defining the stock, i.e., the number of heads at each size/age and the fishing decisions to be implemented by each boat. The model runs until there are no changes in the aggregate variables of the model, i.e., the stock structure is fixed, and the proportion of boats doing one or another does not change.

This model has the following exogenous parameters. First, a fixed number of boats. Setting the number of boats to a high enough level guarantees that there is always a positive number of boats that are not fishing. This avoids a corner solution in which more boats could enter, but there are no more to do it. Second, two different available gears. Boats can choose only from two different gears; each gear has a different selectivity profile that remains constant. Third, the parameters that define the profitability of a fishing expedition: i) fish selling prices, ii) input costs, iii) opportunity costs. Fourth, the parameters that define the fish stock dynamics: i) growth rates between periods according to size/age, ii) natural mortality of fish according to size/age, iii) fertility (number of eggs by fish size). All these parameters are calibrated using data from the Lake Victoria Nile Perch Fishery, as described in the following sections.

The model starts by defining an initial distribution of boats, with 50% not fishing, 25% using gear targeting small fish, and 25% using gear targeting large fish. The initial fish stock distribution given corresponds to the equilibrium fish stock of the model in the absence of fishing.

The model converges to a dynamic equilibrium characterized, firstly, by a particular fixed stock distribution and, secondly, by the proportion of boats i) not fishing, ii) using gear targeting small fish, iii) using gear targeting large fish. Different from other models, this model does not characterize the optimal decision. This optimal decision is known from other models to choose the gear targeting the larger fish and reduce the number of boats to maximize the aggregated profit of all fishing boats (Kammerer et al., 2022; Diekert, 2012). The first best solution is not in the interest of this paper, as this is not a feasible solution given the open-access nature of the fishery and the government's inability to fully control extractions levels.

2.1.1 Fish Stock

The fish stock follows straightforward dynamics, with a supply of fingerlings that grow over successive periods. There are 86 different sizes/ages each cohort goes through. The first size corresponds to fingerlings that hatch out of eggs. The 86 sizes correspond to 8.6 years of growth. Fish in each cohort can die at every step, either from natural causes or from being caught in a net. In the last period, the 86th, all fish that have made it through die from natural causes. Growth is determined by a metabolic rate that changes as a fish grows. Once a fish reaches a minimum reproductive size, it starts reproducing. This slows the growth and produces eggs that populate a new cohort in each period.

In the absence of fishing activities, the stock population converges to a stable stock distribution if enough time is given to the model starting from a suitable initial stock. Importantly, in this model, these ecological dynamics guarantee to reach an internal equilibrium. In other words, under different pressure levels, the stock dynamics will converge to a particular stock distribution.

As the model is defined by time equivalent periods, there are cohorts of 86 different ages. The selectivity is defined in terms of size (length) and not age. With this purpose, the following von Bertalanffy growth equation defines the length that a fish has at each age represented in the model:

$$L_a = L_\infty \cdot (1 - e^{-k\cdot(a-t_0)})$$

In this equation, L_a is the length at age a. L_{inf} indicates the asymptotic size of the species. k is the growth coefficient. t_0 adjusts for the size of the individual at the youngest age, representing the theoretical age at which the size would be zero.

The catch is a function of length, but profits are a function of weight. Additionally, fertility is a function of weight. The weight at each length is defined by the following equation:

$$w_a = c \cdot L_a^b$$

In this equation, w_a is the weight at age a. c and b are parameters and L_a is the length at size a.

Maturity is a function of weight. It is represented by a smooth function with a range between zero and one. It is represented by the following equation:

$$\psi_a = [1 + (\frac{w_a}{n_m \cdot W_\infty})^{u_m}]^{-1}$$

In this equation, ψ_a represents maturity at age a. It is a function of the weight at age a and the mean maturation weight $\eta_m W_\infty$. Around the mean maturation weight, the fish transition between immature and mature. u_m is proportional to the transition zone, the age range at which fish are only partially mature.

Fish that is not caught by a boat can die from natural causes. Only those that survive grow over one period. Natural mortality is defined by:

$$\mu_a = A \cdot w_a^{n-1}$$

Where μ_a is the mortality at age a is a decreasing function of the weight at that age w_a. The parameter A governs the overall level of mortality, being higher for higher predation levels.

Between periods the number of fish of age a evolves in the following fashion:

$$N_{a+1} = N_a \cdot e^{-\mu_a \cdot 0.1}$$

After all cohort grows, there is the need to repopulate a new cohort, this comes from the eggs laid by mature fish.

$$N_{0.1,t+1} = \alpha \cdot \sum_a [N_{a,t} \cdot B \cdot \psi_a \cdot w_a]$$

Where $N_{0.1,t+1}$ is the younger cohort in the next period. It comes from summing up all the eggs that are laid by weight B from each cohort in the present period t and scaling by a factor α that transforms eggs into individual fish in the first cohort of the next period $t+1$.

When starting from a positive number of fish in the first cohort and by letting run the model for enough periods, the stock will converge to a steady state in which the number of fish at each age will remain constant. This steady state is shown in Figure 2.

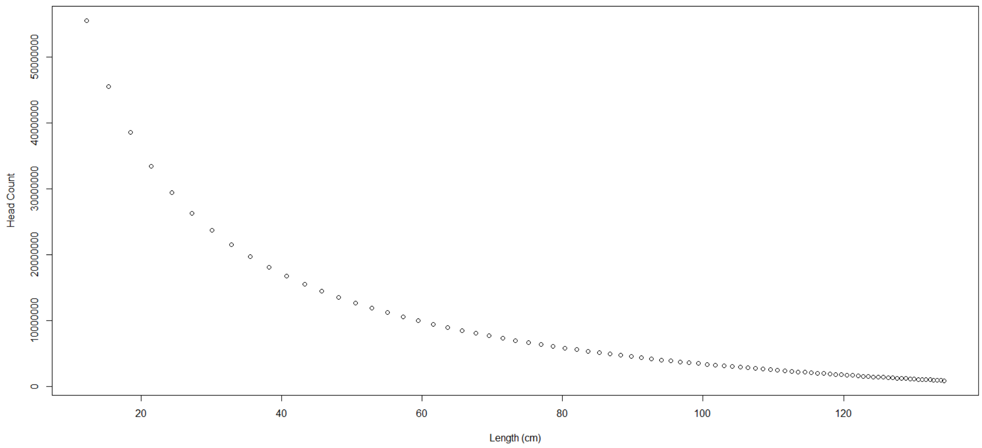

Figure 2: Fishing headcount by length. Equilibrium Scenario without fishing pressure.

2.1.2 Fishing Boats

The basic agent in the model is one boat owner. Each boat owner makes a choice at every period (step). They decide whether to send their boat fishing in the next period and, if the decision is to fish, which gear to use in the next period. This decision is made based on the own profit in the current period, opportunity costs, and the average profits produced by using one or other gear. As these are only individual decisions, the only channel through which other agents' decisions affect each other is through the induced changes in the stock. Agents only use the current period information to make their decisions, they do not anticipate the changes due to future evolving of the stock or incorporate the history of the fishing outcomes. There is evidence that these types of simple decision rules are actually better than more complex approaches to fishing decisions to predic actual fishers' behavior (Carrella et al., 2020; Burgess et al., 2020; Haase et al., 2023).

The key aspect is the profit function which determines the actions that boats take. The profit at the end of each period depends on the decision that was made for that period. If a boat does not go fishing, its owner earns the opportunity costs, G. If a boat does go fishing, the owner's earnings depend on the fishing outcomes:

$$\pi_0 = G$$
$$\pi_1 = 0.5 \cdot [\sum_a p_a \cdot f_a(g, N_a) - C_g]$$

Where π_0 is opportunity cost (the income when not fishing), and π_1 is the income when fishing. $f(g_j, N_a)$ is a production function, one per age class, that takes as inputs the gear that is used g, ($g \in [s, l]$), and the number of fish in that age (N_a). This production function output the weight of fish of the corresponding class that is caught. As the price is dependent on the size of the fish, each output is multiplied by the corresponding price to get the income from selling the fish. The costs of using each gear are taken into account. As the boat owner rewards the crew with half of the profit, the total profit to the boat owner is only half of what remains after paying other costs.

2.1.2.1 The production function

The key aspect of the profit formula is the set of production functions. Each one determines how much fish (weight), at each age, are caught by a boat during a fishing trip. Importantly, the number of fish caught by a boat (i) at each age size (a) follows a Poisson process.

$$f_a(g, N_a) = w_a \cdot n_{i\,a\,g}$$
$$n_{i\,a\,g} \sim Po(p \cdot N_a \cdot r_g(a))$$

In the above eq. $n_{i\,a}$ refers to the number of fish of age a captured by boat i. p_g is the power of the gear g[1], N_a is the density of the fish of age class a[2], and $r_g(a)$ is the

[1] this factor captures aspects such as fishing intensity, gear area, and others that regulate the contact level the gear has with the population

[2] As we are assuming a homogeneous distribution of the stock and a fixed volume, the number figure is equivalent to a density measure

relative selectivity of the gear g for age class a.

The expectation of $n_{i,a,g}$, grows with N_a and $r_g(a)$.

$$\frac{\partial E[f_a(g,N_a)]}{\partial N_a} = w_a \cdot \frac{\partial E[n_{i,a,g}]}{\partial N_a} > 0$$
$$\frac{\partial E[f_a(g,N_a)]}{\partial r_g(a)} = w_a \cdot \frac{\partial E[n_{i,a,g}]}{\partial r_g(a)} > 0$$

The key element to focus on is the selectivity function, $r_g(.)$. The selectivity function follows a normal shape, see figure 3, with the highest point indicating the size the gear selects for, i.e., the optimal size for the gear (Millar and Holst, 1997). At its highest point, it implies that a fish this size that enters in contact with the gear will be captured with probability one (1). Sizes below and above it have a reduced selectivity, implying a non-zero chance that a fish interacting with the gear swims away. This escape probability increases as the sizes diverge from the optimal. Note that the other two parameters $p_g \cdot N_a$ control for the frequency at which fish will be in contact with the gear.

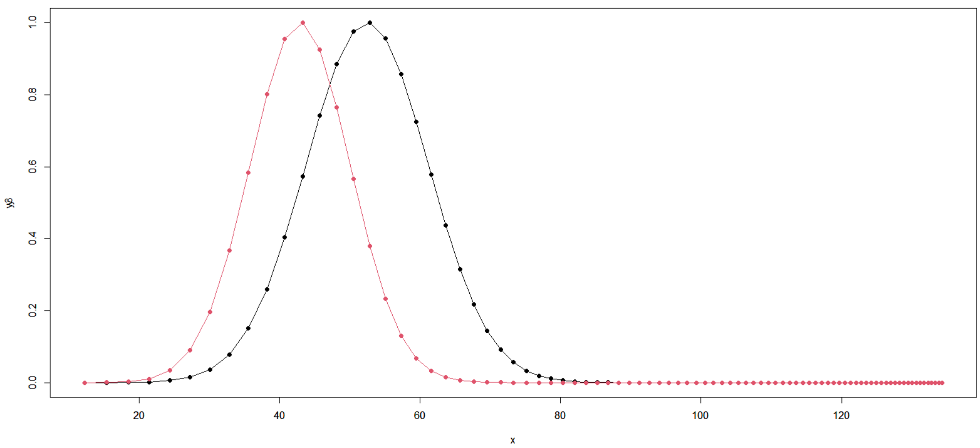

Figure 3: Fishing selectivity for gear targeting **small** and **large** fish.

2.1.2.2 Making a decision for the next period

It is assumed that each boat owner also learns the average outcome of the fishing activities given the gear that is used $(\overline{\pi}_1(g=s)), \overline{\pi}_1(g=l))$. At the end of each period, each boat uses these three sources of information to make a decision on the actions in the next period.

The first decision refers to fish or not to fish. Those fishing consider stopping in the next period if their profit is below the opportunity costs. If their profit is above opportunity costs, they stay in the fishery. Those not fishing consider going fishing the next period, as long as there are fishing boats making profits above the opportunity costs. The probability of entering and exiting hinges on the relative proportion of boats making a profit above or below opportunity costs in relation to the total number of people fishing (if the agent is fishing) or the total number of people not fishing (if the agent is not fishing). When there are more (less) boats making a profit, there are more (less) people going from not fishing to fishing than those going from fishing to no fishing. When the number of boats above is equal to the number of boats below opportunity costs, the number of people leaving are entering the fishery in the next period is equal in expectation. [3]

$$P[A_{t+1}=0, A_t=1] = k_A \cdot \frac{\#(\pi_1 < G)}{\#(A=1)}$$
$$P[A_{t+1}=1, A_t=0] = k_A \cdot \frac{\#(\pi_1 > G)}{\#(A=0)}$$

For those that choose to fish in the next period, the next decision is which gear to use. Conditions are similar. Those whose profit is above the average profit of the alternative gear keep using the same gear. Those whose profit is below the average profit of the

[3] The k_A factor is used to moderate the transition speed between going in and out of fishing. This factor harmonizes transition dynamics between the stock and the fishing decisions, the stock dynamics are governed by the natural growth speed; if the fishing decision is too fast, it could result in a cyclic equilibrium.

alternative gear consider changing gear for the next period. The probability of changing from one to another gear hinges on the proportion of people fishing with the one-gear that is below the average profit of the another-gear. Also, those fishing with the most common gear are less likely to change from one gear to the other. In the model, there are people changing gears all the time. When the average profit is equal between gears, the expected number of boats changing from one to another gear is equal to the number of boats changing from the another to the one. When there is an imbalance, the net flow of boats goes from the gear with the lower average to the gear with the higher average. [4]

$$P[g_{t+1} = j; g_t = i] = k \cdot \frac{\#(\pi_1(g = i) < \overline{\pi}_1(g = j))}{\#(\pi_1(g = i))} \cdot \frac{\min(\#(\pi_1(g = i)), \#(\pi_1(g = j)))}{\#(\pi_1(g = i))}$$

2.2 Model calibration

We set the model exogenous variables using information on the current conditions in the Lake Victoria Nile Perch Fishery. The baseline is the replication of the ecological dynamics, this implies it uses the parameters and structure already defined in the work of Kammerer et al. (2022). For the socioeconomic component, the key exogenous parameters are the fishing costs and the parameters of the production function, i.e., ultimately defining the gear selectivity of the gears. Fishing costs and prices are set using data from self-reporting surveys. This corresponds to a survey implemented in 2021 among 302 Nile Perch fishers. This survey included questions about the catch, prices, effort, costs, and socio-demographics were included. When using data from this source, we use the average response as the input value. A key factor of the exogenous variables is the opportunity costs boat owners face. For this, we use the evidence presented by Onyango et al. (2021) that recover annual profits in the Nile Perch fishery by using a standardized fishing business model. The initial number of boats where set using a value well above

[4] The k_g factor is used to moderate the transition speed between gears.

the reported number of boats in the lake by LFVO (LVFO, 2015).

Only two different gears are used as alternative gears. This decision responds to the goal of using the most streamlined model that helps analyze the consequences of being able to choose between different gears. Using three or more gears, although possible within the model structure, makes the model more complex and slower to run. Also, within reasonable gear sizes, the decision ultimately goes between the ones catching the highest and the ones catching the slow sizes. This seems to be confirmed by some run tests with an intermediate gear. Ultimately, the question of how a higher number of gears affects or modulates the results in this paper is left for future analysis. The data for the selectivity were taken from the use of the most common gillnet sizes and the average capture using hooks methods, as per the analysis of Gómez-Cardona et al. (2022). By choosing these two gears, which are, in fact, the two most common, one can check the results on the composition of boats using one or another in equilibrium, which provides a check on the actual proportion of boats using one or another in the Lake.

Table 1: Socioeconomic Exogenous Parameters

Description	**Parameter**	**Value**	**Source**
Fishers	$\#(i)$	60 000	LVFO (2017)
Fishing Costs Gear (small fish)	$C_{g=s}$	USD 85	Own survey
Fishing Costs Gear (large Fish)	$C_{g=l}$	USD 120	Own survey
Price per kilo (fish)	p_a	USD 2	Own survey
Opportunity Costs (yearly)	G	USD 9 200	Oyango, etal 2022

2.3 Basic Model Outcomes

This section presents the basic dynamics and results of the model. Before proceeding, it is important to highlight this paper does not aim to characterize and analyze the dynamics of reaching an equilibrium and/or changing from one to another. While it is possible based on the model's structure, it is not the main focus of this paper. This will require calibrating the agent's exit/entry and gear-change speed to approximate their real counterparts. There is not enough information to do it accurately. In the present state of the model, we modulate the probability of change between a fishing and a not fishing state and the probability of change between gears to be low enough as to avoid an equilibrium characterized by a cycling behavior.[5]

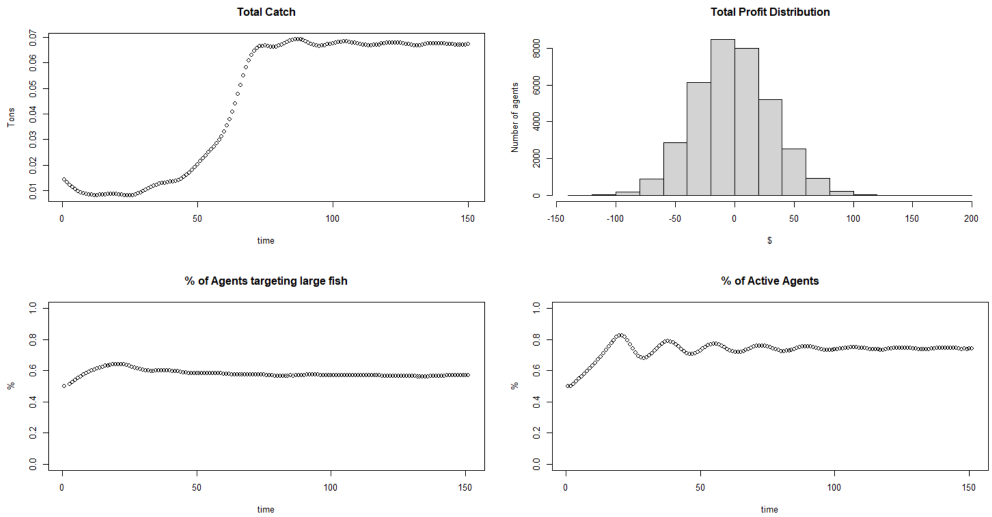

Figure 4: Reaching equilibrium.

Figure 5 presents the basic dynamics of the model. The model is set to start with half of the boats available fishing, of which half use gear targeting small fish, and the other half use gear targeting large fish. Top left, this graph shows the total weight of the catch that is produced from the fishing activities as time progresses. Bottom right, this graph shows the changes in the number of boats doing fishing activities as a proportion of the total as a function of time. Bottom left, this graph shows the proportion of boats using gear targeting the large fish as a function of periods. The stable state that is reached in the last periods is characterized by a profit distribution (after discounting the opportunity costs) equal to zero. Top right, this is the graph of the profit distribution in the last period. In the graphs the distribution of the difference between profits from

[5]When this happens, the values around which the end variables fluctuate are essentially the same as those reached with low transition speeds that avoid cycles.

those fishing and the alternative activity (opportunity costs). In equilibrium, fishing is as profitable as doing an alternative activity.

Note the equilibrium is dynamic as there is a constant flow of boats changing between gears and between active and inactive status. These flows compensate each other in equilibrium, so the proportion of active boats and boats using one or other gear remains constant. The stock is also in a continuous flux state, fish is being caught, and they grow and die. The overall constant effort guarantees that the number of fish that are caught at each size is constant. This keeps the stock distribution constant.

In equilibrium, the following dynamics are playing out. Every fish that is caught is decreasing the number of fish that will be available to be fished in the next periods. It is more likely to catch a fish of a particular age/size if there is less fishing in the previous ages/sizes. The more fish pressure in the smaller sizes, the less profitable will be fishing for the larger sizes, as the reduced number of fish will reduce the catch. Also, the younger a fish is caught, the fewer eggs it will produce. This affects the fishery indirectly by reducing the number of fish for the next starting generation. It takes some time for this effect to take place because the fish population needs to grow and age until it becomes a target for fishing. Fishing that targets large fish has both effects, but these are smaller. On the one hand, only the smaller fish caught are affecting the fishery for small fish, as larger fish are not targeted by this later. There is less affectation of the eggs, as larger fish have had more time to reproduce.

3 Equilibrium Dynamics

We can use the model to understand how sensible the model is to changes in the exogenous variables. Perhaps the most relevant case is the changes induced by the variations in opportunity costs. Note that higher opportunity costs denote a high amount of economic activity in non-fishing activities. Fishing only makes sense if the revenues are higher or at least equal to the revenues of alternative activities. Crucially, increases in economic activity will decrease the level of fishing, i.e., fewer boats will be going into the lake. This is shown in Figure 5, with the blue line that shows the number of boats in the lake as a result of changes in the opportunity costs. With low opportunity cost levels, most of the boats will go into the lake. As the opportunity cost increase, fewer boats go into the lake. What is particularly interesting is how the gear choice evolves. A low levels, the fishery is dominated by boats targeting small fish, and at high levels, by boats targeting large fish. The main transition between these two regimes is rather smooth but fast and occurs in a particular range corresponding to a 0.8 to 1.2 of the reference opportunity costs.

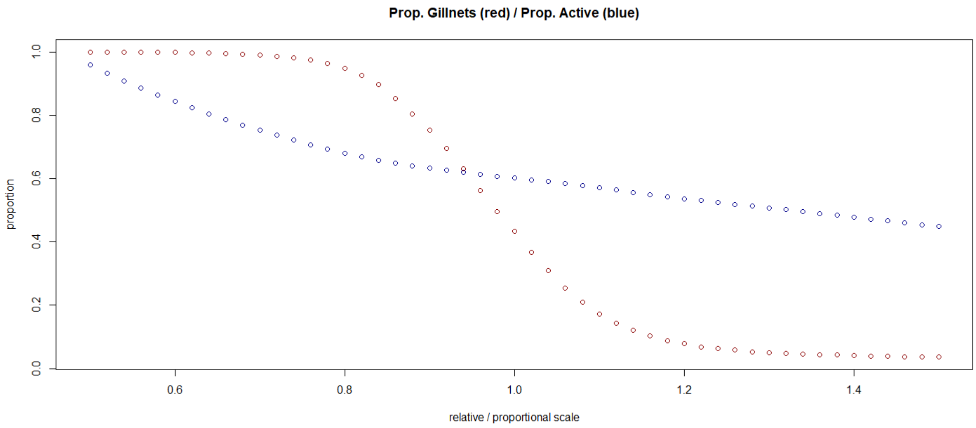

Figure 5: Changes due to economic conditions

This pattern has consequences for the outcome of the fishery. In the next figure (8), the changes in the yield value (beach value of the landed catch) in three different price scenarios is presented. One price scenario has a constant price per kilo, while the other two have an increasing price per kilo (one lower than the other), as is the case for the Nile Perch fishery.

This increase in value is the result of a more efficient extraction when fish is captured at bigger sizes. This can be shown with the changes in the stock (see fig. 9). Particularly

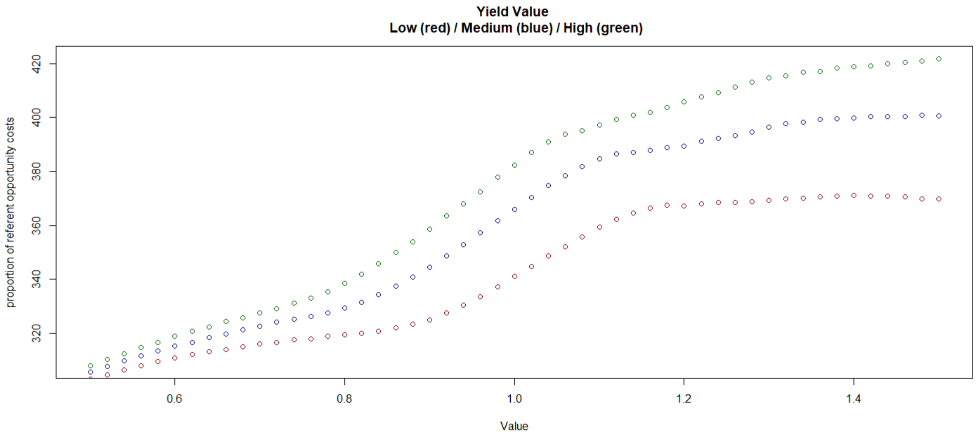

Figure 6: Yield Value outcome due to changing economic conditions. The colors Red, Blue, and Green are used to indicate the pricing of fish based on their size. Red signifies a fixed rate per kilo, while Blue and Green indicate an increase in price as the size of the fish increases. However, the rate of increase for Green is steeper than that of Blue.

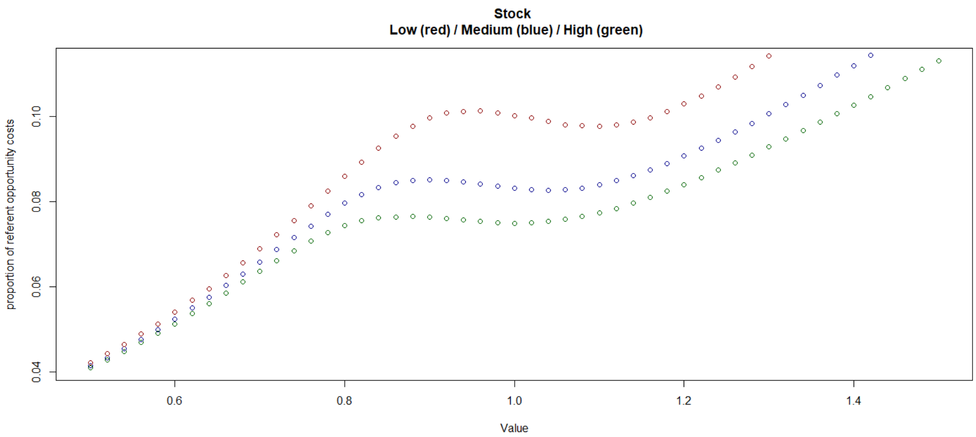

Figure 7: Stock outcomes due to changing economic conditions. The colors Red, Blue, and Green are used to indicate the pricing of fish based on their size. Red signifies a fixed rate per kilo, while Blue and Green indicate an increase in price as the size of the fish increases. However, the rate of increase for Green is steeper than that of Blue.

telling is the fact that the stock is kept approximately constant during the transition period in which boats go from most targeting small to most targeting large fish. There is a reduction in the number of boats, but what should lead to a stock increase due to the effort reduction is compensated by a more efficient extraction. In the absence of gear changes, the effort reduction leads to stock increases. In Figure 9, there are two upward-sloping sections of the curves. The first section is at the beginning when most boats are attempting to catch smaller fish. The second section is at the end when most boats are targeting larger fish.

To summarize, in the model, when fewer boats engage in fishing due to more economic opportunities outside of fishing, there is less pressure on the fish stock, resulting in an increase in yield. Once a certain threshold is reached, some boats find it profitable to target larger fish, which leads to a swift transition in the proportion of boats targeting small versus large fish. This shift ultimately leads to a more profitable and efficient fishery. This also has a consequence of an increase in the overall stock.

Importantly, using the departing values from the current fishery state, the model converges to a situation that is characterized by a mixed use of both gillnets, that target relatively smaller fish, and hooks, that target larger fish. The results of the model coincide with the current situation in the Nile Perch fishery, in which a proportion of around 45% is using hooks (longlines) and the rest of the boats use gillnets (LVFO, 2017).

4 Policy Discussion

To realistically simulate the potential of policies targeting fishing gears in this scenario, we must discard the assumption that governments can completely dictate fishers' gear choices. Instead, we assume that a government, informed by current research, chooses to outlaw gears that target small fish. However, the government cannot simply mandate a change; it can only diminish the profitability of using the prohibited gear. This reduction in profitability can be achieved through various measures, such as imposing taxes, heightening the likelihood and financial penalties of being caught with the banned gear, or initiating campaigns that elevate the psychological costs of its use (Becker, 1968; Nøstbakken, 2008). Rather than assuming a specific method, we generalize this approach by modeling it as an additional linear cost in the profit function.

$$\pi_1 = 0.5 \cdot [\sum_a p_a \cdot f_a(g, N_a) - C_g - G_{g=s}]$$

This implies that the profit function of using the legal (large-fish-targeting) remains as in the base model ($G_{g=l} = 0$) and that we can rewrite the equation for the illegal (small-fish-targeting):

$$\pi_{1,g=s} = 0.5 \cdot [\sum_a p_a \cdot f_a(g = s, N_a) - C_{g=s}(1 + \frac{G_{g=s}}{C_{g=s}})]$$
$$\pi_{1,g=s} = 0.5 \cdot [\sum_a p_a \cdot f_a(g = s, N_a) - \kappa \cdot C_{g=s}]$$

Where the term κ indicates how many times the government policy is increasing the costs of using the illegal gear. We thus define a policy using κ to indicate the change in the baseline costs of using gear targeting small fish. To give some examples. A policy defined by 1.0 is the absence of a policy; in other words, There is no impact on the costs that boats face. A policy defined as 1.2 is a policy that increases the costs of illegal gear by 20%. A policy defined as 1.8 is a policy that increases the costs of illegal gear by 80%. A policy defined as 0.8 is a policy that reduces the cost of illegal gear by 20%. The next figure 8 presents how yield value changes with different policies, i.e., policies that change more or less the costs of gear targeting small fish. The x-axis represents different levels of this policy. Every line represents a different context. The red line corresponds to a situation of relatively low opportunity costs, i.e., 0.75 times the reference opportunity costs. Blue corresponds to a situation of around the same level of opportunity cost as the reference one. Green corresponds to a situation of relatively high opportunity costs, i.e., 1.15 times the reference opportunity costs. The bottom and top black lines represent extremes in which opportunity costs are very low (0.45 times) and very high (1.45 times) the reference value.

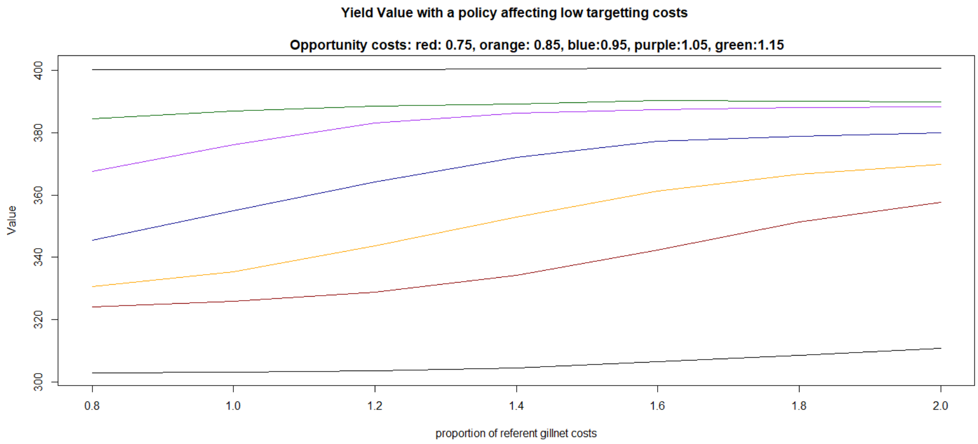

Figure 8: Changes due to economic conditions

Figure 8 makes evident that the same policies can be more or less effective depending on the economic context in which they are operating. Lines appear in order in the graph, with the lower ones in the graph corresponding to lower opportunity costs and the higher ones in the graph to higher opportunity costs. The crucial factor is the trend in improvement as policymakers increase penalties for using small fishing gear. That is, the changes represented in a line at a particular level. The data shows minimal improvement for the extreme cases where most boats either target large or small fish. The lines representing those cases are essentially flat. This is expected as there is little room for change in these scenarios. The policy is most effective when implemented at 0.85 and 0.95 times the reference value, producing greater yield value with smaller increases in the cost of illegal gear.

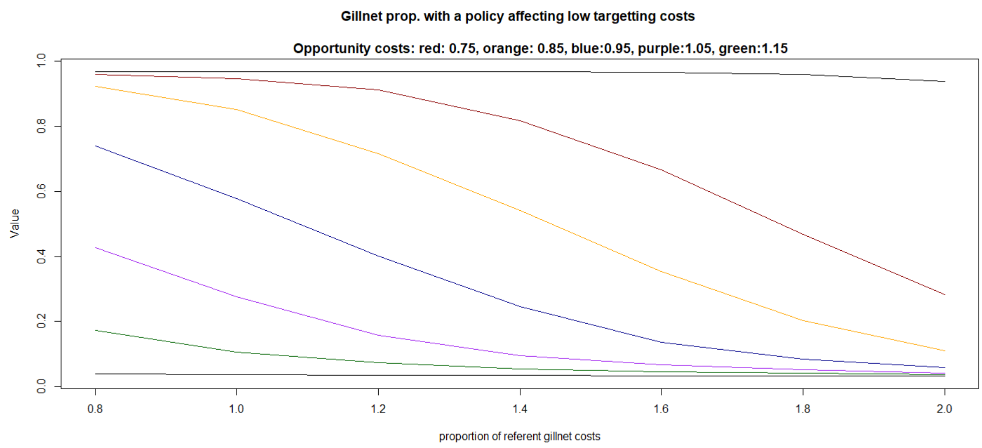

Figure 9: Changes due to economic conditions

To gain a clearer understanding of these patterns, we need to examine how the proportion of boats targeting small fish changes. When it comes to the extremes, there isn't much change. However, in the intermediate ranges, particularly at opportunity costs around the same level that are found in real contexts, even small cost increases can have a significant impact. On the other hand, if the opportunity cost is relatively low (0.75 times the reference value), there are changes, but these changes only become effective at higher cost values.

5 Conclusions

Using an agent-based model that considers both the biological age structure of the Nile Perch and the predominant gear used to capture it in Lake Victoria, this paper reveals non-linear transition dynamics in how shifts in economic conditions influence the fishery's outcomes. These dynamics arise from the autonomy fishers have in deciding which size of fish to pursue, opting either for larger or smaller specimens. Consequently, rapid shifts occur—from a situation predominantly characterized by fishers using gear aimed at smaller fish to one where the focus is on larger fish. It's important to note that these transitions between the two scenarios are not a result of government intervention.

Crucially, these transitory dynamics carry significant implications for fishery regulation via gear-focused policies. Left to its own devices, low fishing pressure stemming from high opportunity costs can foster a more valuable and ecologically resilient fishery. Under such conditions, fishers naturally gravitate towards targeting larger fish. Realistic policies—those that guide rather than dictate fishers' choices—are most effective under conditions where there's room for improvement, such as when a significant proportion of boats are still targeting small fish. However, for these policies to be effective, there must also be a reasonably sizable contingent of fishers already aiming for larger fish. While gear regulation can be an impactful policy tool, its success is inherently tethered to the prevailing economic context.

The model, when run using exogenous parameters that replicate the condition of the Nile Perch Fishery, converges to a situation of mixed use of both gears targeting both large and small fish. This indicates the possibility of the fishery being in a state that is easily influenced by a proper government policy intervention that increases the relative cost of using gear targeting the smaller fish.

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