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Overfishing: Economic Policies in Finite Resource Biological Pools

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Abstract

Common-property fishing is a classic example of the tragedy of the commons. Driven by competition, rational fishermen are forced to overfish to maintain marketplace viability. This shortsighted strategy will lead to the depletion of the common resource pool, and ultimately the destruction of the local fishing industry. In this paper, we present a dynamic differential system of a finite-resource fishing pool to model choices faced by average fishermen. We show that the situation mirrors a Prisonor's Dilemma on the short- and long-terms, where overfishing is always the dominant Nash equilibrium strategy. Additionally, we use the model to analyze a multitude of policy measures to address the problem, and qualify their impact depending on how governments approach burden distribution.

Keywords

Overfishing, common resource, biological pools, externalities

1 Introduction

1.1 A Brief History of Fish

"*The cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery, and probably all the great sea fisheries, are inexhaustible: that is to say that nothing we do seriously affects the number of fish. And any attempt to regulate these fisheries seems consequently, from the nature of the case, to be useless.*"

Thomas H Huxley

For the most part of human history, fishing was considered an environmentally sustainable activity. Ocean resources were treated as if they were infinite and inexhaustible -even by prominent biologists like Thomas H Huxely (Kurlansky 1997). Primitive fishing technologies as well as the relatively small number of fishermen helped preserve local and global supply pools and lend credence to this line of thought. Resource-depletion on the high seas was rarely an issue due to low fishing rates and the small number of human populations dependent on the ocean for food.

The turn of the 19th century saw this view reassessed. The Industrial Revolution had brought new technologies that transformed fishing into a more efficient and lucrative trade. Steam trawlers made it easier to reach further into the sea, and improved navigation facilitated the localization of fish populations (Payne, 2009). Over time, these technologies improved fishing beyond what is biologically sustainable, threatening the livelihood of the very fishermen for whom these technologies were invented.

Realizing the danger, a number of countries including Canada and the US founded the International Convention for the Northwest Atlantic Fisheries (ICNAF) in 1949 (Anderson 1998). ICNAF's mission was to monitor, research and preserve the fishing stocks of a large swatch of the Northwest Atlantic Ocean, including all of New England's fishing zones. Over time, minimum mesh, fish, and net size standards were set and implemented. These regulations are believed to have helped reduce exploitation and overfishing in those waters, although there were deficiencies in monitoring and enforcement.

In 1979, ICNAF was dissolved and, owing pressure from fishermen and their advocates, regulations were relaxed (Anderson 1998). New England's already overfished stocks faced even greater pressure, devastating several fish stocks and driving many fisheries into bankruptcy (Dobbs, 1992; Ingrassia, 1991). Some estimates put fishermen's revenue decline between the 1980's and the 1990's at more than 50%, and the number of species that were pushed dangerously close to extinction in the region at more than 30 (EDF 2011).

To understand what has happened and suggest solutions to the problem, we use a mathematical model that accounts for the major forces at play in the fish market. The model, albeit simplistic, attempts to establish payoffs in a time-dependent dynamic system.

1.2 Modeling

Modeling fish populations is a common academic exercise among biologists. In the 1950's, this type of modeling was coupled with economic theories for the first time to produce predictions about the fish market (Burkenroad and Newcombe 1952). These predictive tools evolved over time to give us an increasingly accurate picture of the fish trade around the world.
For the purposes of this paper, we will build a bio-economic model that produces an output specifically tailored for a normal-form game. In this manner, we will be able to analyze and make predictions about the equilibrium solutions of the model using game theory.

Furthermore, we will be using the model to estimate the effects different factors have on the market, and predict the optimal strategies that regulatory bodies can take to control overfishing and stop the exploitation of fish resources.

We will build this model in three stages:

1. Biological: model a natural fish population experiencing human fishing;
2. Individual fisherman: calculate how many fish are caught given the fish population calculated in step 1;
3. a. Add supply-demand economics: very simplistically, approximate the amount of money made by a fisherman catching the amount fish calculated in step II.
   b. Add the number of fishermen into our model so we can simulate firms' entrance or exit from the market.

After constructing the model, we will qualitatively describe the impact a number of different policies will have on fishermen and the fish market.

2 The Model

2.1 Biological Population

We start with a simple fish population growing at an exponential rate:

$$\frac{\delta p}{\delta t} = gp(t) \tag{I.I}$$

where p is the size of the fish population and g is the growth constant. A table of all symbols used in this derivation is available at the end of the paper.

In a fishing community U of N individuals, we can calculate the overall fishing rate of that community $f_o(U)$ as:

$$\forall N \in \mathbb{N}(\sum_{i}^{N} f_i = f_o(C)) \tag{I.II}$$

where f_i is the individual fishing rating.

Including overall fishing rate (f_o) and biological carrying capacity (K) into **Eq I.I** yields:

$$\dot{p} = gp(t)\left(1 - \frac{p(t)}{K}\right) - f_o p(t) \tag{I.III.I}$$

The solution to this first-order nonlinear ordinary differential equation is:

$$p(t) = -\frac{K(g-f)e^{C\,fK+gt}}{e^{C\,gK+gt} + ge^{C\,fK+gt}} \tag{I.III.II}$$

where C is the constant of integration.

If we set $p(0)=P_o$, fish population at $t=0$, we can solve for the constant:

$$C = \frac{\log\left(-\frac{-fK - gK + gP_o}{f-g}\right)}{f-g} \tag{I.III.III}$$

At this point, the solution is reasonable. We managed to show that should the fishing rate (f_o) be greater than the growth constant (g), we would have a negative growth rate and the population will decline to zero. If the fishing rate was greater or

the two rates were equal, we would have a stable fish population at some conditions-specific equilibrium.

2.2 Individual fishing

For the second stage of our analysis, we need to calculate the individual fishing rate for a unique individual j. For this, we have two fundamental identity premises:

- $\exists i \in C(f_i = f_j)$, and
- $Nf_o(C) - f_j \cong 0$, such that:

$$\forall j \in C \wedge j \neq i \left(\frac{d^2 f_i}{dt^2} \neq \frac{d^2 f_j}{dt^2} \right)$$

Additionally, we assume:

- $f_j \propto N^{-1}$, and
- $f_j \propto r$,

where N is the total number of fishermen, and r is the probability the individual's fishing rate converging to some maximum (i.e. overfish). The reason for this setup will become evident once we have the final system.

The conditions above state, respectively:

- j belongs to the universal domain C.
- j's actions are independent of i for $i \neq j$. This is done to avoid simultaneous causality given equation I.II. In other words, we assume N is big enough that j's actions do not significantly change f_o, nor do they reflect any 2nd moment movement in i.
- The more fishermen there are, the less the individual fishing rate will be owing competition,
- For any individual j, f_j will increase the more likely it is j overfishes, such that:

$$f_j = rf^{max}$$

All assumptions are reasonable in a realistic setting where there are thousands of fishermen, and a single individual's action is not likely to impact the fishing community as a whole.

Based on the assumptions, we can represent the expected value of j's fishing rate as:

$$f_j = \varphi r f^{max}/N \tag{II.I}$$

where φ is a constant encompassing *j*'s fishing capability, including technology, size, fishing efficiency, and in the case of firms, number of fishermen working for the company. Hereafter, we will refer to this constant as *inherent capability.*

Putting this together with Equation I.III.I gives us amount of fish caught by *j* (α_j):

$$\alpha_j(t) = \frac{\varphi f^{max} r}{N} . p(t) \tag{II.II}$$

This equation tells us that fish caught by *j* will increase with:

i. Increasing fish population (linear relationship, built into our model),
ii. Increasing probability of *j* overfishing (i.e. increasing *r*),
iii. Better inherent fishing capability φ.

Furthermore:

iv. Caught fish will converge to a particular value with time iff $g > f_o$.

And it will decrease with:

v. Increasing overall fishing rate (f_o),
vi. Increasing number of competitors (increasing N).

2.3 Economic Payoff

The third step is factoring in basic supply-demand economics to get the total amount of money earned by *j*. First, we assume an Eskimoan market as per Dockner (1989) where:

$$v(f_o N) = (f_o N)^{-1} \tag{III.I}$$

where $v(f_o N)$ is the market value of $f_o N$.

This equation tells us that value decreases with increasing fish market availability (supply) as represented by the number of fishermen multiplied by their fishing rate (f_o). In other words, this is the total biomass of fish that is available for purchase.

Our final equation giving expected return to a fisherman *j* is[1]:

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[1] Note: implicit model assumptions:

- Isolated market where outside forces, i.e. exports and imports, are not factored in.

$$U_j(t) = p(t)\frac{\varphi f^{max} r}{f_o N^2} \tag{III.II}$$

In its differential form, the equation can be written as:

$$\dot{U}_j(t) = \left[gp(t)\left(1 - \frac{p(t)}{K}\right) - f_o p(t)\right]\frac{\varphi f^{max} r}{f_o N^2} \tag{III.III}$$

Figures 2 and 3 provide a graphical representation of this equation.

2.4 Number of actors

The number of other fishermen in the market is not fixed, and it is expected that given decreasing returning, some companies might be forced into bankruptcy and will no longer sustain their ability to fish.

To model this, we assume that the cost to each company i is ϑ_i and the expected return is U_i. Companies will go out of the market when their costs exceed their returns, and new companies will enter the market when the average return is higher than the cost, such that:

$$\frac{\delta N(t)}{\delta t} = -N\big(\vartheta - U_i(t)\big) \tag{IV.I}$$

where:

$$\frac{\delta N(t)}{\delta t} = \begin{cases} -N\big(\vartheta - U_i(t)\big), & \text{if } \vartheta > U_i(t) \\ 0, & \text{if } \vartheta = U_i(t) \\ N(U_i(t) - \vartheta) & \text{if } \vartheta < U_i(t) \end{cases} \tag{IV.II}$$

This equation shows a positive increase in the number of companies if there are still profits to be made. Similarly, if the average return decreases below the average cost,

- All variables, with the exception of the fish population and its dependent variables, are fixed through time. For instance, inherent fishing capability will not increase or decrease with time. This is reasonable in a fishing environment that has reached its satiation point.

companies will go out of the market at a rate proportional to their number times the difference between cost and return.

2.5 Final model

The final time-dependent dynamical model is simply equations III.III and IV.I:

- $\dot{U}_i(t) = [gp(t)\left(1 - \frac{p(t)}{K}\right) - f_o p(t)]\frac{\varphi f^{max} r}{f_o N^2(t)}$

- $\dot{N}(t) = -N\big(\vartheta - U_i(t)\big)$

2.6 Limitations of the model

While the model makes a number of simplistic assumptions stated explicitly as we progressively built it in this section, there are a number of factors that need to be considered:

i. This model can be thought of as modeling a single species or the general population of fish on the whole. In either case, there are considerable deficiencies: neglecting inter-species interactions in the case of the former and ignoring inter-species differences in the latter;

ii. Overall fishing rate, as well as the costs, fishing capability, other factors we assumed constant are likely to change as a function of time rather than remain constant,

iii. Prices will fluctuate not only as a result of changes in local fish market availability, but also as a result of changes in global supply/demand chains.

3 Results

To demonstrate that this situation resembles a prisoner's dilemma, we need to write individual payoffs in a 2x2 matrix. This can be done by changing two variable parameters: r and f_o. The former is controlled by j and represents the probability that j overfishes; the latter by the crowd and represents the crowd overfishing. Thus, we can represent j's utility as a function of both parameters (i.e. $U_j(r, f_o)$)[2]:

[2] Note: The payoff for N-i players was purposefully dropped since we are mainly concerned with individual payoffs. That said, the payoff for society in most cases can be thought of as:

$$U_o(t) = \sum_{i=1}^{N} U_i$$

N-j players

Player j

	Don't Overfish	Overfish
Don't Overfish	X	Y
Overfish	A	B

Where A $= U_j = \frac{\varphi P_o}{N(t)^2} . f_i^{max} / f_o^{eq}$ as $p \to 1, \& \, f_o \to f_o^{eq}$

Similarly: B $= U_j = \frac{\varphi P_o}{N(t)^2}$ as $p \to 1, \& \, f_o \to f^{max}$

X $= U_j = \frac{\varphi P_o}{N(t)^2}$ as $p \to 0, \& \, f_o \to f_o^{eq}$

Y $= U_j = \frac{\varphi P_o}{N(t)^2} . f_o^{max} / f_i^{eq}$ as $p \to 0, \& \, f_o \to f^{eq}$

We can easily see that, under any given set of circumstances, the following is always true:

$$A \gg B \equiv X > Y$$

These are the relative payoffs for a prisoner's dilemma game, where defection (A, B) is always better than cooperating. This is true at time *t=0,* when the game is just beginning. To analyze it over time, we let $t \to \infty$:

N-j players

Player j

	Don't Overfish	Overfish
Don't Overfish	$X \to U_i^{equilibrium}$	$Y \to 0$
Overfish	$A \to U_i^{equilibrium}$	$B \to 0$

Under reasonable circumstances ($0 < t \ll \infty$), we can show that:

$$A > X > B \equiv Y$$

4 Discussion

4.1 Model implications

In this paper, we created a model of a finite common-resource pool and calculated the payoffs for an average user of this pool. Our results show that average fishermen are trapped in a Prisoner's Dilemma-type problem where the Nash equilibrium solution is exploitation of the common resource. Introduction of economic measures reinforced this problem because of the two-level competition built into the model: the first level is for catching the fish and the second is for selling it. An environmentally aware fisherman unilaterally fishing at a responsible rate will be punished harshly in the marketplace; not only is he selling less fish, but he is also selling the fish at a lower price than he would have been had everyone fished at his rate.

On the long run, and assuming fishing strategies and number of fisheries are unchanged, there would be a steady march towards equilibrium. Naturally, this long-term equilibrium is always less than it would have been if the fishing rate were zero, even if the fishing rate is sustainable (i.e. below the natural growth rate). This conclusion fulfills, numerically, Burkenroad's predictions in the *theory of the maximum equilibrium yield* (Burkenroad 1953), which stated that the maximum equilibrium yield is always less than the optimal yield given there is any level of fishing.

Finally, the model shows that the march towards equilibrium is faster the bigger the difference is between the fish's growth rate and the fishing rate. Formally, this means that the rate of change in utility over time is proportional to said difference.

We can use the general conclusions of this model to draft policy recommendations and predict the effect of these recommendations on the fishing market and the average fisherman's utility.

4.2 Controllable parameters

Before suggesting policy recommendations, we need to identify the model variables that can reasonably be controlled by the government, and the impact changing each would have on the expected utility of fishermen. These factors are:

A. Inherent fishing capability (φ),

This can be controlled through regulations on net, fish, mesh size, etc. By imposing regulations on these parameters, the government will be decreasing the expected utility for all fishermen by decreasing their efficiency. In effect,

this will indirectly decrease the number of fishermen and the overall fishing rate (Eq IV.I).

B. Overall fishing rate (f_o),
This can be similarly controlled through regulations on fishing and number of fishermen. The expected utility for fishermen who are still in the market will decrease.

C. Number of fishermen (N),
The number of fishermen is a key variable in the model. It has the largest impact on the utility of fishermen, and controlling it indirectly can drastically change the payoffs according to the inverse square law,

D. Fishing costs (ϑ),
Imposing taxes on fishermen can most directly impact costs. According to Eq IV.I, the imposition of new taxes will drive the number of fishermen down until a payoff-dependent equilibrium is reached.

The above parameters are interrelated: changing one will shift at least one other parameter. The following section considers different policy approaches to the problem by manipulating a set of those parameters.

4.3 Policy recommendations

4.3.1 Fishing quotas

Fishing quotas will, ideally, limit the amount of fish fishermen are allowed to take out of the common-resource pool, thus decreasing everyone's fishing rate to a government-set threshold. In aggregate, the policy will bring the overall fishing rate under the growth rate to allow sustainable fishing.

This solution will work greatly in an environment that has not been overfished before. As figure 2 clearly shows, even fishing at a rate equal to the growth rate will decrease existing stock according to Burkenroad's *theory of the maximum equilibrium yield*. If a common resource pool can sustain a durable long-term decrease, then this policy is ideal.

In a completely egalitarian society, this solution means everyone is allowed to fish the same amount regardless of inherent capability. If quotas are not observed, then fines may be imposed. The fines must be substantial enough that it would be irrational to overfish. In other words, the fines need to *modify* our payoff matrix

enough to incentivize cooperation. This will defeat the Prisoner's Dilemma by changing the game.

4.3.2 Complete ban followed by gradual easing

In case of an environment having sustained heavy overfishing, this solution is the only one. This measure entails a complete ban on fishing to allow the fish population to recover, followed by gradual easing of restrictions. As figure 3 shows, the number of fishermen that can fish while still allowing the population to reproduce and prosper will gradually decrease with time if the fishing rate is greater than the growth rate. However, the converse is also true: the number of fishermen that can sustainably fish will increase with time if the growth rate is *greater* than the fishing rate. As such, a government facing an overfished zone should halt all fishing activities for a year, hand out x fishing licenses the following year, then $2x$ the year after and so on until a sustainable level has been reached as dictated by the biological carrying capacity.

This solution has been implemented in New England in the 1990's when a complete ban on fishing some species was issued (Kurlansky 1997). More recent measures, including a 2010 moratorium on all lobster fishing from Southern New England to North Carolina, are constantly debated. These measures have proved to be extremely unpopular, but are essentially the only way to save an overfished region.

4.3.3 Fishing licenses

This policy is what rational fishermen are likely to lobby for. In its most restrictive form, it will limit the number of commercial fishing licenses to only a few to bring the overall fishing rate down. While this measure can, and would, decrease overall fishing and potentially save the fish stocks, it is different from the fishing quotas policy because it concentrates utility in those with the licenses and deprives everyone else of it. For those with licenses, this policy will decrease competition on the high seas and in the marketplace, and greatly increase their profits. This is because decreasing the competition by, for instance, half will quadruple their profits according to our model.

Naturally, this solution will create a huge monopoly for a few actors and produce inequitable distribution of resources. Autocratic governments might be partial to this strategy as it allows them to restrict fishing privileges to firms or individuals they prefer under the guise of protecting the environment.

4.3.4 Taxes

This fourth solution is similar to the fishing licenses policy because its eventual outcome its decreasing the number of fishermen. It does so by increasing the costs for some to the point where they are driven out of the market. This measure has the advantage of raising revenue for the government while still saving the environment. However, it is likely to be opposed by almost everyone else because it favors big firms that can leverage their short-term losses, and survive tighter profit margins better than smaller businesses can (Holland 1998). Additionally, the burden of taxes is likely to be shared by the consumer who has to pay more for the same amount of fish.

While capitalistic governments might be hesitant to impose taxation, this is the only measure that will both save the environment and require minimal direct governmental interference; the free market will naturally take smaller businesses out of the market without the government having to impose a quota or a license system.

4.3.5 Price stabilization through price controls

This final measure is the most radical, and perhaps the most draconian from an economical perspective. Unlike other proposals we have considered, this one will not directly change any of the parameters in our model. It can, and to be effective should, be implemented in tandem with other policies. Governmental price stabilization's goal is to reduce the incentive to overfish by shielding prices from market forces. In our model, that would be akin to reducing the exponent on N from 2 to 1, and taking economic competition out of the equation.

We believe this decreases the incentive to overfish because fishermen need not worry that others are overfishing and are driving the price of their fish down, thus forcing these fishermen to overfish as well to make up the difference. This self-regressing, destructive cycle can be partially broken this way. A measure like this will provide a stable and predictable return to the average fishermen, especially if coupled with fishing quotas.

The downsides to this approach are well known to economists. If the price point is chosen at an artificially low level, a shortage is bound to happen. If the price point is too high, demand might be severely hampered[3], and considering the particular needs of our problem, this scenario might be more likely than the former. That said, intelligent regulations and effective enforcement can make this strategy a success.

4.4 Choice: Burden distribution

[3] In addition, of course, to the threat of black markets emerging in response.

If governments are willing to accept that a sacrifice is necessary when dealing with finite-resource pools (and that is a tall order indeed in some places), then the choice of policy is dependent on how those governments wish to distribute or concentrate the burden of the sacrifice.

If the government wishes to distribute the burden equally, it will issue quotas that apply to everyone. Otherwise, if the government were to favor a few while shifting the burden of sacrifice to the majority, then it will issue a limited number of licenses to its favorite companies or fishermen (perhaps akin to how the Soviet Union controlled the Caviar trade in the Black Sea by limiting the number of players to only those sponsored by the government). Alternatively, a government can let the free market dictate what should happen by imposing heavy-handed taxes and regulations that will ultimately drive smaller businesses out of the market faster than it does larger ones. In all of those cases, the distribution of the burden of sacrifice is the eventual outcome of the policy that really distinguishes it from the rest.

Figure 1 shows a proposed (and simplified) algorithm to approaching legislation in regards to fishing regulation.

Finally, a quick word need be said here about enforcement. Although we have assumed that perfect enforcement accompanies each of our proposed measures, this might not be the case in reality. Some policies are easier to implement and monitor than others. This is one of the reasons suggestions in this paper might be more suitable for stable, and perhaps wealthier, governments that are able to choose their most preferred policies than governments in less stable or wealthy countries.

5 Conclusion

In this paper, we built a quantitative model of the fishing market to demonstrate the necessity of regulations, and then qualitatively described several proposed policies to address the problem. Eventually, the choice of which policy to implement is highly dependent on the goals of the government as well as the initial conditions of the common-resource pool. The only certain thing about the tragedy of the commons in New England, it seems, is that governmental intervention is the only way to solve the problem.

6 References

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7 Appendix

7.1 Symbols used

Symbol	Parameter	Interpretation	Bounds
C	Fishing community	The universal domain of fishermen in the community composed of N individuals	-
f	Overall fishing rate	Rate of fish extraction of the entire fishing community	[0,∞]
$f_{i/j}$	Fishing rate for i/j	Individual fishing rate for i/j	[0,∞]
f_{max}	The maximum rate of fishing	The maximum fishing rate	-
N(t)	Number of fishermen at time t	Number of fishermen in the fishing community U at time t	[0,∞]
P_o	Initial fish population	Fish population at t=0	[0,∞]
p(t)	Fish Population	Fish population/stock at time t	[0,K]
r	Overfish probability	The probability j overfishes, where 1 means j is overfishing and 0 means j is not overfishing (i.e. fishing at a responsible rate)	[0,1]
$U_i(t)$	Utility function	Utility function at time t for individual i which encompasses the economic value of solid fish.	[0,∞]
v(x)	Market value of good x	The market value of a good, x, considering the total available	[0,∞]
$\alpha(t)$	Fish caught	The amount of fish caught by an individual at time t	[0,∞]
ϑ	Cost	Cost incurred by fishermen to fish, including maintenance, wages, etc.	[0,∞]
ϕ	Inherent capability	The fishing capability of a fisherman or fishing firm.	[0,∞]

7.2 Figures

Figure 1

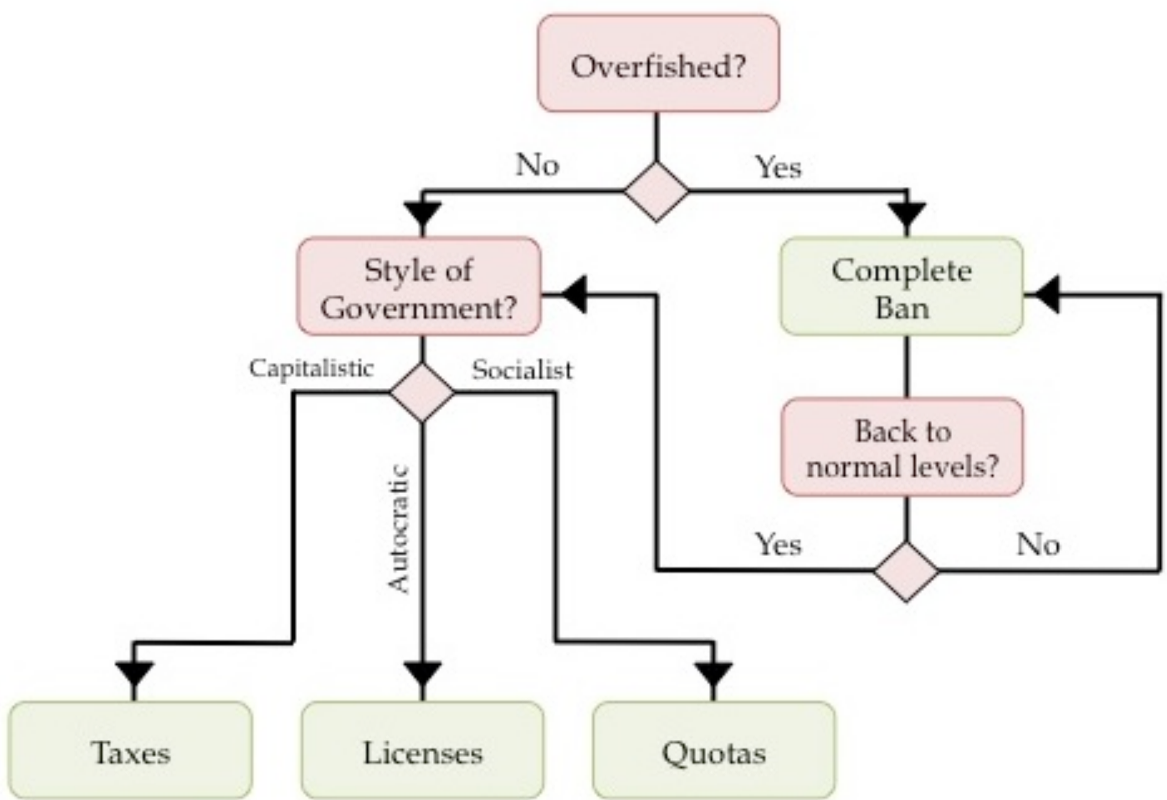

Figure 1: a graphical representation of the policy solution recommendations based on the nature of the problem and government policies. Note that solutions are not exclusive to each style of governing, but they are the most appropriate according to our model.

Figure 2

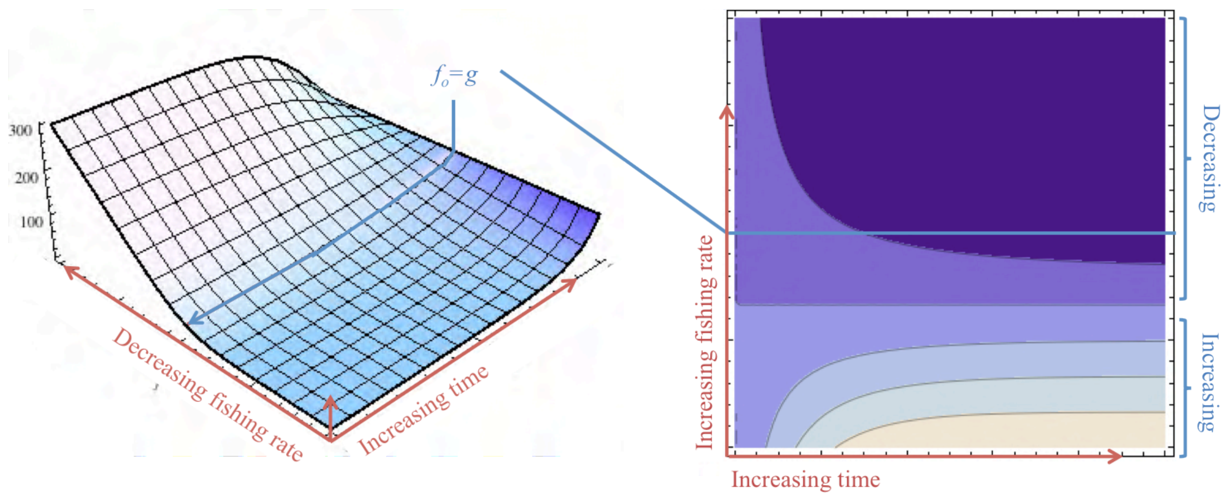

Figure 2: a graphical representation of Eq III.II using arbitrary units. The graph shows how $U_i(t)$ varies with f_o and t, while the growth rate is fixed at 0.1. Note that equilibrium, the point at which the population stops increasing or decreasing, is reached faster the bigger the difference is between growth rate and fishing rate (i.e. $/g\text{-}\ f_o/$). In the case of overfishing, this equilibrium level or plateau is always zero. Also note that unless the fishing rate is zero, the fish population will never reach the environment carrying capacity, and as such, $U_i(t)$ will never reach its maximum.

Figure 3

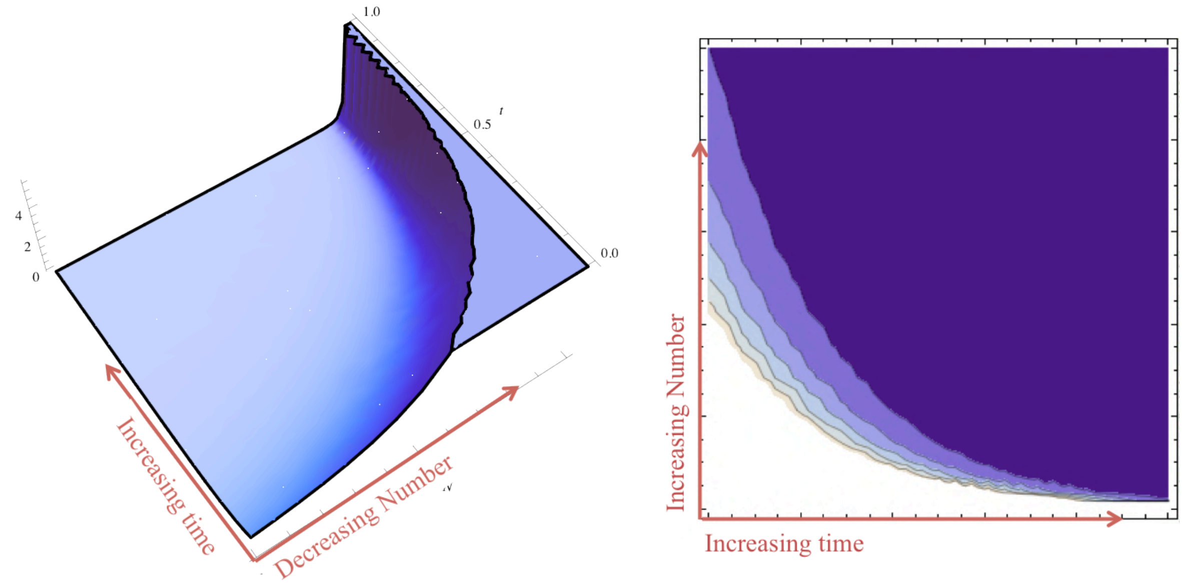

Figure 3: a graphical representation of Eq III.II using arbitrary units. This time, N and t are allowed to vary while $U_i(t)$ is being estimated. In this scenario, overfishing is being simulated. We can see that the larger the value of N is, the less $U_i(t)$ will be. Moreover, larger N tends to reach the equilibrium point, zero, faster.