Dynamics of Fisheries

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Abstract.

In this paper, using a system dynamics approach, we develop a model to investigate the effect of industrial fishing on the average body size of targeted fish populations. Our model demonstrates that in the absence of fishing, larger fish would dominate the fish population, confirming the prediction in the biology literature. However, in presence of fishing activity, population of larger fish collapses. We model and demonstrate how the adaptive behavior of fishermen in choosing smaller gear sizes as fish become smaller over time increases the pace of the collapse. We observe that a side effect of this adaptive behavior in a broader context is an increase in the ratio of catch of untargeted fish species to targeted one. This issue is called bycatch and is disliked both by environmentalist and fishermen.

Background

There used to be a fallacy that the oceans are capable of providing any amount of food for humans [11]. However, human fishing activities have had an enormous impact on the marine life over thousands of years. With the rise of industrial fishing in the early nineteenth century as English fishermen started using steam trawlers, humans have become one of the greatest predators of marine vertebrates [1,2,4-6,11].

Trawlers are designed to pull trawls. Trawl is a special type of fishing net. They are used to catch fish at the bottom of the sea or in other depths (Figure 1). The earlier designs were in use in 17th century. However, it was only around 1950's when trawlers become equipped with diesel engines and turbines. Since then, they have become gradually equipped with fish finders and other electronic aids [23]. These electronic devices are highly effective in locating schools of fish. This has led many fishermen to erroneously believe that fish stocks are not depleted. This is a classic example of observational bias.

In theory, trawls catch fish that are bigger than their mesh size and the smaller fish can escape through the mesh. Trawling has been subject to lots of protests by environmentalist groups. Deep sea trawler are capable of emptying the bottom of the ocean of fish in a matter of few hours. One of the issues with trawlers is the lack of selectivity. The catch comprises of a lot of other species, often unmarketable species which are then thrown to the sea, either dead, or dying. In the terminology of the fishing industry, catch of untargeted species is called bycatch [23].

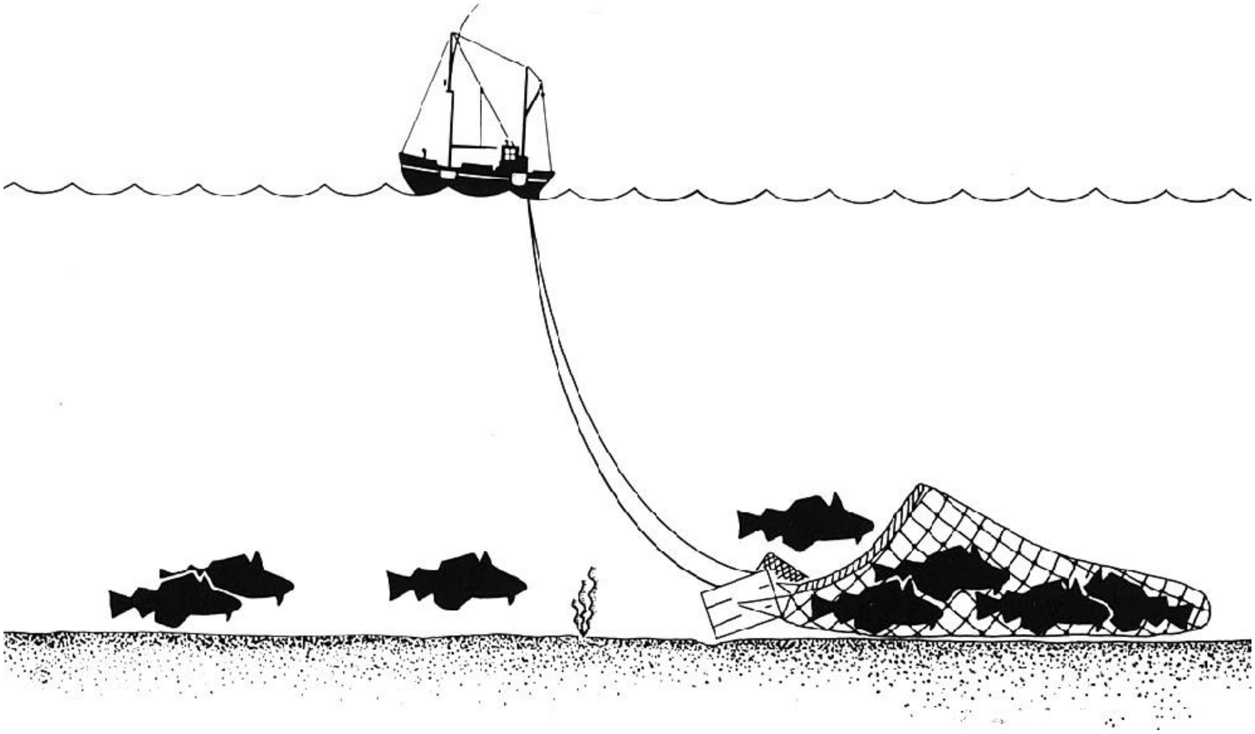

Figure 1. Illustration of a bottom trawler (Courtesy of National Oceanic and Atmospheric Administration, United States Department of Commerce).

Current industrial fishing practices are not sustainable [1,2,4,5,6,7,8]. Around the world, there are many fisheries that have collapsed, depleted or overfished. The first observed collapse was that of Peruvian anchoveta in 1971-1972. The collapse was often attributed to an El Niño event. El Niño is a phenomenon observed in the Eastern coast of South America which causes the oceanic temperature to rise. This in turn causes extreme fluctuations in the weather pattern. However, now there is enough evidence to believe that overfishing contributed to the collapse as well. Another example was that of North Atlantic when most of the cod stocks in New England and Eastern Canada collapsed in 1990’s due to a few decades of overfishing. This actually ended some of the fishing traditions from centuries ago [11]. The global trend of amount of landing (i.e. the weight of fish caught in a year) has been declining steadily since late 1980’s. Note that this can be only observed after correcting for the false landing reports [11]. Many large marine vertebrates are threatened. Among these are tunas and sea turtles. Many species of sharks are subject of huge amount of concerns. For instance, in Northwest Atlantic, the populations of some species of sharks are estimated to have been declined by 75-90% in a 15 year period. The removal of these top predators (called apex predators) has disturbed the whole ecosystem as they have a fundamental role in keeping the populations of their preys in balance. The effect of their removal has cascaded through the whole ecosystem [4,5,8,9]. In particular, humans have been long engaged in what is now called fishing down the food web. It starts by removing the apex predators. Their removal causes the population of their prey to become abundant. Then humans start fishing on the prey. As their populations deplete, the species further down the food web become the new target. As an indicator of type of behavior, the average trophy levels of landings have been in decline in the past few decades. The trophy level is the relative position of a species in the food web with the apex predators having the highest trophy level [1].

It is theorized that the drive behind the fisheries crisis is that of the tragedy of the commons. At the same time, subsidization has played an immensely adverse role. The dynamics of the situation has led to overcapitalization, although a more expanded fishing fleet has not translated to more catches [1,2,11-18].

Marine life is in crisis. The landings have been steadily declining. With increased awareness, new movements for restoring the fisheries have kicked off. A common policy in this regard is to allocate a yearly quota to fishing fleets called total allowable catch (TAC), so that maximum sustainable yield (MSY) can be achieved from the fisheries [6].

One aspect of these fishery management systems is the restriction on the minimum size of the gears used by fishermen. They are in place to protect the juvenile fish and those fish that have not been through the most of their reproductive years. However, this policy works as an evolutionary force for favoring the smaller strains in the same species [22, 25]. The effect of this is favoring fish that grow more slowly, mature earlier, etc. These effects result in a population of fish that are less productive. Unfortunately, current management plans do not give considerations to the Darwinian effect of selective fishing. For sustainable harvesting, management plans that preserve the genetic diversity of the population are necessary [19-20].

Human-induced evolutionary pressure has reduced the genetic variety of fish populations exceptionally rapidly surprising evolutionary biologists, compared to other systems impacted by human activities, or systems where natural selection is the sole driver of the change. A plausible line of reasoning is that human predators directly select the desirable phenotype in its prey. Thus, the magnitude of change is more pronounced compared to the indirect impact of humans on the environment and habitat of a species. On the other hand, human induced evolutionary forces are more consistent than those naturally induced. Furthermore, as the prey evolves, so does the behavior of the humans [20,21]. For instance, as the average fish size of a particular commercial species declines, it is expected that fishermen over time use a smaller gear size to trap a wider population. This means that even the evolved portion of population is no longer safe and those fish are put under evolutionary pressure to become smaller again.

Another issue of particular concern is that of the bycatch. High rates of bycatch are striking. For instance, in some fisheries, for every kilogram of harvested shrimp, about 15 kilograms of bycatch is discarded in the sea, either dead or dying. Often, bycatch consists of threatened species like sharks or dolphins [24,3].

As it is well known to evolutionary biologists, organisms' key events in their life are evolved in a way to produce the most number of offsprings [10]. This is called theory of life history. These keys events, for instance, include the maturation age. It is known that fish under human harvesting evolve to have a faster life schedule which translates into smaller sizes and less productivity [19,20,25]. Unlike humans, fish grow bigger throughout all their life.

In this work, we model the evolutionary response of a species of fish and confirm the prediction by life history theory that under equal condition, the larger fish will dominate the population. A dynamic in which we are interested is that humans also evolve with their methods of fishing. In particular they adjust the gear size. This causes a greater evolutionary pressure, since the smaller fish that were once safe are no longer fit. Hence, as discussed above, this introduces new evolutionary pressure for those fish to become even smaller. This gives a possible explanation why the rate of change in traits of fish caused by fishermen has become surprising to evolutionary biologists. Another observation is that the bycatch rate would grow as humans decrease their gear size in an effort to catch more fish. This happens since the fishermen would subject more of the untargeted population to getting caught.

The modelling

We represent two populations of fish of the same species with two pipelines (Figure 2). As fish grow older, they move within the pipeline. One of the pipelines corresponds to the fast and the other one to the slow life history schedules. Fish in the fast pipeline grow faster, so they mature earlier, die younger, and have smaller body sizes.

Fish enter the pipelines through birth, and at any point they leave a pipeline due to death. We simplistically assume only adult fish are being harvested as governing laws only allow that. The existing population compete for resources. Hence, the mortality rate, as usual, is a function of the carrying capacity and the size of the population.

The amount of allowed yearly harvest is simply the TAC percentage of total adult fish population. The rate of harvest from each of the adult populations depends on the gear size used. A smaller gear size is capable of catching smaller fish as well as the larger fish. A larger gear size is only capable of catching larger fish.

The rates of the harvest from each of the four adult populations (small young, small old, large young, large old) is a function of the gear size in the following way. The total adult population that can be trapped with the specific gear size is computed. A gear size between 0.75 to 1 targets between 100% to 0% of large old adult population using a linear relation. A gear size between 0.5 to 0.75 additionally targets between 100% to 0% percent of large young adult population. That is, it targets the whole large old adult population as well as a fraction of young adult population. Similarly, smaller gear sizes trap different percentages of small old adult population and small young adult population as well as the entire large adult population. Now the amount of harvesting from each of the four groups is proportional to the ratio of targeted population from each group to total targeted population. The gear size has no dimension and it can be thought of as a relative measure with respect to the targeted species body sizes.

Figure 3 shows the full schematic of the model. This model is prepared using the software Vensim®.

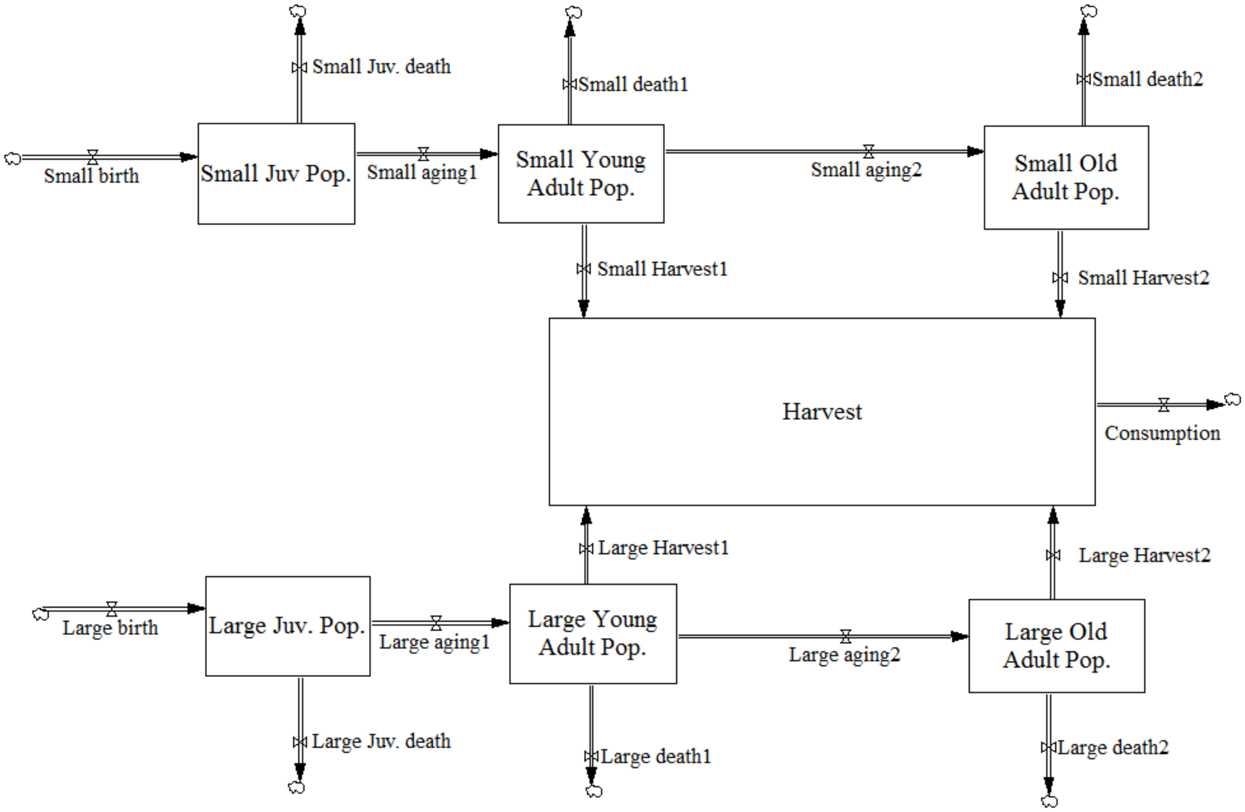

Figure 2. Pipelines of small and large fish population from the same species: Boxed variables are of type level (also called stock). All the other variables are of type flow (also called rate). Small shapes from which some of rate variables originate or to which they end are sources and sinks.

Simulation and discussion

First, we run the model with no fishing activity by setting Total Allowable Catch (TAC) to 0. This corresponds to the equal conditions for all fish. We confirm the prediction by life history theory that larger fish would dominate the population. In Figure 4, the ratio of large adult fish to all adult fish is shown. We start from a worst case where larger fish are in extreme minority. This means that no matter how abundant large fish is initially, they are always going to dominate the whole population.

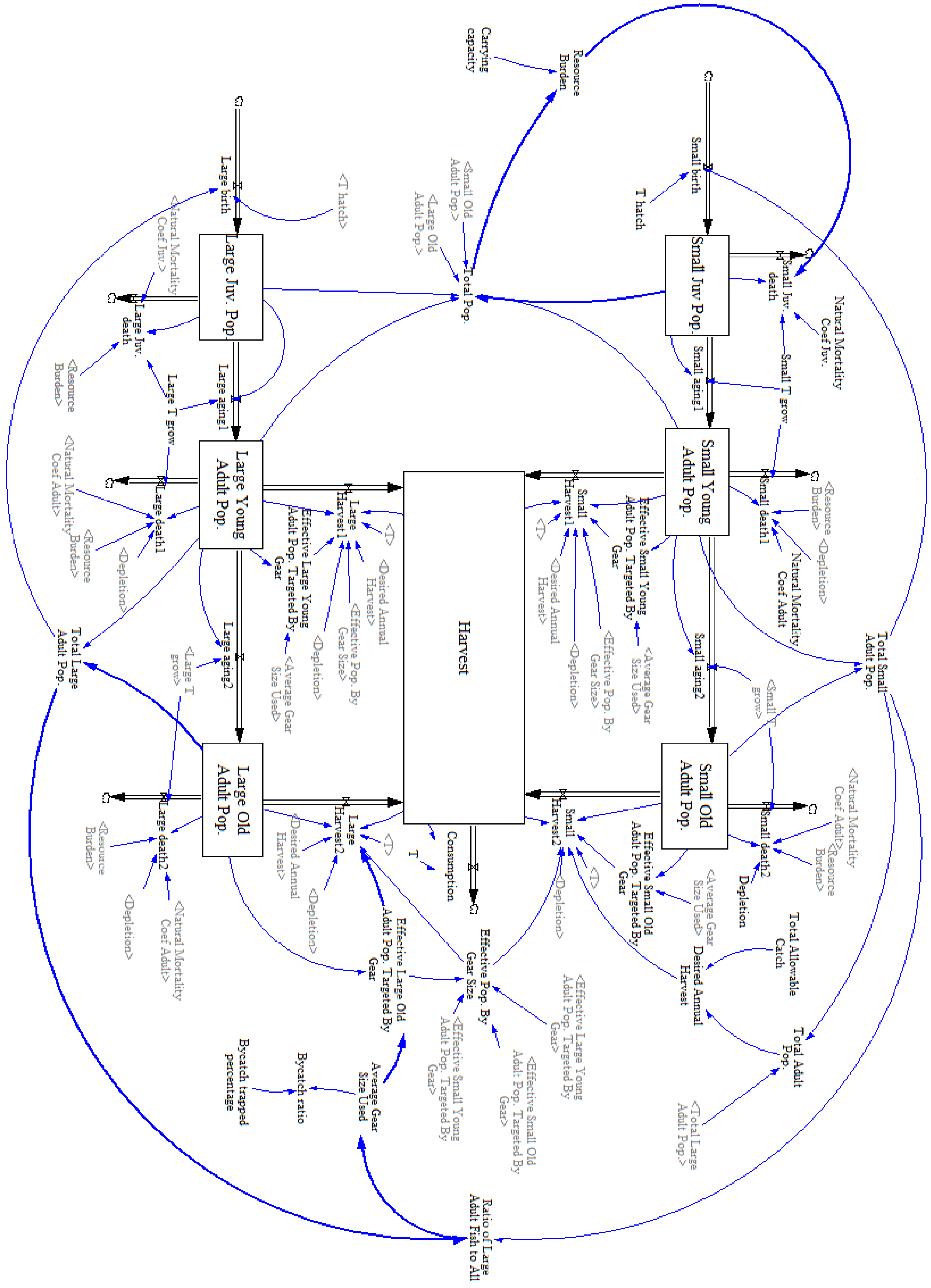

Figure 3. The complete schematic of the model: An arrow represents a causal relationship between the two variables. We have used thicker arrows for some of the conceptually important feedback loops. Variables enclosed by the signs < > are shadow variables (i.e. they are the exact copy of a variable already present in the model). Their sole use is to give a cleaner appearance of the model.

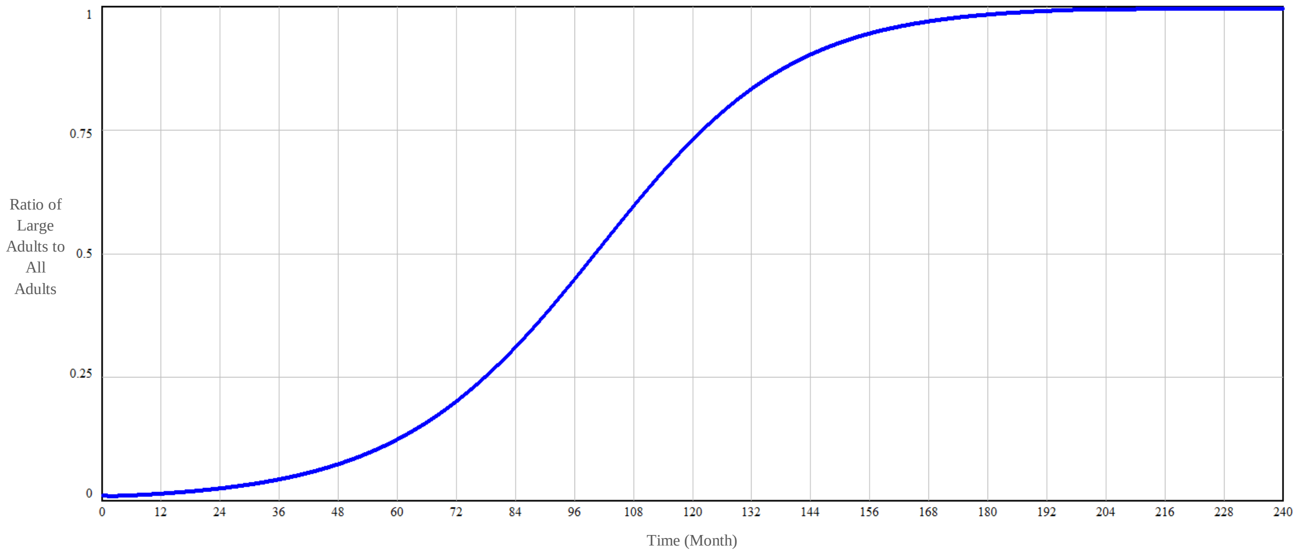

Figure 4. Ratio of large adult fish population to all adult fish population generated by the model.

For readers who are not familiar with the term "dynamics", it can be thought of as the interplay between variables in a system that give rise to some behavior.

An interesting dynamics is that of the average gear size used for fishing (Figure 5). As the ratio of large adult fish to all adult fish declines, the gear size used by fishermen will gradually become smaller with some delay so that they can tap into the small fish population. We consider two scenarios, in one the gear size remains fixed and in the other one the gear size follows the trend of fish's body sizes. This is achieved by setting a new formula in the model for the gear size in each case. For example, comparing the abundance of large fish at a time around 400'th months, in the fixed case, the populations is overwhelmingly comprised of large fish while in the variable case, there is almost no large fish left in the population. This can provide a possible explanation why the fast change in the traits of fish has come as surprising to the evolutionary biologists.

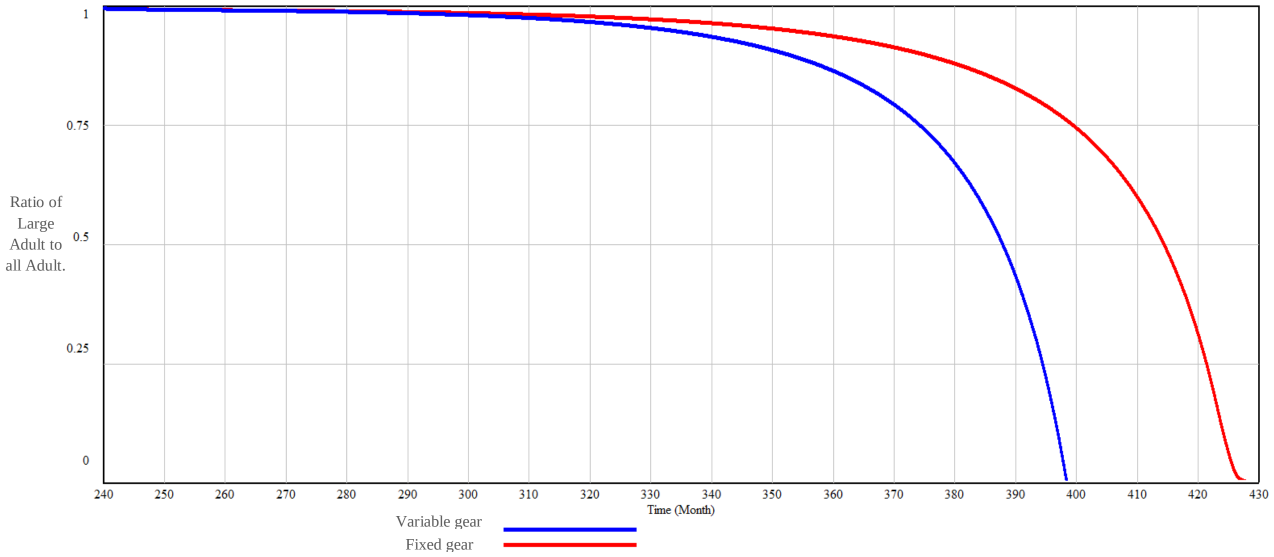

Figure 5. Ratio of large adult fish to all adult fish under two scenarios, one where fisherman stay with a fixed gear size and one where fishermen decrease the gear size by following the trend of average fish size, as generated by the model.

Another observation is that the side-effect of the adaptive behavior of the fishermen in choosing smaller gear sizes is the increase in the ratio of bycatch to targeted fish (Figure 6). This is simply the consequence of the fact that a smaller gear size makes other smaller species also susceptible to being caught accidentally. In other words, the ratio of susceptible untargeted population to targeted population increases which makes it more likely for them to be caught in place of the targeted fish. A drop in the bycatch ratio is desirable to both environmentalist and fishermen. It addresses some of the concerns by environmentalist since there will be a less of impact on the other fish populations, some of which might be seriously threatened species. It also benefits fishermen since they do not have to spend time to sort marketable species from unmarketable ones.

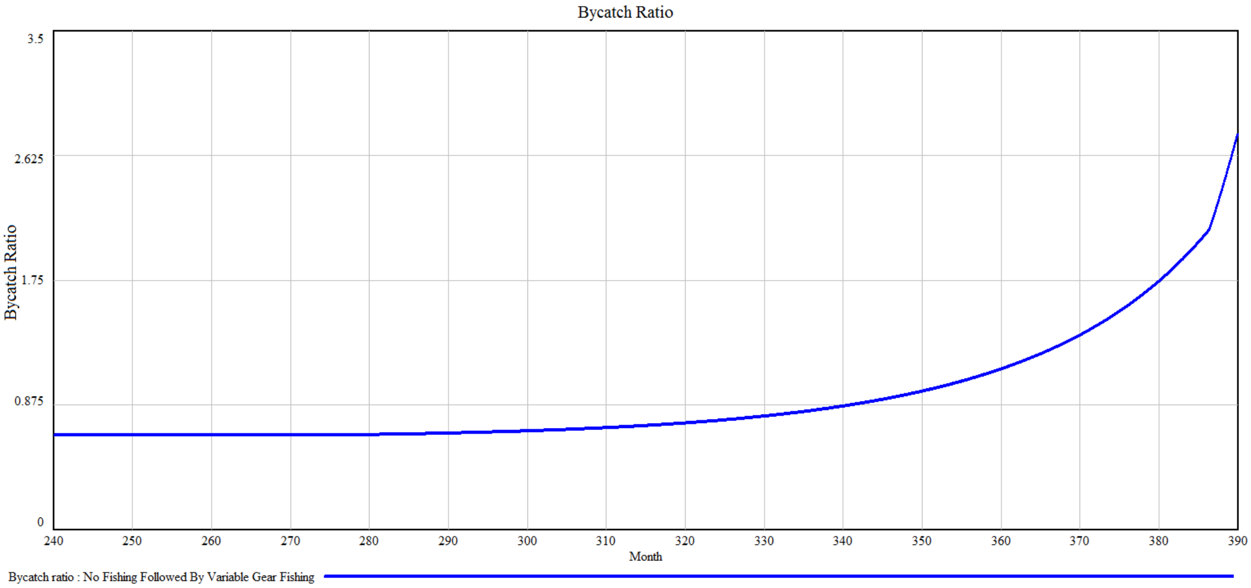

Figure 6. The ratio of bycatch to target fish generated by the model.

Conclusion

Using a system dynamics approach, we demonstrated the evolutionary phenomenon of larger fish dominating the population in absent of fishing pressure. This confirms a prediction made by life history theory.

As mentioned in the background section, the human induced evolutionary pressure is somewhat different from the natural evolutionary pressure. It is usually consistent, adaptive and directly affects the population in this case. Our intuition is that an aspect of this adaptation is the change in the gear size used by fishermen. This intuition was taken into account in building the model. It was shown that under this regime, the collapse of large fish population takes place a lot faster as compared to when fishermen stay with a fixed gear size, giving one possible explanation why evolutionary biologists are surprised by the pace of change in the fish trait caused by human fishing.

Finally, we made an observation about the ratio of bycatch to target fish. The gear size used by fishermen will follow the trend of the average body size of the targeted fish. Hence, a relative decline in the number of large fish would make the size of the gears used smaller. This in turn renders a greater population of untargeted fish susceptible to fishing and hence the rate of bycatch will increase.

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