Between a Rockfish and a Hard Plaice

Team # 133

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Abstract

As demand for seafood increases, the world's fisheries are disappearing. Current estimates posit that seventy percent of the world's fisheries are depleted. Yet there are no exact figures for the number of fish in the ocean. Using 50 years of capture data, the global fish population was modeled in order to determine the number of years, at the present rate of decline, until an ecological crisis is reached. The model is based on a differential equation. If nothing is done, the model projects that the world's fish population will last no more than fourteen years before a crisis occurs. Despite how grave the situation appears, with some dramatic policy changes and rapid growth of aquaculture, it is predicted that the crisis can be averted. The transition period will be difficult, and the fishing industry must make drastic changes, but the complete exhaustion of the world's fisheries is a far worse alternative. New policies will be implemented gradually over a period of ten years. In the future, aquaculture will surpass wild fishing in volume of seafood supplied. Aquaculture has incredible potential, but its own environmental concerns can and must be addressed. Alternative food sources also exist that may ease seafood demand.

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1 Introduction

It is estimated that seventy percent of the world's fisheries are over-fished or are being fished at capacity. Yearly yields are leveling off despite increasing demand for fish. It is clear that the ocean cannot continue to support the current rate of exploitation. It is unclear how long we have before the supply completely crashes and irreparable harm is done to the world's fisheries and whether a crisis can yet be avoided. We decided to use a differential equation to model fish population. Based on biological data we determined the growth rate and carrying capacity of the world's oceans. We then used capture data from last 52 years to model the demand for fish and the supply of fish from aquaculture.

Our model predicted that if present harvest rates are allowed to proceed unchecked, the world's fisheries will be damaged beyond repair within fourteen years. By enacting certain policies and immediately changing fishing practices there is hope for recovery. Fish harvest from the wild will have to be reduced almost in half. Aquaculture, which is rapidly expanding, will have to fill the gap. Aquaculture has an enormous untapped potential, and in the long term, the vast majority of the world's seafood will come from farming fish, like all other major sources of food. Aquaculture is not a perfect solution and has its own problems which we address. In the short term it is the only hope for the seafood industry, and if properly implemented can eventually provide more seafood than the oceans.

It will be difficult to enact sweeping changes to the world fishing policy. Fishing practices vary all around the world, and some nations and cultures are extremely dependent on the ocean for nourishment. However, the alternatives to change are far worse, and it is important that the necessary information to prevent a crisis is made available. By taking both global and local concerns into account, we believe that a solution can be achieved. We also look into future policies aimed at preventing piracy and other illegal activity.

We also analyzed the environmental concerns of both aquaculture and wild harvesting. Using proper methods, aquaculture can be made to be very productive without excessive pollution. The effect of harvesting on wild fish stocks is much more unpredictable and requires a greater understanding of marine ecosystems. Investing in research to both improve fishing technology and understand these environments will help limit the impact of fishing. While it is certain that fish never will be completely absent from people's diets, it is possible that other sources of fish protein and nutrients can be supplemented by different renewable sources.

2 Assumptions

We make a number of assumptions:

- **The ocean is worth saving.** We assume that saving the ocean carries an intrinsic value apart from the fact that it produces fish for consumption. That is, given a choice between lower efficiency fish harvesting and saving the ocean, versus highly efficient fish harvesting which turns the ocean into a marine junkyard, we choose the former.

- **One species.** In general, we do not distinguish between different species of marine life. To calculate a number of constants in our model, we sometimes averaged data from certain "representative" species, such as the Peruvian anchoveta and Alaskan pollock, which were caught in much larger quantities than other species.

- **Uniform ocean.** Although we have historical data on regional fish catches (from the major oceans), we assume for the purpose of predicting the future that there is one ocean, and the geography of fish usage is less important. We feel this assumption is reasonable because fishing technology has increased such that a nation's fishing fleet is no longer constrained to catch from their local body of water.

- **Measurement of ocean fish in mass.** Since ocean fish used for human consumption vary dramatically in size depending on species, we modelled the population of fish over time in mass, rather than number of individuals.

- **Carrying Capacity.** We assume that the fish population in 1950 was essentially equal to the carrying capacity of the ocean. We decided this assumption was reasonable because harvest rates in the 1950's were a small fraction of the maximum sustainable rates.

3 Our Model

A model of the population of marine fish over time provides us with the population of fish for a given year. The rate of change of this population over time should equal the rate of growth of the ocean fish population minus the rate of human consumption of fish. We decided to model the number of fish per year $N(t)$, using a differential equation. Our setup was based on the following formula:

$$\frac{dN}{dt} = G(N) - H(N),$$

where $\frac{dN}{dt}$ is the rate of change of ocean fish, $G(N)$ is the increase in ocean fish due to reproduction, and $H(N)$ is the decrease in fish due to human activities.

3.1 The rate of increase of ocean fish

The rate of increase of ocean fish should be proportional to the current stock of ocean fish, N. The proportionality is determined by two factors, the percentage rate of growth of fish, and the estimated carrying capacity of the oceans. Since the rate of increase should go to zero as N approaches the carrying capacity, we decided to model $G(N)$ using the formula

$$G(N) = rN(1 - \frac{N}{K}).$$

Our constants are r, the average growth rate of ocean fish, and K, the carrying capacity of the oceans.

Since so many different varieties of fish are harvested, it is hard to find an accurate average ocean fish growth rate. We determined r by finding the average doubling time for the twenty most harvested fish species [1]. We found this time by adding up all the species' doubling times, then performing a weighted average based on the global mass of the catch of each species in 2004. The average doubling time we calculated was 5.33 years, corresponding to an r value of 13.876 percent.

The carrying capacity of the ocean and the exact number of fish in the sea is unknown. In fact, even estimates on the numbers of any one particular species are relatively rare. To estimate the carrying capacity K of the oceans, we used the fact that phytoplankton, at the base of the marine food web, sets the limits on the biomass the oceans can support. Two hundred kilograms of phytoplankton can support seventy kilograms of zooplankton, which can support eight kilograms of small fish (such as herring), which can in turn support one kilogram of large fish (such as cod) [2].

It is known from satellite images that the average *net primary production* (the amount of production available to herbivores) of the ocean is approximately 50 Pg [3]. Therefore, this mass of phytoplankton can support approximately $2 \cdot 10^{12}$ kilograms of small fish and $250 \cdot 10^{9}$ kilograms of large fish. Since humans harvest both large and small fish, the ocean's carrying capacity of edible fish is $2.25 \cdot 10^{12}$ kilograms. As capture rates before 1960 were only a small fraction of what they have been for the last three decades we assumed that the population of fish in 1950 was just below K.

3.2 The rate of decrease of fish due to human activities

We decided that the rate of decrease of fish due to human activities should depend on several factors.

- The rate should depend on the *catchability* of ocean fish, a variable representing the ease with which the average ocean fish can be caught.
- The rate should depend on N, the number of fish in the sea.
- The rate should depend on the human demand for fish.
- The rate should also be related to how much fish is produced using *aquaculture*, the cultivation of marine or freshwater fish in a controlled environment. This is an important factor, because the mass of fish produced by aquaculture should correspond to a mass of fish not extracted from the ocean.
- The rate should depend on the *bycatch* of fish, that is, the amount of marine life in a commercial fishing catch discarded as unusable or unwanted.

We modeled the function H using the equation

$$H = (qDN - .95A)\beta.$$

Our variables are $q(N)$, the catchability of the fish, $D(t)$, the human demand for fish over time, N, the number of fish in the sea, and $A(t)$, the amount of fish produced using aquaculture. The constant β represents bycatch. Current estimates place the average bycatch percentage per catch at 30 percent [6], so we set β equal to 1.30.

We reasoned that the qDN term in our model was equal to the amount of fish used by humans(both ocean fish and aquaculture). Using data [10] from 1950 to 2002 (attached in the Supplementary Information section) on the total amount of fish used by humans per year, we looked at the equation

$$\frac{dN}{dt} = G(N) - (\text{Historical Data}).$$

Solving this equation for N gave us values of N from 1950 to 2002. Since we have $qDN =$ (fish usage), we were able to solve for qD values for the last fifty years.

We then reasoned that q should be directly proportional to N (the more fish in the sea, the easier it is to catch a fish). Given the values of qD, N, and the fact that q is proportional to N, we calculated D. We then fit the D values to an exponential curve, yielding the equation

$$D(t) = 1.160377 \cdot 10^{-13}(e^{6.225153} \cdot 10^{-2t}).$$

The correlation between this equation and the D values was very high.

After we determined an explicit function for D, we were able to plot the fish population based off our calculated capture rather than data. Therefore, we could judge the validity of our model by comparing its' values to our actual capture data. Using the function for D yielded a 2002 fish stock of $1.007958 \cdot 10^{12}$ kilograms, while the size of the fish stock calculated using data was $9.527906 \cdot 10^{11}$ kilograms. In other words, over fifty years of running the model for total fish displayed an error of 5.225 percent.

We set $A(t)$ to be an increasing function of t, since production due to aquaculture is growing rapidly. From 1993 to 2002, the amount of fish due to aquaculture increased by 22 million metric tons, from 17.8 to 39.8 million metric tons [8]. Even so, the 2004 Annual Report to the Seafood Industry hopes that a 5 percent annual increase in aquaculture production over the next ten years will meet the increasing demand for seafood. While the amount of seafood produced by aquaculture will surely increase, there are natural limits on the growth of aquaculture. It would be unreasonable to allow aquaculture to expand to the point that the mass of fish produced from aquaculture is greater than half the carrying capacity of the ocean. For a sufficiently large population of fish, catching ocean fish is a less intensive process than raising fish, hence the economics of aquaculture will ensure that some amount of ocean fish will always be caught. We thus set

$$A(t) = 39.8 \cdot 10^9 (1.05)^t.$$

The multiplier of .95 in front of $A(t)$ in our equation for H is due to the fact that approximately five percent of seafood created by aquaculture consists of carnivorous fish such as salmon and tuna [6]. These fish actually consume more in terms of ocean fish meal and pellets than they produce by weight. However, it is believed that in the wild, these fish would consume an equivalent amount of smaller fish to the meal they are fed when aquaculturally raised, hence we effectively ignore these carnivorous fish when considering the effects of aquaculture on our model.

3.3 The entire formula

Our complete formula was

$$\frac{dN}{dt} = rN(1 - \frac{N}{K}) - (qDN - .95A)\beta$$

With the following input parameters:

r	.13876
K	$2.25 \cdot 10^{12}$
$q(N)$	N
$D(t)$	$1.160377 \cdot 10^{-13}(e^{6.225153} \cdot 10^{-2t})$
$A(t)$	$39.8 \cdot 10^9 (1.05)^t$
β	1.30

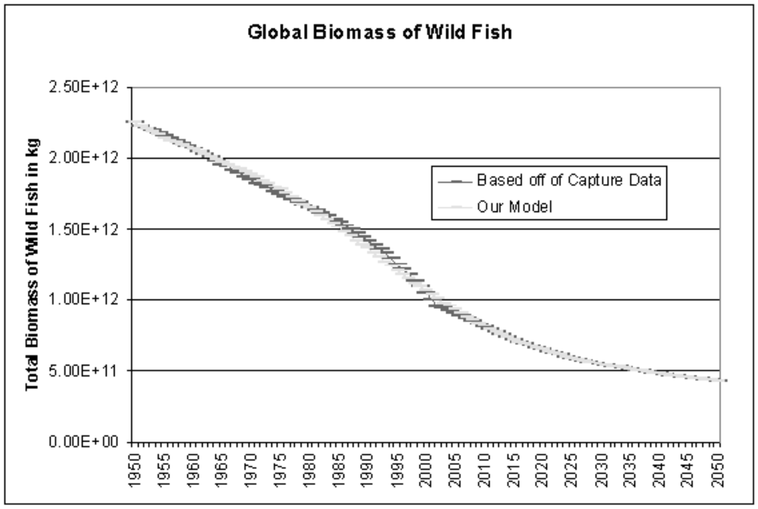
4 Results and Limitations

We solved our differential equation in Mathematica, and made the following discoveries.

- We estimate the current population of fish to be **925 million metric tons**.
- The current rate of harvest is **43.2 million metric tons per year** over the maximum sustainable harvest.
- At the current rates of harvest, fisheries around the world will reach a point of ecological crisis **within the next 14 years**.

4.1 Preliminary results

The following graph demonstrates our model's prediction of fish population versus time.



Our model provides us with the population of fish at a given year. During this year, 2005, the population is estimated to be 953 million metric tons, less than half the ocean's carrying capacity. This means that in the period from 1950 through 2005, humans have reduced the fish population by over one billion metric tons. This is a reasonable estimate, given that by data from the FAO [5], at least seventy percent of the ocean's fisheries are at or beyond capacity. However, we also know we have not reached an ecological crisis. On the other hand, our model predicts that humans currently extract around 44 million metric tons per year more than is sustainable.

The maximum sustainable harvest of the ocean is the value of N for which

$$G(N) = rN(1 - \frac{N}{K}) \qquad \text{is maximized.}$$

To determine this value, we set the first derivative of $G(N)$ equal to zero, and solve for N_*, the maximizing N.

$$G'(N_*) = (rN - \frac{rN^2}{K})' = 0 = r - \frac{2rN_*}{K} \qquad \text{which implies that } N_* = \frac{K}{2}.$$

At $N*$, we have the maximum sustainable harvest of

$$rN_* - \frac{rN_*^2}{K} = \frac{rK}{4}$$

Therefore, the maximum sustainable harvest is $\frac{(.13876)(2.25 \cdot 10^{12})}{4}$, or 78 million metric tons.

The current rate of harvest is recorded as 93.2 million metric tons this year [8]. When we multiply by 1.3 to account for bycatch, we obtain that the total rate at which humans removed ocean fish this year was 121.2 million metric tons. Therefore, the current rate of harvest is 43.2 million metric tons over the maximum sustainable harvest.

We decided to predict the time at which there was an "ecological crisis," where most species of edible fish in the ocean were extinct or on the verge of extinction. We defined an ecological crisis to be point where the total biomass of ocean fish, if considered as a single species, would be labeled endangered. A species can be considered "endangered" when it has undergone a 70 percent reduction from its original population [9]. Therefore, the time at which a catastrophe would occur would be around 2018, extremely close in the future.

4.2 Results in response to future changes

The unpredictability of today's global climate makes it hard to form an accurate picture of what the fish population will look like in the future. There are many possible factors in our model that could change within the next twenty five to fifty years. We think the following changes are the most likely or important.

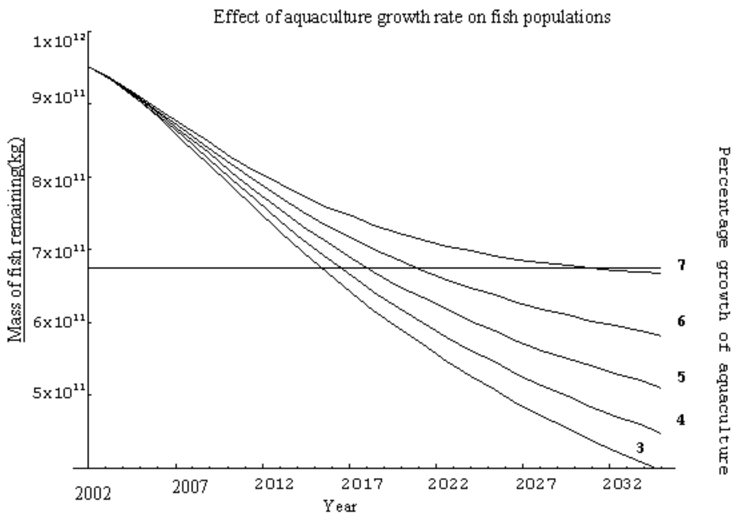
Economic. The major economic changes will relate to aquaculture. We are currently assuming the rate of growth of aquaculture is five percent, but the rate could change to be either greater or less than this number. Increased aquaculture can potentially also have negative environmental effects.

Demographic. The world population will either continue to grow steadily, leading to higher pollution and higher demand for fish, or the world population will stabilize in the near future.

Political. Nations may cooperate to limit total catch from the ocean or to increase aquaculture production.

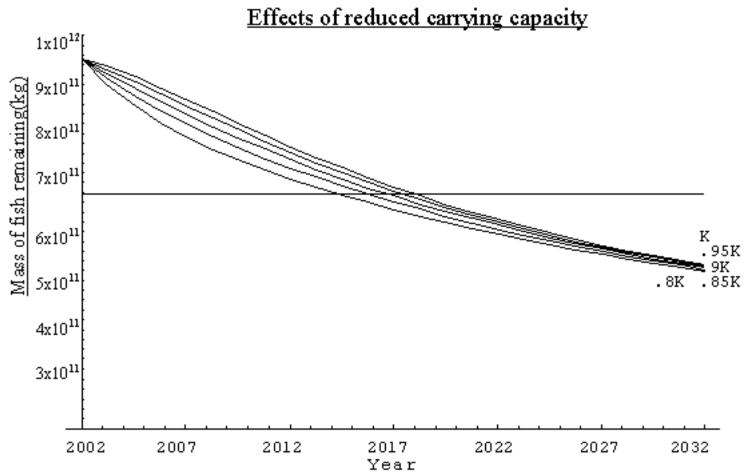
Environmental. There are numerous potential environmental changes. The above economic and demographic changes may lead to increased pollution, or virtual extinction of various species. A large ecological disaster such as an oil spill may occur. Also, global warming is an ever-present factor that could significantly affect the ocean fish population.

We first consider the potential change in fish population due to a different aquaculture growth rate. We believe that the realistic lower bound for this rate is three percent, since there is still plenty of room for both fish farms and technological advancements. A realistic upper bound for a period of 50 years is seven percent annual growth. An average growth rate above seven percents projects aquaculture to produce more fish than half the ocean's carrying capacity in 1950. The following graph provides a visual display of our model's predictions for fish population as the rate of growth of aquaculture varies.



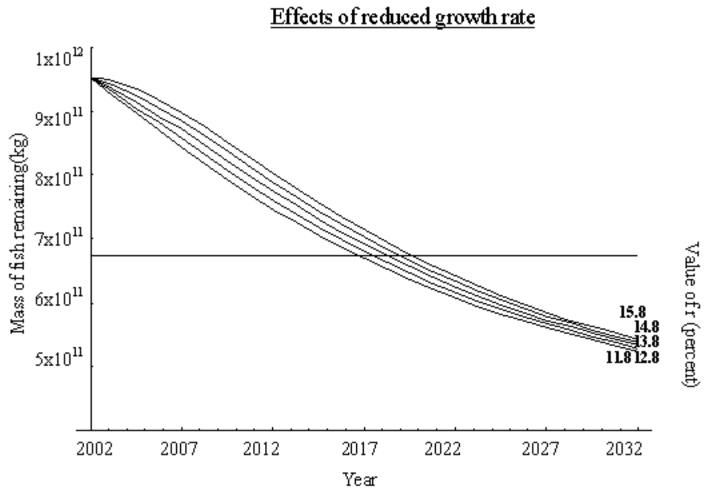
The horizontal line in the graph (and subsequent graphs) is the fish population corresponding to an ecological crisis. Assuming a three percent future growth in aquaculture, the population may reach the crisis value within ten years. However, a seven percent rate of aquaculture growth may be able to delay a crisis for over twenty five years. Combined with other factors, an increased aquaculture rate of growth may be a key part of a sustainable harvesting plan.

We next consider factors which may cause a future change in K. Both an increase in pollution and global warming have the potential to decrease K. The effect of a moderate decrease in carrying capacity in our model is demonstrated in the following graph.



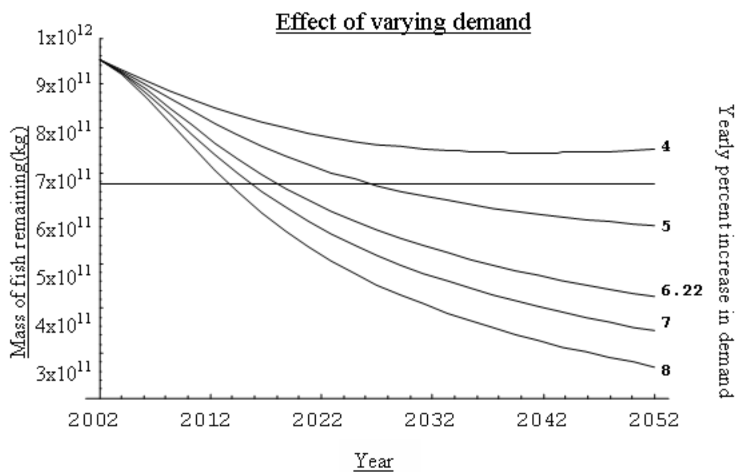
Somewhat surprisingly, our model predicts that a twenty percent decrease in carrying capacity will not dramatically affect the distance of the ecological crisis in the future. In fact, at this decreased K, the ecological crisis will only occur an estimated three years earlier. However, the intensity of pollution may well be more than twenty percent in the long term. We predict that decreases in K can not devastate the fish population much faster than current fishing practices already are.

Several occurrences in the future could affect the rate of growth of fish, r. Pollution and global warming could decrease the rate of growth. The average rate of growth of fish could actually increase if larger fish, with slower rates of reproduction, are caught disproportionately. This has actually been happening over the last few decades, and the population of large fish is estimated to be ten percent of its 1950 value. The following graph shows our model's prediction of fish population change in response to an increase or decrease in r.



We decided to model small increases and decreases in r, where the middle curve in the above graph ($r = 13.8$ percent) represents our baseline(calculated) r. We decided that a change of more than two percent in either direction over the next twenty five years would be unrealistic. Our model predicts that if r drops by two percent, the ecological crisis will arrive a year sooner, and if r increases by two percent, the crisis will be delayed by a year. Therefore, it seems that in the short term, small changes in r resulting from pollution or global warming will not have a significant effect

A particularly important factor in our model is demand, $D(t)$. We expect the percentage increase in demand to rise in the future as population rises, although the yearly rate of increase may rise or decline from its current value based on the rate of increase of population. In addition, the rate of increase of demand may fall if nations can cooperate to limit total catch from the ocean, in the interest of protecting common resources. The following graph demonstrates the predicted effect of varying demand on the total population of ocean fish.



The first noticeable aspect of this graph is that an approximately two percent increase in yearly demand will hasten the ecological crisis to 2013, only 8 years from the present. The second noticeable aspect is that a two percent reduction in demand will alleviate the crisis entirely! This reduction is also independent of any increases in aquaculture, or decreases in bycatch rates. However, it seems very unlikely that a two percent drop in demand could be achieved within the next twenty five years without a major expansion of new protein sources. However relying on this to save fish stocks would not be prudent. The conclusions of our model lead us to believe that a smaller decrease in demand, accompanied with decreases in bycatch due to technology, and increases in aquaculture growth could prevent an ecological crisis and put the oceans on track to replenish themselves.

4.3 The limitations of our model

Although we believe our model makes generally reasonable predictions, it has several limitations.

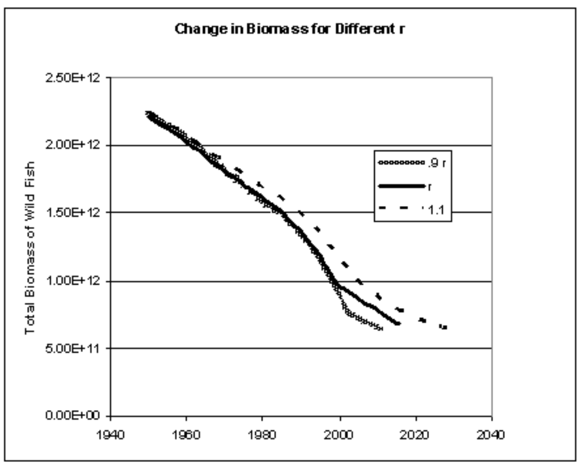
1. One important factor that our model does not take into account is the positive and negative effects of aquaculture on the stock of ocean fish. Nutrients released from a fish farm potentially have both positive and negative effects, by either nourishing ocean life or polluting the habitat. Another negative effect of aquaculture is that fish farms will compete with local life over physical occupation of the ocean. In addition, genetically different species of fish raised using aquaculture may escape into the ocean and interbreed with wild fish, making them more vulnerable to disease. We will consider these effects more later in this paper.

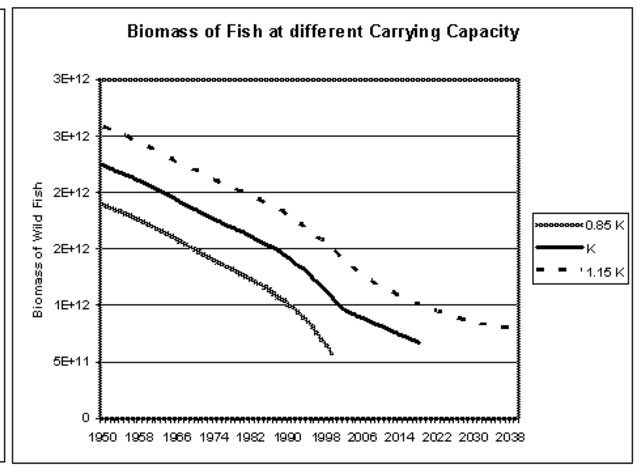
2. Our model's validity generally decreases as time increases. This is because we modelled both demand, $D(t)$, and fish from aquaculture, $A(t)$, as exponential functions with no bound. Realistically, $D(t)$ is bounded above

since the earth's population is bounded above, and $A(t)$ is bounded due to potential lack of ocean space and resources. While we set the upper bound for $A(t)$ much higher, we concluded that our model was quite valid as long as $A(t)$ was less than 100 million metric tons, the approximate amount of fish taken from the sea today. Therefore, our model is valid for at least 25 years (during the range which the predicted ecological crisis occurs), and possible for another 25 years after that. Using our model to predit more than 50 years into the future would likely be highly imprecise.

3. When computing the current fish population from historic data the only variables are r and K. The model is more sensitive to changes in K than r.

The following graph demonstrates the change of our model when r and K have been altered by 15 percent.





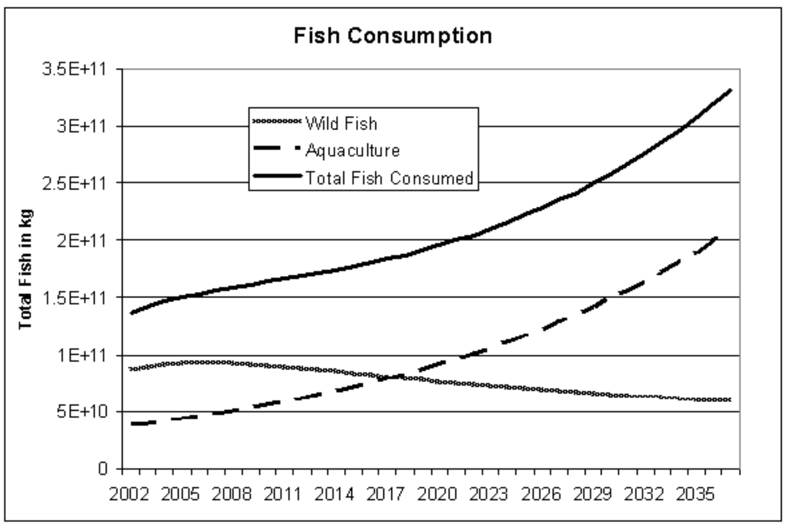
However, we also feel that we probably have not underestimated K, because K is bounded above by phytoplankton data and lower values for K predict that the ocean has already hit an ecological crisis. Our main conclusion, that the ocean is rapidly heading towards a crisis, remains the same for fairly small changes in both r and K.

5 A Fair and Practical Harvesting Policy

The two most prevalent factors affecting fish population in the future are the global increase in demand for fish and the possibility that aquaculture will help ease that pressure. Other factors such as bycatch have an effect, but are not as critical in avoiding a long term ecological disaster. Testing our model reveals that while changing only one parameter can prevent crisis, the amount of change needed to do so was unrealistic. Changing only growth of demand required that the rate of growth of demand be reduced by 35.7 percent. On the other hand, in order for aquaculture to completely alleviate the strains of demand, growth would require a yearly increase of ten percent over the next 50 years. While this rate of growth may be possible for a short term it is completely unrealistic for a period of fifty years. Altering the number for bycatch by itself is simply unable to prevent a crisis. In fact, modeling a complete disappearance of bycatch only prolongs a crisis by about year. We will now look at creating a sustainable global fish harvesting policy by changing all these parameters at the same time.

5.1 Aquaculture

It is clear from our model that the inevitable global increase in demand for fish over the next 50 years will in large part be met by aquaculture.



Sadly, the ocean simply cannot naturally supply enough fish to meet the expected demand. We therefore propose that the governments of the world heavily subsidize the expansion of aquaculture. Although we predict aquaculture will be the savior of wild fisheries, it is not a flawless solution and has its own problems which will be more thoroughly discussed later.

Between 1994 and 1996 the rate of aquaculture production grew between 13 percent and 17 percent [8]. Based on the previous rapid growth of aquaculture and the rapid increase in demand for seafood, we estimate that it would be possible for aquaculture to continue to grow by 10 percent annually for another *ten* years. This growth may be spurred on by subsidies incentive. For example a general tariff on wild caught fish but not farmed fish would encourage greater aquaculture development.

In short, since aquaculture is influenced by economics, we maintain that an intelligent system of government policies can make aquaculture grow at any rate below thirteen percent, provided that the production from aquaculture does not exceed the demand for fish. This claim is additionally supported by the fact that in the model with our policies enacted, the capture of wild fish is reduced, increasing the room for aquaculture. However, as mentioned before, aquaculture development cannot permanently stay at ten percent. After the initial ten year boom we expect a subsidized aquaculture to cool down to a growth of about 6 percent per year for the next decade. For subsequent decades the rate of aquaculture increase would be four, and then three percent.

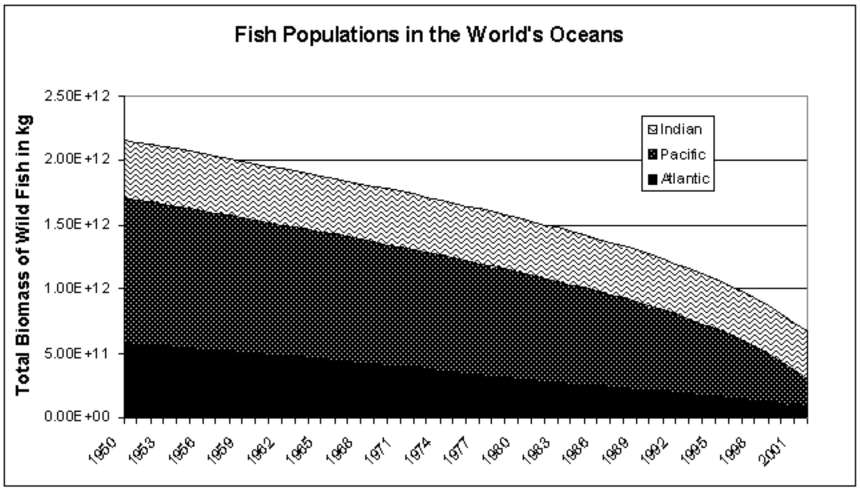
5.2 Regulation of Demand

Controlling the rate at which people take fish from the sea can consist of quotas on the amount of fish captured and economic incentives. When considering these policies, a key question is how to divide up the rights to the sea. Do the oceans belong to those who live on them, to all people, or to countries? While considering the oceans as a public trust owned equally by all people, or at least the people who live close to them, may be the fairest, it is also politically impractical. Currently fishing is dealt with in terms of national takes and this trend is likely to continue. However, dealing with fish purely as an issue isolated to each individual country is also inaccurate, as fish are free to move between coastal borders at will. The transience of fish stocks is an especially relevent issue with some of the most desirable large fish such as tuna, which migrate across the entire ocean. It is therefore essential that the problem of over-fishing be dealt with in a global manner, involving as many countries as possible.

Countries will base their future positions on any reforms on their relative demand for seafood and the stock of seafood in their national waters. Disputes over fishing are also apt to degrade into disputes between the developed and developing world. There is a great deal of bitterness in developing nations that the industrial world only talks of limits after it has already depleted a resource. Certainly any reform measure or economic incentive will benefit or harm different countries to different degrees. Keeping this in mind, it is the goal of our policies to present a system that minimizes a country's resistance to change and protect stocks of wild fish from depletion. Therefore, three factors of paramount importance when considering what changes are politically viable are

- The current distribution of fish in the world
- The divide between developed and developing countries
- The demand that a country has for seafood.

An analysis of the world's oceans reveals that presently, not all oceans are equally endowed with marine life. Using our model separately for each ocean, we find that the Pacific and Atlantic are on their way towards a complete lack of fish, while the Indian Ocean's supply is relatively stable. We determined the carrying capacity of each ocean by assuming that the world's carrying capacity was spread amongst the three major oceans proportionally by size. We were then able to run the model from 1950 using regional capture data [10].



The results of this graph, showing that the industrialized nations bordering the Atlantic and Pacific have already depleted their oceans, are in line with the literature. The fact that the Indian Ocean's supply of fish has been stable so far is most likely due to the lack of development in countries that fish that ocean. The political ramifications of the heavy concentration of fish in the Indian Ocean are not entirely clear. However, it is safe to assume that the countries bordering the Indian ocean will take offense to other countries fishing in or around their waters, especially considering that the newcomers have already expended their own stocks.

It is also not a surprise that the countries demanding the most seafood are the ones bordering the most depleted waters. These countries have a fair part of their economy geared towards the seafood industry. Consequently, the preservation of fisheries should be important to their long term economic health. However, the same reason that preservation is important is also why these countries also have a tendency to discount the potential threat, namely, the fishing industry wants to maximize its profit. Therefore, effective reform strategies in these countries condense into a problem of public awareness. Adding to this problem is the fact that the scientific community is unable to provide exact statistics on the number of fish left in the ocean. Part of this problem is due to the fact that not enough money is allocated to field studies of fish populations. We hope that increased research will push citizens to force change in their countries.

An additional problem is that in the developed world, many fishing fleets are not profitable by themselves. This is largely due to government subsidies. It is vital that these subsidies be withdrawn. It is unreasonable to artificially increase the number of boats, especially as fish populations plummet, though it is uncertain what effect this would have on the yearly catch.

We suggest a two pronged method to reduce global fish takes.

1. A strict quota system for the over-fished Atlantic and Pacific.
2. A system of economic incentives would be ideal for less depleted areas such as the Indian Ocean.

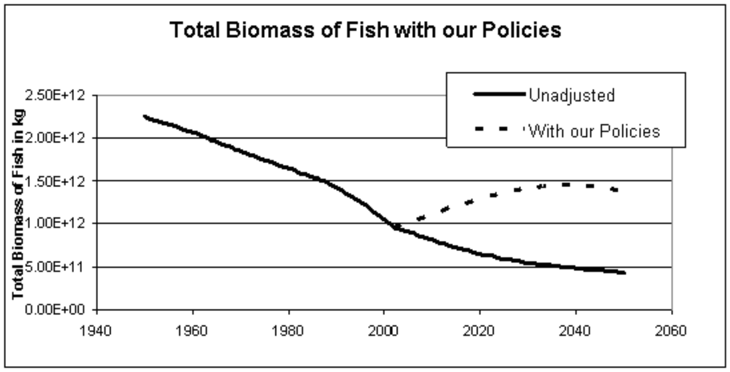
Not only would the incentives recognize that there are still many fish to catch in the Indian Ocean, but they would hopefully sidestep the debates between developed and undeveloped nations.

The takes from the Atlantic and Pacific oceans should be set to fractions of the maximum sustainable harvest. The sustainable catch from these oceans are 18.7 and 39.1 million tons respectively. The quotas should increase with time to reflect that greater fish populations can sustain greater rates of harvest. We divided the maximum yield by the polynomial $(2-\frac{t^2}{2500})$ to provide half the full yield in 2002, and the full yield in the year 2050. Testing these models showed that fish populations exhibited good signs of rebounding in thirty years and had recovered to the level of maximum sustainable yield in fifty years. Deciding which countries would receive how much of these quotas would be determined by a simple geographic slicing of the oceans. The exact areas that countries would get may be controversial, but such a decision must be made. This would ensure that even if some countries were to disregard their quota, the rest of the ocean would be left healthy. This entails a reduction down to about a third of what current capture rates in these oceans are. Such a strong decrease will definitely be met with resistance in the fishing industry. While many fishermen will lose their jobs, the loss of jobs in fishing fleets is inevitable. Furthermore there have already been some pronounced collapses of fisheries, such as the Atlantic cod, or the Peruvian Anchoveta in the 1970's. Although losing some jobs is a negative effect, the alternative is worse; the collapse of the cod fishery led to the unemployment of the entire 40,000 person fleet [11].

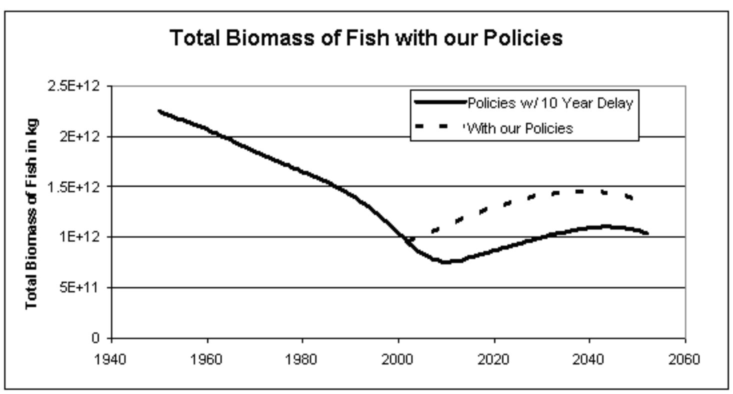
The Indian Ocean currently has more fish than the point of maximum sustainable growth so the growth of the fishing industry can be less regulated than the Pacific and Atlantic. However, we advise a set of incentives to reduce the future possibility of overfishing. One of these incentives would be a tariff on wild fish from the region in order to slow down the amount of wild fish exported. The money gained from that tariff would then be used to lower the price of imported farmed fish. In return, the developed countries could lower some agricultural subsidies and agree to help keep their own fishermen out of Indian Ocean waters. Under this model, we assume that the Indian ocean is able to provide its maximum sustainable yield, 15.61 million metric tons per year. Thus, the total amount fish taken from the wild from all oceans under our policies is (in millions of metric tons):

$$\frac{(18.7+39.1)}{(2-\frac{t^2}{2500})}+15.61$$

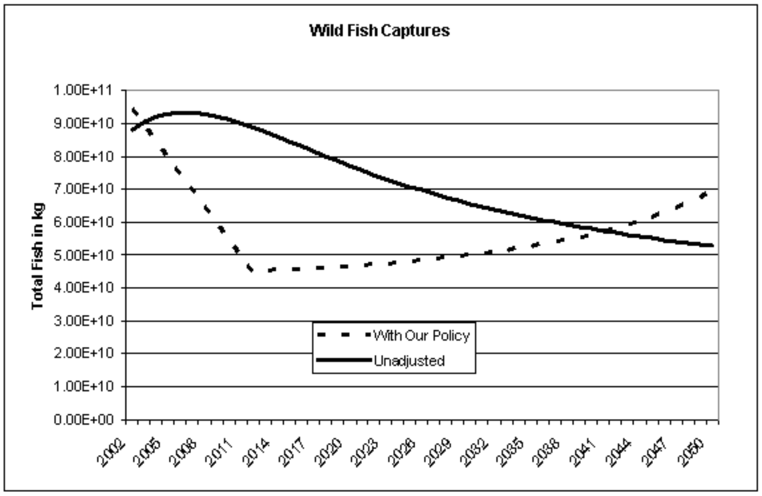
Running this model reveals that in the year 2037, the number of fish will have returned to levels similar to those during the early nineties.



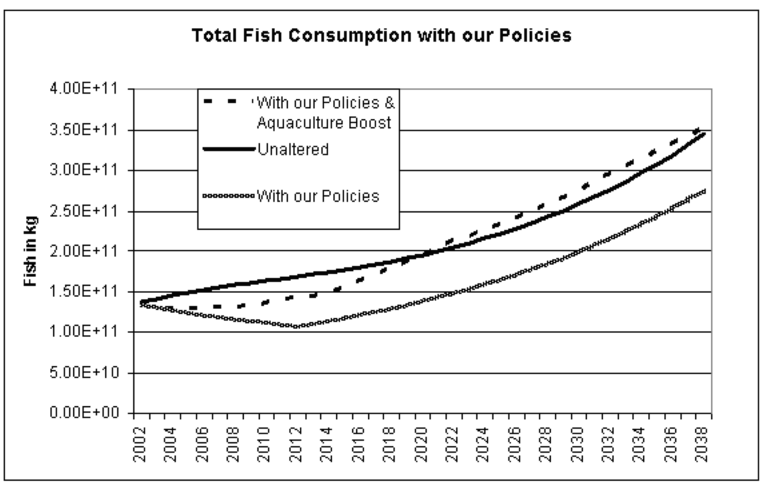
Unfortunately, the total take from the seas in that year would be about 44.5 million tons. This is approximately half the amount of wild fish currently captured from the sea. When aquaculture is added to the wild capture, the total amount of fish available as food is 84.3 million tons. This amount of fish is equal to 63.4 percent of the current value. We also recognize that the immediate adoption of our policies is not practical. The attached figure displays the amount of fish present in the world with a world in which the wild capture rate slowly approaches our advised rate over a course of 10 years.



As evident in the above figure, our policies may look overly optimistic if enacted instantly. They are sensible if enacted over ten years. Similarly, the wild catch under this policy initially decreases and then later catches up with the unaltered rate of wild capture.

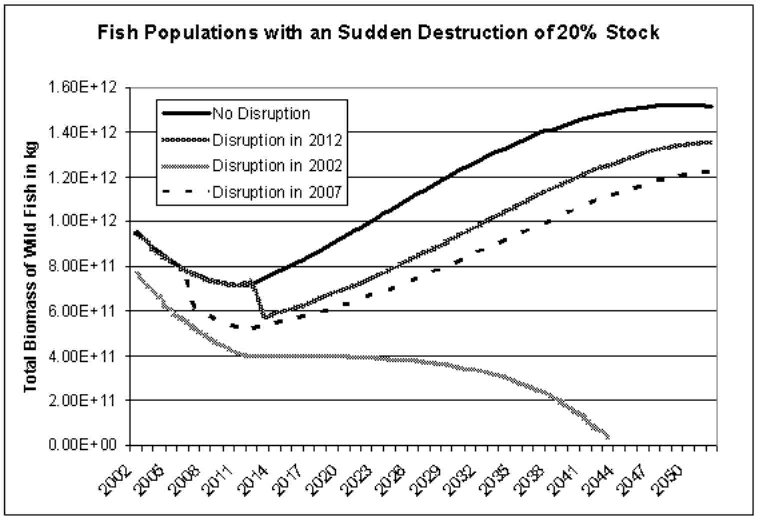


If the added aquaculture bonuses are added onto the wild fish results, the amount of fish consumed is able to match the projected demand fairly well. Indeed proper management of the global fisheries will ultimately yield higher rates of return.



The largest discrepancy between the projected demand and the actual supply if our policies and aquaculture boost are accepted is a shortfall of 17.2 percent occurring in the year 2009. While this is a fair shortfall, some drop in consumption is inevitable if the global fish populations are to be saved and the amount of aquaculture is kept reasonable.

The following graph shows how our policies are affected by an unforeseen event, such as an instant twenty percent drop in the fish population (this may be the result of a tremendous ecological disaster, such as an oil spill)



From this graph, we conclude that as long as such a disaster does not occur within two years, even a massive drop in the fish population will not change our policies' beneficial effects.

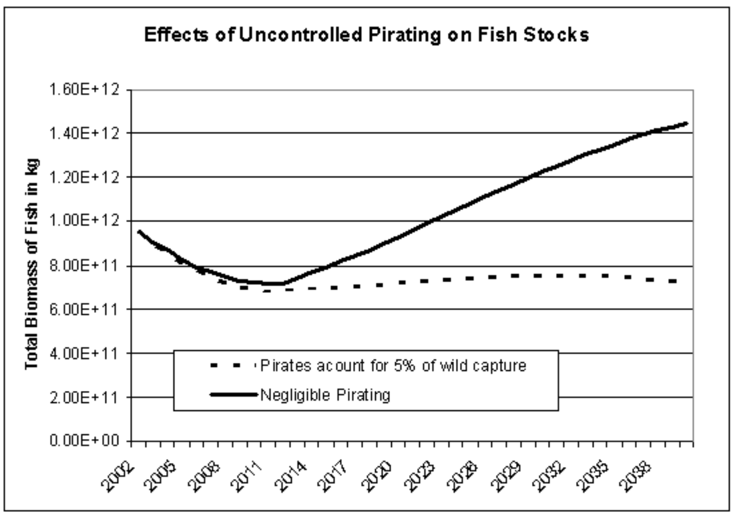
6 Additional Effects and Policies

6.1 Security policy

Developing a security policy to protect marine life from over-exploitation is a complicated endeavor.

- Laws vary greatly from country to country and region to region.
- Many species of fish are highly mobile, making regulation of their catch hard to monitor.
- Some of the current fishing methods, such as dredging and dynamite fishing, have associated negative side effects. It is often profitable to be very careless when harvesting, and have a large volume of bycatch in addition to the usable fish.
- The system of "flags of convenience" is a major impediment to international regulation. A flag of convenience is when a ship operates (in non-national waters) under the flag of a country other than its own, to avoid undesirable fishing laws. The result is that it allows fishing boats to choose the country with the most relaxed fishing laws and sail under their flag.

The first step in developing a worldwide security policy is eliminating the flag of convenience system. This not only benefits the world's fisheries but also the workforce employed on these boats. Some form of international law needs to be developed. It is hard to make laws that are uniform in any way due to the dramatically different situations in various parts of the world. At the very least nations need need to work together and share information so it is possible to obtain an idea of the state of the world's fisheries as a whole. Some changes can be imposed regardless of regional concerns. The following graph demonstrates the effects of uncontrolled piracy on the world's oceans, modelled by a five percent increase in total fish takes above quotas.



We recommend financial penalties imposed for using equipment that causes higher bycatch. There also needs to be an investment in improving fishing technology. Entirely new equipment and methods could also reduce bycatch. Highly destructive fishing methods like dredging and "dynamite fishing" must be completely phased out by more sustainable techniques.

There will undoubtedly be resistance to and even rejection of such radical changes. Some nations may decide that the changes are worse than the present situation and continue with the status quo. The spread of information will be critical to make all nations understand how grave the situation is. It must be understood that the status quo is not sustainable and that however bad the changes seem, the alternative is worse.

6.2 Environmental effects

Even with reduced catches from the world's fisheries there are still many long term environmental concerns.

- There is an alarming amount of bycatch which hurts many species and does not differentiate between those which are endangered and those which are not. The damage from bycatch is especially hard to monitor and assess since it is dumped back into the sea.

- Completely removing a particular species from an ecosystem due to overfishing reduces biodiversity. This can have various negative effects on all nearby species of marine life, such as reducing the resiliency of an ecosystem to natural disasters or diseases.

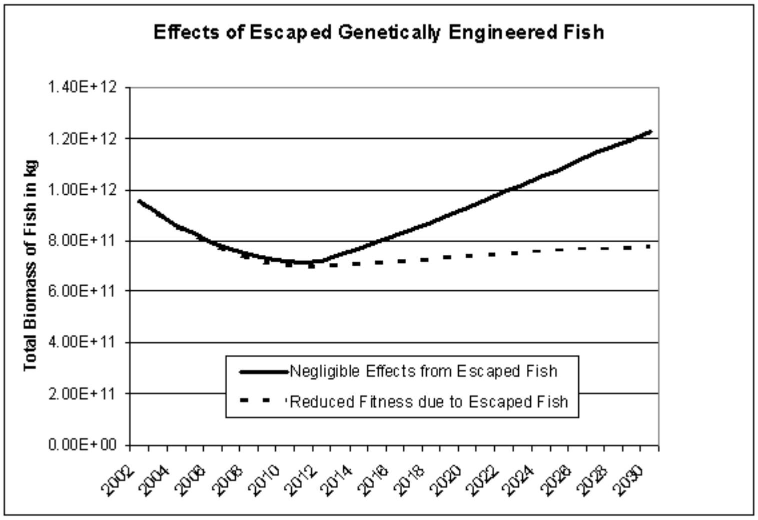
- There are also long term environmental concerns related to aquaculture. Farming fish, like farming anything else, produces larges amounts of waste.

We suggest that incentives should be enacted to discourage bycatch, such as making more efficient fishing equipment less expensive. Investment in research to find less destructive fishing techniques would also be valuable. Research into marine ecosystems is also vital for understanding how fishing impacts the ocean as a whole.

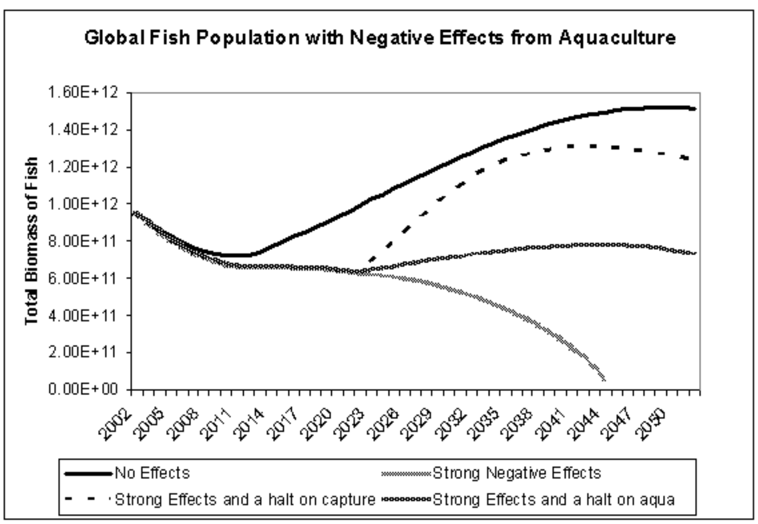
Only aquaculture of herbivorous fish provides any real relief for wild fisheries, because herbivorous fish do not rely on meal made from small wild fish for a large part of their diet. Aquaculture can provide false relief for wild stocks in other ways too. On the coast of Thailand many of the coastal mangrove forests have been converted into shrimp farms. Although the shrimp farms reduced pressure on wild shrimp, the loss of mangroves reduced yields of other fish species that used the mangroves for spawning [12].

The waste from aquaculture has numerous negative effects on the local fish population. As most fish farms are located in the ocean, their waste, in the form of sewage, uneaten food, and antibiotics, are washed out to sea without any treatment. This pollution will accumulate and have a negative effect on wild fish. The problem can be alleviated by using either plant aquaculture or *polyculture*, farming species which feed off each other's wastes in the same place. Plant aquaculture consists of seaweed colonies that surround the fish farms, absorbing wastes and excess nutrients. In fact, these seaweed colonies can be harvested and sold, and often pay for their installation [6]. Wild fish can also be threatened by large scale escapes of farm-raised fish. Once released into the wild, farm fish compete with wild fish and often out compete them due to genetic modifications. Farm fish can also interbreed with wild fish and reduce the genetic variability of the wild populations because the farm populations are genetically very homogeneous.

The following graph simulates the effects of interbreeding between escaped farmed fish and wild fish, through a five percent reduction in r.



While the cumulative negative effects of rapid aquaculture expansion are currently unknown, we expect that by the year 2022 these effects will be better understood. In the year 2020 it would then be possible to readjust the current policies to take into account aquaculture pollution. The following graph displays the results of our model under the strain of aquaculture pollution.



In order to model the potential negative effects that aquaculture pollution might have on wild stocks, we assumed that for every farmed fish produced, the carrying capacity of the ocean would decrease. Assuming the worst case scenario, we modeled that pollution from aquaculture would cut the carrying capacity of the world's oceans in half by the year 2050. As seen in the above figure, our current policies, when added to the potential dangers of aquaculture, are unsustainable. However, if in the year 2020 either aquaculture is stopped and fishing levels are adjusted to the ocean's new carrying capacity, or aquaculture is continued and wild captures stopped, fish populations are able to rebound. One important policy change is strong measures to prevent interbreeding between escaped farmed fish and wild fish. This means both more secure fish pens, and in the case of genetically engineered fish reduced breeding inviability.

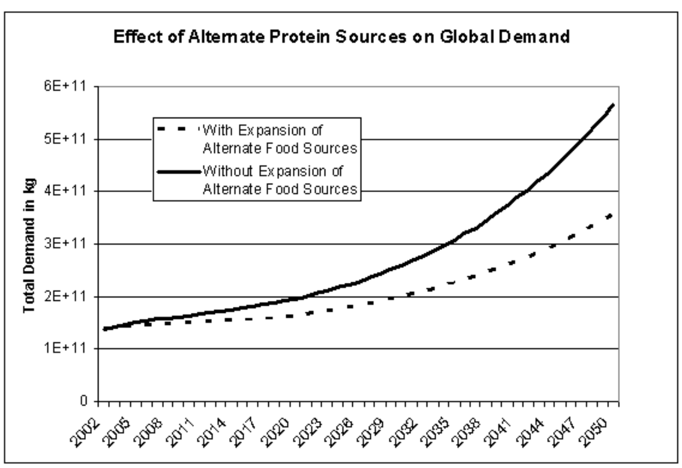
6.3 Alternative technologies

Many cultures around the world rely on fish for a major part of their diet because it a good source of protein and other nutrients. Also in some coastal regions it is the only large stable supply of protein. As world population continues to grow and fish supply shrinks these people may be forced to find another source of food. Expecting cultures to completely change their diets is unreasonable, but using other sources of the same nutrients would help ease demand for fish.

In developed countries a major reason for the popularity of some species of fish is that their flesh contains Omega-3 fatty acids. These acids are considered healthy so a large number people want to eat more fish in their diet. However, there are other sources of the Omega-3 acids that people desire, most importantly certain land plants such as flax. An increase in the production of flax and an increase in people's awareness of other sources of Omega-3 fatty acids (as well as the plight of fish) could reduce long term seafood demand.

It will be harder for cultures that rely almost entirely on fish for protein to make dietary changes. However, it is possible that affordable vegetable proteins such as soybean could be used as a source of protein. It is unlikely to make a significant change not just for economic or environmental reasons but simply because fish are traditional or have a cultural importance.

The following two graphs demonstrate the effects of alternate protein sources on global demand for fish. We adjusted the rate of growth of demand by two percent to account for this change.



7 Conclusion

The world's fish supply is severely threatened by overfishing. Our model shows a complete collapse of fish populations within fourteen years. The Atlantic and Pacific Oceans have already been mostly depleted, and although the Indian Ocean still has relatively stable harvest rates, we believe it is just a matter of time before these rates rise to unsustainable levels.

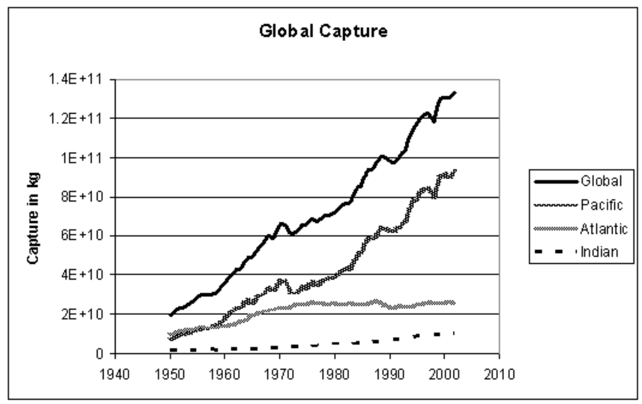
Aquaculture must be expanded at an even greater rate if there is any chance of meeting demand. Fishing must be significantly reduced to allow fish populations to recover to levels where attaining the maximum sustainable yield is possible. Even though the future reduction in size of fishing fleets will be a difficult transition, by gradually enacting these policies over the next ten years, the impact can be spread out and the world's fisheries saved. Additionally, security measures must be implemented to protect wild fish while they are allowed to recover. Also, poorly implemented aquaculture can be as destructive as overfishing. However, if carried out properly, it can eventually provide far more fish than catching seafood from the wild.

We recommend additional funding for research. New fishing technologies that are less damaging to surrounding habitats need to be developed. Marine ecosystems and the impact fishing has on them is poorly understood. More efficient aquaculture techniques can be created that are less dependent on wild caught fish meal and fish oil. Also, alternative sources of the protein and nutrients fish provide should be explored to help reduce demand for fish. The world is near but has not yet crossed the point of no return. Only a swift and organized effort can ensure future generations will inherit an ocean with the amazing diversity of the present.

8 Supplementary Data and Bibliography

Additional Data

		CAPTURE DATA		
	Global	Pacific	Altantic	Indian
1950	19287821000	7412268000	9824229000	861700000
1951	21861962000	8733967000	10977715000	898320000
1952	23754496000	9761561000	11711333000	1019714000
1953	24345183000	10089314000	11839094000	1089055000
1954	26418275000	10928649000	12817852000	1205572000
1955	27929455000	11889899000	13202606000	1268750000
1956	29593670000	12430911000	14030589000	1526985000
1957	30086765000	13377740000	13379859000	1673614000
1958	30644933000	14158283000	13239362000	1544760000
1959	33158789000	15947029000	14052577000	1428485000
1960	35491128000	17736600000	14261331000	1774300000
1961	39155777000	20805482000	14883362000	1626662000
1962	42543180000	23214058000	15754124000	1669106000
1963	43774837000	23942205000	16423190000	1689677000
1964	48459355000	26842257000	17686865000	1953169000
1965	49611273000	25925458000	19553908000	2000154000
1966	53522462000	28666210000	20509333000	2211147000
1967	56922907000	30701263000	21705704000	2285162000
1968	60353667000	33012525000	22640859000	2413024000
1969	58918864000	31984266000	22187240000	2429424000
1970	65322388000	36804455000	23324296000	2684842000
1971	65582676000	36594281000	23505361000	2888702000
1972	61485220000	31745344000	24279774000	2860996000
1973	62068709000	30947403000	25436735000	2987977000
1974	65537599000	33887194000	25563782000	3415823000
1975	65415875000	33421381000	25472608000	3593175000
1976	68927041000	35869014000	26621361000	3652672000
1977	67887126000	34960664000	25888424000	4094599000
1978	70130651000	37283688000	25753148000	4227095000
1979	70755149000	38631376000	25089813000	4176033000
1980	71884158000	38895939000	25545077000	4387591000
1981	74647147000	41717528000	25377528000	4353725000
1982	76782083000	43558278000	25253600000	4605257000
1983	77280731000	43343224000	25710261000	4798698000
1984	83609758000	49305848000	25482902000	5195096000
1985	86248704000	51997140000	25332978000	5258566000
1986	92879744000	58157480000	25264540000	5546623000
1987	94873592000	58245761000	26651043000	5811602000
1988	99467921000	62429375000	26781416000	6030020000
1989	1.0062E+11	64234890000	25496950000	6614247000
1990	97844928000	63079416000	23816577000	6653734000
1991	97445756000	62679626000	23782594000	7073168000
1992	1.00601E+11	64553423000	24706833000	7528361000
1993	1.04359E+11	68311848000	24171152000	8120520000
1994	1.12924E+11	77047007000	24045224000	8147188000
1995	1.16765E+11	79164922000	25282940000	8401155000
1996	1.20555E+11	82961783000	25263568000	8486851000
1997	1.22989E+11	83792211000	26414167000	8838084000
1998	1.18235E+11	79555047000	25641964000	8929585000
1999	1.27221E+11	88035812000	25700644000	9154349000
2000	1.30998E+11	91219860000	26085678000	9228986000
2001	1.30651E+11	90317318000	26547316000	9331657000
2002	1.32989E+11	92735207000	25834416000	9827717000



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