Chapter 5
How Many Fish in the Sea?

5.1 The Professors and the Fishermen (Fig. 5.1)

*While Empires will be born and die, Euclid’s theorems will keep their youth forever.*

(Vito Volterra)

In the years after the First World War, the Italian zoologist Umberto D’Ancona (1896–1964) was working at a set of data on the abundance of various species in the fish markets of the *Veneto* region, in Italy, during the previous decade. Consider that, at that time, there were no methods to estimate the fish populations and very little was known about the abundance of fish in the sea. The best a marine biologist could do was to examine the catch that the fishermen brought to the market after their daily fishing run. But D’Ancona had noticed a puzzling trend: during the war, there had been a remarkable change in the proportions of the various species in the catch. The proportion of predatory fish, such as sharks, had increased compared to smaller prey fish, such as hake. D’Ancona reasoned that this increase in predatory fish was because many Italian fishermen had enlisted in the army and were fighting on the frontline. So, the fishing activity had diminished, the fish could reproduce in peace, and long-lived fish could reach maturity. Hence, predatory fish had more prey than before and their population had increased, too (Fig. 5.1).

D’Ancona was not a mathematician and he didn’t know how to interpret these data quantitatively, but he had a resource that other biologists lacked: he had married the daughter of professor Vito Volterra (1860–1940), one of the most renowned Italian mathematicians of the time. Volterra had never studied fishing before and was not an expert in zoology, but he was curious, as many scientists are, and he found the hypothesis intriguing. Thus, when his son in law showed him the data, he began to think of a mathematical model that could explain them.
After a few years of study, in 1926, Vito Volterra published his article titled *Fluctuations in the abundance of a species considered mathematically* in the journal *Nature* [38]. It became a milestone in the field of population biology. Shortly before, the American ecologist Alfred Lotka had proposed a similar model, although not directly related to fishing [39]. Today, the model goes under the general name of the “Lotka-Volterra” model. It is also called the “prey-predator” model or even the “foxes and rabbits” model with foxes in the role of predators and rabbits in the role of prey. It is curious that neither Volterra nor Lotka ever mentioned foxes and rabbits in their studies, but we know that human imagination unfolds in many ways. Something similar had happened to Jean-Baptiste Lamarck who in the eighteenth century had proposed his theory of biological evolution based on the transmission of acquired characteristics. Today, everyone is talking about Lamarck’s ideas in terms of giraffes lengthening their necks, but poor Lamarck had never mentioned giraffes in his writings!

Fig. 5.1 Ilaria Perissi shows her biodynamic model of whaling in 2019
Interlude: The Man Behind the Models, Vito Volterra

By Ilaria Perissi (Fig. 5.2)

For me, Vito Volterra was one of the main sources of inspiration for this book, not just because of his scientific work but also because of his fascinating personality. His grand-daughter, Virginia Volterra, is today a researcher in psychology at the National Research Council (CNR), an institution whose president was Vito Volterra from 1923 to 1927. So, while working on this book, I thought that it was appropriate to meet her. She turned out to be happy to talk on this subject, even though she never met her illustrious grandfather and what she knew about him had been told her by her grandmother, Virginia Almagià, Vito’s wife. From her description and from the data I could find on the web, the story of the development of the “Lotka-Volterra” model comes out as lively and fascinating.

As for many other scientific discoveries, the equations of fishing were the result of a series of coincidences and human factors. It had to do with the fact that Volterra’s daughter, Luisa (1902–1983), studied zoology in college and she fell in love with her slightly older colleague, Umberto D’Ancona. The two

Fig. 5.2 The young Vito Volterra (1860–1940), ca. 1890
married in 1926 and they worked together as researchers in marine zoology for their whole scientific career. It seems that, initially, Vito Volterra disapproved of this marriage, although we don’t know for which reason. Anyway, as it could be expected, the father couldn’t change the mind of his daughter and, eventually, Vito Volterra developed a relationship of friendship and respect with his son in law. Umberto D’Ancona was indeed a remarkable personality, too. He had fought in the war and he had been decorated for military valor. Later on, he became full professor at the University of Padua, and today he is recognized as one of the greatest Italian biologists of his time. He even wrote an entire book, *La Lotta Per L’Esistenza (The Struggle for Survival)*, published in 1942 and dedicated to the models that his father in law had developed. The Volterra family included many scientists and the tradition remains to this day (Fig. 5.3).

Vito Volterra was not only one of the most brilliant mathematicians of his time but also an enlightened man. He was a great promoter of gender equality in scientific research at a time when women still did not even have the right to vote in Italy (it was introduced only in 1946). In science, women were discriminated against not just in Italy, but everywhere in the world. For example, in 1897, there was a proposal in Cambridge University to grant women formal recognition of their degrees, but it was rejected by 1713 votes to 662. It was only in 1948 that the first degree was awarded to a woman in Cambridge, and the person who received it was the Queen Mother! France was perhaps an exception but, even there, women faced all sorts of difficulties up to recent times. When it was the time of attributing to Marie Curie the Nobel Prize, in 1903, there were suggestions that it should have been given to her husband, Pierre, alone, because no woman ever had obtained one before.

Vito Volterra, instead, was a great believer in the role of women in science. He did a lot to empower them by having many women as coworkers and helping them cultivate their potential and build up careers in various scientific disciplines. Volterra was also a great admirer of Marie Curie, the French scientist winner of two Nobel Prizes. He met her personally during a journey she made to Italy in 1918, and they exchanged several letters, still conserved today. Vito Volterra was also very advanced in his political views. In 1931, he was 1 of only 12 out of 1250 Italian faculty members who refused to swear loyalty to fascism and its leader, Benito Mussolini. His comment was “while Empires will be born and die, Euclid’s theorems will keep their youth forever.” He paid dearly for his political position when he was forced to leave his chair of mathematical physics at the University of Rome. In 1934, he was also forced to resign from his membership in the prestigious *Accademia Dei Lincei* in Italy. During the last years of his life,
he had to live mostly abroad. Only after the fall of the Fascist government, in 1944, he was recognized for what he had been: one of the greatest Italian mathematicians of all time.

A note by Ugo Bardi: We could also say a few words about Alfred Lotka (1880–1949), the other name of the Lotka-Volterra model. Unfortunately, we don’t know much about his personal life, except that he was born to American parents in Europe and that he moved to the United States when he was 22. He and Volterra worked independently and the two don’t seem to have been in very friendly terms with each other. Lotka seems to have been keen to establish his priority in the development of the model. He was also critical of Volterra’s approach [40]. But they were both great scientists who gave fundamental contributions to science.
In any case, it does not matter if we speak of foxes and rabbits (or of lions and giraffes). The work of Volterra and D’Ancona was important in biology for various reasons, mainly because it proved beyond doubt, perhaps for the first time, that human action influenced marine animal populations. At that time, it was normally believed, as sometimes it is still believed today, that the sea is so vast that humans could not do anything that would affect it – an attitude also common nowadays about the atmosphere and climate change. The beauty of this idea was that the demonstration was independent of the estimate of the size of the fish stocks, difficult to do then as now. Volterra could demonstrate the changes looking at how the fish stock varied in time rather than measuring their size. It was an idea that was at the basis of the field that would be called “system dynamics.”

Let us now introduce another scientist whose work is relevant for the present book: Garrett Hardin (1915–2003), a biologist who worked at the University of California, Santa Barbara, for his whole career. Hardin never discussed fishing in his papers, and he does not seem to have ever mentioned the Lotka-Volterra model. But, perhaps unknowingly, Hardin had redeveloped the same model. In 1968, he published an article that would become famous and that remains well-known today, “The tragedy of the commons” [41], in which he laid the foundations for understanding the concept that would later be called “overexploitation.”

To understand Hardin’s work, we must go back to the times in which he lived, the post-war years. It was a period of great prosperity for the Western world: a home for everyone, two cars in the garage, television, holidays on the beach, pensions, medical assistance, and more. This prosperity was not really for everyone, but it was still a great improvement in comparison to older times. Above all, the abundance of food was a new feature in the history of the world, mainly the result of the “Agricultural Revolution,” also known as the “Green Revolution,” that had enormously increased the yields of agriculture through a combination of fertilizers, pesticides, new varieties of cereals and the mechanization of everything. With such abundant agricultural yields, it was possible to allocate a fraction of the cereals’ harvest for feeding livestock, and this, in turn, generated the availability of meat in an abundance that had not been seen in history, probably, from the times when our ancestors were exterminating entire herds of bison by forcing them to plunge down a cliff (Native Americans were reported to do this by Lewis and Clark in 1804). In 1955, Ray Kroc officially opened the first “McDonald’s” restaurant of a chain that would spread around the world, as we all know. Modern industrial fishing did its part, flooding the market with cheap and affordable frozen fish.

It seemed to be the start of a new era. The last famine in the Western world had struck the Netherlands at the end of the Second World War and in its immediate aftermath, but, from the 1950s, the problem of hunger in the West had ceased to exist, except among the poorest fraction of the population. Famines had become a thing of the past, like barbarian invasions and plague epidemics. Hunger still existed in non-Western countries, but it was clear that new technologies would have a positive impact even outside the rich Western world. Indeed, from the 1980s, the great famines of ancient times disappeared everywhere. On the contrary, people began to
worry about eating too much: it was the obesity epidemic affecting many countries today (the problem is not that people eat too much, it is that they eat poor quality food, but that is another story). Starting with the 1990s, we became accustomed to the idea that if hunger still exists, and it certainly exists, it is a local problem of populations left behind and cut off from the rising wave of progress that is bringing everyone (or almost everyone) to a future of abundance.

But there was a problem: with so much food, the world population could grow, and it did. It had reached 1 billion people at the beginning of the 1800s. From there, it had taken more than a century to double, reaching 2 billion in 1928. From then on, it had been growing ever faster: 3 billion in 1960, 4 billion in 1975, 5 billion in 1987, and so on, growing nearly exponentially, reaching the level of almost 8 billion today. But could this rapid population growth last forever? It was a problem that had been noted for the first time by Thomas Malthus (1766–1834). Malthus is much criticized nowadays for allegedly having predicted catastrophes that did not occur, but, if you look at what he actually wrote, you’ll find that he had never made the wrong predictions that others attributed to him. Without the mathematical tools that would have been available only much later, Malthus could only say that there was a limit to the number of human beings that could inhabit the Earth and that sooner or later population growth would have to stop – but he could not say exactly when this would happen, nor how. It was just the concept that the economist Kenneth Boulding (1910–1993) expressed on with the lapidary phrase: “If something cannot go on forever, it will stop.”

Malthus’s ideas came back in fashion in the mid-twentieth century, right at the height of the economic boom and the corresponding population growth. Some people started worrying that all this growth was the result of the abundance of limited resources. Crude oil and all fossil fuels were a finite resource, just as fertile land was. The same was true for the sea. And if they were finite resources, then growth had to stop sooner or later. But when? And how exactly? Could the human population that exploited them continue to grow endlessly at the exponential rate it had assumed in the twentieth century? Where were we going, exactly?

The answer did not come from economics, a field that had taken a different direction in dealing with natural resources. In 1956, the economists Robert Solow (1924–) and Trevor Swan (1918–1989) independently developed the model that would be called the “Solow-Swan model” [42]. It was a model in which natural resources were not taken explicitly into consideration and the growth of the economy was considered to be due only to the availability of capital and labor. The model included also an adjustable parameter called the “Solow residual,” later to be termed “total factor productivity” (TFP). It was not a directly measurable parameter, but it was crucial to make the model fit the historical data. Then, the model’s results could be extrapolated to the future, and the result was continuous, uninterrupted growth provided that technological progress would continue to improve and that the financial system would continue to provide capital to expand the economy – no need to worry about the depletion of natural resources. As you might have expected, these optimistic results had considerable success with the public and the
Solow-Swan model is still the basis of what politicians do when they want to stimulate economic growth. They tend to finance more research or to provide more capital to the economy. The latter method is called “quantitative easing” nowadays.

Meanwhile, Garrett Hardin reasoned as a biologist and not as an economist when he developed what was perhaps the first study of a field that would later be called “bioeconomy” or “biophysical economics,” a way of seeing the human economy as an ecosystem. In his study, Hardin described the simplified case of a local economy based entirely on sheepherding, assuming that pastures are managed as “commons,” that is, access is free for all shepherds. It was a socioeconomic arrangement often observed in rural societies. Here is Hardin’s description of the mechanisms leading to the “tragedy”:

As a rational being, each herdsman seeks to maximize his gain. Explicitly or implicitly, more or less consciously, he asks, “What is the utility to me of adding one more animal to my herd?” This utility has one negative and one positive component.

1. The positive component is a function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly +1.
2. The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision making herdsman is only a fraction of \(-1\).

Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another; and another…. But this is the conclusion reached by each and every rational herdsman sharing a commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all.

These statements are a description of the same mechanisms of overexploitation described by the Lotka-Volterra model. This identity of the models was never noticed by Hardin himself, at least in his writings, but the only difference is that Hardin’s model is expressed in the form of logical reasoning instead of differential equations. In Hardin’s model, the shepherds play the role of predators (foxes), while the grass plays the role of the prey (rabbits).

To understand Hardin’s model, consider that he was not trying to describe a specific, real-world system. Indeed, many subsequent studies, in particular those of Elinor Ostrom (1933–2012) [43] (by the way, she was the first woman to have been awarded the Nobel Prize for Economics), showed that commons are normally managed much better in the real world than in Hardin’s model. Rural communities are anything but primitive, and there is a whole range of local customs, laws, habits, and social pressures that prevent those who exploit a common resource from destroying it to increase their individual benefit. But Ostrom’s work is not in contrast with Hardin’s ideas; on the contrary, it may be considered as confirming it. Like all models, Hardin’s one was valid only as much as the assumptions used, and it was to be understood not as a description of real rural systems but to demonstrate how the basic assumptions of economics would necessarily lead to disaster if applied to the real world.
In practice, Hardin’s model described the behavior of economic agents in a free market, and it demolished at the core the concept of “invisible hand” that Adam Smith (1723–1790) had developed two centuries before. Smith had said that the economy is self-regulating for the maximum good of all, and the words that he wrote in this regard in his book *The Wealth of Nations* (1776) are famous:

It is not from the benevolence of the butcher, the brewer, or the baker that we expect our dinner, but from their regard to their own self-interest. We address ourselves not to their humanity but to their self-love, and never talk to them of our own necessities, but of their advantages.

Smith’s “invisible hand” is one of those fascinating ideas that seems to be so obvious that it spread to the point of generating jokes. Do you know how many economists it takes to change a light bulb? None, the invisible hand takes care of that! But if we think about it for a moment, we see that Smith’s idea is not so obvious at all. There are many good reasons to doubt that the personal interest of individuals is the way to maximize the prosperity of the whole community. We could also question the existence of a thing called “free market” which, in general, is everything but that. But what strikes at the heart of the concept of the invisible hand is Hardin’s model. Using the same basic assumptions of standard economics, the model demonstrates that human beings cannot optimize the exploitation of resources precisely when they act as rational agents, that is, they try to maximize what in economic models is called the “utility function.”

As often happens, it takes some time for new ideas to enter the debate. Thomas Huxley used to say that it is the normal destiny of new truths to start as heresies and to end up as superstitions. At present, the consequences of Hardin’s reasoning and his “tragedy” are still considered heresies, while classical economics has not yet reached the stage of superstition. But, thanks to Hardin, we are beginning to understand the relationship between human beings and the ecosystem of which they are part. The fundamental concept is called “overexploitation,” and it was then developed in more detail by William Catton in his famous book entitled *Overshoot* (1982). It was also put on a quantitative basis by Jay Forrester in his work on developing system dynamics in the 1960s and 1970s [44]. During the same period, Howard Odum and his student Charles Hall developed these ideas more in-depth and introduced several important concepts, such as the “energy return on energy invested” (EROI or EROEI) [45].

Hardin’s model was never very popular with economists and it remains unpopular to this date. Not that economists do not know it, but they tend to ignore it or to dismiss it as irrelevant. It is in large part because science is highly compartmentalized: a biologist like Hardin who starts talking about economics is normally ignored, if not ridiculed. The same would happen if an economist were to start talking about biology (very rare, it seems). Regarding the tragedy of the commons, when economists are forced to discuss it, they seem to believe that yes, maybe there is some logic in the idea, but it can only be a special case that occurs in primitive and non-optimized societies. In our world economists say, the “tragedy” cannot possibly occur because the market is efficient and it always optimizes everything. In any
case, the tragedy can be avoided simply by making sure that all agents can maximize their profits. If the pastures that Hardin discussed were divided into private plots, no shepherd would have any interest in overgrazing his own property. So, problem solved; let us move on to something else. It may be that the fashion to privatize everything in recent times is at least in part a result of a reaction to the concepts that Hardin had proposed.

Unfortunately, this solution does not work in the real world. Consider the mining industry: normally, mining companies have exclusive rights over the resources they exploit but that does not stop their efforts to exploit them at the fastest possible rate. The same mechanism works for many other resources: competition in free market conditions leads operators to think in terms of maximizing their immediate profit; after all, this is what the shareholders of a company want. One problem may be that operators may have optimistic data about the remaining amount of the resources they exploit, but it has been shown by the Norwegian economist Erling Moxnes that even though a resource is privatized and its size exactly known, operators still tend to overexploit it [46]. This may very well be the case of farmers overexploiting their lands, as happened, among many examples in Oklahoma in the 1920s and 1930s. It is hard to think that farmers did not understand that they were turning the land they owned into a desert, but they continued doing so until the “dust bowl” of 1936 ensued.

In the case of the sea, privatization would seem to be impossible: how do you fence the ocean? But human fantasy can devise ways to do almost anything. In this case, the trick is to privatize the catch using “individual fishing quotas” (IFQs) also termed “individual transferable quotas” (ITQs). It works in this way: the government sets a total allowable catch (TAC) for a certain species, and then the TAC is divided into shares and then allocated to operators. These shares can be bought, sold, and leased. This feature is called “transferability.” It is a way to “financialize” fishing with all the problems involved in generating financial games in which ITQs can be traded just as shares are traded in the stock market. Perhaps for this reason, ITQs have become popular, and it seems that more than 10% of the world’s fishing activity is managed in this way.

Does that mean that ITQs are a good idea? Not necessarily. One problem is that those who are financially more powerful can buy out those who are less powerful. Many operators have become excluded from the industry, including individual fishermen and indigenous villages. Maybe ITQs were a success in the sense that some people became rich by trading them, and that may be an indication of higher efficiency of the system. But the problem with modern fisheries is not that they are not efficient enough, it is that they are too efficient! And the ITQ system does nothing, in itself, to reduce overexploitation. Indeed, there is no evidence that the introduction of ITQs has eased the problem of the overexploitation of the sea.

Another factor in the overexploitation of the sea is simply the immense expanse of the oceans and the autonomy of the fishing fleets that put fishermen in competition on all the marine surface, even outside governmental jurisdiction. Although fishing is mostly a coastal activity, a significant fraction of the total is done over international waters (high seas). This kind of fishing is often directed to high-value species, such as tuna, and can bring large profits to the fishing industry. The result is
that competition is especially keen and the problem of overexploitation becomes important. But the quota system is difficult to apply in these areas: states normally maintain a 12-mile “territorial waters” region along their coasts, considered to be part of their national territory. It used to be 3 miles and was described as “cannon-ball range” which tells us about its origins. There exists also the concept of “exclusive economic zone” (EEZ) that extends 200 nautical miles (370 km) off the coast. The EEZ is not supposed to be part of the territory of a state, but states can, and often do, claim the exclusive right to fish or to access other resources present in that area. Outside these regions, the sea is supposed to be “international waters,” not belonging to any state’s jurisdiction. This is known as the doctrine of *Mare liberum* (“free sea” in Latin).

Not that the high sea is a completely lawless zone, there are international rules, conventions, and treaties regulating what can and cannot be done. But it is not always clear who should be responsible for enforcing these regulations, and, often, the situation is similar to that of the Far West of Hollywood movies. You can read an interesting report on the many kinds of shady and illegal practices of open sea operators in the book by Ian Urbina *The Outlaw Ocean* (2019). Piracy, overfishing, polluting activities, and other kinds of misbehavior are common, including the mistreatment of seamen who are often treated as “disposable” depending on the financial needs of the ship owners. Conversely, sometimes the freedom of the international waters allows people to act in ways that they judge as proper, although forbidden on the mainland. For instance, Rebecca Gomperts is a Dutch medical doctor who operates a vessel for the organization called “Women on Waves” that provides abortions outside the territorial waters for women who are citizens of countries that forbid it. In other legally borderline cases, sometimes, someone seizes an abandoned oil rig or some other kind of offshore structure, claiming it to be his personal kingdom, complete with local laws and citizenship rights. This is the case of the “Principality of Sealand,” a “micronation” that claimed as its territory an abandoned Second World War anti-aircraft platform off the coast of Suffolk, England.

Micronations such as Sealand are just an oddity and abortions at sea are more than all a political issue. But the problem of the lawlessness of international waters is serious for fishing. A good example here is the “Turbot War” (the turbot is a species of flatfish, also known as the Greenland halibut). It was fought in the waters off the coast of Newfoundland between Spain and Canada in 1995. It would be a long story to tell and, as you may imagine, both sides claimed to be following the international laws. In brief, the Canadians claimed that the turbot had relocated outside their exclusive economic zone (EEZ) to deeper waters and that quotas should have been established based on their historical fishery yields inside the EEZ. The Spanish claimed that this was an unexplored stock and that they had the right to exploit it. Also, Canada claimed that Spanish boats had crossed the EEZ limit many times to fish illegally within Canadian waters, as well as using illegal fishing gear. It was impossible to find an agreement, and, eventually, Canada sent an armed patrol boat that fired a 0.50 machine gun at a Spanish trawler. Then, a Canadian patrol boarded and seized the Spanish ship. You can imagine the dispute that followed: at some
moment, Spain was even planning to send a military fleet to the North Atlantic to protect the Spanish fishing boats from what they defined as the Canadian pirates. That could have started a real war. Fortunately, that did not happen and the whole story is by now mostly forgotten. But it illustrates the problem with controlling international waters: who is in charge of having the international laws respected? There is a lot of talk about creating new international agreements that could limit the possibility of these fleets of fishing super-boats that fish wherever they like, whatever they like, and whenever they like. In practice, that is turning out to be very difficult and, so far, the problem remains unsolved.

So, what could be done to eliminate, or at least reduce, the problem of overfishing? Theoretically, it would be just a matter of establishing maximum fishing quotas at the international level to be allocated to the various operators. It could work in theory but, in practice, it is very difficult. Indeed, the result of the attempt was a remarkable disaster. Even assuming that quotas could be reliably determined, the well-intentioned attempts taken by governments to impose them clash with the tendency of all economic operators in a free market to maximize their profits. On this, there is an instructive interview that appeared in *The New York Times* in 2012. [47]:

Mr. Pineda, like everyone here, grew up with the bony, bronze-hued fish that they call jurel which roams in schools in the southern Pacific. “It’s going fast,” he said as he looked at the 57-foot boat. “We’ve got to fish harder before it’s all gone.” Asked what he would leave his son, he shrugged: “He’ll have to find something else.”

Clearly, Mr. Pineda understands very well – although perhaps unconsciously – how the Lotka-Volterra model works. But, faced with this attitude, you understand how difficult it is to try to impose quotas. Indeed, so far, quotas have done little or nothing to avoid the destruction of the world’s fisheries. Can we expect that the future will see a change? Maybe, but sometimes being pessimistic means being realistic.

### 5.2 The Equations of Fishing

> One must divide one’s time between politics and equations. But our equations are much more important to me, because politics is for the present, while our equations are for eternity.

(Albert Einstein)

In this chapter, we describe the models that should help us manage fishing. We will not use math for this purpose, but we understand that you may find this chapter a little rough going, so you can skip it without problems. You can also look at the *Moby Dick* operational game described in the Appendix; it uses the same model, except it does not use equations. After all, Einstein is often quoted as having said that even scientists do not think in equations. He may not have said exactly that, but equations are indeed a tool, not something for people to show how smart they are. So, if you want to understand how the models called “dynamic” work, you will find the explanation.
Let us start from the beginning. A “model” is something that describes reality, and it does so in a necessarily approximate way, typically, but not always, using mathematical equations. In some cases, we talk about models that are very precise and robust. Think of Newton’s law: it is an equation that describes the movement of a body subject to the force of gravity. It works very well for many real cases and can be used, for example, to direct a space probe hundreds of millions of kilometers away from the Earth, or, a little more nastily, to direct an artillery shell to explode over the heads of your enemies. Think of the laws of thermodynamics: they describe how the universe works. Or think of quantum mechanics: it tells us how elementary particles behave.

We cannot escape from these laws, such as the one that says that energy is always conserved. Those who claim to have put together some amazing invention that produces energy from nothing can only be scammers. But it is not always possible to put together exact models. Some are more approximate; some are so approximate to be nearly useless. For example, there are models supposed to predict the future of stock prices, not much more reliable than those using the reading of the liver of the victims of sacrifices, as the Etruscans used to do.

With fishing, we are in an intermediate situation. Modeling fishing with equations is neither impossible nor easy, but it is possible if we work on it. As a first step, we can turn to a field of science called “population dynamics.” It’s a science that tries to answer a basic question related to the biological species in an ecosystem: “how much will the population grow?” As often happens, the answer to the question is “it depends.” It depends on food availability, environmental conditions, and metabolism of the species. But, in general, we can say that biological species reproduce in proportion to the existing population. This mechanism is expressed mathematically with a differential equation whose solution is obtained by “integrating” it. In this very simple case, the result is an equation that predicts exponential growth.

Let’s make a practical example, as simple as possible: imagine a unicellular creature, a bacterium that reproduces by splitting in two (in biology, it is called “mitosis”). At the beginning, we have a bacterium, then we have two, then four, then eight, and so on. The result of these constant-time doublings is not exactly an exponential function, but we can consider it as such. It is a function like the one you see in the figure (Fig. 5.4).

In other words, the population of bacteria tends to grow faster and faster: it is what causes epidemics. This book is being written while the COVID-19 epidemic is in full swing worldwide and the growth of the virus diffusion did show a tendency to grow exponentially at the beginning. Doing some math, you could calculate how fast the virus would infect the whole world’s population and even when the mass of the virus population would reach the size of a human being or even more than that. Do you remember that old American science fiction movie from the 1950s, “The Blob?” Yes, something like that (Fig. 5.5).

But, of course, well before a virus or a bacterial colony could reach the size of the blog of the movie and start chasing human beings, limiting factors will emerge. In the real world, the blob would soon die because the cells inside it would not have access to oxygen. Also the SARS-CoV-2 virus soon ceased its exponential growth.
trend for lack of a sufficient number of susceptible human targets. Again, something that shows that the Reverend Malthus was right when he said that a population cannot grow to infinity.

But if a biological population has limits to growth, how exactly does it reach them? Malthus was always vague on this point. Instead, it was the Belgian mathematician Pierre François Verhulst (1804–1849) who published an equation in 1828 that described the limits to growth of a biological population, inspired by the Malthus theory. Sometimes we call it the “Verhulst equation,” but more often, we call it “logistic curve” or “S-shaped curve.” Also here, we can describe the curve starting from a differential equation, but let us just show it in the figure (Fig. 5.6).

The Verhulst curve is similar to the exponential model we talked about earlier on. When the number of individuals is still small and the resources are abundant, there is nothing to stop the growth that continues in an almost explosive way. But, at a certain point, growth starts slowing down: it is the effect of the lack of resources, limited space, maybe the intervention of a predator, or the pollution generated by the population itself. Growth becomes slower and slower until it stabilizes at a certain number of individuals compatible with the ecosystem’s ability to produce resources to keep them alive. The logistic equation is good for many things: it works in certain fields of commerce, in chemistry, and in other fields. But in biology, that is not how populations grow, not usually, at least. The logistic curve is limited in the sense that it considers only a single population, not the complex interaction among populations in an ecosystem.

Fig. 5.4 Exponential function describing the exponential growth mechanism of a population
At this point, we can introduce some details about the Lotka-Volterra model that we have already described in the previous chapter. It is not the perfect model: like all models, it is an approximation and no biological systems can be described exactly by it; there are no known islands where only foxes and rabbits exist. But the Lotka-Volterra model is interesting because it is the starting point for much better and more sophisticated models. The equations of the model cannot be solved exactly. But, if they are difficult to solve, that does not mean that they are difficult to understand.

Here, we must explain some fundamental concepts in the field of system dynamics. The idea is that all models in this field are based on the concepts of “stock” and “flow.” Let’s consider a simple example, often used by practitioners of the field. It is called “bathtub dynamics.” (Fig. 5.7)

Fig. 5.5 “The Blob,” a 1958 science fiction movie. The results of the excessive growth of a population

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The water in the tub is what we call the “stock”; the tap and the drain control the “flow.” By changing the flows, that is, by acting on the tap or on the drain, it is possible to vary the amount of water in the bathtub, or the stock. Of course, system dynamics does not deal just with bathtubs, but we can model many real systems as if they were made of several bathtubs connected to each other, with the flows regulated by valves. In biology, for example, we can see the level of the tub as a measure

**Fig. 5.6** The Verhulst curve or “logistic curve.” The curve describes a dynamic variable that cannot grow to infinity as in the case of the exponential curve because it is affected by the limits of the system to which it belongs.

**Fig. 5.7** The bathtub is often used as a paradigm for the modeling tool called “system dynamics.”
of the number of individuals in a biological population. The flow of water into the
tub is equivalent to the birth rate, while the flow out is the mortality rate. Here, there
is no need for complicated equations: it is obvious that if the mortality of a popula-
tion exceeds the birth rate, the population drops. The reverse is also true.

The system studied by Lotka and Volterra is a typical “stock and flow” system.
There are two connected stocks (two bathtubs, if you like). One represents the popu-
lation of the prey (rabbits) and the other the population of the predators (foxes). Of
course, you can make models with many more stocks than just two, but the key
point that makes the Lotka-Volterra model interesting is that flows are subjected to
“feedback.” It is a concept that we can best understand using an example: do you
remember the model of the exponential growth of a population? We said that the
growth rate of a population is proportional to the size of the population itself. That
is, the flow (the speed of reproduction) is proportional to the stock (the population).
This is a very general concept that defines the concept of feedback: it is when a flow
is proportional to a stock. Proportionality can be negative or positive; they are two
different types of feedback, sometimes defined as “dampening” and “enhancing.”

So, let’s see how these concepts apply to the Lotka-Volterra system. It would be
easy to show it to you by writing down the equations, but we will not do that here.
Let us instead describe how the elements of the system interact with each other.
First, the stock of the rabbits is filled by a flow that comes from the outside; it is
supposed to be grass that we assume to be infinite in this simple model. You could
say that rabbits are machines that turn grass into rabbits. Then, rabbits are killed and
eaten by foxes — it is a flow that goes from the rabbit stock to the fox stock and that
tends to reduce the size of the rabbit stock and increase that of the foxes. You could
say that foxes are machines that turn rabbits into foxes. Also, the stock of the foxes
tends to be reduced because foxes die of starvation if there are not enough rabbits as
food. In any case, the main flow in the model is the one that connects the rabbit
stock to the fox stock. This flow is controlled by feedback effects: it is supposed to
be proportional to both the stock of the foxes and that of the rabbits. If you think
about that, it is logical: the more rabbits there are around, the easier it is for foxes to
find them and kill them. But it is also true that the more foxes there are, the more
likely it is that rabbits will be found and killed.

Now, let’s see how feedbacks affect the flow. Let us say that we start with some
rabbits but very few foxes. In the absence of predators, rabbits reproduce rapidly
 (“like rabbits”) and their population grows. But, with abundant prey, foxes can also
grow rapidly. At this point, with so many foxes around, rabbits begin to be eaten
more quickly than they can reproduce. The rabbit population ceases to grow and
starts declining. Now it is the foxes that find themselves in difficulty: with too few
rabbits to hunt, they begin to go hungry and die of starvation. So, their population
collapses in turn. Then, the cycle restarts. This type of system is very general:
instead of foxes and rabbits, we can have shepherds and grass as in the model
described by Hardin. Or we can talk about fishermen and fish, as in the system that
had originally inspired Volterra.

Let us now see these considerations in a graphical form. The Lotka-Volterra
model produces cyclical oscillations in both the numbers of rabbits and foxes. We
can also trace the number of foxes as a function of the number of rabbits in a
In the basic Lotka-Volterra model, fox and rabbit populations never reach the attractor, but with a few minor modifications, they do (figure below) (Fig. 5.8).

In the next chapter, will show you how to use the Lotka-Volterra model to describe fishing as an economic activity. Here, to complete the discussion, we note that the model can be made more complex by adding other stocks to obtain such a good description of such complex systems that we can use the model to study the entire “world system.”

5.3 Modeling Collapses

The image of the world around us, which we carry in our head, is just a model. Nobody in his head imagines all the world, government or country. He has only selected concepts, and relationships between them, and uses those to represent the real system.

(Jay Forrester)
In the 1950s, a young professor at the Massachusetts Institute of Technology in Boston, Jay Wright Forrester, began using a new generation of digital computers to simulate the interactions of the various elements of machinery and electronic systems. Over time, Forrester shifted his interest to the management and modeling of economic systems. He labeled the new field “industrial dynamics” but, later, the term “system dynamics” became the most used one. From there, another step forward was clear for Forrester: to simulate the entire world economic system. He developed his first model of the world in the mid-1960s when his computers had become powerful enough to be able to solve the complex systems of model equations in a reasonable time.

While Forrester was engaged in these studies, others were examining the same problems. In 1968, Aurelio Peccei (1908–1984) and others formed the “Club of Rome,” a group of intellectuals from industry and academia who had gathered to study and discuss global economic and political problems. Peccei and others quickly concluded that they needed to find ways to quantify the limits of world resources if they wanted to be able to act according to their concerns. In 1968, Aurelio Peccei met Jay Forrester at a conference on urban problems in Italy, on the shores of Lake Como. It was the spark that triggered the series of events that would lead to the study of *The Limits to Growth* in 1972.

One of Forrester’s students, Dennis Meadows, obtained support from the Club of Rome for the project, and he gathered a team of 16 researchers to work on the project. In 1971, Forrester published the results of his work in a book entitled *World Dynamics* [48]. The work of the team directed by Dennis Meadows was published in 1972 [49]. Forrester and Meadows’ team had worked independently of each other, but they had come to the same conclusion: the world’s economy tends to stop its growth and collapse as a result of a combination of the reduced availability of resources, overpopulation, and pollution. This conclusion was a robust feature of the simulations, that is, it changed little as the initial hypotheses were varied (Fig. 5.9).

Both Forrester and Meadows’ group carried out their simulations for a variety of possible hypotheses, including radical technological innovations or the fact that the population could be stabilized by global political actions. In most cases, even for very optimistic initial assumptions, the collapse could not be avoided but, at best, delayed. Only a set of carefully chosen global policies designed to stop population growth and stabilize resource consumption could have prevented collapse and led the world’s economy to a stable state. It implied maintaining an average level of resource consumption not different from that of the 1970s.

As you probably know, nowadays the general opinion on *The Limits to Growth* is not very favorable. Indeed, the study is often demonized and ridiculed with various accusations of “wrong forecasts.” This is more the result of collective amnesia than what the study said [50]. In reality, the trajectory of the real-world’s economy has followed quite closely the curves of the model’s base scenario, which remains valid as an “overshoot forecast of the entire world system. We are not going into details about this point, but we will describe how these dynamic models can be used in fishing.
This kind of approach had never been tried for fisheries, and the first attempt to use a system dynamics model to describe the fishing industry was published in 2009 by Ugo Bardi and Alessandro Lavacchi who examined the case of whaling in the nineteenth century [51]. Later, Ilaria Perissi, with the help of Ugo and Alessandro, made a more general study of the fishing sector, showing that the Lotka-Volterra model also works in many other cases besides whaling [52]. Thanks to these studies, it was now clear that the predator-prey relationship between man, personified by the fishing industry, and the fish, which represents the prey, is a general feature of the overexploitation of natural resources.

The model used by Ilaria was not exactly the one described by Lotka and Volterra, it doesn’t take into account the reproduction of the fish, but various tests showed that this factor was not important in the description of cycles that lasted no more than a few decades. The main factor that creates a single peak, it seems, is that the species exploited by the fishing industry are not isolated species as in the simplified...
assumption of the foxes/rabbits model. They live in a complex ecosystem, and when their number is strongly reduced by hunting, their ecological space may well be taken over by another species. That makes it difficult for a species to regain its original space. For instance, whales have not yet returned to the population levels they had reached before the hunting cycle of the nineteenth century and maybe they never will.

Finding the data for these studies was not easy. The quantity of fish caught (the “prey”) – called also “landings” – is normally available as data published by the fishing industry or by government agencies charged with regulating fishing. That is not the case for the “predator” parameter. It was easy for the case of whaling since Starbuck reported ample data on the fishing fleets in his book [13]. But for many other fishing sectors the data are simply not there. In this case, we can use “proxy” data, assumed to be proportional to the effort of the fishing industry. For example, we can use the labor force employed in the fishing industry in terms of the number of people or in terms of their total salary. Or we can use the capitalization of the industry. Only rarely we can find the number of vessels or the tonnage of the fleet. In general, all these approaches work and describe several cases of overfishing [52].

So, let’s see the first model that was tried using this approach. It was whaling in the United States using the data reported by Starbuck. You see that the fitting is not perfect, but the model does describe the historical data. It shows how whalers were increasing their efforts in terms of number and tonnage of ships but were unable to increase the yield of the fishery because whales just weren’t there anymore (Fig. 5.10).

**Fig. 5.10** The Lotka-Volterra model can describe the dynamics of overexploitation of natural resources, applied to the case of whaling in the nineteenth century. (Data from the book by Alexander Starbuck, 1876) [13]
Let’s move to another example: the collapse of the Pacific sardine in the sea facing California. Sardine fishing had already begun in that area at the end of the 1800s but grew exponentially during the first 20 years of the 1900s in response to the growing demand for canned food during the First World War. From the mid-1930s to the mid-1940s, this fishery was the largest of the Northern and South-Western Pacific coasts, producing an average of over 600,000 tons of fish per year with a peak of over 790,000 tons per year in 1936–1937. The fishing yield began to collapse dramatically a few years later, tanking at no more than 100 tons per year in the 1970s. In 1974, an international moratorium was established on sardine fishing. But, as is almost always the case for such tardy measures, the moratorium was useless to restore that initial abundance (remember the old saying “shutting the stable doors after the horse has bolted?”). Even today, the fishing yields of the Pacific sardine have not returned to the values of the bonanza of the 1930s (Fig. 5.11).

The figure shows the data related to the overexploitation phase in terms of the catch and of the fishing fleet size as a function of time from 1933 to 1957. Note the two typical bell curves that the Lotka-Volterra model attributes to prey and predator. As in the case of whales, once again the simplified Lotka-Volterra dynamics provides a reasonably good description of the experimental data, indicating that, in those years, the sardine stock was hopelessly overfished.

The prey-predator dynamics can describe not only the exploitation of a single species; it can also provide indications on the tendency to overfishing of a whole country’s fishing sector. We could see this by examining the total catch data of the
Japanese fishing industry compared to the capital costs that the sector has incurred between 1962 and 2002. The data on the catch are expressed in total weight per year. The capital is expressed in currency and includes the expenses for fishing in terms of salaries, fuel, capital, replacement of fishing boats, and various equipment. This is a rare case in which it was possible to find data on the invested capital for the fishing industry. As shown in the figure, the historical data show a decrease in the yield of fishing that begins around 1980. Note that these data are related to those of the previous figure, with the sardine catch being one of the main components of the overall catch (Fig. 5.12).

There are several more examples that we can report here. In some cases, it is possible to fit the data quantitatively; in others we can just note how the decline of the fishing yield preceded of a few years that of the fishing effort, the telltale indication of overexploitation. This behavior is the result of the attempt to obtain the maximum profit without realizing that this leads to the depletion of the fish stock.

This phenomenon is not just the trend of specific fisheries, but a global trend. This is revealed by the FAO fishing statistics from the FishStat database: global fish landings reached a peak in the mid-1990s, and then did not increase anymore, remaining on a plateau that lasts to this day. This trend could be correlated with a parameter that is indirectly related to the invested capital: the average power of the

Fig. 5.12 Lotka-Volterra model used to describe the dynamics of overexploitation of natural resources, applied to the most recent case of the decline of the Japanese fishing sector. From Perissi et al. [52]
engines used for fishing at the world level, as shown in the following figure (Fig. 5.13).

As you can see, the engine power of boats continues to grow, but the landings fluctuate around 70 million tons; it does not grow more than that. This should sound a strong alarm bell: this time it is a worldwide crisis. These results show that despite the efforts already implemented by the majority of countries in an attempt to preserve fish stocks, the market demand remains strong enough to cause overfishing all over the world.

At this point, we can summarize what we found. What can we do with these models of fishing? Of course, modelers are always happy to be able to create a model that works, but that is not enough. The important point is that a model that works tells you something about how the real world works. And what models tell you is often very different from what fishermen and administrators publicly say. The standard position of the fishing industry is that the landings are declining not because there is less fish, but because the government, the lawyers, the cheaters, and other entities are damaging the fishing activity, but fish is abundant, and there is no problem of depletion. It is very typical also of individual fishermen.

![Graph showing the trend of catch in the world according to the capital invested in fishing](image-url)

**Fig. 5.13** The trend of the catch in the world according to the capital invested in fishing, measured in terms of the power of the boats’ engines. Data from Watson (2013) [22]
Interlude: How to Become a Catastrophist

by Ugo Bardi

In 2001, I was working in a research program at the Lawrence Berkeley Laboratory, in California. On the morning of September 11, I saw on TV, in real time, the collapse of the World Trade Center. It was a big shock, but also a turning point in my life. Up to then, I had been working mostly on petroleum chemistry, but those dramatic events led me to understand that there was much more than chemistry in the role of petroleum in our life. It was a discovery that led me to move to a different field of research: developing models that could tell us something about the future of humankind (Fig. 5.14).

Fig. 5.14  The September 11, 2001, attacks in New York
It was a journey to a fascinating world. I discovered the concept of “peak oil,” the problem of mineral depletion, the effects of pollution, and those of climate change. The researchers engaged in this field were a mixed lot, most of them tending to develop gloom-and-doom scenarios. Peak oil would bring a catastrophic crash of the economy, and running out of vital minerals would bring us back to the age of our ancestors, maybe those who lived by hunting and gathering tens of thousands of years ago (it was called the “Olduvai model,” the brainchild of the late Richard Duncan). Some people had developed the concept of “near-term human extinction,” sometimes shortened to NTE, as the effect of a catastrophic runaway greenhouse effect that would quickly raise the Earth’s temperatures to levels that would sterilize the biosphere. Those embracing the NTE concept seemed to be positively upset at any hint that humankind might not, after all, go extinct in the near future.

That kind of view is not for the faint-hearted, but I can tell you that it is also incredibly fascinating. I gave my contributions to the predicted doom with several models that I developed, some of which may be seen as even more catastrophic than the average. The main one I called the “Seneca model,” starting from a sentence of the ancient Roman philosopher Lucius Annaeus Seneca: “Growth is Sluggish, but Ruin is Rapid.” I wrote two entire books centered on that subject, one, The Seneca Effect [53], was published in 2017. The other, Before Collapse [54], was published in 2019.

Initially, I wasn’t especially interested in marine resources but that field turned out to be fundamental for my work. It happened, as it is often the case in science, by chance. One day, I found a copy of Alexander Starbuck’s book The History of American Whale Fishing (1876). The decline of whaling had a certain ring of doom to it, so I was curious to see how the data reported by Starbuck as tables would look in the form of a Cartesian graph. Surprisingly, I found that the production of whale oil formed “bell-shaped” curves similar to those that the American geologist Marion King Hubbert had proposed for the production of crude oil. So, I had one of those flashes that you see in comic books as a light bulb lit on the character’s head. As a physical chemist, I was familiar with the Lotka-Volterra model. So why not use it to describe whaling, with whalers as predators and whales as prey? Would it work?

The answer came on an afternoon when I was in bed with the flu. Bored and restless, I began to write and test a model of whaling based on the Lotka-Volterra equations. I used an old laptop so slow that, today, I still wonder how it could execute that algorithm. But, somehow, the old computer ran the program for about an hour and then churned out the result. The model reasonably reproduced the bell curves of Starbuck’s data!

That was the start of a new idea: that of applying the Lotka-Volterra model to study resource depletion and, in particular, the overexploitation of fish. Later, I started tormenting other people to help me with this work: my former students Alessandro Lavacchi and Ilaria Perissi, who are both much better than me at making models and at data fitting. One of the results was the book you are reading, The Empty Sea.
But the models are telling us something very different: the mismatch between landings and investments is a telltale sign that the fishing industry is under strain, trying to get more from less. And it is not working. Despite the increased investments, the catch declines. You do not need sophisticated models to understand what is happening, but a good model makes the situation stark clear: the fishing industry is overexploiting the fish stocks. Then, of course, we should always remember what Upton Sinclair said: “It is difficult to get a man to understand something when his salary depends upon his not understanding it.” That applies perfectly well to the fishing industry. For the people making money from it, it is very difficult to admit overexploitation: it would mean admitting that they must reduce their fishing activity and, therefore, their short-term profits. And this is a no-no in all industries, not just in the case of fisheries. So, there is little that can be done except continue the effort of understanding and modeling overexploitation. Eventually, the message will pass, but it will take time.

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But can we do more with models? After all, the models are supposed to have predictive value, could we use them to better manage fishing? Aren’t models used to set quotas or to develop different ways to avoid overfishing? It would be possible, but it is a complex story and we shall limit ourselves to mentioning just the main elements. Apart from cheating, which is a ubiquitous problem with quotas, the question is how quotas can be determined, and this depends on what models can do and what objectives the regulatory authorities want to obtain.

In principle, when we talk about quotas, we generally consider the concept of “maximum sustainable yield” (MSY). That is, we would like to fish at the highest

Surely, this book could be termed as “catastrophistic,” and, indeed, you have been reading of fish stocks destroyed, fisheries going bankrupt, the sea being polluted, climate change ruining everything, and more assorted disasters. I am normally considered a “catastrophist” myself, but, sometimes, I feel like Groucho Marx when he said: “I don’t want to belong to a club that accepts people like me as members.”

Really, I am not so catastrophistic as it may seem by the books I write. When someone asks me, “but aren’t you sad when you deal with such depressing things?” To this, I normally answer, “Sad? Who, me?” I am an optimist, it is just that many years of work in industrial research made me appreciate the wise attitude of engineers that says “Always plan for the worst-case hypothesis.” It is not catastrophism; it is common sense and I have adopted it as my motto. So, I think we’ll be facing hard times in the future, but also that we still have plenty of chances to rebound and recover. Straight from the catastrophist’s mouth!

(*) A note by Ilaria Perissi: “I can confirm that Ugo is an optimist and that he is not depressed at all! Occasionally, he is just a little absent-minded, as it is typical of professors.”
rate that will not cause the stock to decline or collapse. The concept of MSY has been successful and is part of the United Nations Convention on the Law of the Sea (UNCLOS) of 1982, as well as a cornerstone of the European Union’s Common Fisheries Policy. But are we sure that MSY is such a good idea? One could even ask the question of whether this MSY actually exists. Even assuming that such a thing exists, how can it be determined? Of course, it takes a model of some kind to understand what happens when you start taking individuals out of a population.

Typically, the models aimed at determining the MSY are based on a simple logistic curve of population growth; it is the Verhulst curve we saw in a previous section. If used prudently, this model could help to avoid overexploitation. The problem is that real ecosystems do not follow the smooth curves of models. They are complex systems, and, like all complex systems, they tend to oscillate and deviate from the well-behaved trajectories that modelers would want them to follow. Let’s say that an ecosystem is like a dynamite stick; you are perfectly safe handling it if you have correctly estimated the length of the fuse. But, if you overestimated it, it may explode in your hand. In the case of fishing, if you set a quota just a little too high, you are creating a deadly feedback effect. The more you fish, the fewer fish remain, and the fewer fish remain, the less they reproduce. In the end, you think you are saving the stock, but instead you are pushing it in the direction of extinction. That is what happened with the Newfoundland cod stock.

The Lotka-Volterra model could probably be used to obtain a better estimate for the dynamic growth or decline of a fish population, and, in this way, more reliable quotas could be established. But even this model can’t describe the complex and unpredictable behavior of an ecosystem: no fish species is isolated in the sea. All species interact with each other. Disturbing a population means disturbing all the others with often unpredictable results. So, a model such as the Lotka-Volterra one can tell you that you are overfishing a stock, but hardly what exact level of fishing is safe to avoid overexploitation. It may well be that no model will ever be able to describe exactly such a vast and complicated system as the sea and the creatures inhabiting it. If we understand this point, we should try to be humble rather than pretend to determine miraculous parameters for our use and consumption, such as the MSY. Instead, we should try to do as little damage as possible, but that’s difficult in a world that sees growth as always a success, no matter what the consequences are.