Chapter 6
The Future: The Blue Economy

6.1 The Abyss: The Treasures of the Sea (Fig. 6.1)

In the beginning, there was nothing but the Abyss

(Ancient Sumerian myth)

Green as a color became fashionable in politics in the 1970s, when environmentalism became a political force. Today, Green parties still exist, but they seem to have followed a parable that peaked at some moment in the 1990s, while they are now in decline in most countries. But if the green color seems to be fading as an environmental standard, blue seems to have taken the lead. The concept of “blue economy” often refers to marine resources only, but also to the general concept of sustainability, as we can read in a book by Gunter Pauli The Blue Economy (2009). Blue is definitely fashionable nowadays: we read also of “blue growth” and “blue acceleration” referred to the hopes of expanding industrial activities to the sea.

The concept of Blue Economy has quickly established itself as the term to use for the economy based on marine, lake, and river resources. It is a relatively new concept, so much that the first world conference on the blue economy was held only in 2018, in Nairobi. If we look at the program of the conference, we can summarize the topics dealt with.

1. Tourism and coastal communities
2. Energy and mineral resources
3. Management of fish resources
4. Aquaculture
5. Climate Change and Pollution of the Sea
6. Maritime transport

Almost all the sessions found a way to insert the word “sustainable” in the description of the topics covered, even for the themes of energy and mineral resources which were almost all about offshore oil drilling. That oil drilling can be
An illustration from the 1874 edition of 20,000 Leagues Under the Sea, the novel by Jules Verne. It was one of the first times when the bottom of the sea was proposed as an area to explore, just like outer space. In practice, both space and the seafloor have turned out to be hostile environments for humans. For the time being, we seem to be locked to the surface of our planet, leaving these realms to our robots.
considered “sustainable” is stretching believability, to say the least. But it is precisely what they wrote: “Sustainable Energy” referring to a session where attendees could mainly hear talks on offshore oil and gas extraction.

Other definitions of the concept of “Blue Economy” are similar. You can find several examples on the websites of the World Bank, the WWF, the United Nations and many other international bodies. Among them, the European Commission defines “Blue Growth” as you can read in the paragraph below from their website. It may take some effort to understand what it means but note how the word “growth” is repeated three times in a few lines, which clearly means something. [55]

Blue Growth is the long term strategy to support sustainable growth in the marine and maritime sectors as a whole. Seas and oceans are drivers for the European economy and have great potential for innovation and growth. It is the maritime contribution to achieving the goals of the Europe 2020 strategy for smart, sustainable and inclusive growth.

As you can see, the blue economy is a true fish soup of various activities, seasoned with fashionable words like “sustainable,” “smart,” and the like. Examining the whole field in detail goes far beyond what we can do in this book, but we can see how often we find ourselves dealing with economic sectors partially competing with each other. For instance, mining of the continental shelf with its drilling platforms is not exactly something that goes along well with coastal tourism and fishing. Then, maritime transport seems harmless in environmental terms, but even that gives its problems: the ships are “dirty,” especially the big ones. Typically, they use the worst quality fuel oil for their engines, which means releasing unburned oil and combustion products around. Cruise ships then release all sorts of garbage into the sea, not to mention the damage that ships create for the marine fauna that lives near the surface. At present, one of the biggest risks a whale faces is being hit by the keel of a ship. The whale’s sonar is sophisticated, but it is not made to warn it of an approaching ship.

Finally, there is a topic that is rarely addressed as part of the blue economy: the military use of the sea. Fortunately, it does not happen anymore that the US Navy uses whales as targets for artillery exercises, as it may have been common in the years after the Second World War (it is reported by Farley Mowat in his 1998 book Sea of Slaughter). But, even today, military activities at sea can have a devastating effect on the marine ecosystem. Apart from the pollution caused by large military fleets, one of the problems is the use of high-powered sonar as an antisubmarine weapon by the American navy. “Sonar” simply means sound waves, and these systems emit them at frightening intensity, we talk about around 235 decibels, orders of magnitude higher than the noise of a rock band playing at full volume in front of you. Fortunately, the intensity of these emissions decreases quadratically with the distance, but it remains a big problem for animals that use sound waves to explore their surroundings. For whales, being exposed to such noise is a bit like what happens to your dog on the 4th of July. It is panic: the dog tries desperately to hide somewhere, maybe under the bed. Whales, instead, have nowhere to hide. They may try to escape or to submerge as deep as possible, but that does not save them from
the noise. With their auditory organs damaged, they may lose their orientation and they may end up beached and die.

So, the blue economy as it is understood today is not necessarily sustainable or benign for the environment. Then, what can we expect from this idea? Looking at some of the proposals in detail, we can see that there is plenty of hot air (or maybe hot water) being planned. This is the case of the exploitation of mineral resources of the sea. We will talk about this subject in a special section, but you will see that we should not expect miracles. Something similar can be said for other activities related to the blue economy, including tourism.

Today it is possible to be a tourist in one of the modern submarines that take you to see the bottom of the sea: there are companies specialized in this task, and it is surely something spectacular. In 2019, you could buy a ticket for a submarine ride to the wreck of the Titanic, at a depth of some 3800 m. You had to be rich to do that: tickets were sold at about $100,000 apiece! And maybe you cannot do that anymore after the press reported that in 2019 the submarine “Triton” bumped into the Titanic, fortunately causing no large damage to the wreck, nor to the passengers aboard. No doubt it must have been a remarkable experience for them, but they may not want to repeat it (Fig. 6.2).

Fig. 6.2  The Cyclops 1 manufactured by the company “OceanGate.” Built in 2013, this spectacular research submarine can descend to about 500 m below sea level. Note the acrylic front dome: it is a modern technology that provides passengers with almost 360 degrees of visibility. Submarines like this one, even if unable to go very deep, can take tourists to see the seafloor. It is certainly an unforgettable experience, but it will likely be difficult for passengers to forget that if the thin dome separating them from the water were to break, there would be no escape for them. For humans, the sea depths remain a difficult domain to conquer.
Even if you are not rich, you may still enjoy spectacular views of the ocean. “Whale watching” trips have been popular all over the world, and one of the authors of this book, Ugo Bardi, has tried that, venturing off the coast of San Francisco. The results were not exciting: the whales tended to stay away from the boat, and all the passengers saw was some distant spraying. In exchange, most of the passengers (including Ugo) suffered robust seasickness. But that is life and other whale watchers report more interesting experiences with large whales behaving kindly enough to splash just in front of their boat.

Interlude: Love Among Fish

«Daje, daje, lu vitti, lu vitti! Piggchia la fiocina! Accidiliu, accidiliu!»

“Go, go, I saw it, I saw it! Take the harpoon! Kill it, kill it!”

Domenico Modugno, “Lu Pisci Spada” (the swordfish) (1958)

Writing this book for international readers, we avoided specific references to the Italian culture we are familiar with, reasoning that they would not be understandable by those who are not Italians like us. But we cannot resist the temptation to propose to you a short mention of a delightful Italian song related to fish and fishing. It is Lu Pisci Spada (“The Swordfish”) sung by Domenico Modugno (1928–1994). You may have heard of Modugno, known outside Italy mainly for his song Volare (1958).

Here is the start of the Lu Pisci Spada song. You can easily find the complete version on the Web.

Te pigghiaru la fimminedda,
Drittu drittu ’ntra lu cori
E chiarcia di duluri

(They struck the female, right, right through the heart. And she was crying in pain) (Fig. 6.3)

The story goes on telling how the male swordfish refused to leave his female companion and continued to swim near the boat. The dying female spoke to him and tried to convince him to swim away, but he refused, saying that he wanted to die with her. And, in the end, he was killed by the fishermen, too.

If you can understand Italian (actually, Sicilian) and you hear this song without being deeply saddened, it means that you have a heart of stone. And, as a punishment, the Sea Goddess will sink your boat so that the weight of the boulder you carry in your chest will pull you down to the bottom of the sea, where you will be eaten by crabs and lobsters, as you deserve.

This song is truly a small masterpiece of Italian popular music, but there is a problem: Could it be a true story? Obviously, we cannot expect a popular song to be a treatise of biology, but the story may not be far from reality. Let
A swordfish killed by a harpoon. We cannot say if it is a male or a female fish, but perhaps the tip of the harpoon that killed it went straight through the beast's heart, just as is told in the song by Domenico Modugno.
Although tourism is an important economic sector, its value for the fraction that deals with the sea remains minimal in comparison to the main revenues of the blue economy: fishing or, in any case, the production of food from the sea. According to FAO data, fishing in 2016 produced an estimated value of 143 billion dollars worldwide, probably much more than that considering illegal fishing and fishing for local consumption. In the same year, aquaculture produced fish and other products worth about $243 billion. From these data, you see that food production from the sea is starting to approach a turnover of half a trillion dollars (500 billion dollars). It is not
large in comparison with the GDP of a major national economy, but not a trifle, either. More than all, these data tell you what the real star of the blue economy is: aquaculture.

By now, aquaculture has become a magic word, a technology supposed to solve all the problems of fishing and able to feed everyone in the world. The popularity of aquaculture derives not so much from the absolute value of the turnover, but mainly from the very rapid growth of the sector: 6% a year in the last 2–3 decades, even double-digit growth in certain specific sectors, for instance, salmon. It is impressive that an industrial sector manages to grow so fast when practically all sectors of the economy are in trouble. Of course, this rapid growth may have been the result of industrial aquaculture having started from a very small base. Nevertheless, it has been a remarkable growth that remains today the main factor for the popularity of the concept of blue economy.

So, if the blue economy were something you eat at a restaurant, the main dish would be fish and other marine creatures; the rest would be side dishes. But we should not be surprised: fish, mollusks, and crustaceans were always the main reason why people went to sea, and things have not changed so much today. Then, what is the outlook for the blue economy in its various forms? We’ll examine it in the coming chapters.

6.2 Blue Power: Energy and Minerals from the Sea

ROLL on, thou deep and dark blue Ocean, roll!
Ten thousand fleets sweep over thee in vain.
Man marks the earth with ruin; his control.
Stops with the shore; upon the watery plain
The wrecks are all thy deed, nor doth remain,
A shadow of man’s ravage

Lord Byron “The Ocean” (1788–1824)

In the 1920s, Germany had emerged from defeat in the First World War reduced to a ghost of what it had been before. The number of victims was appalling, the population was still hungry and weakened, and the economy was falling apart under the yoke of sanctions imposed by the victorious allies. Amid the disaster, some people looked for creative methods to get out of the crisis. One of them was the famous chemist Fritz Haber, known for his many inventions, including the process that he invented with his colleague Carl Bosch to extract nitrogen from the atmosphere and create fertilizers (and explosives).

Starting in 1920, Haber worked on the idea of extracting gold from the sea to help the ruined finances of his country. But, after a few years of work (and a boat built expressly for this purpose), he had to give up. There is indeed gold in seawater, but the concentration is abysmally low. We are talking of amounts of a few parts per trillion, something like 8 g of gold for a trillion grams of water. To give you some idea of what that means, a trillion grams of water is a volume equivalent to that of
the Great Pyramid of Giza, in Egypt or, if you prefer, about one thousand Olympic pools. Clearly, having to process so much water to get just one gram of gold dooms the whole process as uneconomical.

Fritz Haber’s failure illustrates how easy it is to overestimate the potential of marine resources. The sea is indeed bigger than the mainland and you would think it should be possible to extract useful minerals out of it, not just sardines and mackerel. So, it is not surprising that we are seeing many ideas and many proposals on how to exploit the sea as a source not only of minerals but also of energy. The numbers seem to support these ideas: the amounts of materials and energy stored in the oceans are gigantic. But are these ideas practical? Unfortunately, beautiful theories tend to go to pieces when confronted with the ugly reality. In terms of energy from the sea, at present we only have prototypes. As for extracting minerals from the sea, we are still limited to minerals that were already extracted thousands of years ago, mainly table salt.

Let’s see the situation more in detail, starting with energy. The various proposals on how to extract energy from the sea can be summarized as:

• Tidal energy
• Energy from sea currents
• Energy from saline gradients (osmotic)
• Thermal energy
• Wave energy

Estimates of the potential yields of these technologies exist. For example, in 2007 the IEA (international energy agency) reported these data:

• 300 TWh/year from the tides
• 800 TWh/year from marine currents
• 2000 TWh/year from the salt gradient
• 10,000 TWh/year from the thermal gradient
• 8000–80,000 TWh/year from waves

These numbers are not tremendously impressive if we consider that today we produce over 15,000 TWh of energy per year in terms of primary energy, mainly using fossil fuels. Only the energy from the waves could exceed this value. In practice, these are purely theoretical values. To date, none of these methods has generated more than prototypes but no commercial technologies that could be replicated on a large scale.

What is the problem? It is the very nature of what we seek to exploit. It is not that the sea does not contain energy; it contains a lot of it. The problem is that “a lot” does not mean “easy to obtain.” This is well-known by those who were struck by the tsunamis of 2004 and 2011. The waves crashing onto the coasts carried huge amounts of energy, but it was unthinkable to use it for practical purposes. The same is true for normal sea waves. The idea to produce energy from waves looks simple: take a float, connect it to a mechanical shaft, and then connect the shaft to an electrical generator. Put the whole contraption in contact with the surface of the sea, and, with the waves pushing and pulling the float, you can produce some electricity. But
if you do a calculation, the yield is poor. In addition, there are excellent possibilities that the first heavy storm that arrives will damage or destroy the machine. The story is the same for tides: the energy involved is large, but the low gradients and low efficiency make it a lost bet for industrial exploitation. Taking out mechanical energy from the sea is not easy. If it were, someone would have found a way to do it a long time ago, but, obviously, that did not happen.

The same considerations apply when trying to exploit the thermal gradients of the sea. Here, the problem is the second principle of thermodynamics. It says that the efficiency of a heat engine is proportional to the temperature difference between the input and the output. In the sea, finding temperature differences large enough to make a thermal engine work at decent efficiency is almost impossible. Some people are trying to do that, and there is even an acronym for this idea “OTEC” (ocean thermal energy conversion). But the prospects are not brilliant. The proponents themselves state that the thermal gradient they can exploit is no more than about 20°C or so [56]. Under these conditions, it is a small miracle if they manage to have an efficiency of a few percentage points. Maybe it can work in some special cases, but do not expect to solve the world’s energy problem in this way. Something similar applies to the energy that derives from the osmotic pressure, that is, from the differences in the salt concentration of the water. The total energy involved is large, but the gradient is small. It is always the second principle of thermodynamics that shoots down our flights of fancy.

Despite all the problems, though, there remains the possibility of drawing energy from sea currents, where we do have a large amount of potentially exploitable energy. The intensity of marine currents is measured in a unit called “Sverdrup” (Sv) which stands for a flow of one million cubic meters of water per second. One Sverdrup is a lot of water, but certain currents flow at hundreds of Sverdrup. Consider that the Antarctic circumpolar current has a flow of 125 Sv, that is, 125 million cubic meters per second. Imagine that: it is a continuous tsunami that circles Antarctica. The problem is that you cannot even dream of trapping the Antarctic circumpolar current to produce usable energy. Just look at any filmed report of ships crossing the Drake Passage from Cape Horn to Antarctica: 800 km of an extremely rough sea. In ancient times, it was a small miracle if a ship can survive the crossing; today it is nearly routine but not quite. Imagine setting up energy-producing equipment there.

The best we could do to produce energy from currents would be to find places close to the coast and where currents are strong. Good candidates could be the Messina Strait and the English Channel. An underwater propeller placed there could produce energy with reasonable efficiency, with the advantage that sea currents are constant enough to provide a continuous and reliable supply. In practice, it is a technology that never took off despite the promises and some practical attempts. It is not clear what went wrong: probably nothing more than the difficulties and costs associated with having to work offshore with a cumbersome and still experimental technology amid bad weather, winds, and storms. Or, maybe, the huge propellers of these machines turned out to be able to make fish stew directly in the sea, not to mention what could happen if a blue whale were to intercept the blades. Maybe, in
the future we could use these technologies at an industrial scale, but, evidently, if it had been easy, it would have been done already.

So, right now, the only energy-producing equipment that can be stationed at sea is conventional wind turbines that can be operated where the sea is sufficiently shallow that the tower of the turbine can be anchored to the bottom. These plants are especially common in the North Sea. There is talk of stationing photovoltaic plants offshore to avoid taking up space on land. This is also possible, although not done right now. Overall, the prospects of abundant energy from the sea are not bright.

Let’s now turn to the subject of mineral extraction from the sea. We already mentioned the failure of Fritz Haber’s attempt to extract gold from seawater, but this did not stop attempts in this field. Here, we need to separate two possibilities: one is the extraction of minerals dissolved in seawater; the other is the extraction of minerals from submarine mines. These two concepts belong to completely different worlds, and we shall examine them separately.

Let us start with the extraction of minerals from seawater. It is commonly done for some minerals, and we discussed in a previous chapter the extraction of sodium chloride, the common table salt. In this case, with 35 g per liter, we have a concentration billions of times higher than that of the gold that Fritz Haber had tried to extract. That makes the extraction of sodium chloride economically feasible even though table salt is much less valuable than gold. But note that, today, just like in the past, sodium chloride is extracted not just from seawater but also from mines on land in the form of the mineral called rock salt. Clearly, extraction from mines is economically competitive, and that tells us something about the high costs involved in filtering or evaporating large quantities of water. It is doable but expensive. Then, table salt is a special case of ions having a large concentration in seawater. Can we extract other minerals?

After sodium, the next mineral ion in the list of the most concentrated minerals in seawater is magnesium. It is about ten times less concentrated than sodium, but it is commercially extracted because the process can produce very pure magnesium for medical applications. The problem with magnesium is the same as with other dissolved minerals having relatively high concentrations, such as potassium. It is not so much a problem of extracting it; it is about separating the less concentrated minerals from the more concentrated ones. In practice, apart from sodium chloride and magnesium, very little is extracted from seawater in commercial amounts.

Theoretically, ions such as potassium, calcium, and a few others exist in seawater at concentrations large enough that it would be conceivable to extract them at reasonable costs, but they are not crucial for the modern industrial society. The only truly interesting industrial metal that could be extracted from seawater is lithium because of the new generation of lithium batteries used for electric vehicles. At present, it is cheaper to extract lithium from sources on land, but it is a reasonably abundant ion in seawater so that in the future it could be extracted from the sea, although only at relatively high costs. Fortunately, we may not need large amounts if batteries will be efficiently recycled.

Can we think of extracting from the sea those minerals that we risk running out of on land? In principle, the idea seems to be promising. Let us take copper as an
example: there are about one billion tons of copper dissolved in the oceans of our planet. It looks like a very large amount and it is: but consider also that we produce about 15 million tons of copper every year from land-based mines. If we were to extract copper at this rate from the oceans, we would run out of it in just about 60 years. Maybe the copper stock in the sea would be replenished by copper leaching from rocks or by human-made pollution, but we do not know how long that would take, nor whether it would provide a durable source. The same problem exists for all those minerals that are crucial for the modern industrial world, at the same time at risk of depletion for the future and, in many cases, already experiencing supply problems right now. Think of zinc, lead, chromium, cobalt, rare earths, and noble metals – they all exist in the sea in very small concentrations as dissolved ions. Extracting them in the amounts used nowadays is simply unthinkable because of the costs involved with processing the enormous mass of water involved.

There is only one exception: uranium. It is well-known that uranium is used as “fuel” for the nuclear industry. It is less well-known that the current mineral production of uranium is barely sufficient to keep the current generation of nuclear plants going, to say nothing about increasing their number. Stepping up production from land mines would be enormously expensive because of the lower grade of the remaining resources [57]. That has generated a lot of interest in the possibility of extracting uranium from seawater.

Let us evaluate the situation. The concentration of uranium in seawater is just over one microgram (one-millionth of a gram) per liter. It is about five times less concentrated than copper but consider that we use much less uranium than copper, just about 60,000 tons of uranium per year to be compared with some 15 million tons for copper. But the task is gigantic anyway: we can calculate that to extract the current uranium yearly demand, 60,000 tons, we should filter a volume of water corresponding to the entire North Sea, assuming we could do that with 100% efficiency [58]. And it’s not just a question of this enormous volume: uranium is used as a source of energy, but extracting it requires energy. So, the whole process makes sense only if the energy required for the extraction process is less than what can be obtained from uranium in a nuclear power plant. This is the concept of “energy return on investment,” often expressed with the abbreviation EROEI [59], understood as the ratio between the energy invested and that obtained. If the EROEI is less than 1, the whole process is a net loss in terms of energy produced. In the case of uranium extraction from the sea, some studies indicate that the EROEI could be significantly larger than one, others that it could be smaller than one [58]. At present, it is difficult to say whether the process could be feasible in the future, but we can say that we are still far from being able to “fish” uranium from the sea as if it were tuna or cod. At most, just a few grams of uranium have been extracted in experimental tests, a far cry from the 60,000 tons per year we would need.

Let us now consider the other possible technology for mining the sea, extracting minerals from the seafloor. Of course, it is already being done for some minerals, and, from many beaches in the world, you can see drilling platforms engaged in extracting oil and natural gas from the bottom of the sea. But can we extract something other than oil and gas? So far, it has not been possible: the only solid materials
ever extracted from the seafloor in commercial amounts are diamonds and coal. The reasons for the seafloor being a poor source of minerals are complicated, and, for details, we refer you to the book by Ugo Bardi *Extracted* (2014). There is, first of all, a problem of cost, but what really dooms the attempt is that the seafloor does not contain minerals of interest to humans. Most of the seafloor is geologically too young to have been able to develop those processes that, on the continents, generated mineral deposits. Undersea mineral resources can be found only in the regions near the coast that are part of the continental plates, where the same geological processes that created minerals on dry land could be active when the sea level was lower than it is now (Fig. 6.4).

Even where underwater mineral resources exist, exploiting them turns out to be difficult and expensive. No true “underwater mine” has ever been exploited, but, in some cases, it is possible to access underwater resources starting from tunnels dug on dry land. Undersea coal mines were exploited in the past in Japan and Canada. Of course, being a coal miner is probably one of the worst jobs in the world, but there is a way to make it even worse, and it is to be a miner in an underwater coal mine. But it is what was done for the coal veins under the island of Hashima, off the coast of Nagasaki, Japan. Today, the mine is abandoned, and only ruined buildings remain on the island, now a tourist destination to remind us of the hard life of the miners of old.

In the future, there might be exceptions to the rule that only oil and gas are extractable from the seafloor. An example is that of the “manganese nodules” found
on the abyssal plains. These nodules are the result of high temperature geological processes occurring at the oceanic underwater ridges where hot magma from the mantle is continuously pushed to the surface by convective movements. These nodules are then slowly pushed away from the ridge by the “conveyor belt” of the seafloor that recycles the seafloor in times of the order of millions of years. In principle, the nodules could be collected in commercial amounts, but the idea has never been put into practice. We have enough manganese from land mines, and it makes little sense today to embark on the expensive and uncertain process of extracting it from the bottom of the sea. No other minerals of industrial interest exist in extractable amounts on the deep seafloor.

Perhaps one day methods will be found that will allow us to exploit the oceans not only for fish but also for the minerals they contain, one way or another. Hoping that it could be done without destroying the marine ecosystem, it is not impossible that if we limited our industrial consumption to levels much lower than the current ones, for example, by recycling what we use, the sea could be a source of “homeopathic” quantities of minerals that could be used to close the cycle of raw materials and allow for a truly circular economy. But, for the moment, this idea remains a dream.

There remains a technology to extract resources from the sea rarely listed among the applications of the blue economy, perhaps because it is not seen as something new. It is desalination, the production of freshwater from the sea. The history of desalination goes back to ancient times, but for a long time, the only possible technology available was distillation. This meant boiling the water and then condensing the vapor, in the same way as is done for making whiskey or cognac. But if for liquors the cost of the process is compatible with the value of the final product, this has rarely been the case for water. Until recent times, desalination remained an expensive process, useful only in emergencies.

Things changed in the 1950s, when Sidney Loeb and Srinivasa Sourirajan of the University of California, Los Angeles, developed the process we now call “reverse osmosis” or “hyperfiltration.” This technology has revolutionized everything, making it possible to obtain pure water at an energy cost of 3–5 kWh/m³ which is lower than that of any other desalination technology. At the current cost per kWh, it means that a cubic meter of desalinated water is sold at about 1 dollar. That makes it marketable for human consumption, although not for agriculture, where it is still too expensive. In parallel, new techniques based on multi-stage flash distillation (MSF) were developed to the point of being competitive with reverse osmosis.

The production of water by desalination has been rapidly growing, and, today, it is estimated that there are almost 20,000 plants in the world, mainly in tropical and equatorial regions, that produce the water necessary for the survival of about 1% of the world population with a total production of about 30 billion of m³ per year. A problem with this production is that the energy needed comes mainly from fossil fuels, so the production of desalinated water creates a non-negligible contribution to global warming. In the future, these plants could use renewable energy, but in any case, the efforts of human beings to produce freshwater from the sea remain very limited compared to what the terrestrial ecosystem does. The estimated amount of
rain produced by natural processes is about 500,000 billion cubic meters of water [60]. For every liter of water produced by a desalination plant, more than 100,000 liters of water come down from the sky. It should be possible to find a way to make all this rain suffice for what we need.

To conclude this section we note that, apart from all the practical and cost problems we have seen, the main obstacle to obtaining minerals and energy from the sea is something that’s not usually considered: pollution. Almost all of the technologies we have been discussing would have devastating effects on marine ecosystems if applied on a large scale. Obtaining minerals from dissolved metal ions would mean filtering unimaginably large amounts of water and the destruction of all the major marine ecosystems. The same considerations apply to the various ideas for technologies to produce energy from waves, tides, or thermal gradients. The plants should be placed near the coast, and their effect on natural ecosystems would simply be catastrophic, including the fact that the sea would no longer be available for fishing or other coastal activities. As usual, despite all the hype about the blue economy, a lot of caution is necessary.

6.3 Globalization: What Future for Maritime Transport?

Globalization has made the financial elite who donate to politicians very, very wealthy … but it has left millions of our workers with nothing but poverty and heartache,

Donald Trump (speech delivered in 2016)

The ancient Romans had a very sophisticated maritime transport system. Their freight ships traveled all over the Mediterranean Sea carrying goods of all kinds but, mostly, grain grown in North Africa and in the East for the rich and populous cities of the opposite shores. Among them Rome, a city that is said to have reached one million inhabitants in the heyday of the empire. So many people in a single city could survive only because they received grain through maritime transport. If the grain had to be taken on the back of donkeys or the like, it would probably have been necessary to use almost all of it to feed the animals before it could arrive at destination. But freight ships were powered by wind and could transport large loads of food at much lower costs than for land transport. The supply of grain to the cities, and to Rome in particular, was so important that the Romans even “deified” it. That is, they created a goddess named “Annona” who was supposed to preside over the transport of grain. Even today the term Annona is used to define the state management of food supplies to a country (Fig. 6.5).

The Goddess Annona seems to have done her job well, and Rome never suffered major famines for most of the imperial period. The grain transport system continued to function until almost the last years of the empire. It was only in 455 CE that the Vandals, who occupied North Africa, decided that plundering Rome was a better idea than selling grain to the Romans. They did exactly that, gaining plenty of gold and a bad reputation still lasting nowadays. The loss of the food supply from Africa
Interlude: Ancient Sea Gods and Sea Monsters – The Medusa of Benvenuto Cellini

From what we can say from archaeological remains, ancient mythological creatures were of all kinds: flying monsters, underground monsters, and run-of-the-mill land monsters, ancestors of our zombies. Sometimes benevolent, sometimes evil, they were part of the imaginary universe of our ancestors. And, of course, there are plenty of mythical sea creatures as well, just think of the Leviathan of the Bible that originated innumerable versions of the story of the whale that eats Job. In classical times, there were also stories about the marine giant creature called Cetus or Ketus, which gave rise to the modern word “Cetacean.” Then, the myth-making machine kept going on, creating more and more monsters. Think of the prototypical Japanese monster, Godzilla. It looks like a dinosaur, but, surprisingly, its name gives away its origin as a marine creature: it derives from kujira which is the Japanese term for “whale.”

The variety of ancient marine deities and monsters is so large that it would take an entire book to describe their taxonomy, but, since we started this book talking about jellyfish, it may be interesting to give some hints about how our ancestors saw these creatures. In English, the term “medusa” for jellyfish refers in particular to the floating form of these creatures. But, in ancient
mythology, “Medusa” refers to one of the three Gorgon sisters, divine or semidivine creatures, daughters of the marine deities/monsters Phorcys and Cetus. Medusa is one of the best known marine divinities of the ancient Greek-Roman pantheon.

Originally, Medusa was a deity of the underworld (“chthonic”), probably to be considered evil. The early images we have of her are clearly inspired by the large, bloated face of cadavers. But mythological views tend to change with time, and the ancients had a nuanced view of the conflict between good and evil. Typically, they tended to find human sides even in the creatures that we call monsters. This is the case of Medusa: the myth evolved with time, casting her no more as a monster, but as a young woman, a priestess of Athena, who had the misfortune of being raped by the god Poseidon in her temple. Besides being raped, poor thing, she was also transformed into a monster by the Goddess Athena, angry at the desecration of her temple.

As a monster, Medusa had certain powers, including her capability to petrify anyone who looked her in the eyes. So, the hero charged to kill her, Perseus, had to use some strategy to avoid being turned into a piece of statuary. So, he approached her using a screen that made him invisible. He cut off her head while she was sleeping. Not exactly the pinnacle of heroism, but that is what the story says.

Fig. 6.6 The bronze statue of Perseus holding the severed head of Medusa, circa 1554. Made by Benvenuto Cellini, it is presently kept at the Loggia Dei Lanzi in Florence.
was the final blow to the old empire that would continue to exist for a few decades longer, but now only as a zombie that wandered among the ruins of European cities.

The grain transportation system of ancient Rome was probably the first example of a “globalized” economic system, at least in terms of what would have been possible at that time, when globalization could only refer to the region of the Mediterranean Sea. But it was a system that worked exactly like ours: it brought resources from the periphery to the center of an empire with the benevolent (and sometimes not so benevolent) control of the imperial navy. In doing so, the system allowed a vastly more efficient distribution than any other possible economic system. In practice, it made it possible to support a population in cities that the peoples of continental Europe could not even dream of. This gave the Romans the military advantage that allowed them to conquer an empire.

The modern system we call globalization is very similar in terms of structure and organization to the ancient Roman Annona. Apart from being enormously larger, it is also based on low-cost maritime transport under the benevolent (and sometimes not so benevolent) control of the imperial navy. The difference is only that today the imperial capital is no longer Rome, but Washington D.C. The origin of the modern system can be found with the first truly global empire, the British one, which dominated the world throughout the 1800s, mainly using maritime trade and a strong navy. The British exported coal everywhere with sail-powered “coaler” ships under the benevolent (and sometimes not so benevolent) control of the British Royal Navy. The British Empire followed the trajectory of the depletion of the resources that made it work: the coal from English mines. When coal production started to decline, it was the start of the end of the empire. The torch of globalization was taken by the American Empire, which based its power on oil production. It is still the ruling empire, today, although showing some evident signs of decline.

Today, ships that load bulk goods, such as coal, are still used. But the backbone of the world’s maritime transportation system is the container ship, a technological evolution that took place after WWII. At that time, the Americans had a surplus of about 500 tankers that they had used to supply with fuel their troops in Europe and elsewhere. They were old-fashioned ships, but it occurred to someone that instead

Perhaps Benvenuto Cellini was the first modern artist who understood the human elements in the story of statuary Medusa, a young woman first raped and then betrayed and killed. In the group of the “Perseus” of 1554, Cellini represented Medusa as a beautiful woman, except for her hair being made of live snakes. The empathy that Cellini felt toward creatures that others saw as monstrous is perhaps something that we too would need to better manage our relations with the natural world (Fig. 6.6).

You can read more on this subject in a contribution by Ugo Bardi in the book entitled The Cnidaria, Past, Present, and Future: The World of Medusa and Her Sisters (2016).
of sending them to the scrapyard, they could be modified and used as transport ships. Since they were not designed for the transport of bulk material, the brilliant idea was to load them with boxes (“containers”), preloaded with goods. It was the origin of the term that is still occasionally used today in English, “box ship,” as an alternative to the more common term “container ship.”

Over time, the dimensions of the containers became uniform, and today they are completely standard all over the world. Containers are transported by sea with special ships, some with a gross tonnage of over 100,000 tons that can carry over 10,000 containers on board. Containers are unloaded in ports, loaded onto trucks or trains, and then taken anywhere by road or rail. It is a transport method called “multimodal.” It is this type of transport that has made it possible to transport goods at low cost everywhere and specifically food (Fig. 6.7).

The existence of good technology for transportation was not enough, in itself, to create a global economic system. To understand how we arrived at the current situation, we must go back to the times after the end of the Second World War, when one of the main problems for the American Empire was how to contain the expansion of the rival Empire, the Soviet one. That meant discouraging the spreading of communism in regions such as Africa and South Asia, but exactly how? The idea that was adopted was to send food to the inhabitants of these regions. It was a success for several reasons, not just humanitarian ones. One of the advantages was that it bound these regions to the Western commercial system, suppressing, at least in part, their food production system, less efficient in comparison to the Western one. An added benefit was that of supporting American agriculture by providing a new market and state subsidies for US farmers. In parallel, new agricultural technologies were developed that would be later known as the “Green Revolution.” Then, of course, the people buying food overseas could not rely on charity alone; they had to
pay for it. That was not a problem for those countries which had natural resources to export, such as crude oil. That meant to bind them to the global economic system, ensuring the supply of strategically critical resources to the Empire. Countries that didn’t have resources to export had to produce something that they could sell for dollars on the international market. It was the policy that turned several Asian economies into manufacturing powerhouses supplying the Western Empire with all sorts of goods. All the elements were in place to use the container ships to bind together all the world’s national economies.

The result was remarkably successful: over a few decades, the globalized economic system spread over the entire Western world and then, with the fall of the Soviet Union in 1991, practically to the whole world. Globalization was and remains primarily a financial system that allows anyone to access goods produced by the global market if they can pay in dollars. The financial system is supported and complemented by a physical system based on maritime transportation that can ship the goods. In this way, agricultural production can be distributed almost everywhere: large famines have become a thing of the past; there have been no more since the 1980s – at least for now. It was a technological and political triumph made possible by maritime transport.

But the future? In many ways, globalization is in crisis. As we said, it is a product of the global financial system that is subject to sudden fluctuations and crises. We saw the system collapsing with the great financial crisis of 2008. For a while, at the worst moment of the crisis, the container ships were all blocked in ports: there was no money to pay for their services. Fortunately, this crisis was somehow ended employing emergency measures, but that does not mean it cannot come back and destroy the globalized system. Then, there are evident trends at the level of national governments to take a more nationalistic stance in world politics. For instance President Trump, in the United States, placed himself as the main representative of a current of thought that sees globalization as obsolete and damaging for national economies. Trump said more than once that he wants to return to an economic system based on sovereign states at least partially independent from each other. Finally, at the moment we are writing, the COVID-19 epidemic is in full swing worldwide, and that has led to shutting down most national frontiers. Even though the global economic machine still seems to be working, the pandemic is a hard blow that may badly damage it.

Whether any (or several) of these factors will soon bring down globalization, it is impossible to say. But we cannot exclude a collapse of the global financial system in the near future. That would necessarily lead to the collapse of the maritime transportation system that brings food everywhere in the world. The consequence could be a return to the time of the great famines, among several more disasters. We could go through a cycle very similar to that of the Roman Empire, although Washington may not be sacked by barbarians. At least, not so soon.

Apart from these trends, there is another problem with the current marine transportation system that could prove to be just as serious as the financial one, if not more so: the fuel problem. Container ships have gigantic engines rated sometimes at 100,000 hp and even more. That is, one of these engines is equivalent to the
engines of at least a thousand cars. There is also one container ship, the Russian *Sevmorput*, that uses a nuclear reactor as a power source. It is the only one in the world, but that gives some idea of the power needed by these floating behemoths. Their gigantic engines are optimized for maximum economic efficiency; it means they burn the cheapest existing fuel: the stuff that goes under the name of “heavy oil.” It is a viscous liquid that could never be used to fuel the engines of road vehicles or planes because it burns badly and pollutes a lot, especially because of its high sulfur content. But it is very cheap and therefore is used for ships, probably because the pollution it produces is not perceived by the people living on land (of course it is perceived by fish but, as we said earlier on, fish do not vote).

It is becoming increasingly clear that these monster ships cannot continue spewing sulfur and unburned hydrocarbons into the sea. There is now a directive from the International Maritime Organization (IMO) that says that, from 2020, the engines of commercial ships will have to emit only a strictly limited amount of sulfur. The first reaction of the corporations managing these ships was very clever (to say the least). Apparently, thousands of ships installed cheat devices that remove the sulfur from the gases emitted by the engines, but – here is the trick – then they discharge it directly into the sea to pollute exactly as much as before. [61] As they say, laws are made to be broken.

But apart from these tricks that can only be temporary, the laws will catch up with ship owners, and ships will have to start using low-sulfur fuels. This is causing a considerable challenge to maritime transport that also reverberates on road transport. To pollute less, ships should use more expensive fuels, and, in practice, they may have to use diesel fuel. But will diesel fuel production be able to support maritime transport? This point is not at all clear, and the oil expert Antonio Turiel claimed in his blog (www.crashoil.blogspot.com) that there is already today a big problem of availability of heavy fuels, independently of the legislations tending to limit their use. This is largely due to the American oil production shifting toward shale oil which is a light oil, poorly suited to make heavy oil or diesel. Turiel argues that the current crusade against diesel engines in Europe is a result of this problem: the limited amounts of diesel fuel that refineries can produce must go to maritime transport, far more vital and important than commuter diesel cars. Of course, the commuters will not be happy, but they have no choice.

At present, the situation of oil production worldwide shows a nearly constant total value but a clear decline for the total production of heavy oil, so Turiel’s interpretation seems to make sense, even though it will take some time to evaluate its correctness. In any case, the problem of eliminating fossil fuels from maritime transport exists, and it will become more and more important in the future because of both the gradual depletion of oil resources and the need to combat global warming. So, how will ships move? In the case of road transportation, we know that a good solution is to use electric motors and batteries. But, for a ship, carrying enough batteries for a transoceanic journey, it is a much bigger challenge. It would take another ship just to carry the batteries, a bit like the old locomotives hauled a “tender,” a coal-car that contained the coal they burned. Maybe it would not an impossible solution for ships, but surely clumsy and expensive. Nor can we think of using
photovoltaic panels on board to recharge the batteries: they can power the auxiliary systems, but they would not be enough to make a big ship move.

On the other hand, it is also true that the old Roman oneraria ships did not use fossil fuels; they used sails. And the sail was used for maritime transport up to just over a century ago. Could we use sails to move a 100,000 ton container ship? Not easy, but perhaps not impossible, either. The largest sailing vessel ever built was the German *Preussen*, launched in 1902 with a tonnage of 11,250 tons. It was about a tenth of a modern container ship, but the difference was not so large to make a comparison unthinkable. It seems that the *Preussen* was a good and reliable ship, too bad that it was rammed and sunk by mistake by a steamship in 1919 (Fig. 6.8).

So, perhaps we could see a return of sails for maritime transport. And, indeed, there are already many examples of enterprising people who have restored and refurbished old sailing ships and used them for short-distance maritime cabotage. These old ships will not replace the modern containers, but there are proposals to build new sailing ships specifically for medium-range freight transport. See, for example, the company “Green Heart Project” in Japan (greenheartproject.org). There is also talk of futuristic sailing ships, in some cases pulled by kites instead of traditional sails with the idea of catching the stronger winds at higher altitudes. Other proposals try to solve the problem of the costs of the large crew necessary for the management of sails in traditional ships. In this new generation of sailing transport vessels, all the equipment would be controlled by electric motors operated by computers and using solar energy obtained through photovoltaic panels.

Is it possible that the future of maritime transport is in the past, or rather in the return to sailing? Why not? After all, the future always surprises us.

Fig. 6.8 The *Preussen*, launched in 1902. With its tonnage of over 11,000 tons, it was probably the largest sailing vessel ever built.
6.4  Aquaculture: Solutions That Worsen the Problem

Expecting carnivorous fish aquaculture to solve the problems of the decline of traditional fishing would be like expecting Enzo Ferrari’s cars, rather than the emphasis on public transport, to solve the Los Angeles traffic jam problem

(Daniel Pauly)

Once, it was common for families to keep chicken in the garden. Today, it is rare, but those who have tried report that a hen can be an intelligent animal that runs to meet you when you get back home as if it were a dog. But chicken can be good pets only if they have enough space to move, peck, and scratch on the ground as they like. Otherwise, if they are forced to live in a confined space, they will rapidly eat everything alive, leaving only the bare earth and a horrible stench. Things are not very different for modern industrial chicken farms. Battery cages are still widely used in the world, and they consist of individual steel cages where chicken can’t even move. The modern poultry farms are supposed to be better, but they are not supposed to make chicken happy. They have little space to move, live on a cement floor, are often treated with antibiotics and pesticides, suffer from parasites, and undergo the amputation of the beak (without anesthesia). Often, you can smell a chicken farm from far away. There have been several cases of companies advertising their products as the result of “happy chicken,” but in more than one case, they were caught by environmentalists who documented plucked, sick, and dying chicken kept in steel cages.

The history of chicken breeding is an example of the long evolution of the relationship between humans and wild animals. Over just a few thousand years, we went from a life of hunters and gatherers to one of shepherds and farmers. In the beginning, our ancestors simply followed the herds, but soon they started confining herbivores inside stables and fences. In the early days, herds continued to feed with what they could find in their usual habitats, but gradually they came to depend completely on the food that humans provided. In the long run, we have arrived at the current situation where animals are confined in the minimum space necessary for them to survive and are fed with industrial foods that maximize their rapid growth; they are controlled; managed; freed from pests, often treated with chemicals to prevent sickness; and, finally, slaughtered. They are then replaced with new ones produced by breeding farms specialized in reproduction.

The story of what we call now “aquaculture,” fish breeding or “farming” in confined spaces, goes in parallel with that of shepherding and farming on land. Its origins are ancient: Tacitus (first century CE) tells us of Publius Vedius Pollio, a wealthy Roman citizen at the time of Emperor Augustus, who had developed the habit of punishing his slaves by having them eaten alive by the moray eels he kept in a pool. At the time, it seems that the moray was more appreciated as food than today (but probably not by Pollio’s slaves). But the Romans also raised eels and oysters and probably other kinds of fish. The same did the Chinese, on the other side of Eurasia with various types of fish and also shrimp and shellfish.
With the fall of the Roman Empire, fish farming did not disappear in Europe, especially for freshwater species. It was not aquaculture in the modern sense; it was, rather, a method of management of the fish fauna of lakes and rivers. The fish could be fed with food waste, or, in some cases, people would repopulate areas where the fish had disappeared due to natural reasons or to overfishing. This type of fish farming has continued almost to our days in Europe, but, up to recent times, it remained a marginal activity compared to conventional fishing. Something similar was done in China, typically on a larger scale with shrimps and carps raised mainly for local consumption. These small-scale activities resembled certain modern versions of “sport fishing” or “recreational fishing” where amateur fishermen sit around a small pond to catch farmed fish. The fish is then often thrown back into the water in the scheme called “catch and release.” This type of fishing is supposed to be for fun (but certainly is no fun for the fish!).

Things have changed a lot in recent times. During the past few decades, the farming of marine animals has ceased to be a family-based activity. It expanded to a wide range of different species, and it became an industrial activity. It was the result of the problems with overfishing that began to take their toll on conventional fishing in the 1980s. The impossibility of maintaining the catch of some prized species, for instance, salmon, stimulated investments into raising the fish in tanks. It was quickly discovered that it was possible to breed not only salmon, but many other high-value species: sturgeon, sea bass, trout, and many others. A symbiosis rapidly developed between aquaculture, that produced highly valuable fish, and the traditional fishing industry that moved to catch fish species of no value for humans to be transformed into fish meal and then used as food for farmed fish.

With traditional fishing declining, aquaculture went on along a curve of phenomenal growth. In 1970, aquaculture produced less than 4% of fish worldwide. Since then, it has continued to grow at a rate of over 11% a year, showing some signs of slowing down in recent times, but still growing. In 2000, aquaculture had reached 27% of planetary fish production. In 2013, the mass of fish produced with aquaculture exceeded that of beef production. It is an equivalence to be taken with some caution: fish contains about half the calories of meat for the same weight, but it is a fact that was described as a small triumph by the aquaculture industry.

Today, OECD-FAO (2018) reports that global fishing production is around 160 million tons per year, including aquaculture and traditional fishing. But, while the production of traditional fishing is static or decreasing, that of aquaculture continues to increase. The point of intersection, the moment when aquaculture will reach the same level of production of traditional fishing, might soon arrive or perhaps has already arrived. Of course, with its more than 80 million tons of food produced yearly, aquaculture is still far from having reached the level of production of traditional land-based agriculture, with over 4 billion tons of food produced per year. But it is still a remarkable result considering that the caloric value of fish is much higher than that of most agricultural products. In terms of total economic yield, we do not have specific data for aquaculture, but the whole fishing industry had a budget of about 120 billion dollars in 2010 for the trade in fish products, which is three times what the world spends on flour [62] (Fig. 6.9).
So, the last few decades saw an incredible revolution in fish production, something comparable to the famous “Green Revolution” which, starting in the 1960s, enormously increased the yields of crops, with aquaculture transformed from a family business into a global industry. As one might imagine, China plays the lion’s share (or, perhaps as a more appropriate image, the shark’s share) with over 60% of world aquaculture production. China is followed by other countries in Southeast Asia: Indonesia, India, and Vietnam, etc. Whereas Asian countries are still specialized in freshwater species, North America and Canada are focused on salmon aquaculture, a rapidly growing industry. Europe is still somewhat behind in this field but growing. For example, while in Italy sturgeons went extinct in the 1950s, today there are fish farms in Italy that produce sturgeons and caviar. And in 2019, the press reported that a sturgeon that had escaped from a farm had been captured in the Adriatic Sea. It was a creature from the past reappearing in our times: a little like the dinosaurs of the “Jurassic Park” movie.

The aquaculture revolution has gone largely unnoticed by the public, mainly because it has caused no changes in people’s habits. All kinds of fish are still on sale at the supermarket or at the fish market, the names are the same, and so is the color. Prices have remained approximately the same, too. The only difference is the label that states in small characters where the fish has been caught or raised. But only those who make the effort to read it notice that what they buy is not any more fish caught in the sea, but fish produced in an aquaculture farm. The average customer
also does not normally realize that the red-colored salmon on the shelves not only comes from a fish tank, but it is artificially colored to look like the wild kind. Not that fresh fish has completely disappeared but mostly is now in the form of low-value fish, sardines, herring, and little more. Some specialties of the past resist as wild fish, such as cod in the form of fish sticks, although no longer caught in its traditional areas of the North Atlantic. But, if you want caviar, you can find it only from aquaculture.

In more than one way, we could see aquaculture as a success story: another example of how human inventiveness has succeeded in replacing an overexploited resource. Just like shale oil mostly replaced traditional oil in the US market, farm-raised fish largely replaced wild fish on the world fish market. But is it true that aquaculture is such a success as it is often described? As always happens, excessive enthusiasm is not a good thing, and we need to examine in some detail the evolution of the industry to understand what’s going on.

Fish farming is sometimes subdivided into three categories: (1) extensive, (2) intensive, and (3) hyperintensive. Of these, the simplest one is the kind called “extensive.” It is a technology we can compare to traditional pastoralism. Just as in pastoralism, herds remain in the habitat they had occupied as wild creatures; in extensive aquaculture fish continue to live in their natural environment. It is just that their movement is limited by semisubmerged cages or other kinds of barriers. Fish can find their natural food in these cages, although their sustenance is usually supplemented with food provided by humans. Providing food to caged fish is called “fertilization” in analogy with agricultural practice. Extensive aquaculture can be done in both freshwater and saltwater, but in the first case, freshwater, there may be no need for the metal cage if there is a closed body of water suitable for the purpose. In the second case, saltwater, cages are often placed at sea, near the coast (this is typically referred to as “mariculture”). Often, the tanks are used to raise more than one species with the idea of recreating part of the trophic chain of the natural environment. This is called IMTA (integrated multi-trophic aquaculture). For example, the dejections of certain animals can be used to support the growth of plants or algae, and these can be food for the fish. The limit on the density of fish that can be raised in these cages is often determined by the amount of oxygen available. This, in turn, depends on the strength of the currents and the presence of phytoplankton that produces oxygen.

Intensive aquaculture is a much more complex activity, closer to industrial processing than to agriculture in the sense that it is performed at fish densities much higher than those of extensive aquaculture. The idea of intensive aquaculture is to overcome the limits of the natural environment and to increase the productivity of the system by forcing the fish to live in unnaturally crowded conditions. This condition compares to that of animals kept in stables or corrals on land. One problem with intensive aquaculture is the lack of oxygen in the tanks: so many fish all together may simply suffocate. For this reason, water is continuously pumped in and out of the cages. In this kind of aquaculture, feeding is normally fully provided by humans.

Finally, there is the extreme case, hyperintensive aquaculture. It is the aquatic equivalent of battery cages for chicken on land. The water is continuously
renewed with a pressure system ("current system" or "raceways"), and sometimes additional oxygen is directly supplied. The tank is a kind of spaceship where the various parameters such as temperature, lighting, salinity, etc. are continuously adjusted and optimized. In some cases, the water flow is at least partially recycled, and the outgoing water, loaded with bacteria and ammonia excreted by the fish, can be treated and purified to be used again with considerable water savings. That procedure also reduces the environmental damage outside the tanks. Hyperextensive aquaculture is the kind that produces maximum fish density, maximum production, and maximum profits and also, in some cases, maximum pollution.

All these systems have similar features and problems. To understand how they work, we need to answer certain fundamental questions.

1. Where do the fish come from?
2. How to feed the fish?
3. How to manage the polluting waste?

In principle, fish could reproduce inside the farming tanks, but that is rare. More frequently, there are companies specialized in fish breeding that produce young specimens (the "fry") to be sold to the companies that feed and grow them in aquaculture tanks. When the young fish are placed in the aquaculture tanks, people use the term "sowing" in analogy with agriculture.

Feeding fish in their tanks is a fundamental issue that affects the cost and the sustainability of the whole process. In the old, family-based kind of aquaculture, fish like carp or tilapia could be fed with low-cost agricultural products or simply kitchen waste. In some cases, the farmed species can find food by themselves; this happens mainly for aquatic plants, mussels, clams, and other invertebrates. But, in industrial aquaculture, fish are normally carnivorous; salmon is a good example. Now, you surely remember the old saying, "big fish eat small fish." It is true: these fish eat meat, and that means it is simply impossible for these fish to find enough food by themselves while kept inside a tank. That is, unless they turn cannibalistic, and sometimes they do. So, the fish must be fed high-protein foods. Not that they have to eat 100% meat; in part they can get used to proteins and carbohydrates of vegetable origin. But there are limits to that, just like lions in zoos cannot be fed spaghetti.

The problem with raising carnivorous fish lies mainly in a well-known fact in biology, called the “10% law.” It says that at every passage from one trophic level to another (e.g., from herbivore to carnivore), about 90% of the metabolic energy involved is lost. That is, it takes (approximately) 10 kg of herbivores to make 1 kg of carnivores. So, to make a 100 kg lion, it takes a ton of antelope or zebra. That is the reason why no one eats lion steaks: raising carnivorous animals is always expensive. That is true also for salmon and tuna: the 10% law tells us that it takes about 10 kg of high-protein feed to produce one kg of farmed fish.

So, aquaculture has been relying on fish of low economic value to feed high-value farmed fish. That has a simple reason: few protein-rich feeds are so cheap as some kinds of fish. For instance, the fish called "sand eel" is a typical choice as a
source of fish feed. No one wants to eat sand eel at the restaurant; everyone wants salmon, so the idea is to turn fish eel into salmon through aquaculture. But, if economically it makes sense, in terms of the efficiency of the process, it is a disaster. Think about it: you have to start from sand eel fishing, then turn sand eel into fish meal, then feed salmon in tanks, and finally use the salmon to feed human beings. This low efficiency of the process is a problem for the image of the industry. If people realized that by buying farmed fish, they are throwing away ten times the food they bring home, they would probably be more cautious in what they buy or, at least, in supporting aquaculture as a technology for food production.

In part because of this image problem, the industry has been trying to reduce the amount of fish in the feeds they use. This is not impossible: carnivorous fish need protein-rich food, but they are not fussy about where the proteins come from. A century ago, sometimes horse meat was used to feed fish. That was possible because there was a large horse population in the United States and in Europe, and nobody in the United States wanted to eat horse meat. But, with the diffusion of motor cars, the horse population plummeted and fish feed made with horse meat became too expensive. Today, the feed contains various kinds of protein. In part, it is from waste products of animals raised on land (chickens, pigs, cattle, etc.), and, in part, it may contain cereals such as grain and barley which do contain some protein and also have the virtue of “binding” the pellets in a form that makes them easy to pack and to transport. Sometimes, it is triumphantly said that farmed fish are environment-friendly because they eat only vegetable food. Normally, that is not true, although there may be fish farms where the fish are fed only proteins of vegetable origin. But, in almost all cases, animal protein, and in particular fish meat, remains the main component of the feed pellets.

In any case, farmed fish eat a largely unnatural diet: no wild salmon feeds on pork or horse meat, nor on barley flour. Such a diet may not be the best way to produce healthy fish, but what counts for the industry is just that the fish will survive the time necessary to grow large enough to be collected and sold on the market. Another consequence of the unnatural diet is that the quality of farmed fish is often inferior to that of the wild species. For instance, farmed salmon are grayish, not pink like wild salmon. Here, we have an interesting story that illustrates the relationship existing between nature, technology, and marketing. The pink color of wild salmon meat is the result of the habit of salmon of eating shrimp that contain a protein called astaxanthin. It comes from the algae that shrimps eat, and it works as an antioxidant. Astaxanthin is not pink when bonded to other proteins inside the cells of an animal, and, as a consequence, shrimps are not pink in nature. Crustaceans are almost always gray or white in their environment or just after being caught. But, as we all know, shrimp and most crustaceans become red when cooked. That’s because astaxanthin “denatures” when it is heated and acquires its characteristic red color. All the animals that eat shrimp tend to have this reddish color, not only salmon but also other fish, such as sturgeon and birds like flamingos. Incidentally, astaxanthin is also considered a food supplement for humans that can help reduce various ailments that are attributed to free radicals, from diabetes to high blood pressure. It is
not known whether astaxanthin also makes human flesh pink once cooked, but this is interesting only for cannibals.

So, farmed salmon do not eat wild shrimp and therefore are not pink; they are white like most fish. But, miraculously, the farmed salmon you buy at the supermarket is always nicely pink, actually intensely pink, almost dark red. As you can imagine, it is because it is artificially colored. Sometimes natural astaxanthin extracted from shrimp is used, but a similar molecule called canthaxanthin is more common. In the latter case, the coloring goes under the name of “E-161” in Europe. Or you can use beta carotene (E-160a), or artificial dyes. Hoffman-La Roche and other chemical companies offer salmon breeders a choice of colors known as “SalmoFan” which allows them to choose exactly the shade of pink they want to impart to their salmon.

There is no reason to be surprised about the habit of artificial coloring: it is part of what we now call “marketing.” Even chicken in supermarkets is often treated with artificial coloring; the meat of farmed chicken is often perceived as too white by consumers: they prefer a certain yellowish-pink color. About salmon, it is said that customers are willing to pay more the darker the red of the fish. Let us say that there is no evidence that the dyes used to color foods are harmful to humans, and in any case, the taste of food does not change. But there remains the fact that they are selling you a product that looks like something it is not.

Apart from artificial coloring, fish in intensive or hyperintensive tanks have plenty of problems that do not appear in the wild. First of all, there is the issue of cannibalism [63]. Occasionally, it is known to occur in wild fish as well, but the problem is worsened by the crowded conditions of fish tanks. Then, the fish in tanks are often in poor health, and they are easy prey to parasites and all sorts of pests and diseases that spread rapidly in the crowded tanks. Antibiotics are often used to combat these phenomena in aquaculture. A recent study published in Reviews in Aquaculture [64] reports that:

We observed that 67 antibiotic compounds were used in 11 of the 15 countries between 2008 and 2018. Among these countries, 73% applied oxytetracycline, sulphadiazine and florfenicol. On average, countries used 15 antibiotics and the top users included Vietnam [39], China [33] and Bangladesh [21]. On environmental and health risks, the review revealed sufficient evidence that directly links antibiotics use to food safety, occupational health hazards and antimicrobial resistance. Environmental risks included residue accumulation, aquatic biodiversity toxicity, microbial community selection for antibiotic resistance and the emergence of multi-antibacterial resistant strains.

A problem that may be related to aquaculture is that of the spreading of parasites such as worms of various types. A parasite you may have heard of is the anisakis, a nematode (cylindrical worm) that typically infests anchovies but also bluefish, and other types of fish, and is sometimes found in sushi [65]. Anisakis generates in humans the pathology called anisakiasis which, fortunately, normally causes no more damage than a bad stomachache that lasts a few days, although it may also generate an anaphylactic shock in some people. Then, there are crustaceans such as the Ceratothoa italica, which typically infests sea bream and sea bass. Another crustacean parasite is the sea louse that infests salmon (Lepeophtheirus salmonis).
It seems that these external fish parasites are not harmful to humans, but they are not a good thing for the fish (and not a pleasant sight for human customers who notice them in the fish they bought). It is also known that they find an especially suitable environment in the tanks of intensive aquaculture. They are often kept under control in the tanks using pesticides such as endosulfan, which is very toxic even to humans. Fortunately, endosulfan is prohibited in Europe and the United States, but it is found in traces in fish imported from countries like India and Southeast Asia. It is said that these parasites are on the increase everywhere in the world and the aquaculture industry is sometimes blamed as the source of the infestation occurring in wild fish. These claims cannot be proven: the increased number of infestations and pathologies could be just the result of better detection methods. It may also be that their increasing diffusion among wild fish is the result of pollution, rather than of aquaculture tanks. It is, nevertheless, a suspicion that cannot be ignored.

Interlude: Alexandra Morton and the Wisdom of the Salmon

Daniel Pauly tells us a rather chilling story in his book *Vanishing Fish* (2019) about how he visited the independent biologist Alexandra Morton in the 1990s, in the Echo Bay area of the Broughton archipelago, in Canada.

Alexandra immediately took us around on her tiny motor boat, which dragged a net in the shallows water. We caught about a hundred little fish, mainly young salmon. Each and every one of them carried large sea lice on their bodies, of a size corresponding to a dinner plate on the chest of a human, some had had two lice attached to them, and there was little doubt that these lice had their origin in the salmon farms across Echo Bay (Fig. 6.10).

Later, when visiting the DFO (“Department of Fisheries and Oceans”) research vessel “Ricker,” I heard from no less than the Director of research of the DFO’s Pacific Research Station in Nanaimo say publicly, before senior members of her staff, that Alexandra had manually “spiked” young salmon with individual parasites. I knew that this was a horrible lie and just the beginning of a concerted effort to discredit Alexandra’s findings work.

![Fig. 6.10](image) A young specimen of salmon infested with sea lice, flat crustaceans that stick to the skin of the fish
And when I heard that the DFO had conducted a cruise in the Broughton on R/V Ricker and found “no parasitized young salmon” I knew that when you do not want to find young salmon with sea lice, you go sampling with a research vessel of 190 ft that cannot operate in shallow waters, the only place where young salmon can be found (Fig. 6.11).

Alexandra Morton is an incredibly fascinating character. She was born as Alexandra Hubbard in 1957 in Connecticut, a place not close to the sea. Her father was an artist and her mother a writer. She married Canadian wildlife filmmaker Robin Morton in 1981, who died in a diving accident in 1986. She spent years studying the behavior of killer whales, orcas, off the coast of British Columbia. She wrote at least four books about whales, but, in time, her interest shifted to salmon also because of the rapid growth of salmon aquaculture on the coast of British Columbia.

This is how she describes her activity in her website, https://www.alexandramorton.ca/meet-alexandra/.

For nearly 40 years, I have dedicated my life to restoring the balance between the people and the wild salmon off the coast of British Columbia.

In 1984, I followed the whales into a remote inlet off the west coast of Canada and made it my home. There were no roads, electricity or telephones, but wild salmon and wildlife thrived, as well as a community of people.

When the salmon farms first appeared, we were told they would be good for us. Then the toxic algae blooms and sea lice developed, and the wild salmon die-off began.

First, the whales I was studying left, then the salmon populations crashed, and then my beloved community began to fade away. Today there are only 8 people left in the village and 27 Norwegian-owned salmon feedlots dot the area.

And here is how she describes the disaster that salmon farming has brought to wildlife, again from her website.
When we hold millions of salmon in net pens in the ocean, the natural laws that kept disease under control are broken. Salmon farms cause disease levels to rise to beyond those wild salmon are built to survive. The industry cannot fix this as long as it uses net pens in the ocean. Nets will never contain viruses, bacteria, or parasites. Whether the salmon farms introduce new pathogens or amplify local pathogens, this is dangerous to wild salmon and herring.

Salmon are built to move. The sick and weak are left behind, consumed by predators. This stops bacteria, viruses, and parasites from multiplying. Predators are nature’s highly efficient cleanup crew.

When contained, salmon are forced to swim around in cages where disease spreads easily from fish to fish. Without predators, each sick fish remains infectious much longer, pumping out pathogens until they waste away and die. Scientists recognize salmon farms as disease production facilities.

This is the fight Alexandra Morton is engaged in. She has been doing for years, and she has even been culturally adopted, dressed, and named Gwayum’dzi by the people of the “first nations” of the coast of British Columbia, fighting to protect their way of life from the overexploitation of the sea resources by the salmon industry. A hard fight, but, who knows? She may win against her much more powerful enemies!

Speaking about pollution in aquaculture, we also need to mention the environmental impact of cages and tanks. These tanks take up space that cannot be used from other activities near the seashore. In the case of extensive aquaculture, the need for space is often an important problem. In Norway, the plants are often located in the fjords where they impact on the currents and the local ecosystem. In the Philippines, shrimp aquaculture has destroyed an important fraction of the coastal mangrove fields that serve as habitats for many marine organisms, as well as tsunami barriers and hurricane-generated waves. Then there is a question of fish escape from the tanks that can lead to the spread of species that are not native to where the plants are located.

And then, of course, there is the problem of managing effluents. Fish dejections contain organic material, nitrogen, phosphorus, and various compounds which, if they spread in an uncontrolled way, can cause various problems, such as “eutrophication” of the waters close to the plants, or uncontrolled growth of algae and other organisms that consume the oxygen of the water and make the life of local fish impossible. To combat this problem, breeders make use of a technology called “aquaponics” which is a combination of aquaculture and hydroponic agriculture. The idea is to use the effluents from breeding tanks as fertilizers for agricultural products. If it works, it is a good idea that at least partially “closes the circle” of the nutrient and waste cycle. But it also takes energy and may not work as well as it is said to.
Another problem is that fish in extensive aquaculture tanks are sometimes seen as legitimate targets by predatory animals, from seagulls to sharks. This generates a series of problems that include the need for safety nets or more simply someone who spends his day with a shotgun in hand, killing the birds that fish in the tank. This is not good for various reasons, including the fact that some of these predators, like albatrosses, are at risk of extinction.

Finally, there is a question that surely is not the least important one: animal welfare. This is an ethical question that goes beyond pure profit. Battery chicken farms on land are forbidden by law for ethical reasons in Europe and in some US states. Thinking about that, it is curious to talk about chicken bred in “inhuman” conditions, but that is the point. If we are truly human, we cannot imagine making other living creatures suffer under conditions that we humans would never accept for ourselves, even if this brings a profit to those who do. If this applies to chicken and other land animals, it must also apply to salmon and other farmed fish. Packing them in tanks as if they were sardines already in their cans is an inhuman practice that we can no longer accept. The vision of dying, sick, and infected fish comes to us from certain documents such as the recent Artifishal film (2019), and it makes one shudder. We are becoming increasingly aware that the environment around us is what makes us live and that if we do not respect it, the environment will not necessarily respect us.

So, is aquaculture an ecological and sustainable practice, as the industry claims? Or is it an unnatural activity that produces profit by harming both humans and fish, as some environmental groups say? As always, the truth is not all on one side. If aquaculture is not always as bad as some maintain, it is also true that its proponents tend to exaggerate its virtues. Considering all the pros and cons, aquaculture can be seen as an interesting technology that has the potential to produce high-quality nutrients for humans. But it can also do great damage to human health and to the environment if it is poorly managed. In some cases, it may well be a financial scam to make money out of naive investors.

In the end, aquaculture should neither be demonized nor glorified: we cannot expect it to solve the problem of world hunger alone, nor even to represent the apex of the circular economy. It is a technology with many problems but also able to provide solutions. It must be regulated and controlled so that it can be useful for what it can do. But, as usual, when a lot of money is involved in a growing economic activity, it is difficult for regulators at the government level to intervene to curb growth to reduce the damage and improve the quality of the product. So, it is likely that, at least for the near future, we shall continue seeing aquaculture growing and invading coastal areas with tanks and equipment. It will take time before the public understands what is being done, and governments feel that their intervention is truly necessary.
6.5 The Sustainable Sea: The Red Pill or the Blue Pill?

Fishermen, as a class, have extremely poor observation skills about anything that has to do with fish that is not necessarily visible in the course of their daily actions.

Thomas Henry Huxley, report to the Royal Committee on Fisheries, 1863. [66]

In 1949, the American naturalist Aldo Leopold wrote *A Sand County Almanac*, one of the first books where the need for conserving the natural environment was noted and discussed. Among other things, Leopold wrote:

….. I have lived to see state after state extirpate its wolves. I have watched the face of many a newly wolfless mountain, and seen the south-facing slopes wrinkle with a maze of new deer trails. I have seen every edible bush and seedling browsed, first to anaemic desuetude, and then to death. I have seen every edible tree defoliated to the height of a saddlehorn. Such a mountain looks as if someone had given God a new pruning shears, and forbidden Him all other exercise. In the end the starved bones of the hoped-for deer herd, dead of its own too-much, bleach with the bones of the dead sage, or molder under the high-lined junipers.

It was one of the first times that someone questioned the practices of management of natural resources that involved the extermination of predators. Up to not long ago, it was commonplace to define as “vermin” animals believed to be harmful to agriculture or, in general, to human interests by competing with human hunters for prey or with farmers with the products of agriculture. Then, it was commonplace to engage in the extermination of these enemies of humankind, sometimes with explicit financial support from local or national governments. So, it was considered sacrosanct to eradicate the wolves from the territories where they lived by killing them on sight. Not just wolves were considered vermin; the idea was to kill all large carnivores including bears, wildcats, birds of prey, and many others. The concept of vermin was sometimes extended to human beings, and up to the mid-nineteenth century, in some regions of North America, a bounty was offered for every native American killed, and that’s surely not the only example of a practice that was, unfortunately, common in history and still ongoing in some places. In the sea, cetaceans were often considered as vermin since they were seen as competing with fishermen for fish. Still today, many fishermen rejoice when they see a beached dolphin.

The problem with this idea is that the elimination of predators upsets the whole ecosystem, as Leopold noted for the case of the deer. The same problems exist for marine animals: the idea of killing dolphins to catch more herrings is not only brutal, but also counterproductive. But neither hunters nor fishermen seem to be able to realize that predators stabilize the trophic chain and that they are their friends rather than their competitors. In the sea, there is the additional element that not only whales and dolphins keep the lower trophic levels in check, but they fertilize the sea with their dejections. That increases the phytoplankton population with positive effects on all populations.

Unfortunately, as you may imagine, it is difficult to make these concepts understood in a world fixated on maximizing yields and growth. We have the same
problems with some of the current ideas on how to manage marine resources. We already described how the concept of “maximum sustainable yield” (MSY) is not only difficult to apply because of the resistance of the fishing industry, but it could be flawed in itself. Biologists often say that in an ecosystem, “you cannot just do one thing.” It means that you cannot consider a species as isolated, and whenever you act on a population, the result is an impact on all the other populations, at all trophic levels. But this is exactly what the MSY concept does, calculating the allowable fish quotas utilizing a model that sees the stock being exploited as if it were isolated in the sea.

But, perhaps, the concept of MSY could be saved if we frame it in a more general way, let us say more holistic, that is, applying it to the whole biosphere and not to individual species. In this way, we group together all the trophic interactions, and we can use basic physical consideration to calculate what the sea can give to us and what we could take from it. So, what is the MSY for the whole sea?

To answer the question, let us start with a quantitative assessment of the biomass that exists and that’s produced on our planet. Data can be found in a recent work by Yinon M. Bar-On and others [67]. In the figure, we show how the masses of the various organisms are distributed. From this diagram, we can calculate that the total biomass on Earth corresponds to about 550 gigatons (Gt) of carbon (Fig. 6.12).

Plants are by far the most common organisms on our planet because they are the “autotrophs,” the first trophic level, the one that collects sunlight and uses it to combine water and carbon dioxide to form the molecules that are the basis of biological life. The following trophic level is made out of heterotrophs in the form of unicellular creatures, first bacteria and then others, which are the simplest and most common creatures. Since the creatures at this level depend on plants for the energy they consume, it makes sense that their total mass is smaller. Multicellular creatures in the form of animals are a further step up in the trophic level, and it is logical that they are a small fraction of the total.

Now let’s remove plants and unicellular animals from the diagram and see the distribution of animals only, again from the same article [67] (Fig. 6.13).

Here we see that the arthropods (a category that includes insects) are by far the largest animal group, both on land and at sea. Note how fish is an incredibly abundant mass, far superior to those few wild animals that remain on land. Mollusks and various types of worms follow. Also note how large is the mass of the cnidarians, a phylum that includes jellyfish. They seem to be light, even ethereal creatures when you see them swimming inside a tank, yet, there are so many Cnidaria in the oceans that their total mass is nearly two times larger than that of humans. Livestock is also an impressive category in terms of its total mass. Among mammals, humans are an anomaly with their total mass much larger than that of all wild creatures together on land, mammals, and birds, reduced to a tiny fraction of the total. No wonder that almost nobody lives by hunting, today.

But these data do not tell us much about the distribution of life between land and sea. For this, we need another set of data, again from the article by Bar-On et al (Fig. 6.14).
We see that the land biomass is by far the most abundant, followed by the “deep zone” of the planetary subsurface, that we do not normally perceive, populated mostly by bacteria and the unicellular creatures called “archaea.” Surprisingly, the seas contain only about 1% of the biomass of land. Other estimates give slightly larger fractions, but no more than ca. 2%, and the unbalance remains. So, if the total biomass on Earth corresponds to 550 Gt of carbon, the biomass in the sea is no more than about 5–10 Gt [68].

Why is the sea almost empty? The main reason is related to the structure of plants. On land, plants are complicated machines composed of roots, trunks, branches, leaves, and more. Most of their mass is biologically inactive, mainly wood which is metabolically dead. But wood serves various necessary purposes: it manages the flow of nutrients from the soil to the active cells in the leaves and provides support and mechanical resistance to the plant. In the sea, instead, photosyn-
6.5 The Sustainable Sea: The Red Pill or the Blue Pill?

**Fig. 6.13** Distribution of animal biomass. Data from Bar-On et al. 2018 [67]

**Fig. 6.14** Biomass distribution for marine, terrestrial, and subterrestrial systems given by Bar-On et al. 2018 [67]
thetic plants are mostly in the form of unicellular creatures, they are the so-called blue-green algae, or cyanobacteria. These small cells don’t need rigid structures; they get the nutrients they need directly from the water they are immersed in and they are practically all photosynthetic surface. So, their total mass is not so large as that of plants on land.

There follows that the metabolic rate per unit mass for marine plants is much larger than for land plants simply because marine plants don’t have to carry the enormous burden of trunks and roots. The experimental measurements confirm that this is the situation. The “net primary productivity” (NPP) measures the amount of carbon fixed by photosynthesis corrected by subtracting the amount lost by plant respiration in the form of carbon dioxide. It is measured in gigatons of carbon (Gt) per year. There are various estimates of this parameter, but, generally, the data indicate that the NPP is about the same for the land and for the sea productivity; both are of the order of 50 Gt of carbon per year [69, 70, 71]. This is a surprising result: the molecular mechanisms of photosynthesis are the same on land and in the sea, but the oceans cover a much larger area of the planet, about 70% of the total. So, why is not the sea productivity larger than that of the land? Again, there are reasons for this: it has to do with the availability of nutrients that limit the amount of biomass that can populate the land and the sea.

To understand this point, we can start from the fact that the entire ecosystem uses sunlight as a source of energy to build living matter. But, to build anything, you need building materials, and, in biology, they are called “nutrients.” The four main nutrients used by life are carbon, hydrogen, nitrogen, and oxygen. Then, there are the elements called “macronutrients,” calcium, sodium, chlorine, sulfur, phosphorus, potassium, magnesium, and others. Finally, many more elements are needed in traces for some specific metabolic mechanisms. Life can exist only where nutrients can be found. And not just that: life needs to be able to recycle these elements in a very efficient way; otherwise it would either run out of nutrients or suffocate in its own waste, or both things at the same time.

Let’s start with the availability of the four essential elements: carbon, nitrogen, oxygen, and hydrogen. Oxygen and nitrogen exist in molecular form in the atmosphere. Carbon and hydrogen are also present in the form of carbon dioxide (CO$_2$) and water (H$_2$O). On land, carbon dioxide is absorbed directly from the atmosphere by the leaves of land plants. Land plants can also absorb water using their leaves, but normally prefer water in liquid form, absorbed by the roots. Living creatures on land depend on rain for water, and, in some cases, sophisticated mechanisms of water vapor transport have move water from the sea to the interior of the continents. This is mainly the effect of the “biotic pump” generated by the forests [72].

In the sea, the situation is similar for the four essential elements. Of course, marine plants have no problems with the supply of water, while the other main nutrients, N$_2$, O$_2$, and CO$_2$, can be found in the form of gases dissolved in seawater. But the supply of these nutrients in the sea is not so abundant as it is on land because their concentration is lower in seawater than in the atmosphere and it tends to decline with depth. The nutrient decline goes together with the absorption of sunlight by the water, and the result is that photosynthetic life in the sea is possible,
typically, only within a layer of no more than a few tens of meters from the surface. This region is called “euphotic” or “photic.” Below the euphotic layer, the sea is dark and contains very little oxygen, a condition termed “hypoxic.” Of course, photosynthetic creatures cannot live in the dark, but some fish can survive at great depths with little or no oxygen by reducing their metabolic rates; others undertake periodic vertical migrations to breathe. Marine mammals do that, too, periodically reaching the surface to replenish their metabolic system with oxygen.

Overall, the four essential elements are continually exchanged from the biosphere to the atmosphere and back, and, normally, there are no problems of scarcity nor of recycling for creatures living on land or in the sea. The situation is much more complex when we look at the macronutrients: phosphorus, sulfur, calcium, and others. These elements do not normally have gaseous forms that can be found in the atmosphere. They exist in forms usable by life only as ions dissolved in water. That is a serious problem for land-based plants. Rain is basically distilled water, and it does not contain minerals in significant amounts, so where can these nutrients come from? The land-based biosphere has solved the problem by using a variety of strategies; the main one is the humus, the name for the fertile soil in which plants grow their roots. It is a true biochemical laboratory that continuously collects and recycles dead animals and plants, making the minerals they contain available to the roots of living plants.

But, no matter how efficient the humus can be, it cannot recycle minerals at an efficiency of 100%. A fraction will be necessarily washed away by rain and carried to the ocean by river runoff. To reintegrate these nutrients, the main source is the periodic outflow of rivers that collect them from the erosion of the mountains. Do you remember how Egypt was called “the gift of the Nile?” It was because the periodic floods of the Nile replenished the nutrients that agriculture had removed from the land. Volcanoes can also spread nutrients in the form of small particles carried by the winds. Then, lava flows are notoriously highly fertile after they cool down to room temperature. Wind can also collect small sand particles from deserts and distribute them at very long distances. It appears that the Amazon forest receives a constant resupply of the minerals it needs in the form of dust that comes from the Sahara Desert [73]. Another possibility for plants is to obtain minerals from animal dejections or animal carcasses. Since animals are mobile, they may feed someplace and excrete or die somewhere else, in this way transporting minerals from one place to another. In recent times, human beings have taken to resupply the plants they cultivate with natural and artificial fertilizers.

In the sea, the situation is different. On land, minerals are concentrated inside rocks, and the limiting mechanism is the energy-expensive process of turning them into ions that can be dissolved in water and then absorbed by life. In the sea, minerals are already dissolved in water but tend to be dispersed uniformly over a very large volume. If the oceans were still, the concentrations of mineral nutrients would be uniform and insufficient to maintain life as we know it. But that’s not the case: there exist regions in the sea where nutrients are abundant and support abundant life. These regions are mainly the result of minerals carried to the sea by river runoff. Less important but not negligible local sources are volcanoes. Hydrothermal vents
are fissures on the seafloor emitting hot water laden with minerals leached from the rocks underneath. They are also an important source of minerals for sea life. Dust carried by winds can also fertilize the sea, and, just as on land, the excreta of animals are an important source of mineral nutrients for plants. In particular, whales are an important factor in fertilizing the oceans – at least they were before the extensive extermination of the past two centuries [74].

These sources of nutrients, in themselves, would not be sufficient to support an abundant marine life if they were not coupled with some way to recycle minerals. Here, the problem is that, as we already mentioned, life in the sea tends to concentrate in the euphotic zone, a few tens of meters below the surface. But there is no mechanism that concentrates minerals in this region, nor an equivalent to the humus layer on land that tends to recover and redistribute minerals from dead creatures.

When a marine animal dies, the minerals it contains follow the destiny of the dead body and tend to sink, since living tissues are denser than water. Have you noticed what happens when you float on your back in a pool? What keeps you afloat is the air in your lungs while your legs and your arms tend to sink. Aquatic animals (and people) can stay afloat only because they keep swimming, or because they keep air in some parts of their body. Fish have the swim bladder; mammals can use their lungs. Dead creatures, instead, do not breathe, to say nothing about being able to swim, and therefore tend to sink. But, in the process of decomposition, gases may accumulate inside the dead body and create sufficient buoyancy to keep it afloat or, in some cases, cause it to resurface after it had sunk to the bottom. There is a legend that if you are a professional killer, you should always gut your victim with a knife before sending him or her to sleep with the fishes. In this way, gases will not accumulate inside the belly of the corpse, and it will not resurface to reveal the crime. The authors of this book do not have experience as hired assassins, so they simply report this legend. But we can say that it makes perfect sense from a biophysical point of view. (Isn’t it remarkable how many things you can learn from this book?)

In any case, the fate of dead marine animals is always the same. They may float for a while, but, eventually, they will sink to the bottom. There, the carcass will be gradually decomposed by the various scavengers specialized to operate even at great depths. But, if the nutrients remain there, they are not available anymore for the euphotic zone. Fortunately, water currents can recover, at least in part, nutrients from the bottom of the sea. This is a complicated process, and to understand it we need to examine the bottom of the sea. You see it in a schematic form in the figure (Fig. 6.15).

The area closest to the coast is called continental shelf, and it is geologically part of the continent to which it’s attached; the only difference is that it is underwater. Its depth increases very slowly with distance from the coast until we reach the continental slope that forms the limit of the continental plate. At the bottom of the continental slope, there is the continental rise, an underwater hill composed of accumulated sediments falling from the slope. Farther away, the bottom of the ocean is normally called the “abyssal plain” that starts at a depth that goes from ca. 3000 to 6000 m.
On the continental shelf, the low depth allows currents and winds to stir the water so that the nutrients at the bottom can normally return to the surface. That cannot happen for the nutrients that sank at great depths, over the abyssal plain. But, even in that case, the nutrients can be recovered with the phenomenon called “upwelling,” the rise of deep oceanic currents when they meet the edge of a continent. We already noted in this book how this phenomenon plays a fundamental role in fishing off the Peruvian coast, with the yield strongly affected by the conditions called El Niño and La Niña. Both are seasonal meteorological conditions; they cannot affect deep oceanic currents. But they do affect the uppermost surface region of the sea and can prevent the nutrients from reaching the surface.

In the end, nutrients in large concentrations are available in seawater only near the coasts as the result of either current upwelling or river runoff. Away from the coast, the concentration of minerals becomes lower and lower, and, as a consequence, the high seas are poor in life. They are often defined as “marine deserts” even though they are not completely lifeless. Now we can understand the reason why the productivity of the seas is not larger than that of land. It is because most of the seas are a desert.

At this point, we can examine these results in view of the human interest in these matters: What can we get from the sea (and from the land as well) in terms of food for humans? The net primary productivity, NPP, is the key parameter for this evaluation. It measures how fast an ecosystem can replace biomass that is taken away. Overall, Krausmann and coauthors [75] estimate the human appropriation of the total NPP (HANPP) is about 25% of the total production. But, again, comparing sea and land generates surprising results. According to FAO data, more than 99.7% of human food in terms of calories comes from the terrestrial environment; less than 0.3% comes from the oceans and other aquatic ecosystems. Just to give you some idea of the amounts involved, consider that, according to FAO data, the world production of grain has been of some 2.2 billion tons in 2017. Fish production (including crustaceans, mollusks, and other aquatic animals) is just 80 million tons per year, although it is surely larger if we take into account unreported and illegal fishing. So, grain is produced in an amount that is about 30 times larger than that of fish.
In the end, we can calculate that the human appropriation for the sea resources is of the order of 0.1\%, perhaps even smaller, of the net ocean productivity. A very small value in comparison with that of land, about 25\%.

So, how could it be that such a small appropriation has allowed humans to deplete so many fish stocks? Isn’t this story of the “empty sea” an exaggeration? Alas, no. The high NPP of the sea is all the result of the extremely high metabolic rate of phytoplankton. But humans do not fish phytoplankton; they fish at higher trophic levels, those of crustaceans and fish. Here, we face the phenomenon called the “reverse trophic chain.” On land, there is about 1000 times more plant biomass than animal biomass, and that’s part of the normal way trophic chains function. In the sea, it is the opposite: the animal biomass is nearly 30 times larger than the plant (phytoplankton) biomass, again because of the extremely high metabolic rate of the marine autotrophs that allows animals to accumulate biomass. So, humans are exploiting an abundant resource in terms of total mass; that is why fishing may be such a rewarding activity for fishermen, sometimes nearly miraculous. But this great abundance turns out to be illusory because fish reproduce slowly, and so it is easy for humans to deplete the stocks. The actual appropriation level of fisheries has been estimated at around 8\%, and in some cases even larger, as reported by Pauly and Christensen in 1995 [24], and today, the appropriation level is surely larger. No wonder that so many fish stocks have been depleted and destroyed.

This assessment confirms the basic thesis of this book: that we are taking more fish from the oceans than the productivity of the oceanic ecosystem can replace. That’s remarkable because humans are not aquatic apes, and their presence on the sea remains much more limited than it is on land. There are no more than about 250,000 registered ships in the world, and, even considering the unregistered vessels, there may be no more than 2–3 million people at sea at any given moment. That small number has been sufficient to empty the sea of most of its large creatures, starting with whales, all the way to tuna and salmon. But that should not be surprising: probably similarly small numbers of humans were sufficient to wipe out most of the land megafauna during the past few tens of thousands of years. Human hunting, whether targeted at whales or mammoths, is so efficient to be extremely destructive.

Probably, the people who manage the fishing industry never made calculations about the metabolic rate of phytoplankton, and we may assume that they don’t even know what NPP is. But they understand that the yields of their traditional, high-value prey, from salmon to tuna, are going down. So, they are reacting by moving toward lower and lower trophic levels, smaller fish of kinds that humans are not normally happy to eat but that can be used to make feed for aquaculture. This is a strategy that can work, at least for a while: lower trophic levels are more abundant than higher ones, and the race to the bottom is going all the way to targeting invertebrates, crabs, lobsters, and the like.

But even the abundant stocks of small fish are being rapidly depleted, and, if we continue moving in that direction, we could aim directly at fishing phytoplankton? That’s part of the idea of the “blue growth,” and it is believed that it would open up an enormous resource of biomass. After all, if whales can live mainly on phytoplankton, why can’t we humans do the same?
We could; in theory. And the perspectives look bright. It is not that the mass of plankton is so large, but, as we saw, the primary oceanic production of phytoplankton is huge, able to quickly replace the mass removed by fishermen or other predators. Of course, despite all the hype on blue growth, nobody wants to eat plankton; it is thought mainly as feed for aquaculture. But even that may change in the future: hunger makes people willing to eat anything. Do you remember the “soylent green” of the movie 2022: The Survivors (1973) with Charlton Heston? It was supposed to be made with human flesh for human consumption. That was science fiction, of course, but nowadays perceptions about food change rapidly, and we already mentioned how the industry is engaged in developing recipes to make plankton palatable for humans. If we could convince people to eat plankton, maybe fried, battered, roasted, or whatever, it would be possible, in theory, to find a new source of food to satisfy the need of a growing human population.

Alas, beautiful theories tend to go to pieces when they clash against the ugly reality. Natural resources always seem to be abundant when people start exploiting them, and then it turns out that they are not. Overexploitation is always lurking in the background: anything can be overexploited and normally everything is. Fishing phytoplankton is an especially risky idea: it involves exploiting a resource that exists in relatively small amounts. It only looks so abundant because it reproduces so fast, but we are speaking of no more than a few billion tons at any given moment, and the projected human consumption is of that order of magnitude. Make the same mistake that fishermen do all the time, overexploiting the resource, and the result is the collapse of the stock. And if the stock of the lowest trophic level collapses, everything collapses. But destroying the phytoplankton stock means the destruction of the whole marine ecosystem, a good illustration, if ever there was one, of the military strategy called “scorched earth.” Humans already won their war against the whales in just a couple of centuries of hard fighting. If they start a war against plankton, how long would it take for them to destroy this new enemy? Maybe just decades?

This terrifying scenario is the result of an approach that follows the same pattern as that of ancient hunting and gathering. Hunters catch what they find, when they find it. Fishermen do the same, and, as we already saw in earlier chapters of this book, this strategy nearly guarantees the overexploitation and the destruction of the resources, no matter of what kind. Couldn’t we instead apply to the sea strategies that would be, in principle, able to maintain a better balance with the capability of resources to reform before they are destroyed?

A step toward better control of the exploitation of the sea would be to move from the equivalent of hunting and gathering to the equivalent of animal husbandry. That means, basically, that fishermen become the owner of the fish even before they catch it because the stock they are allowed to exploit is confined in a closed space, or in a specific region. We already saw how modern aquaculture does exactly that, raising fish in closed tanks or in closed water bodies. But, as things stand, aquaculture is a poor equivalent of husbandry. The problem is that most fish are carnivorous animals, while those raised on land as livestock are normally herbivores. So, raised fish are fed mostly with wild fish, and the result is that aquaculture becomes one further
factor that pushes the fishing industry to overexploit the resources of the sea. It may be possible, in the future, to create fish species that could be raised on an herbivorous diet, but that would simply turn aquaculture into an appendage of land-based agriculture, changing little to the problem of managing the resources of the sea.

There remains another possibility: managing the sea in the same way as agriculture is managed. That is, taking control of nearly all the phases of growth of the resources. In part, it is already done in aquaculture, where the term “seeding” is used in analogy with farming practice when young fish are introduced in the tanks. On a larger scale, this is the way caviar production was managed in the Caspian Sea in Soviet times, when the government financed repopulation facilities that produced young sturgeons to be released into the sea. That was an expensive process, surely possible for a high-value product such as caviar and also for most products of the aquaculture industry. Whether that could be done on a much larger scale is debatable.

And then, why not fertilize the sea? In agriculture, mineral fertilizers are commonly used, and the same could be done also in the sea, especially in the regions which lack a sufficient concentration of mineral ions. It has to be done with care: in excessive amounts, fertilizers can lead to the eutrophication of large marine areas, creating oxygen deficiency and generalized animal death. It is a phenomenon typical of shallow seas. For instance, the Adriatic Sea which was especially affected by the release of phosphorus-containing detergents in the 1970s. You could say that it was being fertilized, but the creatures that most benefited from this inflow of minerals were algae. The result was the phenomenon called eutrophication with the associated oxygen depletion that killed practically all the fish and turned most of the Adriatic Sea into a stinking puddle.

But fertilization of the sea could have a future of large-scale utilization. Already in the 1990s, it was noted that over geological times, there was an inverse relationship between the concentration of CO$_2$ in the atmosphere and the presence of desert areas on the continents [76]. This relationship seems to be due to a surprising concatenation of cause and effect. When there are large deserts on land, wind erosion generates dust that is deposited on the oceans, fertilizing the plankton, so lowering the concentration of CO$_2$ which, in turn, leads to lower temperatures, aridity, and more dust in the atmosphere, even creating ice ages. It is part of the incredible complexity of the terrestrial ecosystem.

Once the mechanism of fertilizing the oceans with dust from the deserts was discovered, there came the idea that it could have been artificially reproduced by scattering fertilizers, mainly iron sulfate, in the nutrient-poor areas of the oceans [77]. The initial idea was not so much to help fish stocks to regrow or to increase in size, but to promote the growth of phytoplankton that would absorb CO$_2$ from the air to counter the effects of the combustion of fossil fuels and mitigate global warming. One of the proponents, John Martin, is reported to have said, “Give me half an oil tanker full of iron sulfate and I’ll bring you the next ice age” [78]. Since then, the idea has been the subject of a few practical experiments, and it has been presented in the press as a reckless form of “geoengineering” designed to play dangerous games with the planetary ecosystem.
Martin may have been somewhat optimistic in the evaluation of the consequences of his idea. The perspectives of fertilization to fight global warming are still being evaluated and discussed, and a paper by Harrison [79] estimates that macronutrient fertilization of the oceans could at best remove 10%–20% of the current human carbon yearly emissions. That would have only a marginal effect in the effort to fight global warming. Apart from the climate effects, the small-scale experiments performed so far indicate that mineral fertilization does generate phytoplankton blooms in the ocean. That could be a way to refurbish the fish stocks badly depleted by overfishing, although it is a possibility still largely to be explored.

Fertilizing the sea remains an idea steeped in the concept that managing the Earth’s resources means maximizing the yield for human consumption. That is supposed to be feasible without destroying everything, although this point is often forgotten. Nevertheless, from the data reported so far, it seems clear that, theoretically, we could push the exploitation of marine resources to higher levels than the current ones. This is, after all, the basic idea behind the concept of “blue acceleration,” the most optimistic version of the idea of “blue economy.” But the fact that something is possible also does not automatically make it desirable.

It is a very general point that the Russian researchers Gorshkov and Makarieva make in their studies of the biosphere [80], emphasizing that the complexity of the system is not random but an important feature that allows the biosphere to adapt to changes much better and in a less traumatic way than do systems created by human beings. According to them, we should not appropriate more than about 1% of the net production of the biosphere if we do not want to destabilize the entire ecosystem, but we exceed that by far both on land and in the oceans. So far, we have not seen huge disasters happening just because it takes time for the ecosystem to collapse but the risk is that, eventually, it will.

Perhaps we are still in a condition where we have a choice: the red pill or the blue pill. In the iconic description of this choice, in the first Matrix movie of 1999, the red pill meant the unpleasant truth, while the blue pill stood for remaining in ignorance. In the case of the sea, choosing ignorance means continuing to be guided solely by economic convenience. It means catching what is there, when it is there. It means continuing to descend from one trophic level to another, until we arrive at the bottom and, in this way, destroying the level that holds the entire marine ecosystem together. We can, if we want, transform the blue and rich sea into a stinking brown puddle. Is this what we want to do? Maybe not, but it is where the pill of ignorance is taking us.

The other pill, instead, means knowledge. It means evaluating the sea and its creatures for what they are and not just as resources subordinated to human growth. It means leaving the oceans in peace to let them recover from the destruction that humans have inflicted on them during the past few centuries. It means seeing the oceans returning to be that richness of life that they were once. Is it possible? Knowing humans, it seems unlikely that the pill of knowledge will be chosen over the pill of ignorance. But it is not decided yet. The future will be what we want it to be.