5 Climate change impacts on marine ecosystems

> There can be no doubt that climate change will alter marine life. Changes in ecosystems usually have multiple natural causes, but increasing carbon dioxide levels in the atmosphere and global warming are now playing a critical role. The extent of the coming disruption to biotic communities is unknown.

Biological systems under stress

> Marine life forms are fundamentally well adapted to natural variations in environmental conditions. They can even tolerate extreme situations for a limited time. But climate change is altering some habitats so severely that the stress becomes too great for many species. Where several unfavourable factors combine, the cumulative effect can cause the extinction of species.

Changing habitats

Stress is a common phenomenon nowadays. Not only people suffer from stress. Marine plants and animals are also subject to stressors – pressures brought on by changes in their habitat conditions. Stress has been around forever. But it has clearly been intensifying in recent years as a result of climate change. Sometimes stress is triggered by just one stressor. In the ocean, for example, it could be due to increased sedimentation from a storm burying bottom dwellers, or an algal bloom causing light deficiency in deep water layers. Unfortunately, however, climate change often introduces several stressors at the same time, leading to "multiple stress". At a particular location and time, the temperature, light availability and pH can all drift outside the range optimal for an organism. Sometimes introduced species can also act as stressors – as predators, pathogenic agents, or feeding competitors.

As an additional complicating factor, the various stressors do not always act independently. In some cases the effects can be additive, or even amplified. This amplification does not lead inevitably to immediate death. In many cases the stressors initially only impair the productivity of an organism in some way. Interactions of the weakened organism with its environment, with predators, parasites, competitors, pathogens or reproductive partners are thus altered. These effects can significantly exceed the primary effects of the stressors such as the stress caused by light deficiency. The various linkages are further illuminated in the example of the bladderwrack seaweed described below.

Too many environmental changes at once

The most common stressors on marine ecosystems amplified by climate change include:

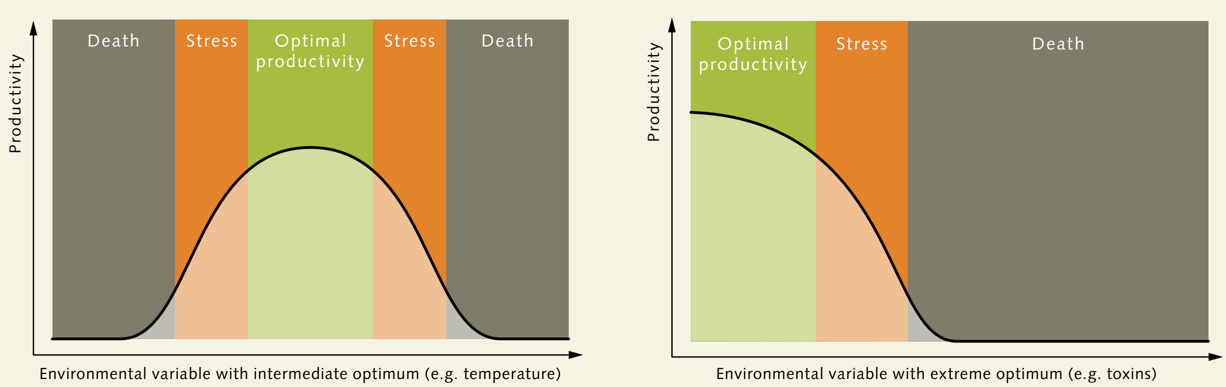
- gradual acidification of seawater, accompanied by inhibition of the calcification process, which is the formation of calcium carbonate by marine organisms (Chapter 2);
- warming of seawater and associated secondary effects, including more pronounced stratification of the water column, increased metabolic rates of the organisms, or changes in the solubility constants, which affect the amounts of certain dissolved substances in the water such as gases or carbonates;
- an increase or decrease in salinity in marginal seas, and the accompanying adverse effects on the ion budgets of living cells (Chapter 2);
- eutrophication, which is an excessive accumulation of nutrients, and other kinds of chemical pollution of seawater. Climate researchers predict increased precipitation rates for wide areas of the Baltic Sea region in the future. Increased rainfall washes more fertilizer from farmland into the sea (Chapter 4);
- changes in near-coastal current and sedimentation processes caused by human construction projects, which, in part, may be carried out as a response to climate change and rising sea levels. These include harbours, breakwaters and dykes (Chapter 3);
- the spread of exotic species into new habitats. The compositions of communities will doubtless be changed as a result of multiple stress. In addition, geographic distribution zones could shift so that species

The origins and impacts of stress

Within its habitat an organism is influenced by various environmental factors to which, as a rule, it is quite well adapted, even under significant fluctuations. This adaptation of the organism to the abiotic conditions in its range, that is, the chemical and physical conditions, has taken place over thousands or even millions of years, over evolutionary time scales. Stress is produced when these environmental variables lie, either temporarily or continuously, outside the range to which the biological system (a cell or species) is adapted. These kinds of stress situations can be generated in various ways:

- when temporary fluctuations in the abiotic conditions occur (for example, seasonal or weather anomalies);
- when pelagic organisms (i.e. free-swimming in the water column), such as planktonic larvae, drift away from the centre of their habitat and colonize the margins of the distribution area where the environmental conditions are not ideal;
- when climate zones shift more rapidly than species can evolutionarily adapt to the new conditions.

Organisms are not always defenceless or at the mercy of change. They are quite capable of adapting to new conditions and responding to stress. Adaptation is possible in three ways. The quickest of these, phenotypic plasticity, can be observed within days or weeks: individuals adjust to new conditions in their habitat by changing their growth form, metabolism, or diet. Of course this is only possible to a limited extent. Relatively rapid adaptations over a few generations are also possible through selective processes. When genotypes exist within a population, i.e. individuals have certain traits that are not immediately apparent but are contained in their genetic makeup, and these individuals are better able to cope with the new conditions than others of their species, then they will assert themselves fairly quickly. The productivity and survival of the population is thereby assured. Evolutionary processes in the classical sense, such as the random occurrence of a mutation that allows survival in the changing environment, are generally too slow in most species with long-lived generations to keep up with the habitat changes caused by climate change.



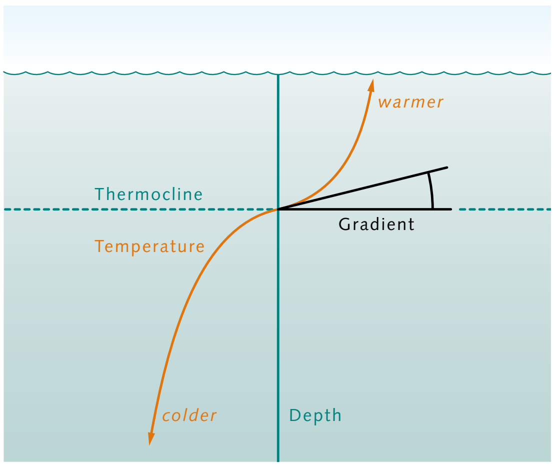
5.1 > Different environmental variables have different effects on organisms. Many plants or animals thrive best at moderate temperatures – the intermediate optimum (left). If it becomes warmer or colder the situation deteriorates. The productivity of the organism declines. The "extreme optimum" follows a different pattern: in a clean environment the organism functions optimally. If toxins spread in the habitat, productivity declines. In both cases the animal or plant experiences stress that can lead to death. If the stress persists for an extended period, then species in the affected area can even become completely extinct.

die out in their native habitats. It is also conceivable that exotic species could become newly established in regions outside their former range.

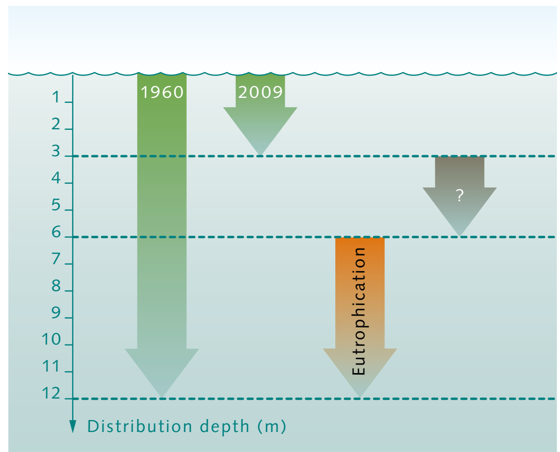
Bladderwrack – a species under constant stress

The bladderwrack, *Fucus vesiculosus,* is a seaweed of temperate latitudes commonly found in the North and Baltic Seas. It primarily colonizes the **intertidal zone**, but can occasionally occur in water depths of up to 12 or even 15 metres. The bladderwrack serves a number of important functions in the ecosystem. It is both a food source for various organisms and an important provider of oxygen. It offers protection for juvenile animals and serves as a **substrate** upon which diverse species can colonize. Its population in the western Baltic Sea has decreased by more than 90 per cent over the past four decades – in many areas it is no longer observed at depths of 12 metres, but only down to 3 metres. Its decline at greater depths has long been attributed to eutrophication – an environmental stressor (Chapter 4). It was presumed that an overabundance of nutrients in the water led to an increased density of plankton blooms, which restricts the amount of light penetration reaching the sea floor. Furthermore, it was assumed that a light deficiency on the sea floor during a plankton bloom would limit the bladderwrack's ability to defend itself against predators. In addition, it appears that under decreasing light conditions the bladderwrack is less able to defend itself against bacteria. But this explanation is inadequate, first because the bladderwrack can store energy and therefore survive darker periods, and second because it can still thrive under very low light conditions. Even considering that increased numbers of organisms such as microalgae grow directly on the bladderwrack's surface under eutrophic conditions, leading to added competition

5.2 > The bladderwrack *Fucus vesiculosus* is widely distributed throughout Europe. It could die out in some areas as a result of climate change.



5.3 > The boundary zone between warm, near-surface waters and the deeper cold waters is called thermocline. The gradient is a measure of how rapidly the temperature changes in the thermocline. A high gradient means rapid changes over short depth intervals.



5.4 > In 1960 the bladderwrack could be found to a depth of 12 metres in the western Baltic Sea; in 2009 only down to 3 metres. The light deficiency caused by eutrophication contributed significantly to its disappearance between 6 and 12 metres – yet it cannot explain its absence between 3 and 6 metres.

for light and food between the algae and the seaweed, it still should be able to survive down to 6 metres. Only below this depth would the energy deficit caused by light deficiency and feeding competition be severe enough to be fatal. So this alone cannot explain why the plant is becoming scarce at depths below 3 metres.

Now it is believed that the decrease in bladderwrack abundance at the relatively shallow depths of between 3 and 6 metres has other causes: For one, the warming of seawater, which can be clearly detected today, leads to a general increase in metabolic rates, so that predators become hungrier and bacterial attacks more intense. In addition, abrupt temperature differences at changing water depths impair the capability to defend against aggressors. In the summer a thermocline is often present, precisely at depths of around 4 to 5 metres. The distinctive temperature change here within a few centimetres of water depth becomes even more pronounced as the water temperature rises. If the depth of the thermocline oscillates up and down, a bladderwrack living at these depths experiences rapid and large temperature fluctuations – which diminishes its defensive capability. Furthermore, a new biotic stressor has appeared in recent years: the red algae *Gracilaria vermiculophylla,* which was introduced from South-East Asia. The habitat requirements of this species are very similar to those of the bladderwrack. The problem is that, unlike the bladderwrack, the red algae can reproduce asexually, which makes it especially prolific. Furthermore, it is more tolerant of fluctuations in local abiotic conditions and also less attractive to predators. And still further, predators of the bladderwrack even use the red algae as a protective cover to hide from their own enemies. Another problem is that chemical secretions from *Gracilaria* diminish the germination potential of *Fucus* eggs.

So *Fucus* is clearly exposed to a number of stressors along with their direct and indirect effects: light reduction, colonization and predator pressure, and competition with algae for nutrition. All of these together hinder its growth and germination processes. The *Fucus* population is thus experiencing an ever decreasing ability to offset its losses from predation and competition. The example of *Fucus* clearly illustrates that, although the direct effects of climate change alone may be minor, they are nevertheless devastating because of changes in the interactions among various organisms.

Disruption to the plankton cycle

> Recent experiments and studies show that climate change – and global warming in particular – is pushing established biological systems off balance. This can have a devastating effect on some organisms. What is most disturbing is that the natural rhythm of the ocean's most important food source, the phytoplankton, is changing.

Essential single-celled organisms

Plankton is a vital food source for life in the ocean. Phytoplankton, algae and cyanobacteria, take up nutrients dissolved in the water, grows, and undergoes cell division. Biomass is thus produced, on which zooplankton such as copepods feed. The zooplankton, in turn, is eaten by fish and their larvae. Plankton therefore plays a key role in the **biogeochemical** cycle of the ocean. Disruptions to plankton development caused by climate change will thus have a critical impact on the functioning of the entire **pelagic system**.

The copepods
Copepods belong to the crustaceans. They are found in both saltwater and freshwater. Although most of these animals are only a few 100 micrometres to a few millimetres in size, they are the most species-rich group of the crustaceans (around 14,000 species), and make up the largest share of marine zooplankton. Copepods therefore represent an important food source for fish and other pelagic animals.

Faltering plankton growth

Plankton predominantly comprises short-lived organisms. As a rule, these reproduce so rapidly that several generations may be produced within a single year. The development of planktonic organisms generally follows a regular annual cycle that begins with a spring bloom of the phytoplankton. At this time the increasing light availability promotes a rapid increase in the abundance of phytoplankton. Only a few weeks after the winter minimum the biomass reaches its annual peak value, following which it undergoes a continuous decrease. This is, for one, because of the zooplankton feeding on the phytoplankton, but also because of large amounts of the dissolved plant nutrients being consumed during the bloom and sinking to greater depths. So the phytoplankton finds ever decreasing amounts of nutrients in the water.

In nutrient-poor and cold marine regions the spring bloom represents the only influx of nutrition for the zooplankton during the year, while in other regions it represents the greatest such influx. So the spring bloom is also very important for the nourishment of fish that feed primarily on zooplankton. The benthic organisms, in turn, also benefit from the large amounts of organic material sinking to the sea floor, the dead remains of both phytoplanktonic and zooplanktonic organisms.

Because the plankton consists of short-lived organisms, it reacts rapidly to physical and chemical changes in the ocean and to fluctuations in nutrient availability. The size of populations can sometimes vary greatly within a few days or weeks. Depending on conditions the actual composition of the plankton assemblage can change, with certain species suddenly becoming predominant. Variations due to climate change have definitely already been observed. Some of these are consistent with expectations. Just like the earlier fruit tree blossom on land, the spring bloom of plankton begins earlier in many marine regions. In addition, the ranges of some planktonic species are shifting toward the poles in response to ocean warming.

One example is the northward expansion of a characteristically temperate-zone copepod, *Calanus helgolandicus*, a small crustacean that is displacing *Calanus finnmarchicus*, a species native to Scandinavian latitudes. Since both species are important sources of food for fish and have similar food requirements, this will probably not have grave impacts on the functioning of the ecosystem. But not all changes in plankton communities are so benign. In some cases warming of the water causes zooplankton offspring to hatch too early and starve. This has been demonstrated in water-tank experiments.

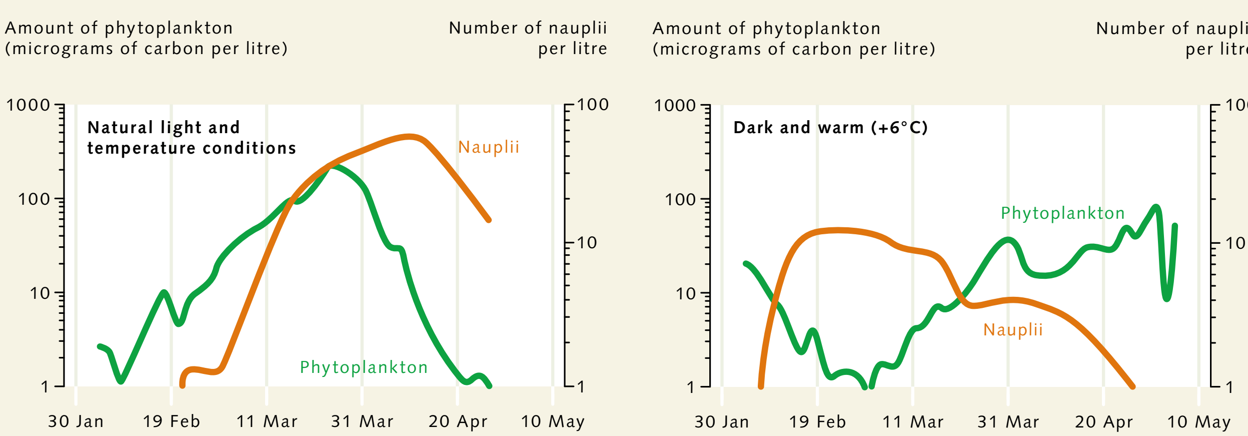
Plankton experiment: Climate change in a tank

Researchers have experimentally investigated the impacts of climate change on the spring bloom of phytoplankton. Tanks measuring 1.4 cubic metres were filled with planktonic organisms corresponding to the developmental stage of the phytoplankton in late winter. The tanks were then exposed to different amounts of light and different patterns of spring temperature development in climate chambers. The experiments simulated the present-day average spring temperature sequence, as well as patterns reflecting warming of 2, 4, and 6 degrees Celsius. The results were impressive. The spring bloom occurred 1 to 1.5 days earlier per degree of temperature increase. An increased light supply amplified this effect.

The zooplankton reacted even more strongly to warming: the copepod larvae, called nauplii, hatched up to 9 days earlier per degree of temperature increase. The consequences of this were disastrous because most of the nauplii hatched before the spring bloom of phytoplankton. There was no food available for them so they starved, and an entire generation was lost.

Not only did the warming cause a shift in the timing of the spring bloom. The total biomass of phytoplankton as well as its composition was also altered – to the detriment of the zooplankton. Under normal conditions large-celled **diatoms** dominated, which are a good food base for copepods. Under warmer conditions the smaller **flagellates** dominated. These, however, are not an optimal food source for copepods. The implications are obvious: the animals grow more slowly; they produce fewer eggs and therefore fewer offspring.

But the warming of seawater can have further negative consequences beyond those for the food chain "phytoplankton – zooplankton – fish". It also impacts on the storage capacity of the greenhouse gas CO_2 in the ocean, the "biological CO_2 pump" (see text box on the following page). Under warmer conditions the respiration of zooplankton and bacteria is enhanced, which produces CO_2. This means that the CO_2 initially taken up by phytoplankton is released back into the surface water. The proportion of CO_2 that remains fixed in the biomass and sinks to the sea floor as organic material, to finally be incorporated as carbon in the sediments, is therefore reduced. This is a serious problem because it represents a fatal feedback mechanism for climate change: Due to climate change a natural process is weakened that has until now been able to extract a portion of the anthropogenic CO_2 that is so harmful to the climate.



5.5 > Phytoplankton reproduction (green line) normally begins with the increase in light availability around the end of winter, before the hatching of the zooplankton larvae (nauplii, red line). This ensures that there is enough food available for the zooplankton. But if less light is available and the water is 6 degrees warmer, the zooplankton hatch before the phytoplankton bloom, and the larvae starve. This is an especially disturbing scenario because it is exactly what researchers are predicting for the Baltic Sea: less light due to increased cloud cover with an accompanying rise in water temperatures due to climate change.

The CO_2 pump in the ocean

In oceanic biogeochemistry, the transport of organic carbon via sedimentation down to the deep water and finally to the sediments of the ocean is referred to as the biological carbon dioxide pump. Initially, carbon dioxide is taken up by phytoplankton during photosynthesis and converted into organic carbon. However, most of this carbon is released again during respiration, either by the phytoplankton itself or by zooplankton and bacteria, which feed on phytoplankton or its dead remains.

Near-surface respiration cycles carbon dioxide back into the water, from where it can return to the atmosphere. Only a minute fraction of the organic matter produced in the surface ocean sinks down to waters below the permanent thermocline. These waters of great oceanic depth do not get into contact with the atmosphere on a seasonal basis. Only this fraction of the primary production of organic carbon acts as a drain on atmospheric carbon dioxide and can be termed the CO_2 pump.

5.6 > The mauve stinger, *Pelagia noctiluca* whose painful sting is normally not deadly to humans, has become increasingly abundant in the Mediterranean Sea in recent years.

Mounting threat of harmful algal blooms

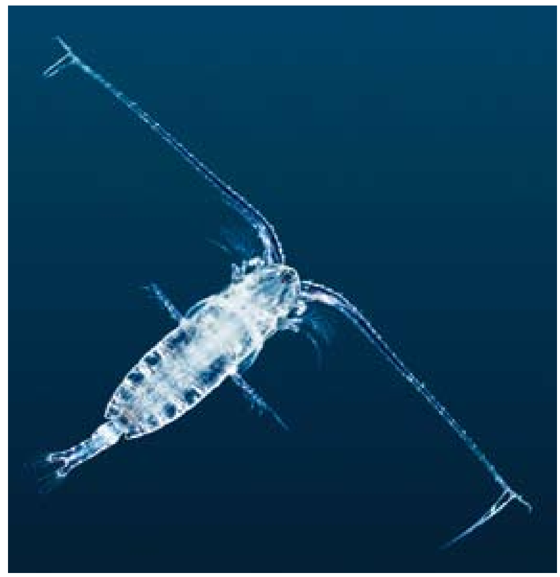
Harmful algal blooms (HABs) are massive growths of toxic or otherwise harmful phytoplankton. HABs are becoming ever more frequent worldwide. It is not yet known, however, why this is. Eutrophication, the increased concentration of nutrients in the water, is considered to be the main cause, but climate change also appears to play a role. Harmful algal blooms normally occur in the summer months when the water column is thermally stratified. A warm, light surface layer overlies a colder, heavier deep layer. The warmer the surface water, the more pronounced the temperature gradient is at the thermocline between the layers.

A strong temperature gradient prevents water masses from mixing at the thermocline, because the density difference between the cold and heavy water, and the warm and light water, acts as a barrier. Nutrients from greater depths are therefore prevented from circulating to the surface. So when the nutrients near the surface have been consumed by phytoplankton growth, there is no source of replenishment. The vertical barrier between a zone with enough light and insufficient nutrients, and a zone with insufficient light and abundant nutrients, which is characteristic of the summer, is thus reinforced.

Relatively large mobile phytoplankton species have an advantage here. With vertical migration they can move back and forth from the deeper nutrient-rich water to the shallower layer penetrated by light where photosynthesis is carried out. Such species include numerous dinoflagellates and, especially in the Baltic Sea, cyanobacteria, which can regulate their specific gravity to rise and descend like a diver. One problem with this is that both groups include numerous toxic species. If mussels consume these organisms, then the mussels become dangerous or even lethal to humans.

The planktonic organisms may also release some of the toxins directly into the water. In some cases these are even detectable in aerosols, small droplets wafting in the air that are produced by breaking waves in the surf. An especially notorious culprit is the dinoflagellate *Karenia brevis*, whose periodic blooms off the coast of Florida cause mortality of fish, poisoning of mussels, inflammation in swimmers and, in extreme cases, asthma attacks in visitors to the beach. Experts attribute the increased incidence of these blooms to general climate warming.

5.7 > The dinoflagellate *Karenia brevis* occurs primarily in the Gulf of Mexico. Its nerve poison, Brevetoxin A, can lead to inflammation and asthma attacks in humans.



5.8 > Small crustaceans like this Calanus-species are widely distributed in the oceans and one of the most important food sources for fish.

As mentioned, there are also numerous toxic groups of cyanobacteria. Investigations so far have focused on cyanobacteria that live in freshwater – especially in waters that are used as sources for drinking water or where bathers are in danger from cyanobacteria. But toxic strains of various cyanobacteria such as *Nodularia spumigena* have also been verified in the Baltic Sea.

Trouble with jellyfish

Beside more frequent HABs scientists are also observing explosive growth of jellyfish populations. The impacts of such proliferation are quite well known: injured swimmers, clogged fish nets, feeding competition for fishes, and predation of fish eggs and larvae. The possible causes of these burgeoning populations are somewhat controversial. One significant problem, presumably, is overfishing. Fish that feed on zooplankton are in feeding competition with the jellyfish. If the fish are absent, then the jellyfish have an abundance of available food. It is also known that jellyfish are more robust than many species of fish, especially in the sense that they can tolerate much lower oxygen concentrations. Oxygen deficiencies in the oceans, in turn, occur increasingly as a result of eutrophication. More biomass is created because of eutrophication. As a result, more organic material sinks into the deep water where it is decomposed by oxygen-consuming microorganisms. The result is a general decrease in oxygen. Climate change, which causes warming of the ocean surface, can exacerbate this situation. The warming slows down exchange processes because the oxygen-rich surface water mixes less with the colder deep water. Only small amounts of the oxygen consumed by microorganisms at greater depths are replaced. Increasing jellyfish scourges could therefore be a result of combined stressors. Climate change will therefore lead to a restructuring of the pelagic biocoenoses, which will disadvantage the classical food chain "phytoplankton – zooplankton – fish". Jellyfish, on the other hand, will benefit from that. Presumably overfishing and eutrophication of coastal waters will have additional synergistic effects that will worsen the situation.

Species encroaching on alien territories

> For a long time now people have been transporting organisms from one part of the world to another – sometimes unintentionally, but in some cases deliberately. Entire ecosystems have been transformed as a result. Climate change could exacerbate this problem because warmer waters may favour the establishment of immigrating species.

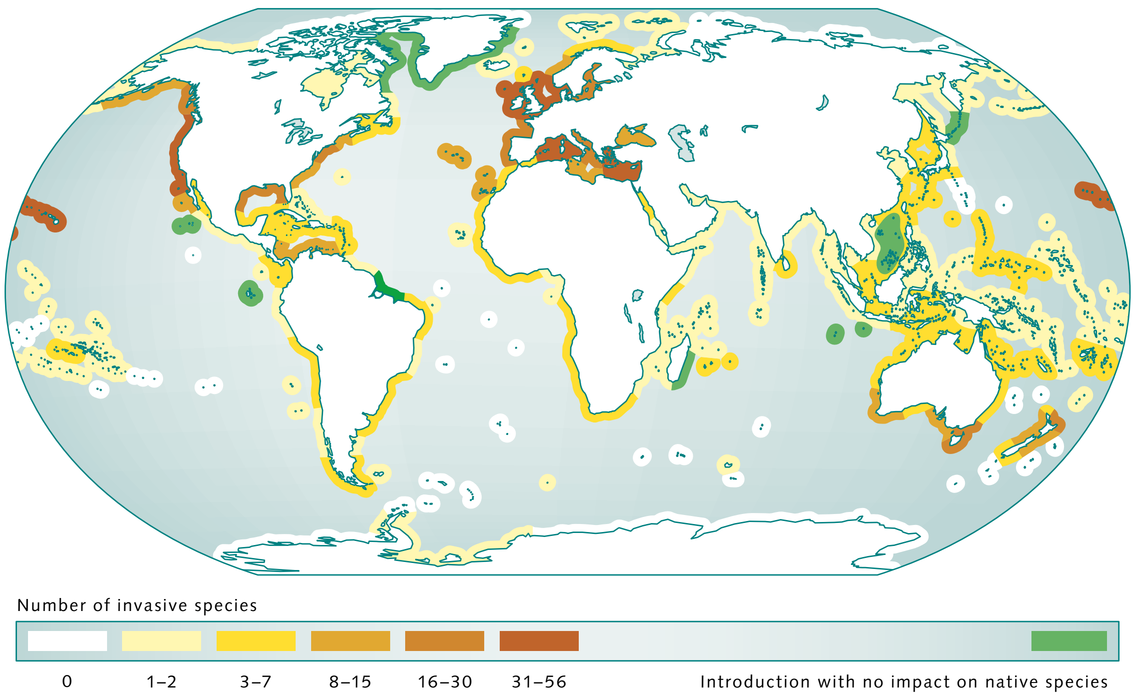
Causes of the dispersal of marine organisms

Since humans began to sail the seas, other species have been travelling around the globe with them. These are not limited to useful plants and animals, nor to pests such as pathogenic agents or rats, but also include significant numbers of marine organisms. Historical records and archaeological finds show that the sailing ships of the early explorers were colonized by up to 150 different marine organisms that lived on or in the wooden hulls, or used the metal parts such as anchor chains as a **substrate.** If the growth became a nuisance, the organisms were scraped off while at sea. In other cases the organisms remained on the rotting hull of a ship when it was scrapped and could no longer be repaired. It is hardly surprising then that many wood-boring species such as the shipworm *Teredo navalis* are found around the world today. However, it is no longer possible to determine whether these species were already cosmopolitan before the European voyages of discovery. It is common knowledge, however, that humans have contributed to the dissemination of many species. Increasing numbers of marine organisms are now transported over the oceans as a result of globalization, trade and tourism. It is estimated that the water in ballast tanks used to stabilize freighters is alone responsible for transporting tens of thousands of different species between geographically-distant regions. Most of these exotics die during the trip or at the destination, while only a small fraction are able to successfully reproduce and form a new **population**. But a study of six harbours in North America, Australia and New Zealand has shown that, in spite of all obstacles, one to two species were able to successfully establish themselves per year at each of the sites investigated.

Geographical barriers can also be overcome by canals. Over 300 species have already migrated through the Suez Canal from the Indian Ocean into the Mediterranean Sea. In addition, rivers and other waterways are responsible for species exchange, such as between the Baltic Sea and the Black Sea. Another important cause for the dispersal of marine organisms is the trade of living marine organisms for aquaculture, aquaria and the food industry.

Specialists divide the coastal waters of the world into a total of 232 ecoregions which are either separated from each other by geographical barriers such as land bridges, or are clearly different from each other with respect to certain environmental characteristics such as salinity. According to a report issued in 2008, new species have already been introduced by humans to at least 84 per cent of these 232 ecoregions.

Investigations in the North and Baltic Seas show that at least 80 to 100 exotic species have been able to establish themselves in each of these areas. In San Francisco Bay, 212 foreign species have already been identified, and for the Hawaiian Islands it is assumed that about a quarter of the marine organisms that can be seen without a microscope have been imported. Relatively little is known about the distribution of microorganisms or other plants and animals that are hard to identify. Species records are also sketchy for many marine regions where access is difficult. Experts assume that in future exotic organisms will have better chances to establish themselves in some regions due to climate warming. Organ-



5.9 > Invasive species thrive particularly well in certain coastal ecoregions of the Earth. Most affected are the temperate latitudes. Regions where immigrants do not encroach on or displace native species are shown in green.

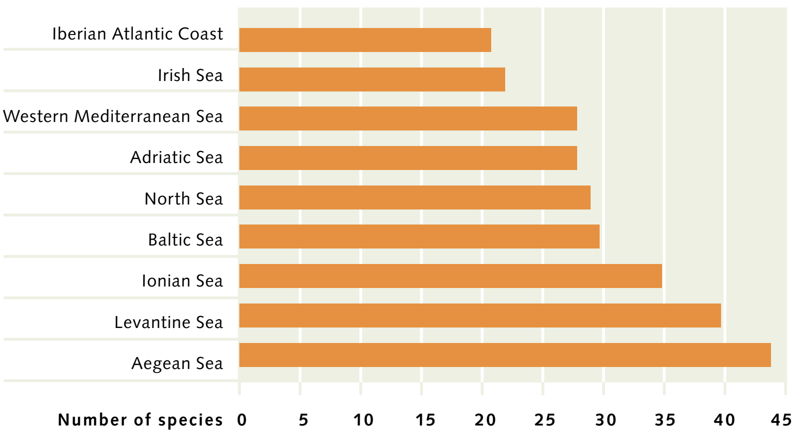
isms from South-East Asia, for example, which prefer a warm climate, could take root in regions that were previously too cold for them.

New species alter biodiversity

Many exotic species infiltrate the native flora and fauna without dominating them, thus increasing the diversity of the species association. Natural catastrophes can completely destroy habitats and be fatal to entire species communities. In these cases a completely different species assemblage develops in the affected regions through the influx of new species. An example of this is the Baltic Sea which was formed after the last Ice Age – that is, in the relatively recent geological past – and is only around 7000 years old in its present form as a brackish sea. One indigenous species alone evolved there, the alga *Fucus radicans.* All other species native to this area today migrated from habitats such as the North Sea or the White Sea. The immigration of species from other regions is thus not always problematic nor caused by human activity.

Since Christopher Columbus travelled to America in 1492, exchange between distant parts of the Earth has steadily increased. It has thus become more likely that species will encroach on ecoregions that are far removed from their natural areas of origin. Sometimes the new species create problems. They may displace a number of native species and thereby lead to a decrease in biodiversity. This is especially likely to occur if they have no natural enemies in the new location. For example, within only 15 years of its initial discovery in Monaco the Australian green alga *Caulerpa taxifolia* had overgrown 97 per cent of all the suitable ground between Toulon and Genoa, and had spread into the northern Adriatic and as far as Sicily. The alga produces a repellent substance that makes it unpalatable to most herbivores. There are organisms that feed on *Caulerpa* and have adapted to the repellent, but these species are not present in the Mediterranean Sea.

The Asian algae *Sargassum muticum* and *Gracilaria vermiculophylla* also formed practically monospecific stands in some coastal areas after their introduction to



5.10 > The number of ecologically or economically problematic imported species in the most affected marine regions of Europe.

Europe. The northern Pacific seastar *Asterias amurensis,* on the other hand, established itself in south-eastern Australian waters in the mid-1980s. Only 2 years after it was first detected in Port Philipp Bay, a large bay off Melbourne, more than 100 million specimens were estimated. This starfish too found practically no natural enemies in its new habitat, enabling it to decimate stocks of native starfish, mussels, crabs and snails. The biomass of the starfish eventually exceeded the total amount of all commercially fished marine animals in the region.

Cases of newly imported species displacing native species have been documented in 78 per cent of the 232 coastal ecoregions of the world. Many cases have been reported from the temperate latitudes in particular, those regions of the Earth where it is neither extremely hot nor extremely cold. With the exception of Hawaii and Florida, the 20 coastal ecoregions most strongly afflicted by invasive marine organisms are located exclusively in the temperate North Atlantic and North Pacific or in southern Australia, and nine of these regions are in Europe. Some places, like San Francisco Bay, are now dominated by non-native species. There, the encroaching species are often considered to be a threat to marine biodiversity, although so far not a single case is known in which a species introduced from outside has caused the extinction of native organisms.

Economic impacts of alien species

Introduced marine organisms can inflict economic losses on fisheries. The warty comb jelly *Mnemiopsis leidyi*, native to America, brought about a collapse of the coastal fisheries in the Black Sea 25 years ago, an area already greatly weakened ecologically at that time due to overfishing and eutrophication. Specimens that were probably introduced with ballast water were first sighted there in 1982. The jellyfish spread rapidly and ravaged native species, especially fish, by feeding on their eggs and larvae. The commercial fishery harvest decreased by around 90 per cent. In 1989 counts of 240 specimens per cubic metre of water were made, the greatest concentration of *M. leidyi* in the world. Only the unintentional introduction of another comb jelly, *Beroe ovata* – a predator – was effective in repelling the population and allowing a comeback of the fish population. Invasive species are also causing problems on the eastern coast of North America. There the European common shore crab *Carcinus maenas* caused a decline in the clam fishery harvest. In some cases invasive marine organisms can even present a hazard to human health. One example of this is illustrated by microalgae of the genus *Alexandrium*, which produce a nerve toxin. Species of *Alexandrium* have recently been discovered in many coastal areas where they probably did not exist just a few decades ago. Such phenomena can obviously have extremely negative effects on tourism.

Introduced species are not only transported unintentionally in the ballast water of ships. Entrepreneurs often import marine organisms from other countries to non-indigenous habitats for aquaculture breeding. This may provide short-term commercial profits, but also poses the risk of imported species displacing native organisms, leading to intermediate- or long-term economic or ecological damage. Studies have shown that at least 34 per cent of the 269 introduced marine organisms investigated were deliberately imported for aquaculture breeding. One example is the Japanese giant oyster *Crassostrea gigas*, which has taken up residence and established itself in at least 45 ecoregions. Between 1964 and 1980 in particular, large amounts of young oysters, called spat, were imported into Europe. In many cases the ecological impact was devastating. In North America and Australia the giant oyster forms dense colonies that displace native species. Furthermore, they frequently cause eutrophication of the coastal waters because they excrete indigestible particles agglutinated with mucus, which cause the additional organic contamination of the water. The presence of giant oysters in France has also led to pollution of the waters. In addition, a decline in the zooplankton as well as larger animals has been observed. In the Netherlands and Germany the giant oysters tend to settle on blue mussel banks. This is threatening an important species of traditional fishery.

It is assumed that besides the giant oyster at least 32 additional species have been unintentionally introduced into the North Sea, including the common Atlantic slippersnail *Crepidula fornicata* and the alga *Gracilaria vermiculophylla*, both of which have proven to be ecologically problematic. In order to avoid this kind of hazard in the future, a standard assessment system would be helpful. This could be used to estimate the potential of a species displacing other organisms. In addition, it could be used to weigh up the advantages and disadvantages of introducing an external species to a certain habitat.

By comparing problematic and harmless imported species, experts have been trying for some time to identify characteristics that indicate a high potential for displacement of the native species. For example, some algal species float while others sink. Whether the species drifts and can thus easily disperse depends essentially on this factor. But so far it has proven difficult to draw conclusions about the displacement potential of a species based on individual traits. Perhaps it will never be possible to make confident predictions about the behaviour of a species in a new location, because numerous critical factors are at play. This prediction is further complicated as a species establishes itself in a new habitat over an extended time period, living through numerous phases. After an initial expansion phase, during which a species thrives, there usually follows a decline before the species has completely adapted to the new habitat. Before the displacement potential of a species can be confidently estimated, it has to be known which phase the species is in at a given time. But that is very difficult to determine.

Combating the introduction of species

In 2004 the IMO passed a convention to deal with ballast water treatment. The first countries to sign the agreement, together representing around a quarter of worldwide sea traffic, committed to installing ballast-water treatment systems in their seaports and to carrying out regular inspections of ballast water. From 2016 onwards such systems will also be mandatory on board ships. International cooperation is also strengthened through initiatives of the ICES, which agreed in the mid-1990s on a code of conduct for the handling of exotic species in aquaculture, and recommended quarantine procedures, among other measures. The existence of the European common market has made the exchange of species between member states easier. The commercial transport of oyster larvae, as an example, is now practically equal in significance to ballast water as a cause of species introduction within the EU. At the same time, the import of oysters from non-EU regions has largely been eliminated. International cooperation within the EU has, on the one hand, improved protections against the import of species from non-European bioregions, but on the other hand it has exacerbated the exchange of species between bioregions inside the EU.

Can future introductions be avoided?

Caution is necessary when dealing with foreign marine organisms because species introduction is largely irreversible. Any kind of mechanical removal of established species is virtually impossible. Many species go through microscopic dormant or larval stages during which they are free-floating. During such phases the organisms defy all efforts to control them. It may be possible to introduce natural enemies to the new habitat, but then these organisms could later become a threat themselves. Government policy and environmental management will therefore have to take a stronger stance to control the primary causes of species introduction. It is important that this includes uninterrupted monitoring of aquaculture and ballast water, for example. Unilateral efforts at the national or local levels, however, will hardly be effective. International strategies practiced by all states bordering an ecoregion have greater chances of success.

Marine biodiversity – a vital resource

> For a long time the significance of biological diversity in the world's oceans was unclear. It is now known to play a vital role in maintaining the functionality and productivity of ecosystems. It also makes habitats more resilient to environmental change. But the well-balanced species communities are becoming increasingly unstable.

The rapid disappearance of species

Biological diversity in the oceans has decreased dramatically since industrialization began in the 19th century. The primary causes for the losses include the destruction of habitats by trawler fishing, pollution and eutrophication of the seas, as well as the steady progress of climate change. Biological diversity is probably declining more rapidly than ever before in the history of the Earth. But at the same time, only a small fraction of the species in the deep sea and polar oceans have so far been identified, making the loss of species in the oceans much more difficult to record and evaluate than on land.

Why is marine biodiversity important?

Every ecosystem performs certain functions that are critically important for organisms. One of the most important functions of marine ecosystems is the production of plant biomass from sunlight and nutrients (primary productivity), which represents the basic food source for all life in the ocean, and ultimately also for humans. Around half of the worldwide primary productivity is achieved by microscopically small plants, the phytoplankton, which grow and divide in the ocean. Another function performed by ecosystems is the creation of habitats, or structures, in coastal ecosystems. For example, macroalgae, seagrass and corals form large undersea forests, meadows or reefs that provide habitats for many other species such as molluscs, crustaceans and fish. Kelp forests and seagrass meadows in the Baltic Sea are vital **habitats** for the fry and juvenile fish that grow up here before swimming into the open ocean as adults. Gastropods and small crustaceans likewise feed on microalgae growing on the kelp or seagrass. They thereby ensure that the structure-forming plants are not smothered, and are allowed to grow – that is their contribution to the ecosystem. The molluscs and crustaceans that feed on microalgae are the basic food source for larger predatory crustaceans and fish.

Seagrass and kelp itself have relatively long life spans because they are poor food sources for grazing crustaceans and molluscs. They store nutrients in their biomass for a long time, including nitrogen and phosphorous compounds transported by rivers from agricultural areas to the sea. Seagrass and macroalgae thus function as a kind of biological purification system in coastal ecosystems.

Scientists have addressed the question of whether the dramatic decline in biological diversity has consequences for the stable functioning of ecosystems. After 10 years of intensive study, the answer is clear – yes, it does. Experiments in coastal ecosystems, particularly seagrass meadows and kelp forests, have shown that biological diversity in the oceans is essential for maintaining the ecosystem functions described above. Species diversity was decreased in various ways during these experiments in order to compare the ecosystem functions of species-rich with species-poor areas. In one field experiment, for example, the number of seaweed species was artificially reduced by removing some at the beginning of the growth period. The total algal biomass in this species-poor area did, in fact, decrease, thereby resulting in a decline in the food for consumers as well as the number of available **habitats**. In another experiment, the number of grazing

5.11 > Hundreds of fish species live in kelp forests like this one off California. These include the yellowtail rockfish or "greenie" *Sebastes flavidus.*

species that feed on the microalgae growing on seagrass was reduced. It was found that the species-poor grazer communities consumed fewer microalgae than species-rich communities. The shortage of grazing species resulted in a slower growth of seagrass because the increased growth of microalgae repressed photosynthesis in the seagrass.

These two experiments indicate that a decrease in biological diversity has a negative impact on the structure of the habitat, regardless of whether the number of species of producers (macroalgae) or consumers (grazers) is reduced.

How does biological diversity work?

Different species have different physical and biological requirements. It is precisely these that explain the positive effects of biological diversity. There are some algal species that grow optimally in strong light while others prefer lower light conditions. This means that some species of algae grow toward the light and form a crown like that of a tree, while other forms grow better in the shadow beneath them. This has two ramifications: first, the two forms can live together without one depriving the other of its needs, and second, they make optimal use of the available light. Together they produce more food for other species than would one form alone. This complementary use of available resources, the so-called "complementarity effect", is an important positive characteristic of biological diversity.

On the other hand, a particular ecosystem function such as grazing on seagrass is often performed by individual, very efficient species. For example, isopods and gastropods, two invertebrates that feed on algae, each have different nutritional preferences. Grazing gastropods have a strong rasp-like tongue which they use to graze on thin layers of microalgae, while isopods prefer the larger forms of filamentous algae. If the algal flora on

Kelp forests
Dense forests of algae where kelp is predominant are called kelp forests. These are characterized by long, thin, brown and red algae that can grow up to several metres long. Kelp forests mainly occur off the west coast of America, the coast of Argentina, the west coast of Africa, and off Australia and New Zealand. Kelp forests are unique ecosystems with characteristic species associations.

blades of seagrass is dominated by thin growths of microalgae, then the seagrass is mostly grazed by the gastropods. If the water has a higher nutrient content, then fibrous algal forms predominate, and isopods work to keep the seagrass free of algae. Which of these two varieties of grazer performs this job depends on the ambient environmental conditions. If an ecosystem function is carried out primarily by a single species rather than several, it is referred to as the "selection effect". The particular environment selects, so to speak, the current optimally functioning species.

Not only is the number of species important. Also significant is how many individuals of each species are present, or which species is predominant. Because of the selection effect, natural communities are usually composed of a few predominant species and a larger number of species with fewer individuals. Under stable environmental conditions, ecosystem functions, such as the creation of plant biomass, are often sustained by predominant species with optimal traits. The numerous but less abundant species play a subordinate role in these functions. But if the environmental conditions change, they are often called to task. A previously unimportant species can suddenly become predominant.

In the oceans also, a location often has only a few predominant species. There are even extreme cases where a single species prevails over all others. These ecosystems include seagrass meadows and kelp forests. In these cases biological diversity is achieved not by the abundance of species, but through the genotypic diversity of seagrass plants within a single species. Although the plants all belong to the same species, there are hidden differences in their genetic makeup.

Where in other situations species diversity sustains the ecosystem, in the seagrass meadow the genotypic diversity fills this need – that is, the invisible genetic differences between individuals of the same species. In fact, in seagrass meadows where several different genotypes were experimentally planted, the result was a greater density of shoots and a greater total biomass. The number of grazers also increased. So because of increased genotypic diversity, the general ecosystem function of biomass production was enhanced. More seagrass was present and there was an increase in food availability for predatory fish due to the abundance of grazers. Even the ecosystem's ability to resist certain disturbances and environmental changes can be improved through genotypic diversity. In one case a seagrass area with high genotypic diversity recovered after an extreme heat wave more quickly than areas with lower diversity.

In a world experiencing climate change the diversity of less abundant species or genotypes will presumably become increasingly important. These represent a kind of potential "biological insurance" for the sustainability of ecosystem functions. They may possess as yet unknown traits or genetic information that would make them capable of adapting to the new environmental conditions, and therefore be more productive and resilient than the original predominant species or genotypes.

To what extent is biodiversity under threat?

Because of rapid changes in water temperature, salinity and nutrient concentrations, and due to overfishing, habitat destruction and the introduction of foreign species, global biological diversity in the oceans is rapidly declining. There is no doubt about this: the disruptive forces are cumulative and will cause further species to disappear. This will then cause a decrease in the stabilizing function of the formerly diverse communities, with potentially hazardous results – habitats that cannot perform their ecosystem functions, or that lose their resilience. Coral reefs, for example, with their great biological diversity, are being transformed by overfishing and nutrient inputs into species-poor habitats where only a few algal species dominate. Too few reef fish remain to keep the corals free of algal overgrowth, so that new coral larvae have difficulty establishing themselves.

The European bladderwrack forests, in turn, are being displaced by species-poor communities predominated by filamentous algae. Filamentous algae are a poor habitat for juvenile fish and many other organisms. For one thing, they produce less oxygen and for another, they only store nutrients for a short time because, in contrast to bladderwrack forests, they are relatively short-lived, and are a favourite food for gastropods and crustaceans. This is further exacerbated by the fact that the filamentous algae and massive phytoplankton blooms resulting from higher nutrient concentrations effectively block light from the new bladderwrack seedlings. As a result, their growth is severely hampered.

The disappearance of a species that provides an important ecosystem structure, in this case the bladderwrack, can alter the environmental conditions and thus also the habitat to the detriment of other species. One important eventual consequence is the further decline of biological diversity, so that in the future the ecosystem can no longer perform its function.

Conclusion

Impacts and repercussions

Global climate change will inevitably lead to more or less simultaneous changes in numerous environmental variables during the coming decades and centuries. How strongly individual species and communities are affected by these changes depends on a variety of factors. It is not yet possible to estimate to what extent the living conditions in various marine ecosystems will change regionally. Antarctic planktonic algae could actually benefit from the warming of seawater, just as freshwater species in the eastern Baltic Sea could benefit from a salinity decrease in their ecosystem. In some habitats, the introduction of foreign species could even increase the species diversity for a time. In most cases, however, a geographical shift of environmental parameters will lead to a stress situation that exceeds the tolerance of some organisms. For example, due to future warming, the bladderwrack, which is adapted to cold water, will be stressed beyond its tolerance limits at the southern margin of its distribution off Portugal.

This abiotic stress would also be intensified if the change occurred more rapidly than the species could adapt to it. Species that cannot adapt to the abiotic changes will have to retreat to more favourable habitats in order to survive. But if they cannot spread rapidly enough or far enough, or cannot assert themselves in their new communities, they will die out. In both cases a local displacement of species can be expected. Sensitive species will disappear while opportunistic, more adaptive species will become more abundant. These will also include many introduced, alien species.

A restructuring of the species makeup of a community can eventually change the functionality of the community. Which ecosystem functions the marine communities perform in the future, whether the existing communities perform them better or worse, whether functions performed in the past completely disappear or just shift seasonally or spatially, all of this depends on whether the ecological functions of a disappearing species can be taken over by the species present or those newly introduced. In individual cases ecosystems may be able to cope with the regional changes of the species community, for example through immigration. But from a global perspective, species will be lost and ecosystems will undergo fundamental change.

The potential consequences of the loss of a species are impressively illustrated by the classic example of the sea otters native to kelp forests. Sea otters feed, in part, on sea urchins, which eat kelp. Because in the past sea otters were extensively hunted in some areas, sea urchin populations burgeoned, leading to the widespread destruction of kelp forests. Consequently not only were habitats changed, but even the near-coastal currents were altered in some areas.

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