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Biological Sciences review

Marine Biology

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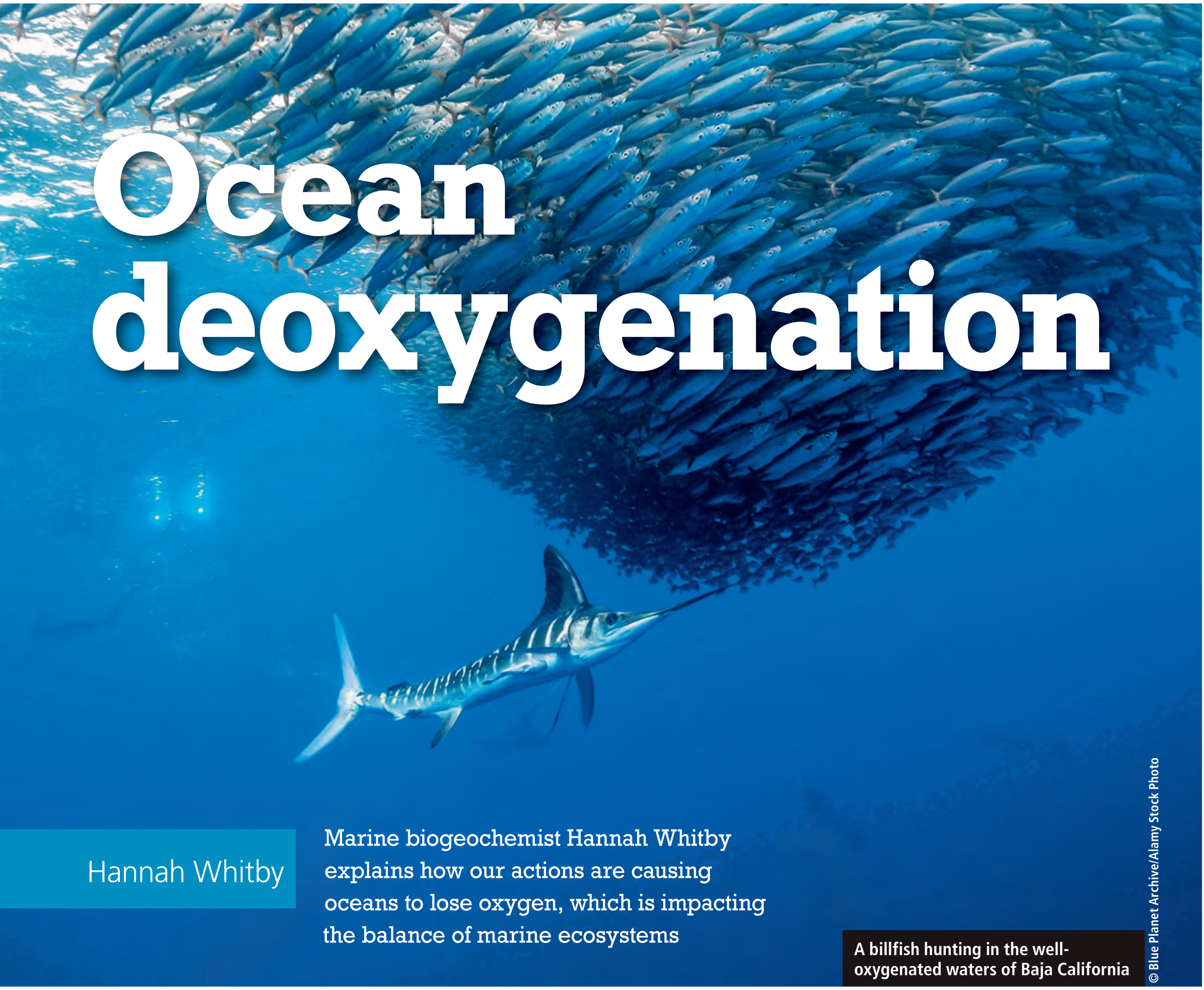
Ocean deoxygenation

Hannah Whitby

Marine biogeochemist Hannah Whitby explains how our actions are causing oceans to lose oxygen, which is impacting the balance of marine ecosystems



A billfish hunting in the well-oxygenated waters of Baja California

EXAM LINKS

AQA Energy and ecosystems
OCR A Ecosystems; Populations and sustainability
OCR B Management of the environment; The impact of population increase
Pearson Edexcel A On the wild side; Biodiversity and natural resources
Pearson Edexcel B Ecosystems
WJEC Eduqas Population size and ecosystems; Human impact on the environment

The ocean is the largest biome for multicellular organisms on Earth. It is the habitat with the highest faunal biomass as well as the greatest number of individual organisms. However, the oxygen-depleted zones in our oceans are expanding and the number of coastal dead zones is increasing. This threatens all aerobic marine life, and people who depend on the ocean for nutrition and livelihood. Ocean deoxygenation decreases biodiversity, shifts species distributions, displaces or reduces fishery resources and expands **harmful algal blooms**.

The balance of marine life has already been altered – deoxygenation favours some species over others. Some organisms, such as certain species of microbe, jellyfish and squid, fare quite well in low-oxygen waters and their numbers are on the rise. Large fish, however, such as tuna, swordfish and sharks, cannot cope without well-oxygenated water, showing stress responses and even suffering physiological changes, which can lead to issues such as infertility. Changes in the distributions of fish species can have significant negative socioeconomic impacts, and disrupt the ocean's food-provisioning ecosystem services.

What aerobic organisms need

The concentration of oxygen (O_2) in seawater determines whether that water is able to support the life of aerobic organisms. Water with an oxygen concentration below $6\,mg\,dm^{-3}$ is considered oxygen deficient. Seawater with an oxygen concentration below $2\,mg\,dm^{-3}$ is considered hypoxic, and below $0.5\,mg\,dm^{-3}$, anoxic.

Box 1 Processes that impact oceanic dissolved oxygen concentrations

Dissolved oxygen concentrations are quite consistent throughout the 'mixed layer' of the ocean – the upper layer that is homogenised by wave action (Figure 1.1). Below the mixed layer and the euphotic zone, when there is no longer adequate light for photosynthesis, oxygen concentrations quickly decrease. At these mid-depths are regions known as 'oxygen minimum zones' (OMZs). In deeper waters the oxygen concentrations tend to be slightly higher, with dense, cold, oxygen-rich water transported from the poles.

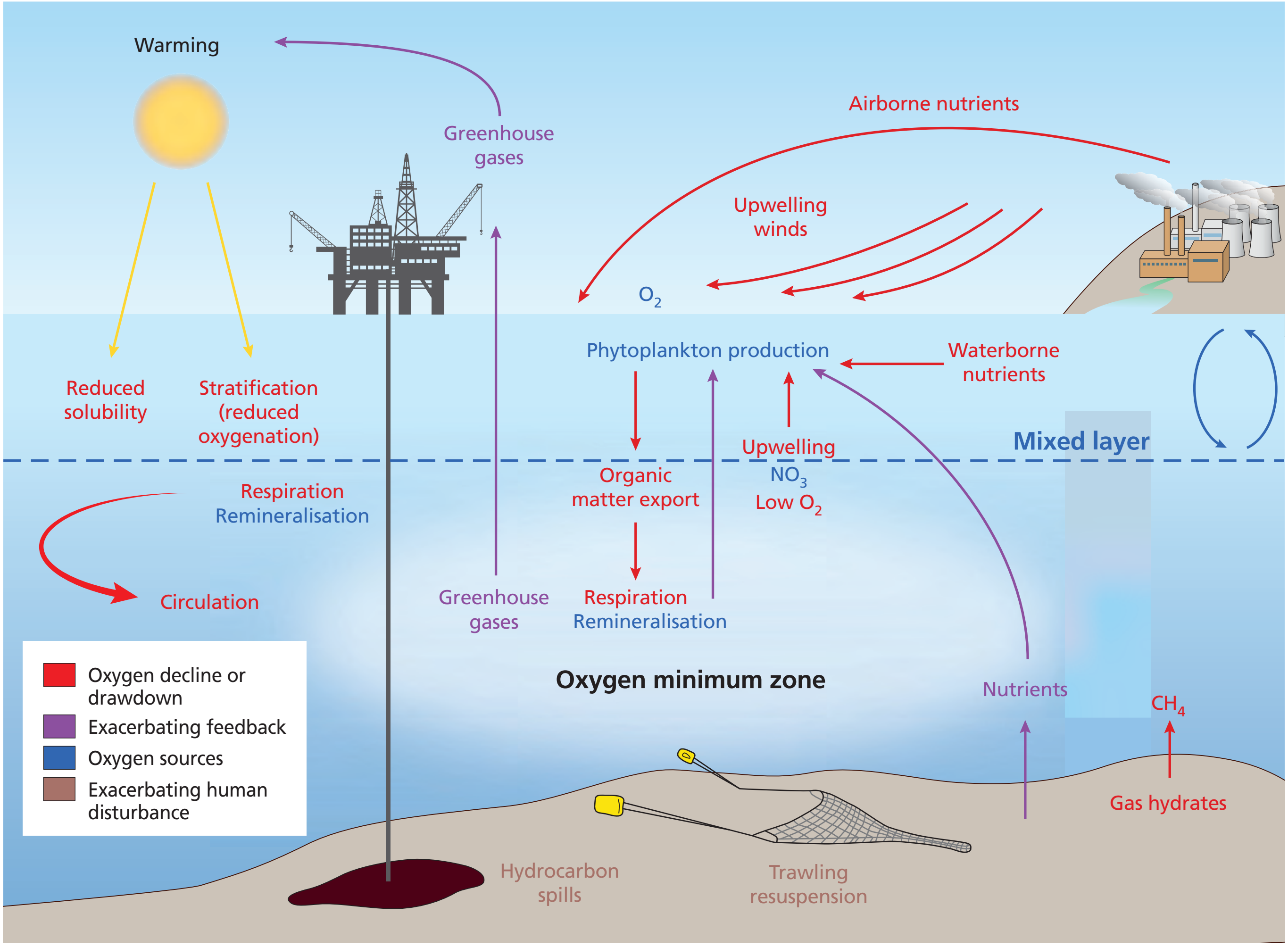


Figure 1.1 Processes affecting ocean oxygen content

While there are some exceptions, such as a few tiny, mitochondria-lacking animals, most organisms cannot survive in anoxic conditions. However, the size, intensity and frequency of anoxic regions around the globe are increasing with climate change. Anoxic regions are often referred to as dead zones, because most marine life either dies or leaves the area. Habitats that would normally be teeming with life become biological deserts.

As temperature and salinity increase, the solubility of oxygen – how much oxygen can dissolve in water – decreases. In contrast, oxygen solubility increases with increasing pressure at depth. Cold, deep waters can therefore hold more oxygen than warm, shallow waters. However, oxygen concentrations tend to be highest in upper waters (~200 m) and diminish with depth. This happens because the main inputs of oxygen to the ocean are from exchange with the atmosphere and photosynthesis, which requires light, and so can only happen in sunlit waters (see Box 1).

In contrast, the process of aerobic respiration, which consumes oxygen, does not require sunlight. Since aerobically respiring organisms live throughout the water column, oxygen is removed via respiration at all depths. When the supply of oxygen from the surface is lower than the use of oxygen in deeper water, oxygen becomes depleted.

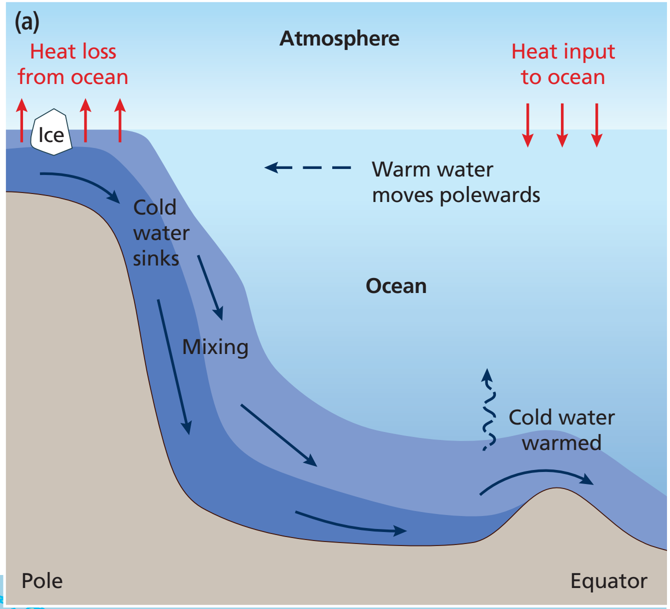
Temperature plays a key role in controlling oxygen solubility. At cool high latitudes, near the poles, surface water oxygen concentrations can be around 350 μmol dm^{-3}, compared with around 200 μmol dm^{-3} at tropical low latitudes. Gases can therefore enter the water in one location, get transported long distances by ocean currents, and then be released in another region as conditions change. This means that the oceans can act as either a sink or a source of gases. The transport of water around the globe

Box 2 Water circulation in the oceans

In the Arctic and North Atlantic Oceans, around Greenland and off the coast of Canada, very cold, dense, oxygen-rich water at the surface meets warmer water from the tropics. As they meet, density differences cause the cold water to sink below the warm water, forming 'deep water' (see Figure 2.1a).

This cool, oxygen-rich deep water is then transported along the ocean conveyor belt (see Figure 2.1b), providing a very important oxygen source to the bottom layers, until it eventually warms and surfaces in the Pacific and Indian Oceans. Very little respiration occurs at such depths but, since the water travels very slowly, the oxygen does slowly get taken up.

Oxygen concentrations in the deep Atlantic are therefore higher than in the (warmer) deep Pacific. Some areas of the sea floor can, however, be anoxic if they are not supplied by the movement of oxygenated deep waters. Hydrocarbon spills, trawling and the release of **methane hydrates** from the sea floor can also contribute to deoxygenation of bottom waters, as these supply additional nutrients and stimulate respiration (see Box 1).



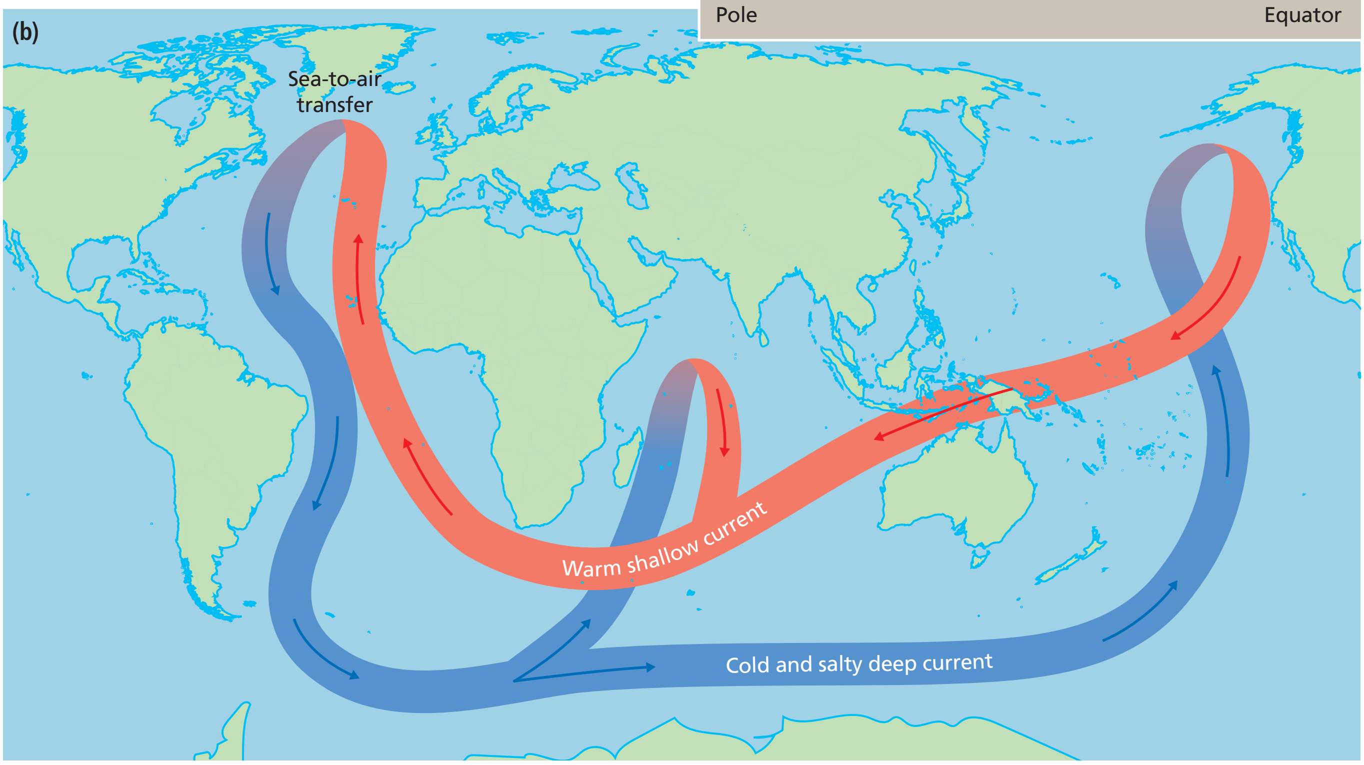


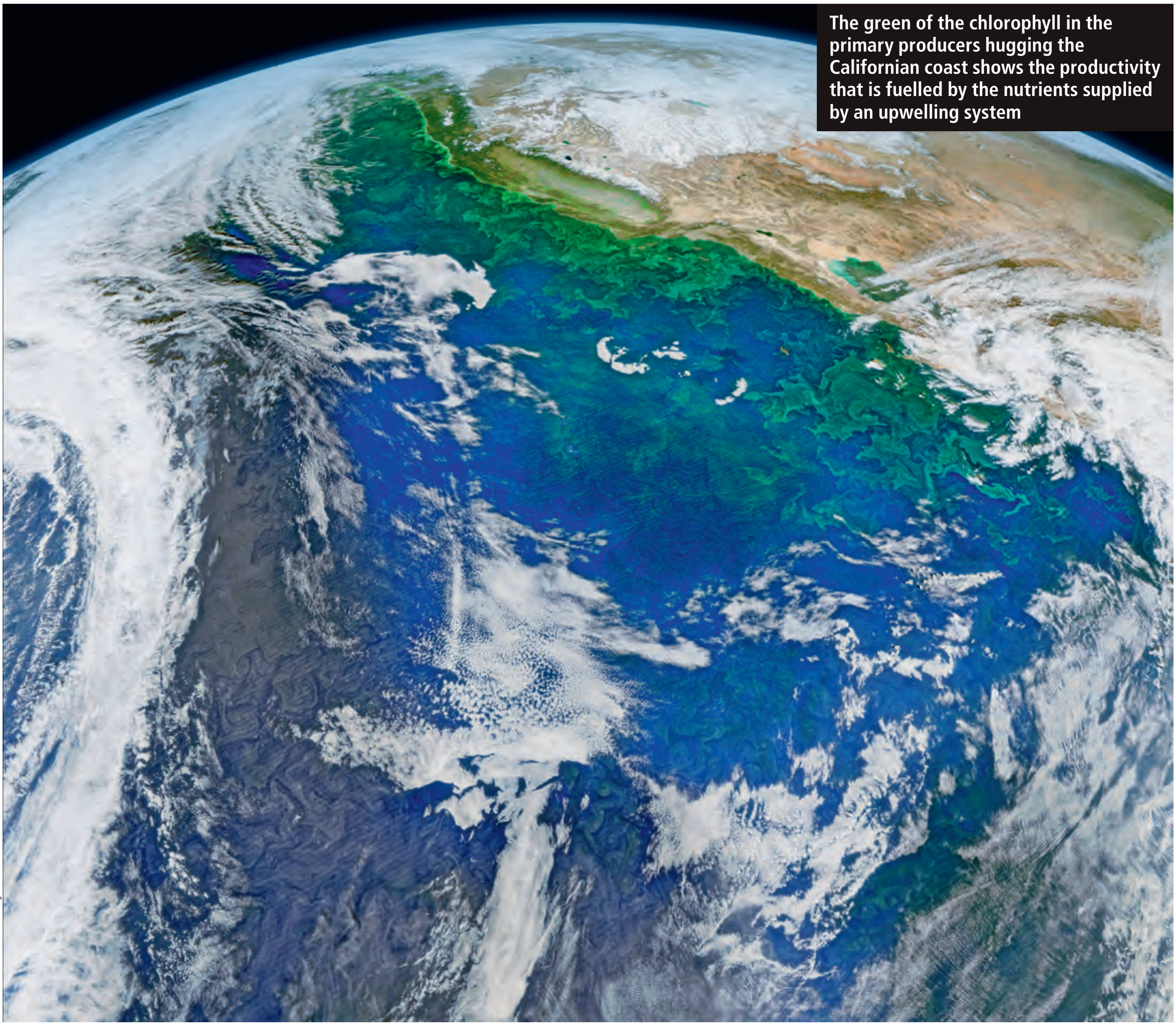
Figure 2.1 (a) The formation of oxygenated 'deep water' as cold water sinks below warm water at the poles. (b) Thermohaline circulation – the 'ocean conveyor belt'

by ocean currents is called thermohaline circulation – the 'ocean conveyor belt' (see Box 2).

Oxygen minimum zones

An oxygen minimum zone (OMZ) describes the depth at which oxygen saturation of the water column is at its lowest. This happens at depths of around 100–1500 m (see Box 1), depending on local conditions. OMZs make up around 8% of the ocean by volume. The largest OMZ is in the eastern tropical North Pacific. It covers around 1.3×10^6 hectares, and has led to changes in species composition. For example, gelatinous zooplankton are now the main inhabitants of water where billfish used to hunt vast shoals of fish.

Some regions are prone to deoxygenation and always have an OMZ. Others have zones that return annually. Some areas have naturally low oxygen concentrations, while others are caused, or exacerbated, by anthropogenic activity. Regions



© NASA Photo/Alamy Stock Photo

The green of the chlorophyll in the primary producers hugging the Californian coast shows the productivity that is fuelled by the nutrients supplied by an upwelling system

TERMS EXPLAINED

Benthic Anything relating to, or happening at, the bottom of a body of water (e.g. on the sea floor).

Harmful algal bloom An accumulation of algae that causes problems to other organisms when present in sufficient numbers.

Methane hydrates Crystalline structures of methane molecules (CH_4 gas) trapped within a lattice of water molecules.

Stratification The division of something into layers.

prone to deoxygenation tend to have an increased supply of nutrients, or be where the deep water circulation cannot penetrate, such as the Black Sea and some deep-sea trenches.

The addition of nutrients to surface waters can stimulate blooms of phytoplankton. An abundance of photosynthetic microorganisms boosts the oxygen concentration in the surface waters. However, when the cells die and sink, they are decomposed by aerobic bacteria. This eutrophication depletes the oxygen in the water. In coastal areas, nutrients can come from agricultural runoff, sewage and industrial activity, such as sugar milling and paper pulping.

Nutrient-rich regions also include upwelling systems. Such systems are formed when ocean currents and seasonal winds force surface water near the coast to move offshore, pulling the deep, nutrient-rich water up towards the surface (see Box 1). Upwelling systems are some of the world's most productive ecosystems. A 25 900 km^2 region off the west coast of Peru, for example, is one of the richest fishing grounds in the world.

Regions of coastal upwelling only cover 1% of the total area of the oceans, but provide about 50% of our fish harvest. When certain conditions align, such as the warming of surface waters during a marine heatwave (see 'Marine heatwaves', Biological Sciences Review Vol. 36, No. 1, pp. 10–15), hypoxic conditions can become even more intense. This develops OMZs that cover a larger area and persist for longer. Warming reduces the solubility of oxygen

Nemopilema nomurai – jellyfish that can thrive in deoxygenated waters

© Professor Shin-ichi Uye

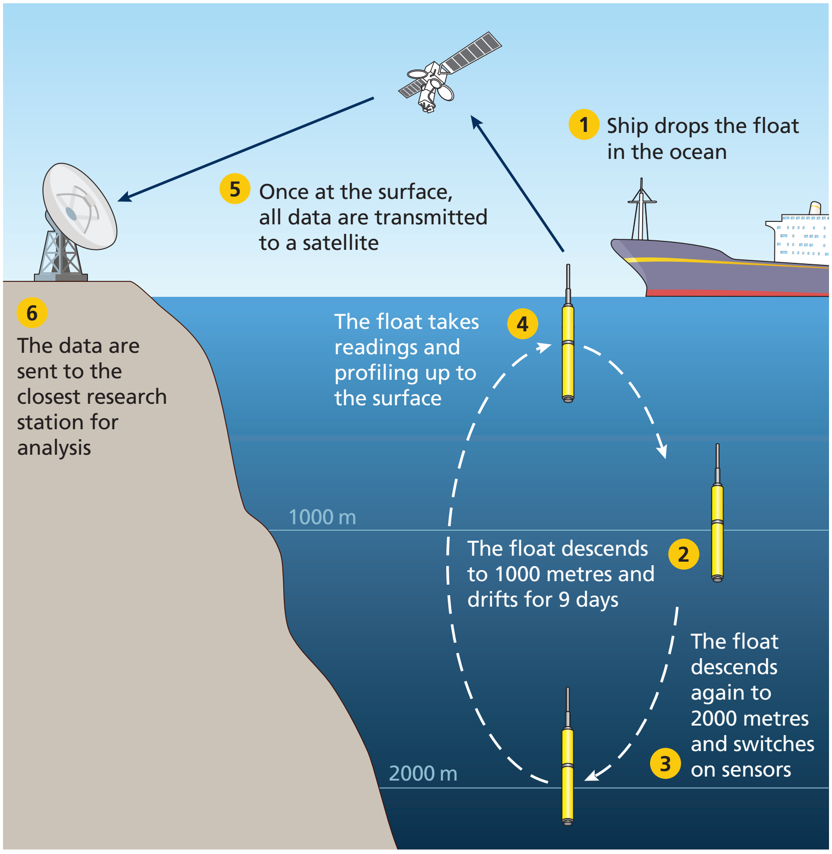


Figure 1 The cycle of an Argo float

in seawater and also increases **stratification**, which forms a barrier to the vertical mixing of the ocean, limiting the exchange of oxygen with deeper waters.

Being naturally oxygen-poor systems, upwelling regions are particularly vulnerable to ocean deoxygenation. As an OMZ expands up into shallower water, deoxygenated water may reach the continental shelf, causing hypoxia and fish kills, and affecting **benthic** communities. This can lead to reduced catches for fisheries and the collapse of regional stocks.

Large organisms use more oxygen than microbes, so many will flee if they can, or else die of oxygen starvation. As larger organisms die and their corpses sink, their carcasses are decomposed by aerobic microbes, which use up even more of the limited oxygen. These extreme events can lead to harmful algal blooms, altered community structures and ultimately a region becoming a dead zone. Climate-driven hypoxia and associated blooms of harmful algae degrade habitats, damage ecosystems and increase mortality rates.

How do we know that the ocean is losing oxygen?

We can model changes in global ocean oxygen concentrations based on our understanding of

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Atlantic croaker – one of the few fish that can survive in dead zones, but which is not faring well. Large numbers of females have been found with testes-like organs instead of ovaries, a sexual deformation that causes infertility

ocean chemistry and the variables that affect oxygen solubility, such as temperature. Studies suggest that overall, the ocean is predominantly losing oxygen faster than it is gaining it. A recent modelling study estimated that the global ocean dissolved oxygen content of 227.4 ± 1.1 petamoles (10^{15} mol) has decreased by more than 2% (4.8 ± 2.1 petamoles) since 1960.

While 2% may not sound like much, this is the loss from the ocean oxygen content across the globe, with some regions hit harder than others. For example, the Arctic Ocean accounts for 7.6% of this oxygen loss, even though it represents only 1.2% of the global ocean by volume.

As well as spatial variation in oxygen loss, on the vertical scale the greatest losses occur between 100–300 m, where many organisms – from the bottom of the food chain to top predators – spend much of their time. Overall, this means an expansion of low-oxygen zones and a decrease in viable habitats for organisms that do not tolerate low oxygen concentrations.

However, models predict that if carbon dioxide (CO_2) emissions caused by human activities, and thus global warming, were stopped, deoxygenation would largely stop in the upper ocean. The deep ocean, however, would continue to lose more than 10% of its pre-industrial oxygen content even if CO_2 emissions were stopped today. This means that on long timescales, deep ocean ecosystems are at the greatest risk.

While models include real data, ocean oxygen data are sparse and thus models must extrapolate across vast regions and depths where there are no data, or there are only data from a single timepoint in the past 50 years. However, localised concentrations can be highly variable. Oxygen concentrations in surface waters can change even from day to night, so the time of sampling influences the data. We therefore need to improve model functioning and future forecasting. To do this we need lots of accurate global ocean oxygen data and long-term monitoring, to see if these estimated changes can be verified.

One way of doing this is through the international Argo network (see Resources box), which uses profiling floats to record various parameters, including temperature, salinity and currents, around the world (see Figure 1). There are around 4000 floats reporting every 10 days. These floats work by descending to deep waters, drifting for a few days, before floating back up again, recording the conditions on the way up, and then sending the data by satellite back to the analysts.

Anyone can access the latest data on the Argo website. There is no central funding body. Each of the countries involved has to obtain its own funding to buy floats, to prepare, launch and operate them, and to process and distribute the data. Each float costs around £10 000–80 000, depending on the specification, so not all floats are kitted out with every sensor. Some areas that are frequently ice-covered, such as the Arctic Ocean, are problematic for such floats, but thanks to programmes such as Argo we are steadily increasing global ocean oxygen data.

The future

Ocean models predict a decline in the dissolved oxygen of the global ocean of 1–7% by the year 2100. This will be due to a combination of processes mainly driven by warming, particularly the reduced solubility of dissolved oxygen and reduced oxygenation of the deep ocean. Such a decline in the oceanic oxygen content will impact ocean nutrient cycles and the marine habitat, with potentially serious consequences for fisheries and coastal economies. Globally, we need measures in place to minimise anthropogenic nutrient inputs to the ocean and combat climate change.

RESOURCES

The explosion of jellyfish populations in low-oxygen waters:
https://tinyurl.com/jellyfish-explosion

The process of upwelling explained:
https://education.nationalgeographic.org/resource/upwelling

The discovery of animals living in anoxic zones:
http://news.bbc.co.uk/1/hi/sci/tech/8609246.stm

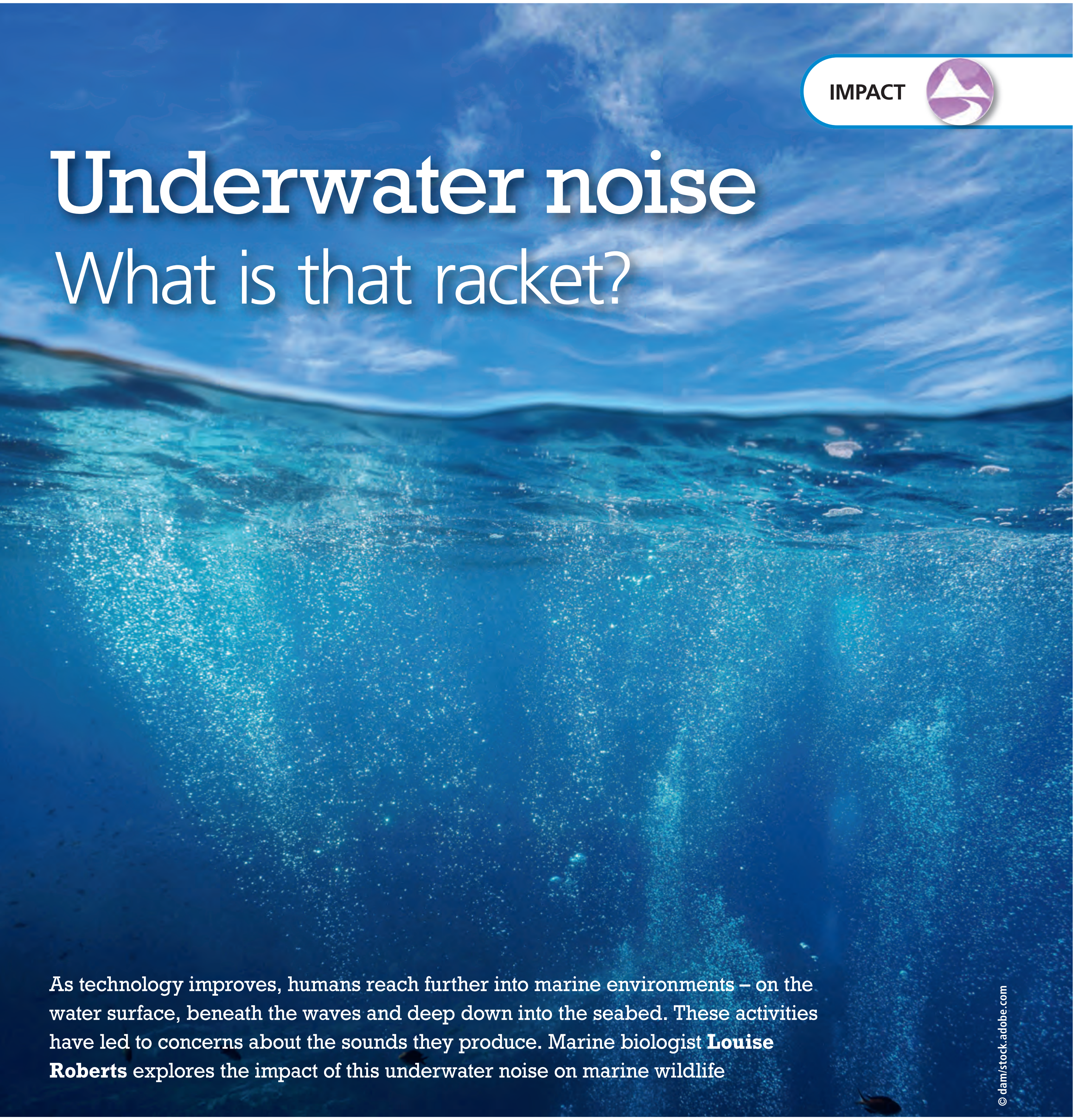
More on the spread of oceanic 'dead zones':
https://phys.org/news/2015-04-ocean-dead-zones-disaster-fish.html

Details of the Argo project: **https://argo.ucsd.edu**

KEY POINTS

- Our oceans are increasingly becoming depleted of oxygen.
- This reduces biodiversity, unbalances ecosystems and threatens the livelihood of people who rely on ocean produce.
- The causes include climate change and nutrient runoff.
- We have only recently developed the technology to make accurate and widespread measurements of ocean oxygenation.

Dr Hannah Whitby is a senior lecturer in oceanography at the University of Liverpool. She is interested in the interactions between trace metals and organic compounds in natural waters.



Underwater noise

What is that racket?

As technology improves, humans reach further into marine environments – on the water surface, beneath the waves and deep down into the seabed. These activities have led to concerns about the sounds they produce. Marine biologist Louise Roberts explores the impact of this underwater noise on marine wildlife

Humans undertake many activities in the marine environment, recreationally, commercially and industrially. Underwater sounds are produced by ships and boats, by fishing activities, by gas, oil and renewable energy acquisition, and even on a small scale when we swim and go scuba diving (see Figure 1).

The construction of offshore platforms, such as for oil and gas, is particularly noisy. In order to build a platform at sea (e.g. to support a wind turbine) the platform must be anchored to the seabed. One way to do this is to hammer long cylindrical piles – often tens of metres wide – into the seabed. Each hammer blow produces a sound in the water column and vibration in the seabed. Construction events may take weeks or months.

Other sounds are more continuous, such as the hum of a boat engine. Different sizes of boats – used for fishing, recreational activities and exploration – produce sounds of varying frequencies, amplitudes and durations.

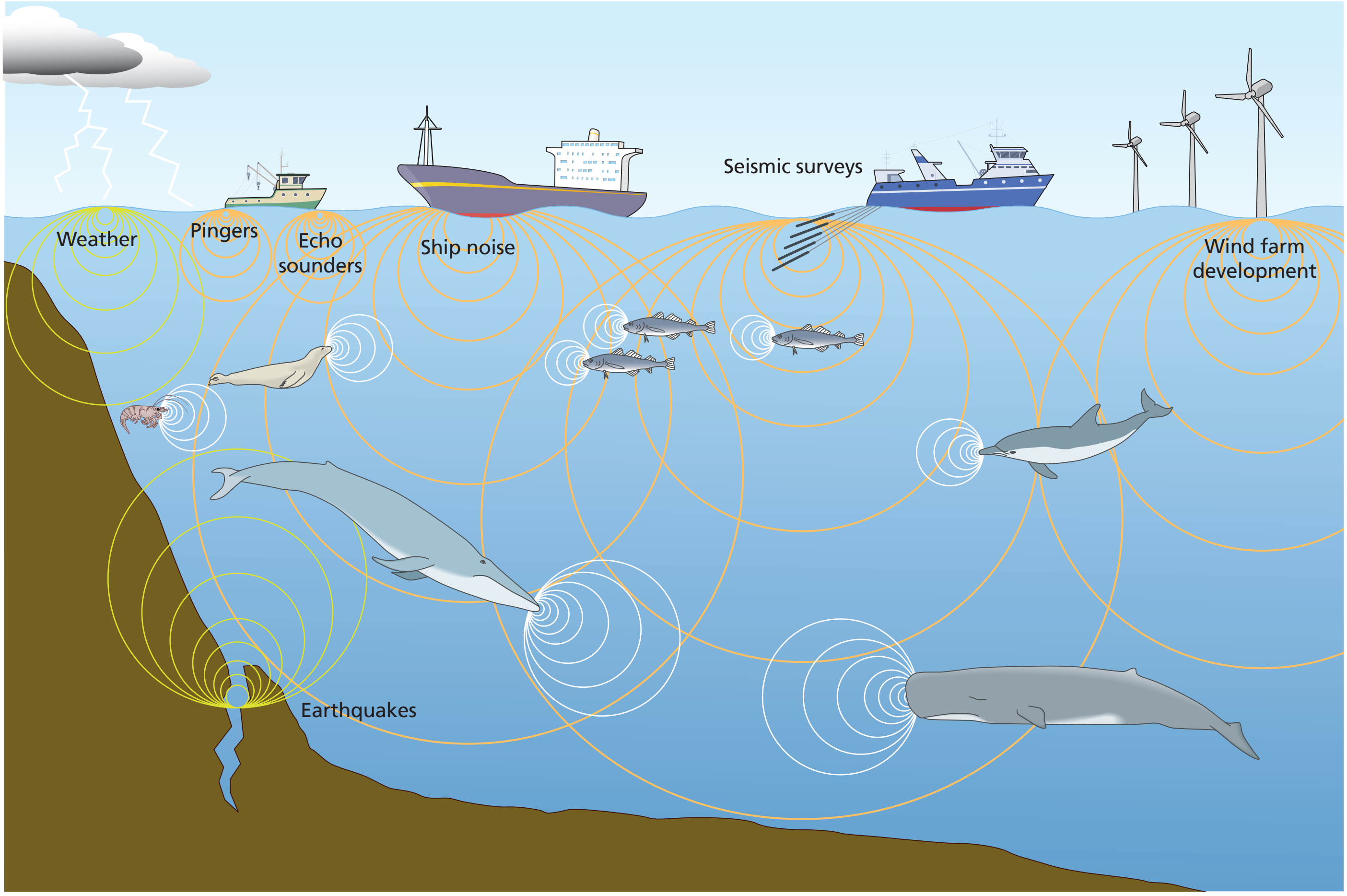


Figure 1 Sources of underwater noise from human activities and biological sounds in the marine environment

Workboats surround the construction of an offshore platform

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TERMS EXPLAINED

Anthropogenic Generated by human activity.

Chemical cue A chemical stimulus that promotes or triggers a biological response.

Hearing sensitivity and frequency range Measures of how sensitive an animal is to sound, and the frequency range (Hz) of the sounds that it can detect. Humans can hear from around 20 Hz to 20 000 Hz.

Quadrat A square frame used in ecological sampling to mark a standard unit of area, within which biological features can be counted or characterised.

Soundscape/vibroscape The pattern of sounds or vibrations in a landscape/environment.

Sound propagation The transmission of sound waves through a medium, such as water or air.

Why is underwater noise a problem?

Many marine organisms use sound in water in the same way that we use sound in air. Sound is used to communicate, to find resources such as food and to navigate. Sounds and vibration travel long distances under water and sound travels five times faster in water than in air. Its velocity is affected by the properties of the water, including temperature, salinity, pressure and depth.

Sounds travel much further than light, which means that aquatic animals can hear across a larger distance than they can see. Some marine mammals and fish actively produce sounds, while others do not (see Box 1). However, scientists have shown that many marine organisms sense a distribution of sounds in a similar way to how we perceive a visual landscape. They call this a **soundscape**, while in the seabed/sediment a **vibroscape** of vibrations may also exist.

The **hearing sensitivity** and **frequency range** of marine animals vary between species. For example, whales have a very wide hearing range, and can detect low-pitched as well as high-pitched sounds, whereas bottom-dwelling fish have a more limited range. Crucially, the hearing range of marine animals often overlaps with the frequency range of **anthropogenic** sounds (see Figure 2). This means that they can detect anthropogenic noise, which may then affect them.

Effects of anthropogenic noise

For chemical pollutants the amount – dose – of the chemical dictates the severity of an animal's response. A high dose may be lethal, while a lower dose may cause disorientation. The same is true for underwater noise. The impact range of a noise source varies with the **sound propagation** conditions, together with the properties of the noisy activity (for example, its duration and repetition). We can predict these using mathematical models to estimate noise levels at a particular distance. The dose of sound an animal receives also depends on its hearing capabilities, and on its position in relation to the noise source.

Box 1 Natural sounds

There are many different sounds in the underwater world, just as there are in air, although our human ear does not work well under water, so we sometimes forget this.

Natural sounds are produced by physical events, such as waves crashing, bubble movement, water currents and even earthquakes. Animals produce sounds. You might be familiar with whale songs, but fish and invertebrates make sounds too. For example, the Atlantic cod (*Gadus morhua*) produces 'grunts' during courtship, and some shrimp 'snap' when they stun prey.

Coral reefs have so many animal sounds that fish and invertebrate larvae can use sound to locate reefs in which to settle. We can assess whether a reef is healthy or unhealthy just by listening.

Cod fish produce sounds during courtship

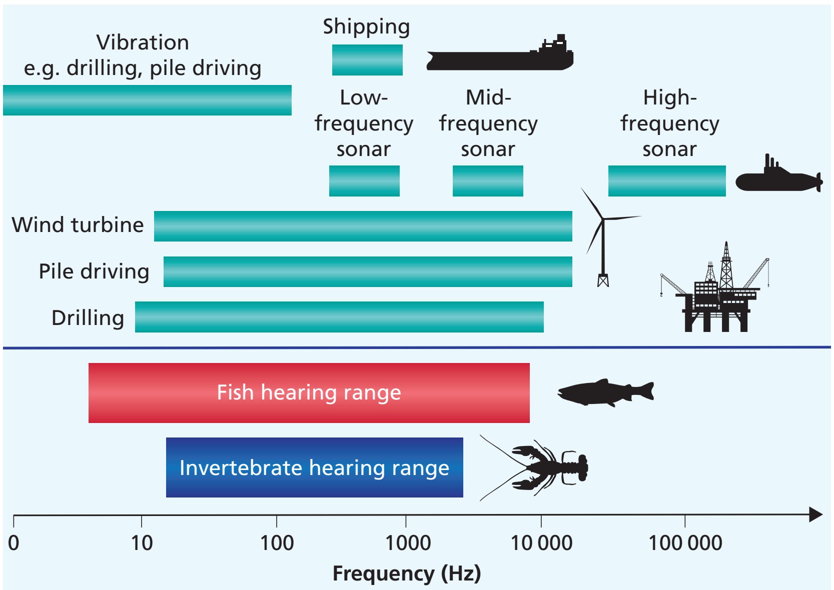


Figure 2 Approximate hearing ranges of fish and invertebrates, compared with the frequencies of anthropogenic noise

Case study – testing whether noise affects a marine animal

One way to test the responses of animals to noise is to undertake experiments in their natural environment. For 3 months in 2018, I worked and lived on Appledore Island in Shoals Archipelago on the east coast of the USA, in a marine laboratory called Shoals Marine Laboratory. It is a fantastic place to undertake scientific work because researchers from all over the world work there. My workday involved snorkelling every day to do my experiments.

Aims and methods

I wanted to know whether hermit crabs (*Pagurus acadianus*) respond to noise. These animals live in areas rich in human activity and its accompanying noise. Hermit crabs are common crustaceans. You can find a related species (*Pagurus bernhardus*) in rockpools in the UK. They have a soft body, which needs protection from damage and predators. To protect the body, the crabs occupy an empty gastropod (marine snail) shell – rather like a mobile home.

I used a **chemical cue**, which we already knew smelt like an empty gastropod shell. I knew that the hermit crabs would not be able to resist this scent, because they are on a constant hunt for a better home. I put the cue inside a small plastic bottle with mesh on top, and used it as bait to attract the crabs.

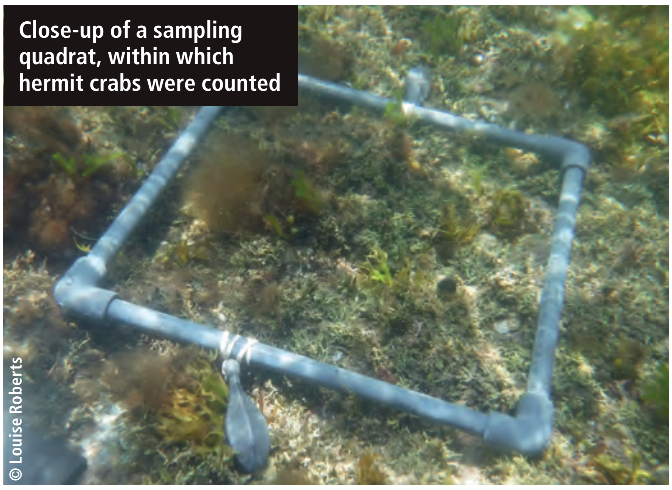
I set up **quadrats** across the seabed, each containing a chemical cue. Next to some of the quadrats I created noise by hammering into the seabed. For control quadrats, the hammering did not take place. At the start of each test I counted the number of crabs inside a quadrat. I did this by diving down to the bottom, counting, then resurfacing to breathe. Then the quadrat was exposed to either noise or silence for 5 minutes. My question was, 'do numbers of hermit crabs differ between the noise and control sites?'. Figure 3 shows the results.

Interpreting the results

Looking at the graph we see that, regardless of whether the quadrat was subsequently noisy or quiet, there were typically one or two crabs at the first count. This was as expected, because there were crabs in the experimental area. After the 5-minute treatment period, regardless of noise or quiet, there were always more crabs on the second count. That made sense, because crabs would be attracted to the chemical cue. But the more important finding was that fewer crabs came to a quadrat when it had been noisy, compared with when it was quiet. The noise deterred some individuals from coming – it prevented them from orientating to, and gathering around, the 'smell' of a new home.

Conclusions

Why might these results have happened? We need more tests to find out. Perhaps the noise affected how the crabs detected the chemical cue, or distracted them from their shell-searching behaviour. Either way, it was clear that the noise had an effect on shell-searching in these crabs – a behaviour that is important for their survival.



Close-up of a sampling quadrat, within which hermit crabs were counted

Acadian hermit crabs that have been attracted to a chemical cue (white container)

Acadian hermit crab (*Pagurus acadianus*)

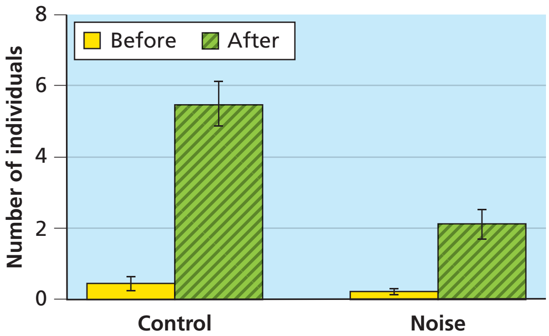


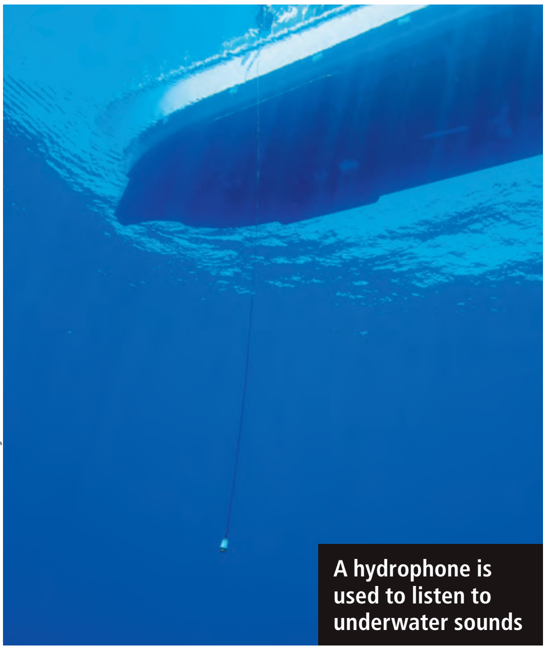
Figure 3 Number of hermit crabs present in quadrats before and after a 5-minute exposure to either silence (control) or noise (mean ± standard error (SE) of the mean, where SE = standard deviation/$\sqrt{n}$; n = 30 quadrats for both).

Table 1 Potential effects of anthropogenic noise exposure on marine organisms

Impact	Effects on individuals	Effects on populations
Trauma to tissues and organs – e.g. gas-filled organs	Injury or death	Mortalities, changes in size and age structure of population
Damage to auditory system	Temporary or permanent hearing loss	Increased mortality risk, leading to reduced abundance, reproduction and growth
Masking of biologically important sounds	Disruption of behaviour – e.g. reduced communication and spawning	Increased mortality risk, leading to reduced abundance, reproduction and growth
Changes in behaviour	Direct behavioural modifications – e.g. avoidance reactions, stress responses	Displacement from preferred habitats, disrupted migration and spawning, reduced growth and reproduction
Changes in physiology	Altered metabolism, slower growth, release of stress hormones	Reduced population growth and reproductive output

The effects of noise upon animals can be categorised according to their severity (see Table 1). Very close to a high-amplitude source, noise may cause immediate or delayed mortality, for example by rupturing tissues. Permanent or temporary hearing loss may be caused by noise when hair cells in the ear are damaged. Further away from the source, animals may be unable to hear other sounds because of the noise, or display behavioural changes, such as leaving the area or cessation of feeding. These effects may be short lived or long lasting.

Scientists use a device called a hydrophone to listen to underwater sounds. Hydrophones contain a ceramic material that responds to changes in pressure, such as those created by sound waves. The response is an electrical signal, which can then be recorded and amplified. The electrical signal is analysed in terms of its amplitude (loudness), frequency (pitch) and pattern over time. See the 'Resources' box for how to build a basic hydrophone.



A hydrophone is used to listen to underwater sounds

Looking towards an acoustic future

Humans will continue to use the oceans, and there will always be noise to some degree. However, we can mitigate its impacts. First, we need to know the dose of sound that causes a particular response. In the case of marine mammals, for which we have plentiful data, we can then set sound exposure criteria to regulate the level of noise put into the water, ensuring that it is below a damaging level.

To reduce noise in the water, we can change the sources themselves – for example, using quieter boat engines – or we can time our activities to avoid biologically significant places or times, such as avoiding a feeding ground where animals gather. The difficulty is that, for most marine animals (especially fish and invertebrates), we still have no idea how well they hear, and if or how they respond to noise. This means that we cannot set accurate exposure criteria to protect them. With more scientists working in this research field, we need to build up evidence to support the regulation of underwater noise pollution.

RESOURCES

The Discovery of Sound in the Sea (DOSITS) website is written by scientists from all over the world, including the author:
www.dosits.org

Sound and coral reef restoration:
https://www.bbc.co.uk/news/science-environment-59567875

Can we fix ocean noise?
https://tinyurl.com/ocean-noise

How to build a simple hydrophone:
https://tinyurl.com/simple-hydrophone

'Costing the Earth' – sounds in the seas:
https://www.bbc.co.uk/sounds/play/b068w44v

THINGS TO DO

- Visit the websites of the Marine Biological Association and the Marine Conservation Society to learn about the marine environment and how you can help.

Dr Louise Roberts is a lecturer in marine biology at the University of Liverpool. She is interested in how animals use sounds and vibrations, how they hear and produce sounds, and how they respond to anthropogenic changes such as noise.

Marine heatwaves

When you can’t cool down in the sea

Hannah Whitby

Marine biogeochemist Hannah Whitby explains how heatwaves can strike in the ocean, affecting marine organisms of all kinds

EXAM LINKS

AQA Populations in ecosystems
OCR A Ecosystems
OCR B The transfer of biomass through a food chain
Pearson Edexcel A Ecological terms; Biotic and abiotic factors; Climate change
Pearson Edexcel B Ecosystems
WJEC Eduqas Population size and ecosystems

Marine heatwaves are short periods of abnormally high temperature in a sea or ocean. They can last from a few days to a few years, and can extend across areas from tens to thousands of square kilometres. Marine heatwaves can happen in any sea or ocean basin (see Figure 1). They can threaten whole ecosystems, reduce biodiversity, lead to mass mortalities of organisms of all sizes, and impact fisheries, tourism, and **aquaculture** industries.

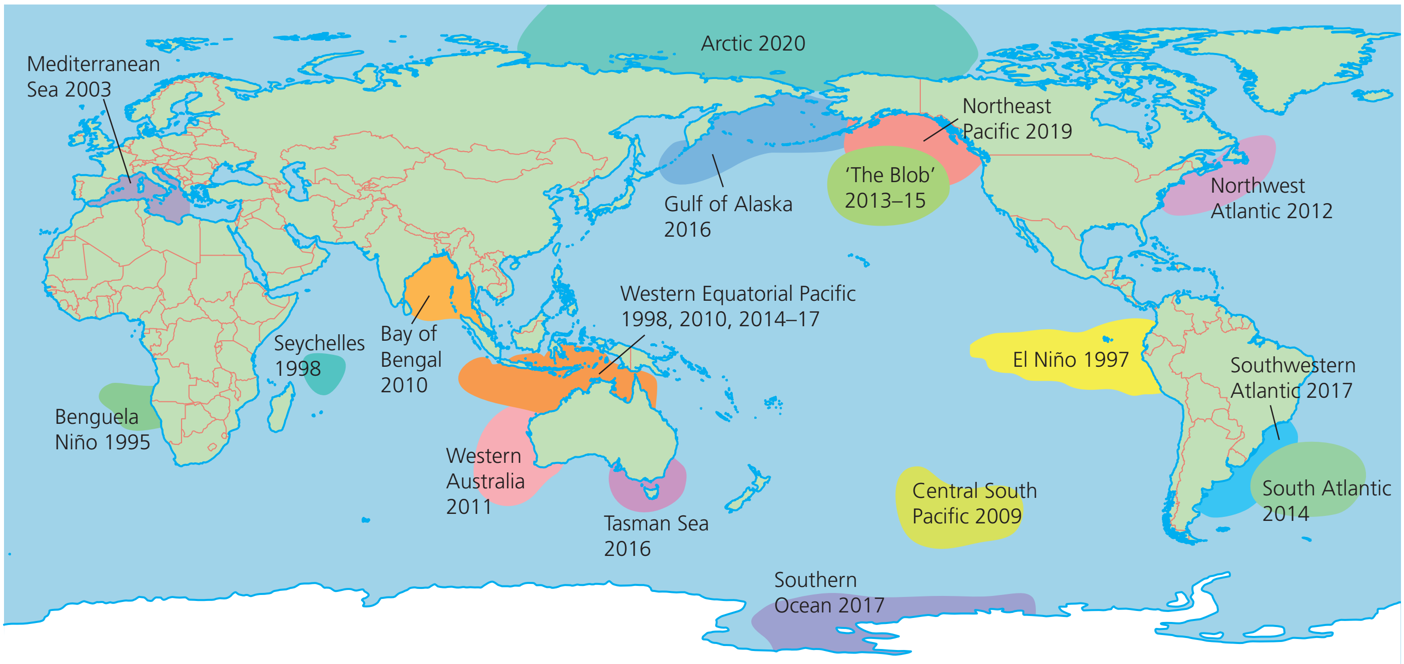


Figure 1 Locations of some key marine heatwaves

Algal bloom in Kennedy Bay, New Zealand

How do we measure marine heatwaves?

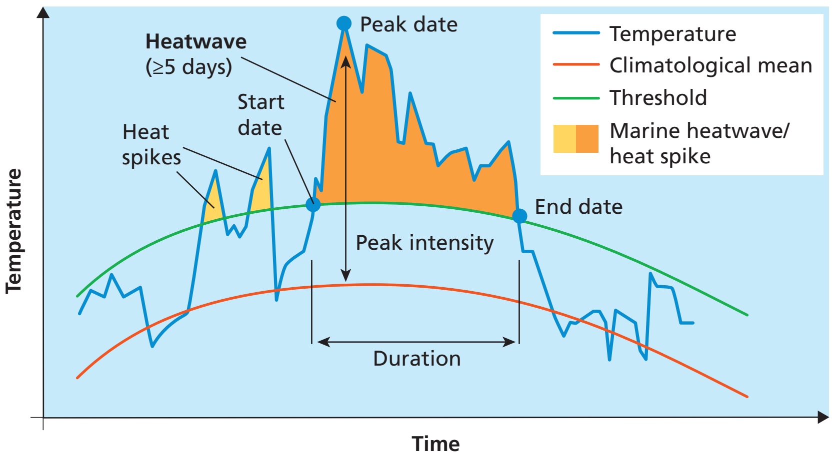
In 2018 a formal definition of a marine heatwave became widely accepted within the scientific community. Temperatures must have exceeded a seasonal threshold for at least five consecutive days (see Figure 2). Shorter heat spikes are not considered a heatwave, and any gaps of under 2 days are considered part of the same event. The duration of the event is the amount of time that temperatures are above the seasonal threshold.

Like hurricanes, marine heatwaves can change over time, and so we need a way to categorise them in order to communicate their development and impact effectively to the general public. Category 1 is classed as moderate, category 2 as strong, category 3 as severe and category 4 as extreme. Moderate heatwaves are by far the most common (around 80% of all heatwaves). Fortunately very few are category 4 (extreme) events.

A global phenomenon – on the rise

Marine heatwaves have become more frequent and intense over time (see Figure 3). Their effects on marine life have, therefore, become more noticeable. Due to climate change, the oceans are warming faster than previously recorded which increases the likelihood of marine heatwaves occurring.

When temperatures go only slightly above or below what is defined as their ‘coping range’, organisms are able to adapt. The odd



Source: Adapted from Holbrook *et al.* (2020), ‘Keeping pace with marine heatwaves’, *Nature Reviews Earth & Environment*, 1, pp. 482–93, **https://doi.org/10.1038/s43017-020-0068-4**

Figure 2 Defining a marine heatwave

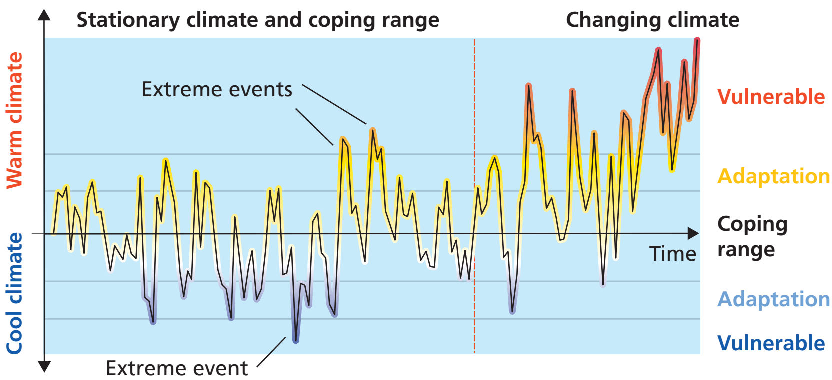
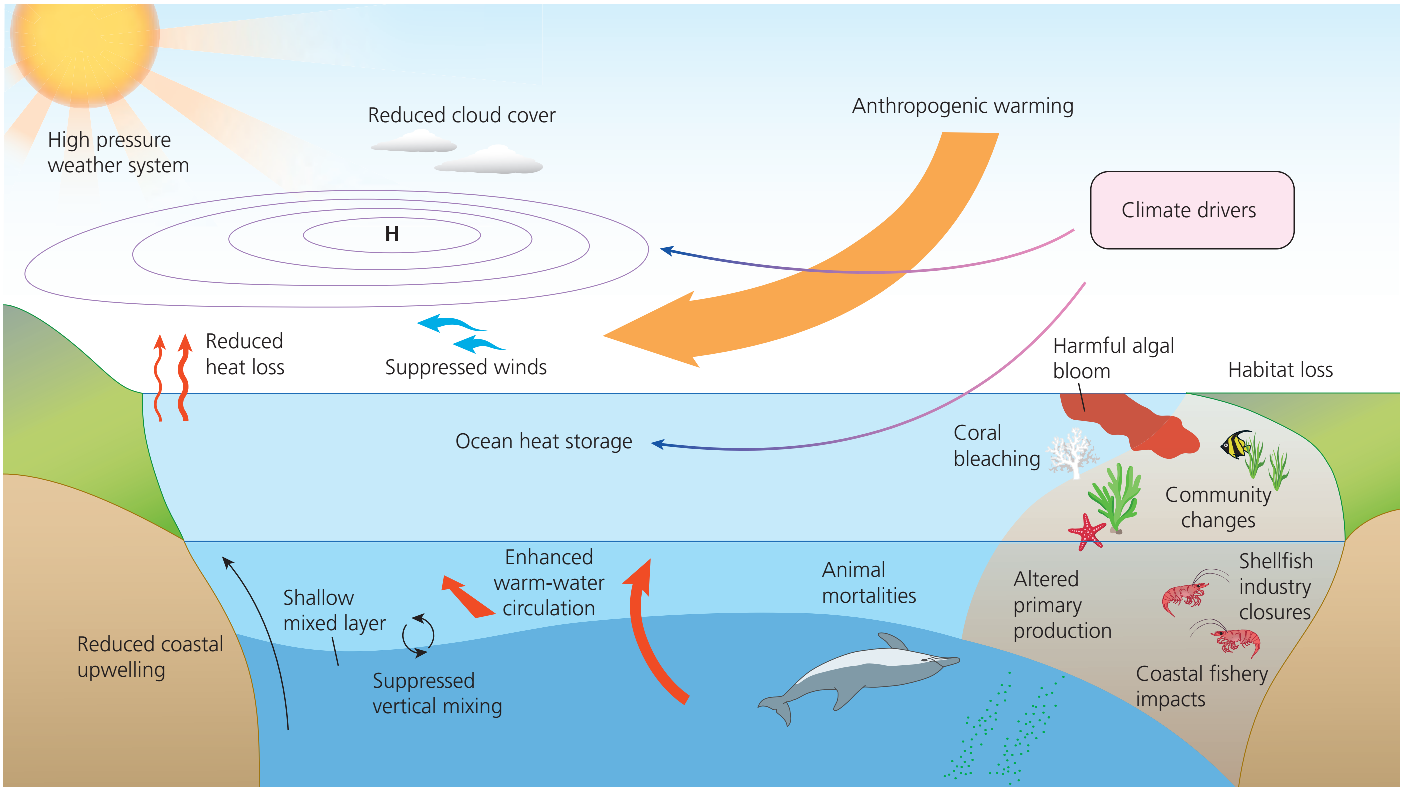


Figure 3 The effect of climate change on coping range



Source: Adapted from Holbrook *et al.* (2020), 'Keeping pace with marine heatwaves', *Nature Reviews Earth & Environment*, 1, pp. 482–93, **https://doi.org/10.1038/s43017-020-0068-4**

Figure 4 The main drivers and impacts of marine heatwaves

extreme event can lead to mass mortalities, but communities recover over time. However, temperatures are rising quickly, above the range where communities are able to adapt, and extreme events are becoming more frequent, not allowing communities the time to recover.

What triggers a marine heatwave?

Each marine heatwave is unique, with different factors dominating each event (see Figure 4) and individual habitats having varying resilience. The most common drivers of marine heatwaves are the transport of water by ocean currents and the exchange of heat with a warm atmosphere. Winds can both enhance and suppress warming. Climate patterns like El Niño (part of the natural cycle of warm and cold sea surface temperature conditions in the Pacific Ocean) can also change the likelihood of events occurring in certain regions.

The main atmospheric and ocean drivers of marine heatwaves are shown in Figure 4. The left-hand side of the image shows the key processes, which, when several occur simultaneously, can induce a heatwave. Imagine a warm day with little wind out in the open ocean. A high-pressure system combined with reduced cloud cover increases solar radiation to the ocean, warming the sea surface, with no wind to remove the heat.

Warm water and suppressed winds lead to reduced vertical mixing and stronger **stratification**. In other words, the top, warmer layer of the ocean becomes shallower and more separated from the cooler, deep water below. This forms a pocket of hot water at the surface. In shallow waters, bottom-dwelling (**benthic**) communities such as corals and seagrasses, and the organisms that live among them, may not be able to escape. Critically, these are often key habitats for juveniles and important breeding and feeding grounds for many species of fish, invertebrates, marine mammals and reptiles, from seahorses and sea stars to bottlenose dolphins and sea turtles (see pp. 34–37).

These unusual conditions can sometimes lead to blooms of harmful algae, which tend to favour

TERMS EXPLAINED

Aquaculture The breeding, growing and harvesting of fish, shellfish and aquatic plants.

Benthic Anything relating to or occurring at the bottom of a body of water (e.g. on the sea floor).

Stratification The division of something into layers. In oceanography, layers of water can be separated by strong temperature and salinity gradients (relating to density).

Upwelling When deep, cold water – usually rich in nutrients – rises toward the surface.

warmer waters. These are algal species that cause problems to other organisms when present in sufficient numbers, either because they release toxins or have a physical structure that can affect the health of other species.

Such blooms can result in mass mortalities of organisms across the food web, and also affect humans through contaminated food and economic losses resulting from their impacts on fisheries and tourism. Later, as the algae die and sink, bacteria break down the excessive organic matter by respiration, which uses up oxygen. Enhanced aerobic respiration, exacerbated by the fact that warmer water holds less oxygen than cool water, can lead to deoxygenation.

While not all of these scenarios occur during every heatwave, the effects can cause larger animals to leave the area or suffer from a variety of stressors, including lack of food, sickness and low oxygen concentrations. Marine heatwaves have been linked to mass mortalities in many different animal species, including mammals and seabirds. They are also associated with kelp forest and mangrove die-offs, as well as coral bleaching (see Biological Sciences Review Vol. 35, No. 3, pp. 16–19).

Notable marine heatwaves

One of the most extreme events on record occurred off Western Australia in 2011. It was after this event that the term 'marine heatwave' first came into use. It lasted 66 days between January and March 2011, with 12% of those days classed as extreme. Surface temperatures were more than 3°C above the long-term monthly average, periodically reaching up to 5°C higher in some areas.

Sudden changes in water temperature had been recorded off Western Australia, but there had been no previous records of such high temperatures. The effects of the heatwave were visible almost immediately. Fisheries reported bleaching of corals from January, and thousands of dead fish washed up along the coast between February and May. Deaths of juvenile dolphins, whale sharks, seahorses and commercially important invertebrates, including rock lobsters, were also reported.

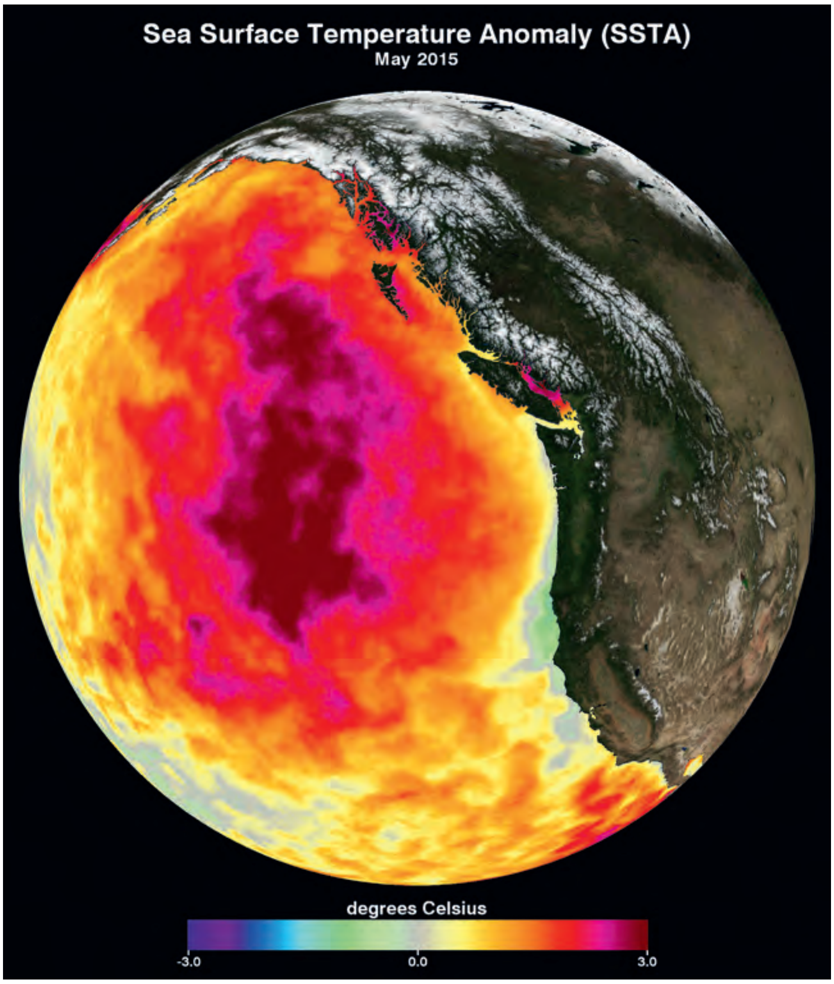
After higher-than-average sea surface temperatures for several weeks, a sudden further temperature spike to 30°C in late February resulted in Roe's abalone, a commercially important bivalve, suffering grave losses in some regions. Numerous scientific studies have since linked the heatwave to the poor condition of a variety of animals, including penguins and sea turtles.

Abnormal behaviour among fish and invertebrates was also noted during the heatwave. There were strandings of hundreds of sunfish, while Australian salmon displayed higher feeding rates and changes in preferred prey. The heatwave resulted in lower catch rates for commercial fisheries, and, within catches, unusual species compositions and poor condition of landed fish. Prawns, however, thrived under the warmer conditions, with higher-than-average catches of king prawns recorded in March–April 2011.

The aftermath

Local communities and biodiversity suffer during a marine heatwave, but effects can persist for a long time after the heatwave has passed. Marine heatwaves affect ecosystem structure, by boosting certain species and suppressing others. The higher

Bleached coral on the Great Barrier Reef



Source: Gentemann, C. L., Fewings, M. R., García-Reyes, M. (2017), 'Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave', *Geophys. Res. Lett.*, Vol. 44, pp. 312–19, doi: 10.1002/2016GL071039

Figure 5 Differences in sea surface temperature in the northeast Pacific Ocean in May 2015, as compared with the monthly average, due to the Blob. Waters warmer than expected are indicated by red, pink and yellow colours

temperatures can drive the presence of invasive species, as species typically found in warmer climates move in. This can cause problems for the existing community, from competition and introduction of diseases to habitat destruction and excessive predation.

PRACTICE EXAM QUESTIONS

1 Figure 4 of the article refers to anthropogenic warming.
  a What does the term 'anthropogenic' mean? [1 mark]
  b Explain the major source of anthropogenic warming. [3 marks]

2 Figure 4 also shows stratification of the sea.
  Suggest how this stratification could reduce the growth of the community of phytoplankton (photosynthetic protoctists) in the upper water layer. [3 marks]

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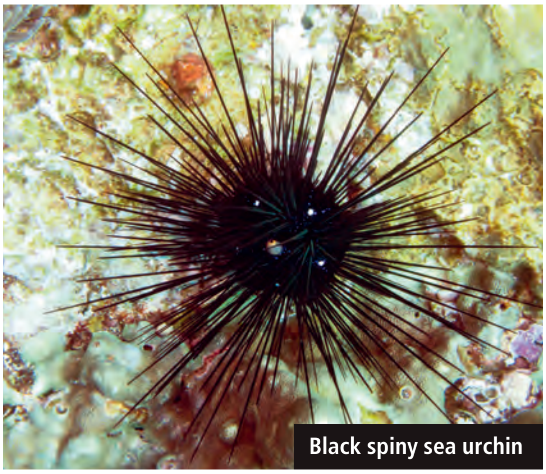
An increase in 'tropicalisation' of the communities often remains after a marine heatwave. Following the 2011 heatwave off Western Australia, much of the dominant kelp seaweed that provided a range of critical habitats was lost. The area was rapidly colonised by shorter, turf-forming seaweeds and bottom-grazing tropical fish, including rabbitfish and parrot fish, which prevented the kelp from regrowing. Long-term changes to fish communities followed the heatwave.

One example of a rogue species making the most of a marine heatwave is the spiny sea urchin. Studies have shown that these animals can withstand heatwaves better than some of their competitors. They have high thermal tolerance and an ability to adjust to change. They can even pass on protective mechanisms of heatwave survival to their offspring. Sea urchins usually play an important role in maintaining the structure and functionality of benthic ecosystems, but they can also be a pest. They can wipe out natural communities and commercially important species, such as abalones, through competing for food and damaging critical kelp habitats.

The northeast Pacific 'Blob'

One of the most destructive marine heatwaves on record was the 'Blob'. It covered a vast area of the northeast Pacific Ocean between 2013 and 2015, reaching around 1600 km wide and 90 m deep, and stretching from Alaska to Mexico by the summer of 2014 (see Figures 1 and 5). While not the most severe heatwave in terms of temperature, with mean temperatures around 2.6°C above the seasonal average, the Blob was unprecedented in magnitude and duration (lasting 711 days). Regionally, there were reports of sudden temperature spikes, including one of +7°C within 1 hour recorded by a buoy off the coast of Oregon.

The biological impacts of the Blob were some of the most extensive ever recorded.



Black spiny sea urchin

The production patterns of phytoplankton (microscopic autotrophs) were altered, with persistent blooms of harmful algae detected by satellites. This in turn led to shifts in distributions of zooplankton (very small animals, such as krill).

These effects at the base of the food chain resulted in changes to the population dynamics and behaviour of many fish species, including Alaska pollock. Ultimately, this led to mass mortalities of birds and mammals, including otters and fin whales. This was primarily due to a lack of food across such a vast region, with reports of many stranded, starving sea lion pups along the California coast. Beach surveys of dead birds washing up along the west coast of the USA estimated that the total mortality of common guillemot alone was around one million birds – thought to be the biggest seabird die-off on record.

The Pacific Ocean is more prone to marine heatwaves than other ocean basins. Marine heatwaves led to three mass coral bleaching events along the Great Barrier Reef in 2016, 2017 and 2020. From 2019 to 2021 another expansive event became dubbed 'Blob 2', breaking previous temperature anomaly records for the area (with mean temperatures at 4°C above the seasonal average and temperature spikes up to 6°C higher in some areas). This event triggered an outbreak of harmful algae in 2021, culminating in a record-breaking economic loss of over 8 million US dollars for Japanese coastal fisheries.

What does the future hold?

Heatwaves of all categories are becoming more common, but the trend is towards category 2 (strong). Satellite sea surface temperature data show that more of the oceans are experiencing heatwaves, increasing the number of annual marine heatwave days by more than 50% globally since the early 1900s. In some regions, such as the Indian and Arctic Oceans, the frequency and severity of heatwaves is increasing even faster. While marine heatwaves are less common in the Atlantic Ocean than in the Pacific, they tend to be of stronger intensity.

Since 2020, there have been marine heatwaves in all ocean basins. The Arctic Ocean is experiencing a growing number of prolonged marine heatwaves classed as severe, which recent satellite data suggest could be even stronger than those observed elsewhere, and which are expected to have serious impacts on wildlife.

Such extreme events lead to ecosystem vulnerabilities and, ultimately, to permanent changes to marine ecosystems. In a warmer climate we are more likely to experience these vulnerability-causing extremes. We are already experiencing more frequent heatwaves, which last longer and are more intense, with unprecedented ecological impacts.

The longer the duration and/or the higher the intensity of a heatwave, the greater impact it will have on marine life. With the projected climate warming yet to come, we can expect future continuation, and possibly acceleration, of marine heatwave events.

Common guillemot in flight

KEY POINTS

- Marine heatwaves are increasing in severity due to climate change. They can have both short- and long-term effects on organisms.
- Populations of a few, often harmful, species are boosted, while others are damaged, leading to community changes.

RESOURCES

'"Unheard of" marine heatwave off UK and Irish coasts poses serious threat'
www.theguardian.com/environment/2023/jun/19/marine-heatwave-uk-irish-coasts-threat-oysters-fish-high-temperatures

Live and historical marine heatwave tracker:
www.marineheatwaves.org/tracker.html#

Learn more about marine heatwaves:
www.iucn.org/resources/issues-brief/marine-heatwaves

www.marineheatwaves.org/all-about-mhws.html

Find out about the latest research into marine heatwaves: **www.marineheatwaves.org**

Dr Hannah Whitby is a lecturer at the University of Liverpool. She is a marine biogeochemist, interested in the interactions between trace metals and organics in natural waters.

SPOTLIGHT

Seagrasses

The biggest plants on the planet

Why do underwater meadows matter? Why are they threatened, and what are we doing about it? Plant scientist Liz Sheffield explains

We tend to take grasses for granted. Whether playing football, eating cornflakes or lying on a beach mat, we seldom acknowledge the crucial role played by these versatile plants.

Most humans rely on one or more of the 3500 or so species of grasses – such as corn, wheat and rice – for food. However, all of us – through the air that we breathe – benefit from grassy meadows that few of us have seen. Just 1 m^2 of these underwater meadows of seagrass has been estimated to produce 10 dm^3 of oxygen per day. When the sun is shining, a healthy clump of seagrass gives off bubbles so plentifully that the water looks like champagne.

Seagrasses grow in the shallows around every continent except Antarctica. Accurately documented meadows occupy 177 000 km^2 worldwide, but as some species grow at depths of up to 50 m they undoubtedly occupy at least 300 000 km^2 (probably an area considerably larger than the British Isles). These plants therefore make a very important contribution to both oxygen production and carbon storage. But their global significance does not stop there. They are called 'ecosystem engineers' because of their critical role in our coastal waters. Just as terrestrial meadows are species rich, underwater meadows support a huge diversity of other organisms. What makes these plants so efficient and important?

Adaptation

The story started around 100 million years ago. By this point in evolutionary time there was a rich diversity of grasses growing on the land. Their fast

Box 1 How grasses grow

One key to the success of grasses is the way in which they grow (see Figure 1.1). They exploit the horizontal plane through the growth of their stems. Sometimes these extend along the surface of the sand, or soil, but others lie just beneath the surface.

Grasses exploit the vertical plane through their fast-growing leaves. Unlike many plants, the area where cell division is concentrated in grasses is in the base of the leaf, not the tip. This means that the tops of the leaves can be removed – such as when we mow a lawn, or when a grazer feeds – and the plants can replace the lost material.

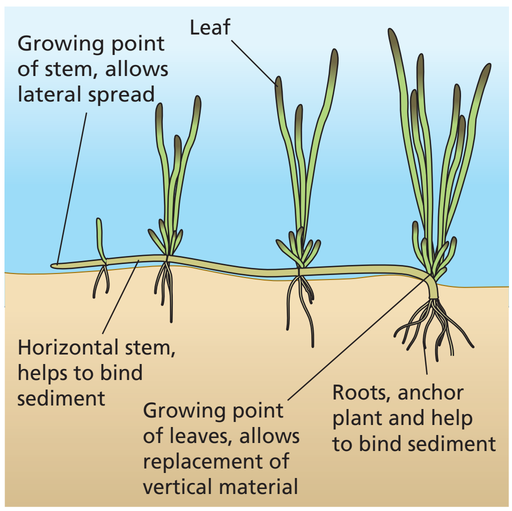


Figure 1.1 The structure of seagrass

Box 2 How seagrasses reproduce

Seagrasses exploit their watery environment in three ways in order to reproduce. One way for them to reproduce sexually uses the sea floor. The male flowers of deep-growing grasses release rafts of pollen that are negatively buoyant, and so sink. These rafts, which resemble strings of frog spawn and are referred to as 'pollen noodles', are carried along the seabed by currents, tidal flow or animal (for example, crustacean) pollinators. The pollen gets caught on the stigmas – the receptive surfaces of female flowers – which protrude out of the sediment.

Another sexual method of reproduction, characteristic of shallow-growing seagrasses, exploits the water surface. In these grasses, the anthers protrude out of the water, so when the pollen noodles are released at the water surface they are carried to the stigmas of the female flowers by currents or the returning tide (see Figure 2.1).

The third method is via asexual reproduction. In common with many horizontal-growing plants, seagrass stems can branch, allowing potentially indefinite spread (see Box 3), while fragments of stem can regenerate from grazed or damaged plants.

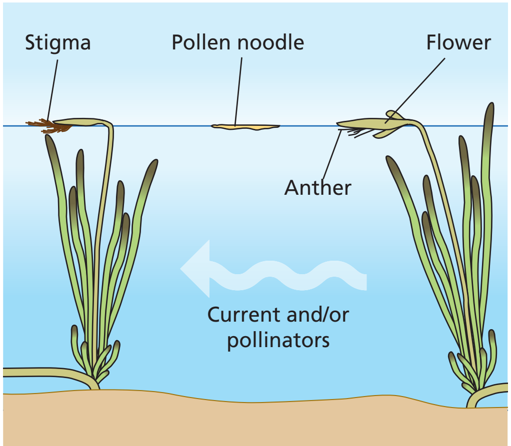


Figure 2.1 Sexual reproduction in shallow-growing seagrasses

Box 3 'World's largest plant is a seagrass that clones itself'

This was the title of a recent article in *Smithsonian* magazine, which reported research carried out in Shark's Bay, Western Australia. The scientists mapped 18 000 genetic markers in samples of Neptune grass (*Posidonia australis*) and found one individual that covered 200 km^2. Their research also revealed that this individual was a polyploid – containing the full complement of genes from both its parents – so was very likely to be unable to reproduce sexually. They attributed the massive reach of this plant to asexual reproduction, via horizontal stem spread over perhaps 4500 years.

Unusually for an asexually reproducing organism, the plant is highly resilient to variations in its environment. It experiences a wide range of water temperatures (from 17°C to 30°C in some years) and levels of salinity (as the bay is shallow, evaporation can cause the salinity to rise to twice its usual levels). The researchers hypothesise that this plant has a small number of somatic mutations across its range that help it persist under local conditions. However, they state: 'This is just a hunch, and we are tackling this hypothesis experimentally. We have set up a series of experiments in Shark Bay to really understand how the plant survives and thrives under such variable conditions'.

TERMS EXPLAINED

Epiphyte A plant that grows on another plant.

Seaweed This is not a scientific term, but is used to refer to a range of simple, macroscopic photosynthetic organisms (algae – members of the Protoctista) that grow in marine environments.

growth rate and ability to recover from grazing by herbivores (see Box 1) allowed grasses to dominate in many terrestrial ecosystems, as they still do to this day.

The marine ecosystem at the time was dominated by **seaweeds** – but then the first of what are now more than 60 species of seagrass started to adapt to life in the ocean (perhaps driven by the rising sea levels that have characterised the postglacial period). Among the adaptations that made this possible were the loss of stomata and a thinning of the waxy cuticle – both features that limit water loss in plants that live on land.

Terrestrial grasses rely on wind to carry pollen from plant to plant, which is clearly impossible under the water, so seagrass reproduction shows many additional adaptations (see Box 2). Once all these were in place, seagrasses began to dominate the world's subtidal coastal areas rich in the sand or silt grasses need for anchorage.

Present-day seagrasses range from plants with leaves the size of your fingernail, to some that grow up to 7 m tall. The horizontal stems allow them to populate the seabed (see Box 3), while the vertical leaf blades soak up the Sun and send sugars down to the stems. As you might expect, just as meadows on the land have grazers, those under the sea have theirs.

Seagrass grazers

One group of seagrass grazers comprises the turtles. These canny reptiles first snip off the tough, old, topmost portion of the seagrass leaves,

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A sea turtle (*Chelonia mydas*) eats seagrass

A Blue Meadows project buoy, alerting users of the bay to the seagrass beneath

© Falmouth Harbour Commissioners

before dining on the juicy new growth near the growing point at the base. Once they have established a neatly trimmed lawn of everlasting, new succulent food, they keep coming back to the same spot, over and over again.

Manatees and dugongs (also known as sea cows and sea elephants) are rather more destructive, because they root out and 'hoover' up the fleshy stems from the silt or sand – you can watch this happening at **https://tinyurl.com/grazing-dugongs**. A small herd of dugong can consume an area of seagrass the size of a football pitch every day. But the grass is well adapted to withstand this pressure – even tiny fragments of stem left behind can regrow and will eventually re-establish the meadow.

Ecosystem engineers

Seagrass communities therefore support some significant herbivores, but their role does not stop there. They also provide a valuable habitat for a huge range of other organisms, including fish, shrimp, rays, crabs, molluscs and the young of many animals that use the vegetation as a nursery ground (see Figure 1). Without such places to hide from predators, many of the young of these animals would not survive. Cuttlefish and squid, for example, lay their eggs in the grass, and the hatchlings rely on the cover that the grass provides.

Seagrasses also protect the rest of the marine ecosystem by binding the mud and silt that runs into the sea from river systems and as a result of human activity (e.g. coastal excavations). Seagrass meadows also have a huge capacity to soak up the nitrates and phosphates in fertilisers and sewage runoff. However, there is a limit to this tolerance, and many seagrass systems are now listed as endangered because the input of human-generated pollutants and/or silt is too much for the plants to deal with.

A threatened ecosystem

An over-abundance of nutrients (eutrophication, Biological Sciences Review Vol 35, No. 3, pp. 34–37) would not at first appear to be a bad thing, but it affects the grasses indirectly:

- Most of the grass leaves have organisms attached to their surfaces. If these organisms are photosynthetic – **epiphytes** – they will be stimulated to grow bigger, reducing the light that can reach the grass leaves.
- The tiny photosynthetic organisms in the water – phytoplankton – are usually too spread out to make much difference to the light reaching the seagrasses. However, when fertiliser or sewage runoff boosts the nutrients in the water, the phytoplankton can multiply so prolifically that the water becomes thick with them. This reduces the light getting through to the grasses, limiting photosynthesis.
- Many phytoplankton species release toxins that can cause mass mortality of other marine life, including grasses.
- Many seaweeds have high tolerances for nutrients, and therefore fast-growing green seaweeds, such as the sea lettuce, can out-compete and thus replace the seagrasses.

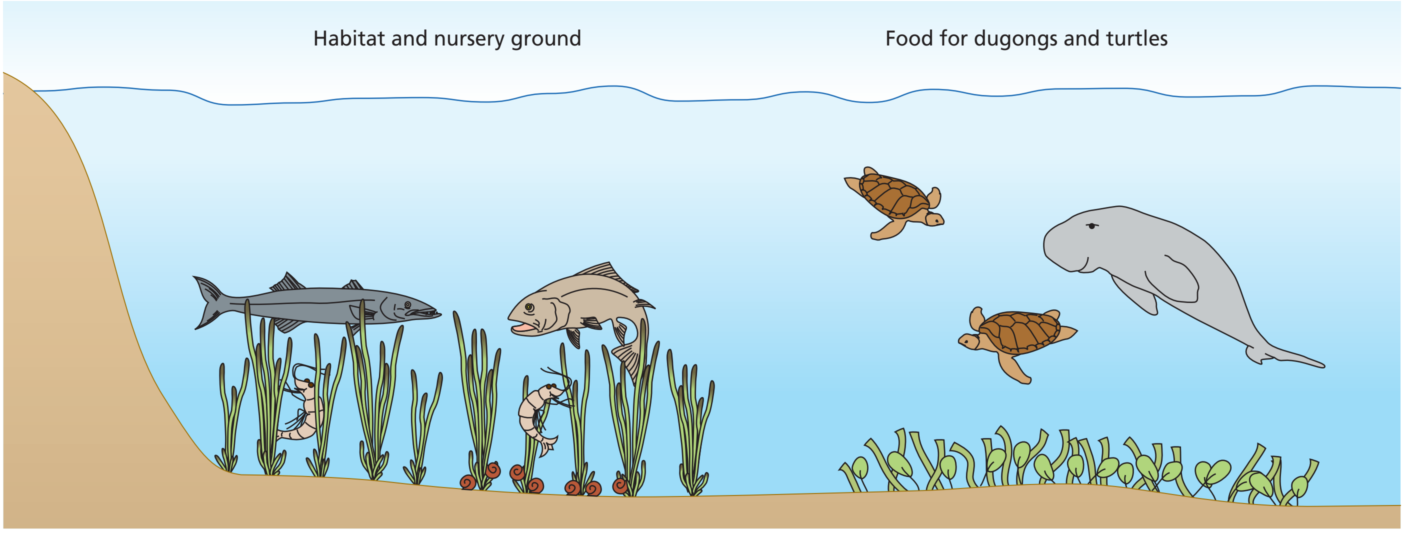


Figure 1 Seagrass communities provide a valuable habitat

Additional threats are posed by power boats, which rip the grasses out of the sediment and stir up silt, dredging by fishermen, and coastal developments, such as marinas.

These impacts mean that seagrass beds are among the world's most threatened ecosystems, with the current rate of loss estimated to be the size of two football pitches per day. Although they represent only 0.2% of the world's ocean area, these beds are vast carbon stores – representing about 15% of the ocean stores of carbon. Estimates suggest that 83 000 tonnes of carbon can be stored by 1 km^2 of seagrass. In comparison, estimates for land forests are only around 30 000 tonnes per km^2. Therefore, when seagrass beds are damaged, they release far more carbon than when an equivalent area of forest is destroyed.

Rays of hope

Governments in many parts of the world have passed legislation to protect seagrass beds. This includes restricting coastal development and pollution, limiting the speed of recreational boats, and preventing dredging or anchorage of vessels. In 2022, the global charity Ocean Conservation Trust launched a 700-hectare seagrass protection project. 'Blue Meadows' is designed to let leisure and commercial boat users know where seagrasses lie beneath the surface, and to work with them in minimising disturbance of the meadows, allowing the grasses to regenerate. A pilot has already begun in Falmouth, UK, where buoys have been placed in three key areas to protect over 20 hectares of seagrass meadow – equivalent to 20 football pitches. The project also includes research aimed to develop scalable, cost-effective techniques for restoring the seagrass meadows already lost.

If you are on holiday in an area where there are seagrasses, they are best enjoyed using a mask and snorkel, but please do your bit to protect them – avoid standing up in the beds or disturbing the sediment.

Things to do

You can be part of reMEDIES partnership's efforts to 'Save Our Seabed' by volunteering, joining an event, or getting your school involved in the education programme: **https://saveourseabed.co.uk/get-involved/**

RESOURCES

Sea change for seagrass: **https://bluemeadows.org**

'Dugongs and sea turtles at risk after Queensland floods wipe out seagrass, study shows': **https://tinyurl.com/seagrass-wipeout**

'World's largest plant is a seagrass that clones itself': **https://tinyurl.com/worlds-largest-plant**

Springwatch episode with focus on seagrasses: **https://tinyurl.com/springwatchseagrass**

'Seagrass flowers visited by invertebrates': **https://tinyurl.com/seagrassflowers**

The Marine Conservation Society website's section on seagrass beds: **www.mcsuk.org**

'Natural wonders of the Caribbean 2 – seagrasses': **https://tinyurl.com/Caribbean-seagrass**

'Why Do Seagrass Meadows Matter? Carbon Storage, Coastlines, Water Quality and Biodiversity': **https://tinyurl.com/seagrass-matter**

Professor Liz Sheffield is associate pro-vice chancellor (education) at the University of Liverpool and chair of the Biological Sciences Review editorial board.

spotlight

Finding Nemo's mother

Life on a coral reef

Real life coral reef biology is rather different from that depicted in the film *Finding Nemo*. Clownfish parental care stops when clownfish eggs hatch, and if a female dies she is quickly replaced. Reproductive biologist Liz Sheffield explains, and outlines some of the challenges faced by coral reef inhabitants

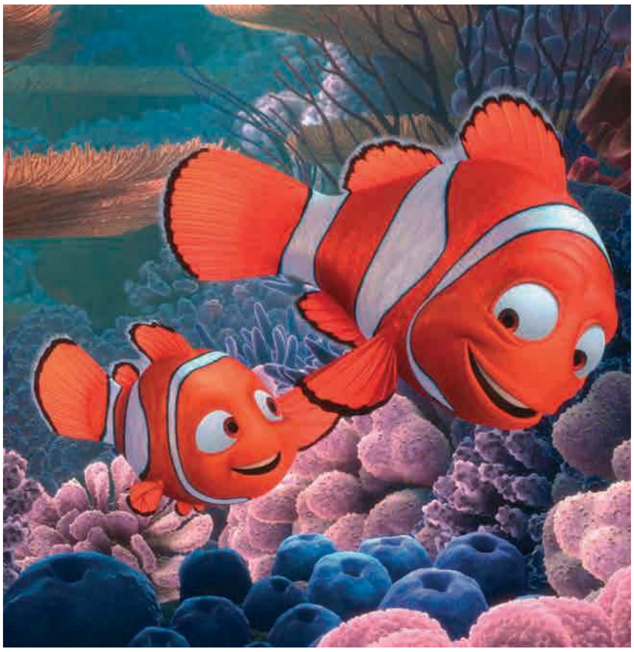
Key words

- Ecosystem
- Sex change
- Climate change
- Conservation
- Coral reef

As in the film *Finding Nemo*, clownfish do live 'in' anemones. The fish benefit from the protection afforded by the stinging tentacles of their host, but are themselves unaffected, probably thanks to their thick mucus covering. The anemones gain protection from their own predators, as resident clownfish aggressively defend their hosts. Movements of the fish also stir the water around the anemones, increasing the amount of oxygen that reaches their hosts. And waste products from the fish provide valuable nutrients for the anemone. So the relationship between clownfish and anemones is described as a mutually beneficial **symbiosis**.

Clownfish reproduction, however, does not reflect the story of the film. Females do lay eggs, and males are assiduous fathers — but that is where similarities between real life and the cartoon end. The first sign that a female is ready to reproduce is when both she and her mate clean their **spawning** site. The female then deposits a line of eggs onto the cleaned surface. The eggs are sticky, so they adhere to the surface, and the male follows closely behind the female, depositing sperm over the eggs. The pair repeat this process

Figure 1 Clownfishes and their host anemones in a coral reef ecosystem



over and over again, until the 200–1000 eggs in a clutch have been fertilised.

The male then assumes most of the caring responsibilities — he cleans and aerates the eggs. But the female stays nearby to defend the nest aggressively against any predators that threaten the brood. As the embryos develop over the next few days, the male works increasingly hard to ensure their successful development, eventually spending almost all the hours of the day and night tending the eggs. When the eggs hatch, parental care ceases completely. Indeed, the larvae must quickly migrate away from the nest site to avoid being eaten by their parents.

Clownfish hierarchy

Clownfish society is more complicated than simple pairs of males and females. In most locations you will find four or five clownfish associated with each anemone (see Figure 1). Only the biggest two fish reproduce. The largest fish is the female, and she dominates the hierarchy. The next largest fish is the male that will fertilise her eggs. The other two or three smaller fish play no part in reproduction. However, if the female dies, the male undergoes a remarkable transformation over the ensuing few weeks and becomes a fully functional female. The next largest fish in the hierarchy becomes a functional male and this pair enjoy the breeding privileges of the group. This process is called sequential hermaphroditism — in which organisms change from functioning as one sex to another during their lives (see Box 1). This phenomenon is common among plants and invertebrates, but also occurs in several genera of reef fishes.

Coral reef ecosystems

Among the attractions of coral reefs for divers and snorkellers are the stunning diversity of colours of the inhabitants, together with the warm, clear waters. Clownfish are brightly coloured, but the colours of the hard and soft coral animals that form the reefs, and the anemones that live with them, are not those of the animals themselves. To understand what makes coral reefs so colourful we first need to consider the food chains that underpin them.

As we know, the primary source of energy for the vast majority of ecosystems is sunlight. In most familiar ecosystems, sunlight is captured via photosynthesis in green plants and converted into a form that other organisms can use. In terrestrial ecosystems, plants are usually easy to identify — they are free-living, stand-alone structures with which we are all familiar. In coral reef ecosystems, they are less easy to spot.

Much of the photosynthesis carried out in coral reefs occurs inside animals. Soft corals, such as the finger coral shown in Figure 2, have single-celled photosynthetic partners living inside them. These single-celled organisms are algae — a non-scientific term used for a huge collection

Box 1 Sequential hermaphroditism

In an intact hierarchy (see Figure 1.1a) the female runs things. Making clacking sounds with her jaws, she gives orders to the subordinate male and the gentlemen-in-waiting. If she is removed or dies, the male begins to show aggression and dominance, and courts the smaller fish (see Figure 1.1b). His brain controls these behavioural changes, but we know relatively little about the mechanisms that underlie his sex change to female.

Changes in the brain are transmitted along a pathway from the hypothalamus to the pituitary gland and then to the gonad. A gonad is a reproductive organ and male clownfish have an ovotestis — including both male (testicular) and female (ovarian) tissue. The ovary is in an immature state, with only oogonia and primary oocytes. Once sex change starts, the testicular tissue degenerates and ovarian tissue matures. By the time it is over, the fish can lay eggs, but can never recover the ability to make sperm. Steroid hormones, especially oestrogen, are thought to be key regulators in this process.

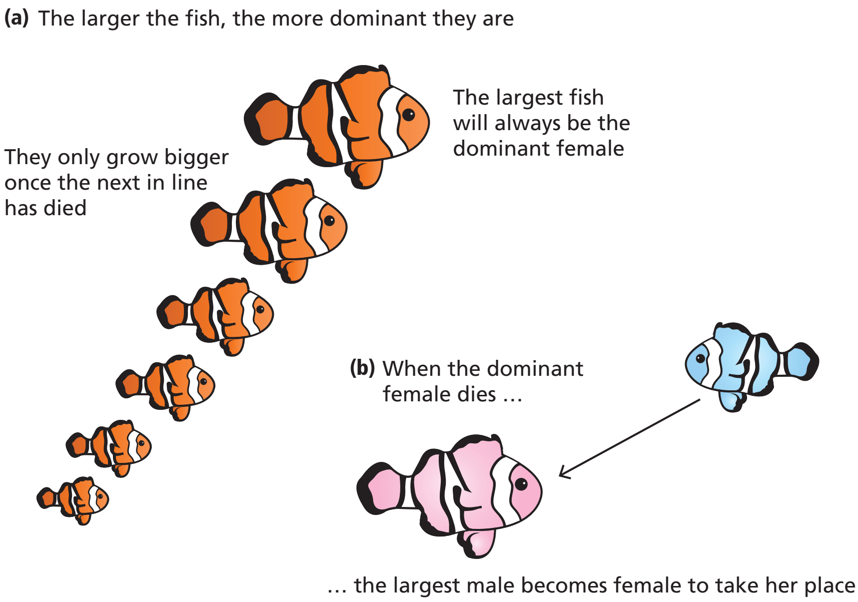


Figure 1.1 (a) Hierarchy **(b)** Sequential hermaphroditism

Figure 2 Close up of *Sinularia* — a finger coral

of photosynthetic organisms living in wet places that range from massive seaweeds to tiny blue-green bacteria only visible under high magnification in an optical microscope. They all have the green pigment chlorophyll, but many have accessory pigments of oranges, reds or browns, that give their hosts their characteristic colours.

The algae are found inside cells just under the surface of the tentacles of coral animals and anemones, as shown in Figure 3(a). This is another example of a mutually beneficial symbiosis. The algae gain protection from herbivores along with carbon dioxide and nutrients from the animals' waste products. They are accommodated in structures with large surface areas exposed to sunlight, optimising rates of photosynthesis. This provides the host animals with the oxygen and organic metabolites essential for their survival. Relationships such as these are key to the enormous productivity of coral reef ecosystems.

Warm water can hold less oxygen than cold, and tropical water typically has a low concentration of inorganic ions. This means that there are fewer free-living (planktonic) algae in tropical waters than in temperate marine ecosystems. Although this makes for crystal clear waters, which is great for viewing the inhabitants, it is not great for ecosystem productivity. Without the photosynthesis carried out by the algae living inside the animals, coral reef ecosystems would not survive. This is why coral damage (see Box 2) and coral bleaching — when algae die or are expelled by their hosts, leaving them colourless — are of huge concern to environmental scientists.

Coral bleaching

The balance between plant and animal in a coral symbiosis can be disrupted by both biological and environmental factors. If the algae succumb to disease, their pigmentation (and hence colour) is lost and the calcium carbonate skeleton of the animal becomes visible through their transparent tissues (see Figure 4). Since the 1980s it has become

BiologicalSciencesReview*Extras*

Alga: what's in a name? Find out at www.hoddereducation.co.uk/BioReviewextras

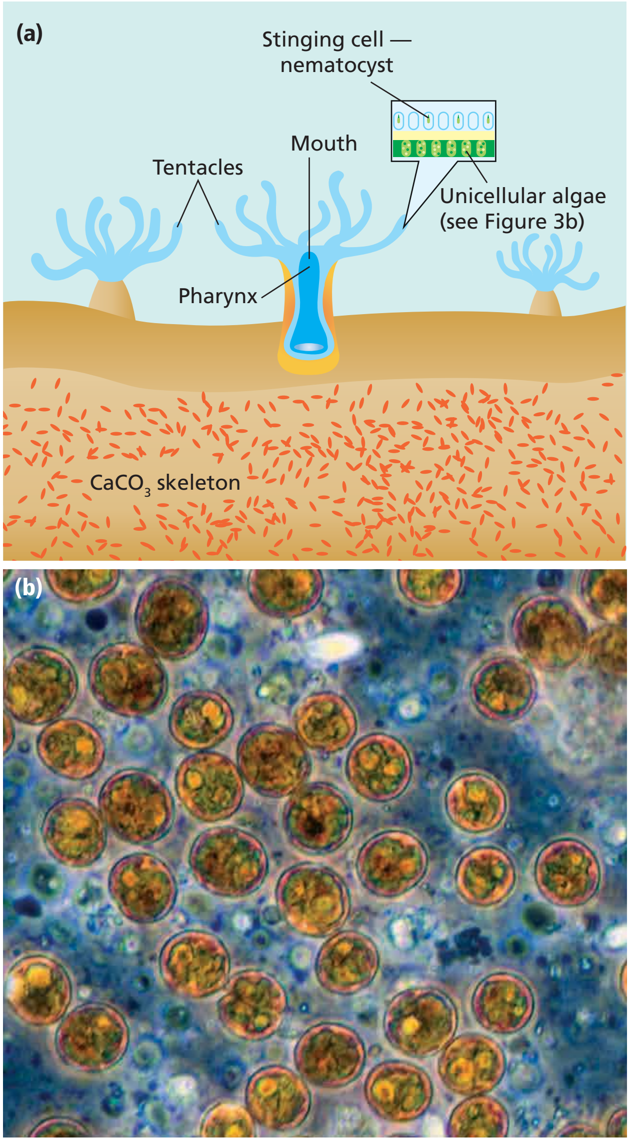


Figure 3 (a) Diagram explaining coral anatomy **(b)** Microscopic image of symbiotic algae inside a *Sinularia* coral ×1000

Figure 4 Bleached area of *Goniopora* — a hard coral

Further reading and viewing

Superb footage of clownfish (anemone fish) including an attack on a diver: **www.youtube.com/watch?v=8rSlA_ywEec**

More on coral bleaching and climate change: **www.globalcoralbleaching.org**

'Heat-tolerant genes could help corals adapt to climate change', *New Scientist* 25 June 2015: **https://tinyurl.com/kln78rl**

'Don't find Dory' — an explanation of why you should not buy a blue tang: **www.youtube.com/watch?v=0-8Uc-FLrmI**

Box 2 Threats to coral reefs

While water temperature poses the greatest problem, corals face several other **anthropogenic** challenges. The use of fossil fuels has led to acidification of waters all over the Earth. Burning fossil fuels generates waste gases including sulfur and nitrogen oxides, which combine with atmospheric water to form acids. Carbon dioxide released from fossil fuel use combines with seawater to make carbonic acid — further acidifying the oceans. The skeletons of corals are based on calcium carbonate, which dissolves in acid. The lower the pH of seawater, the more coral animals struggle to secrete their skeletons and the slower their growth.

Herbivorous fish graze on free-living algae on the surface of corals, keeping the corals clean and allowing their symbiotic algae to photosynthesise. Over-fishing reduces the numbers of these grazers, and allows seaweeds to grow over the coral surfaces, blocking out sunlight and eventually killing the coral. **Eutrophication** can produce a similar effect. Coral reef waters are usually too nutrient-poor to allow prolific growth of seaweeds, but the addition of extra nutrients can tip the balance and cause rapid colonisation of coral surfaces.

Dynamite fishing — the process of dropping explosives into the water to stun or kill fish — is exceptionally deleterious for coral reefs. I was recently diving in Indonesia, where huge tracts of the underwater environment (and the beaches) are strewn with dead coral rubble generated by dynamite fishing. Although the practice is now illegal, it still goes on in some areas and recovery takes many decades.

increasingly clear that global warming is causing large-scale coral bleaching. When the **thermal tolerance** of the symbiosis is exceeded, coral animals react by destroying or expelling their algae. Even without global warming, natural fluctuations in the Earth's temperature can make things worse. The **El Niño event** of 1997–98 was blamed for wiping out 16% of the world's shallow reefs.

Although coral reefs occupy only about 0.1% of our oceans, it is estimated that they support about a quarter of all marine species. They are especially important to juvenile fish, which rely on them for shelter while they grow to sufficient size to enter the open ocean, so coral reefs are vital to the 500 million or so people who rely on these fish for their food or income. An estimated 93% of the heat generated by global warming is absorbed by our oceans, so seas the world over are now significantly warmer than they were (see Figure 5). This is why research is underway, aimed at understanding how some reefs cope better with threats than others, and therefore might provide materials we could use to aid reef recovery.

One project involves studying corals in naturally acidified waters. These species could perhaps be transplanted to replace corals wiped out by acidification caused by humans (see Box 2). Other projects involve identifying corals with genes that confer resistance to heat and thence breeding heat-tolerant corals for seeding into reefs affected by global warming, as well as sinking structures into habitats suitable for colonisation by coral animals and thus starting artificial coral reefs. Hopefully these approaches, combined with worldwide agreements to limit fossil fuel use, will mean that future generations can continue to enjoy the beauty and bounty of coral reefs.

Terms explained

Anthropogenic Human-induced change.

El Niño event A natural phenomenon that occurs when trade winds weaken in the central and western Pacific. Surface water temperatures off South America warm up, because there is less upwelling of cold water from below.

Eutrophication Excessive concentration of nutrients in a body of water, e.g. from agricultural run-off from land, which causes dense growth of aquatic plants.

Spawning The release of eggs and sperm into water.

Symbiosis *sym* = together; *bios* = life, so the word simply means organisms living closely together. Some relationships are deleterious to one of the partners, e.g. where one is a parasite; others are beneficial to both – referred to as mutualism.

Thermal tolerance The entire temperature range that permits survival of a species or symbiosis.

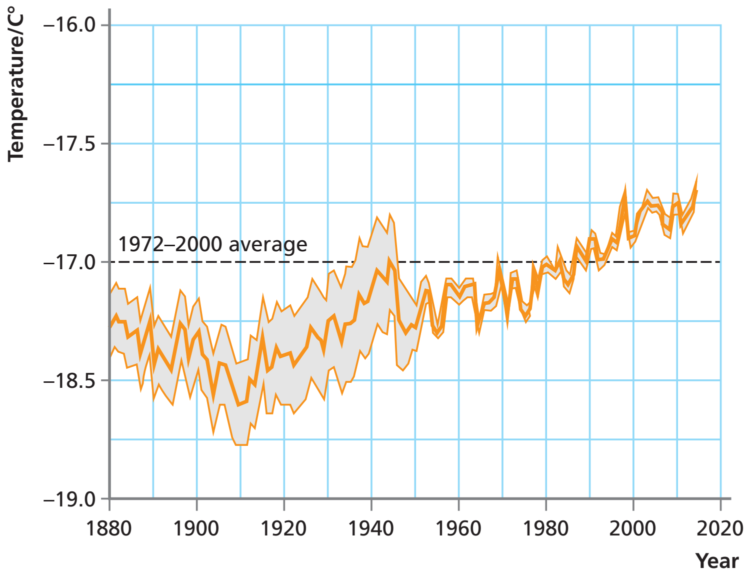


Figure 5 Average surface temperature of seas worldwide 1880–2020. The shaded band shows the likely range as there were few accurate measurements taken at the time

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It's a hard life on the rocky shore

How organisms cope with a constantly changing environment

On rocky shores organisms often find refuge in rock pools. These can be abundant with life and extremely diverse compared with the surrounding exposed rock

Jack Thomson

Rocky shores provide us with a rare opportunity to view and study an entire natural community. Marine biologist Jack Thomson describes the behavioural and physiological mechanisms that shore-living animals use to deal with the world around them, in particular their individual behavioural coping styles when faced with challenge

Rock pools are an interesting distraction on seaside holidays. Shrimp mill about searching for food, periwinkles, limpets and whelks crawl on the rocks, while crabs and fish make the most of shelter, hiding away until night when they can forage more safely. Seaweeds (algae — plants) provide animals with both protection and food. But life on rocky shores can be very hard — and I'm not referring to the rock itself. Acted out under the cover of seaweed are fascinating interactions between organisms and with their environment.

Key words

- Behaviour
- Ecology
- Habitat
- Species
- Community

Rocky shores are one of a range of different **intertidal** habitats that constitute a distinct environment somewhere between entirely marine and entirely terrestrial. The principal feature of a rocky shore is that the substratum is hard and impenetrable to all but a few animal species.

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Go online for more discussion about what algae are: **www.hoddereducation.co.uk/bioreviewextras** (Vol. 30, No. 1)

This means that animals are on the surface and, therefore, easily observed by researchers. But, compared with shores with soft sediment — sands and muds where animals can bury themselves — there are few opportunities for animals to escape from harsh environments, predators or competitors. The composition of the **communities** that are found on a rocky shore reflects how these organisms cope with both biotic (other organisms) and abiotic (physical and chemical) challenges.

The tides

The shore is dominated by environmental rhythms. The day–night cycle has an important influence on the ratio of respiration to photosynthesis in plants, and also affects animal physiology. The production of the hormone melatonin in fish and some invertebrates varies depending on the availability of light and on the time of day, and this hormone can influence behaviour. Many animals forage at night and thus avoid being seen by predators.

Another distinct rhythm on the shore is the tide — the rise and fall of the height of the sea relative to land, leaving the shore exposed or submerged. The tide rises and falls twice each day (with some unusual exceptions), with a cycle period of 12 hours and 25 minutes. The amplitude of the tide — how high and low the water goes — is largely a result of the gravitational pull of the Sun and Moon. Over the course of a month, as the relative positions of the Moon, Sun and Earth change, the pull of the Moon and Sun on the sea increases to a maximum when the Sun and Moon are aligned (spring tide) and decreases to a minimum when they are not (neap tide) (see Figure 1).

For a certain period each day, intertidal organisms are submerged or exposed, and this varies over the course of the lunar month. Those at the bottom of the shore spend the majority of their day under the water while those at the top may only be submerged for a few minutes. Unless they've found a rock pool or clump of seaweed in which to shelter, exposed animals face rapid and large changes in temperature and risk drying out (desiccation). Even those in rock pools face difficulties as the community in the pool steadily uses up oxygen and the temperature increases on hot, sunny days. The salinity of water in the pool also changes, either increasing as water evaporates or decreasing as freshwater rain falls or runs off the land into the pool. Until the tide returns, these animals are therefore under increasing physiological stress. Some are capable of protecting themselves. For example, periwinkles withdraw into their shell and seal themselves in using a hard **operculum**, a feature mostly absent in terrestrial snails. Animals must also be able to resist the impact of waves crashing against the rocks. This factor differs between shores, varying with the aspect and gradient of the shore, and with the weather. Some shores have high wave exposure, others are more sheltered.

Gastropods, such as whelks and these periwinkles have a hard outer shell that protects them from predators and a harsh environment. Many marine snails also have a hard plate, or operculum, which covers the shell's opening, and reduces desiccation

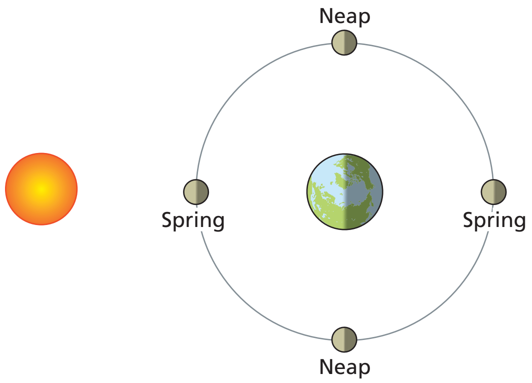


Figure 1 Relative positions of the Sun, Moon and Earth during the lunar cycle, and how these influence the tides. Spring tides have the widest range between high and low tide, neap tides the smallest

Zonation

Abiotic factors such as the tides limit the extent to which aquatic animals and algae can extend up the shore. Being marine, most of these organisms

Terms explained

Community An assemblage of species living in the same geographical area.

Habitat An ecological area occupied by a particular species.

Intertidal Land between low water and high water tides.

Operculum A tough plate of calcium carbonate used to seal the shell of a gastropod, which prevents water loss and predation.

Pheromone A chemical produced by one animal that alters the behaviour of another.

Range The area over which a particular species is found.

Sessile Fixed in one place.

Zonation The structuring of a community by biotic and abiotic factors into discrete zones consisting of particular species or groups of species.

thrive better closer to low tide, where submersion time is greatest. When submerged they can respire and feed most effectively. Only those animals with physiological adaptations to resist the extremes of the high shore can extend their **range** into this environment. However, since all of these organisms are competing for limited space, the lower extent of the range of most organisms is defined by biotic factors including competition and predation.

The interplay between physiological tolerance to the environment and behavioural responses to competitors and predators results in zones of discrete groups of species. Each zone hosts those organisms that are best suited to, and best able to compete for, conditions at a particular shore height. Rocky shores provide one of the best-known examples of **zonation**, and this can often be clearly observed from just a short distance away as regions of different colour running horizontally along the shore. These colour bands are formed by bands of macroalgae — the large seaweeds. The seaweeds most tolerant to desiccation are found at the top, and the least tolerant are at the bottom on the low shore. Brown seaweeds show a conspicuous change in species at different tidal heights. On very exposed shores, where waves can rip them from the rock, seaweeds are replaced by mussels and barnacles, which also form distinct zones.

Biotic interactions

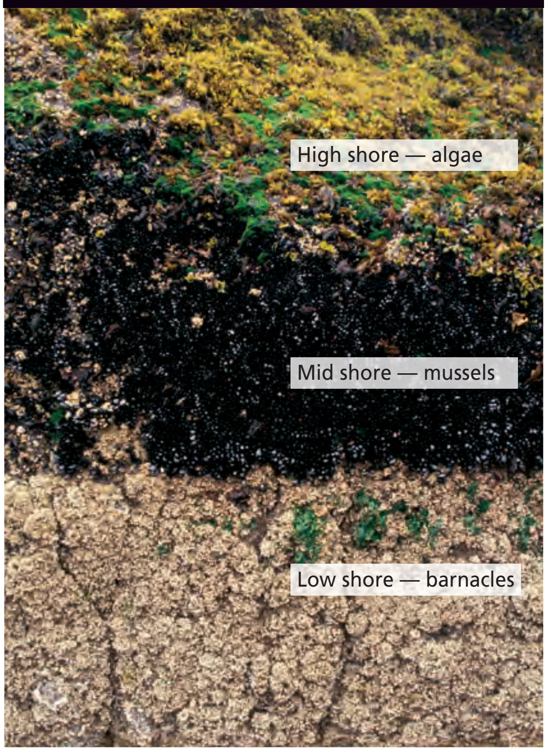
The biological interactions between and within species in a community involve a complex interplay between predation, grazing, competition and its inverse, facilitation (see Box 1). On rocky shores, potential competitors may be kept in check by predators, but competition is a major force driving community structure, especially when predators are absent.

Competition comes in many forms but is invariably over resources, such as space, food or mates. In rocky shore rock pools, cracks and crevices are in high demand, especially higher up the shore where submersion time is short. When space has already been taken, newly arriving organisms, such as water-borne larvae, may either fail to find room or may settle on top of other organisms, killing or displacing them.

Shore crabs are among the most motile of common residents on sea shores and generally aren't restricted to a particular shore height. They synchronise their movements up and down the shore with light and tidal movement. Competition among these animals is often focused around access to food and mates. When crabs come into contact with each other while foraging, they fight over available food and even engage in **kleptoparasitism** where one crab steals food from the claw of another. Males also compete over access to females, which they sense largely through the presence of sex **pheromones** in the water. Male crabs then hold on to a female until she is ready to copulate. So large is

A contest between anemones. The anemone on the right has its fighting tentacles inflated and strikes down on its opponent

Three distinct zones on an exposed rocky shore, consisting of algae higher up but giving way to mussels in the mid shore and barnacles in the low shore



Shore crabs can be extremely aggressive and take a fighting stance when faced with a threat

the inclination to obtain a potential mate that male crabs will grab and hold on to any inanimate object coated with these pheromones.

Some animals cannot move around so freely, so successfully competing for high quality territory becomes paramount. Beadlet anemones belong to a group of animals called Cnidaria (*Cnide* from the Greek work for nettle), which includes corals and jellyfish. Anemones may appear **sessile** but they can move around, usually very slowly. They position themselves in prime spots where, when submerged, they extend their feeding tentacles, embedded with stinging cells, and capture plankton (see Biological Sciences Review, Vol. 30, No. 2, pp. 12–15) or larger animals such as shrimp or fish. Suitable spots with ready access to food brought in by water currents are limited. They may not be submerged frequently enough, or already be colonised by algae or barnacles. So when an anemone is positioned in a good spot, it fights hard to keep it.

Anemones have a hidden arsenal. Lying beneath the feeding tentacles is a separate type of stinging tentacle, used specifically for fighting other anemones. When challenged, they inflate these tentacles with water and strike them down on their opponent, sometimes causing quite severe damage (see top photo and extra resources). Opponents repeatedly strike and sting each other until one cannot take any more and slowly retreats.

The extent to which these anemones fight depends on where on the shore they are found. Those higher up the shore are more likely to be aggressive than those found lower down. This seems counter-intuitive, since positions lower on the shore, where submersion time is longer, are usually held by the most competitive individuals. It may be that, since good, sheltered spots are in even shorter supply higher on the shore than lower down, anemones have to work harder to keep them.

Understanding how communities grow and develop, and how they respond to challenge, is an important component of ecology, and rocky shores provide an excellent example for the amateur and professional. Few other habitats boast such a range of environmental conditions in such a small space, nor have such diversity so clear to see.

Box 1 Facilitation

Individuals of the same or different species often compete for resources such as food and mates. In contrast, ecological facilitation describes positive, beneficial interactions within and between species, which encourage the development of diverse biological communities. For example, the presence of dense aggregations of barnacles on the high shore has been shown to act as a buffer to high temperatures, reducing rock temperature by several degrees Celsius. This in turn enhances the survival chances of other, temperature-sensitive species. An influx of blue mussels into the previously polluted South Docks in Liverpool not only provided a secondary habitat for other organisms but also improved water quality owing to the mussels' efficiency as filter feeders. This resulted in a dramatic increase in biodiversity over a period of just a few years.

Further reading

More information on rocky shores and the challenges organisms face there: **www.marbef.org/wiki/Rocky_shore_habitat**

Information on sandy shores — also a tidal habitat but with very different ecology: **www.marbef.org/wiki/Sandy_shores**

Lots of information about the wonderful range of organisms found on rocky shores: **https://tinyurl.com/y77zq6tz**

Find out more about tides: **www.ntslf.org/about-tides/tides-faq**

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Go online for 'Sea anemones stinging, fighting, swimming, reproducing and contributing to human health'
www.hoddereducation.co.uk/bioreviewextras

Dr Jack Thomson is a lecturer in marine and behavioural ecology at the University of Liverpool. He studies how aquatic animals respond to environmental challenges, including the influence of 'personality' on behaviour.

Key points

- The rocky shore is a dynamic environment with regular submersion by seawater and exposure to the air.
- Shore organisms face a range of challenges from other organisms and from their changing environment.
- How they cope with these challenges defines their position on the shore.
- Motile and sessile organisms use different strategies to cope with the stresses of life on the shore.

Biological Sciences update
OCTOBER 2020
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Remote control

DEAN MILLER/SCHMIDT OCEAN INSTITUTE

Liz Sheffield reviews recent advances in deep sea and aerial remote technologies

Over the last few months most of us have accessed information, entertainment and much of our social interaction on a screen. But practical research has not stalled, and scientists able to work remotely have made some particularly exciting progress.

Deep sea life

The research vessel *Falkor* is funded by philanthropy. During the global pandemic, researchers connected with the vessel and her crew remotely from their homes while it surveyed and sampled the deep waters of Eastern Australia using an underwater robot called *SuBastian* that streamed 4K video (see Figure 1). The research team identified new species of fish, snails and sponges. While shallow corals in the Great Barrier Reef region are currently suffering their third mass bleaching event in 5 years, *SuBastian*'s footage revealed no evidence of bleaching in corals living below 80 metres.

The robotic dives of the latest expedition were live-streamed via The Schmidt Ocean Institute's channel on YouTube and 112 hours of high definition underwater video allowed the researchers to share their knowledge and excitement about the discoveries around the world. They also interacted directly with the public via chat and commentary, finding — as have so many zoos, wildlife parks and museums that live-streamed during the pandemic — a huge appetite for remote interaction with organisms and the natural world.

ROV SUBASTIAN/SCHMIDT OCEAN INSTITUTE

Figure 1 *SuBastian*'s remote-controlled manipulators gently grasp a *Nautilus* shell bearing a black coral, 550 m deep at Herald Cays. Researchers can extract and sequence the coral's DNA and assign it to the correct family

Next page

Biological Sciences update
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Detection of death

Oceans cover more than 70% of the Earth's surface but forests cover more than 30% of the Earth's land surface and many are difficult or dangerous to investigate directly. People can 'disappear' in forested areas and many missing persons have had to be presumed dead. The search for missing bodies usually starts with pedestrian surveys and cadaver dog teams. But when search areas are extensive or the terrain is rough, ground-based searches can be challenging and resource-intensive. Drone-based remote sensing strategies might be the way forward.

The average adult human contains about 2.5 kg of nitrogen, much of which is released and converted into ammonium compounds when the body decomposes. These compounds and the microbes associated with the body (the necrobiome) change the surrounding soil. Nitrogenous compounds in the soil can spike to levels 50 times higher than when fertiliser is added. This influences both the microbes in the soil (the soil microbiome) and plant composition.

Increased leaf nitrogen increases chlorophyll production so the spectral signature of the fluorescence being generated and reflected from the leaves alters. This means that alterations in the canopy of the leaves on trees in the 'human decomposition island' of a body can potentially be detected by drones carrying biochemical and infrared thermal sensors.

With trees acting as environmental sentinels, forensic investigators can make decisions that maximise resources and keep search teams safe in conflict zones. Vegetation that is currently considered an obstacle has the potential to become a significant asset in the detection of human remains.

BLACKZHEEP/ADOBE STOCK

Weblinks

'First completely remote at-sea science expedition in Australia's coral sea marine park discovers new corals and possible species never seen before', Schmidt Ocean Institute, 24 June 2020: **https://tinyurl.com/y6f2azab**

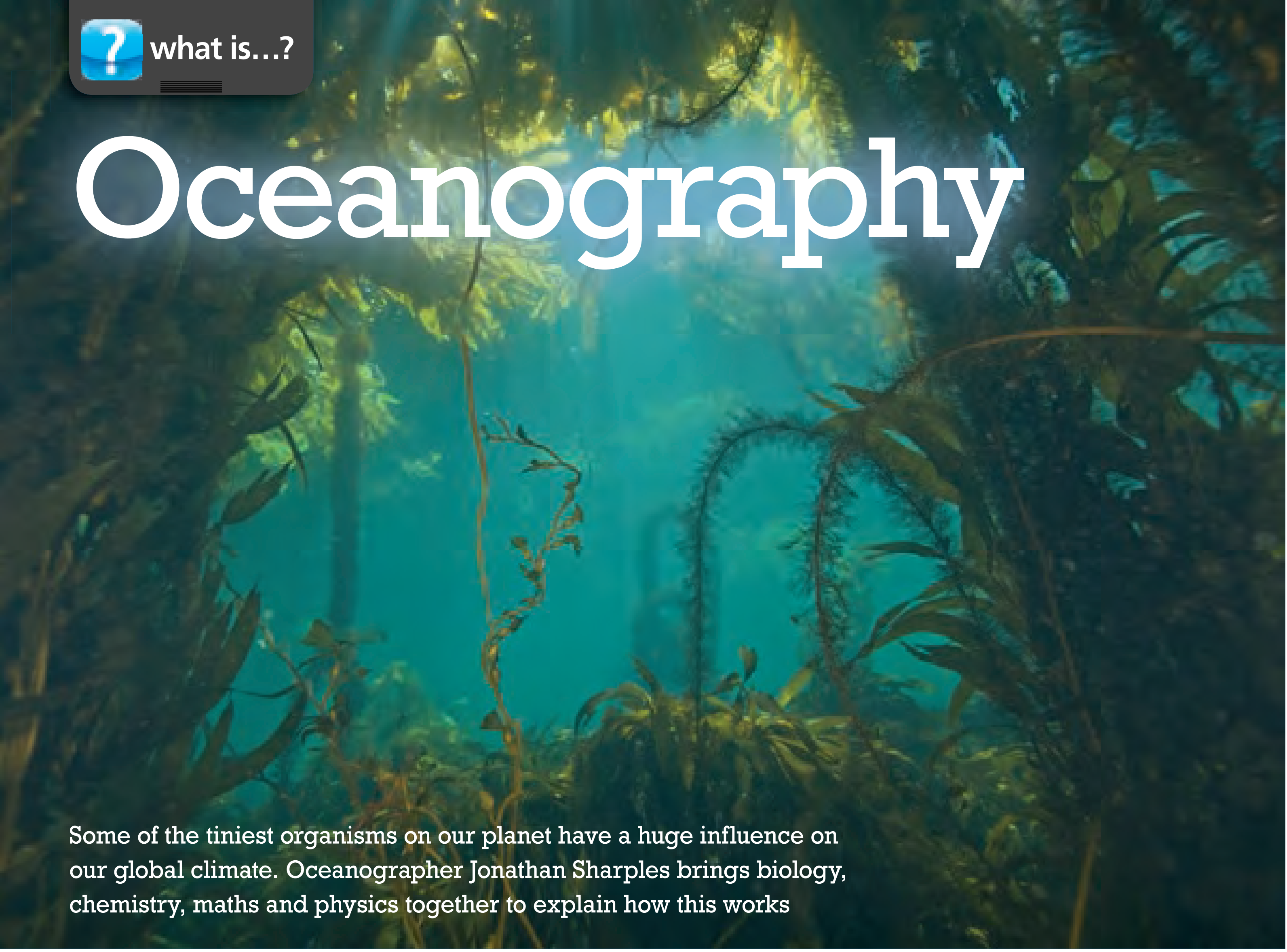
'Australian scientists discover new corals on most comprehensive deep-sea study of Great Barrier Reef and Coral Sea Marine Parks', Schmidt Ocean Institute, 8 Sept 2020: **https://tinyurl.com/y22vnoqs**

Body farm website: **https://tinyurl.com/yxcn3ywy**

Activities

Find out how unique biochemical signatures might allow human remains to be distinguished from those of other animals, and discuss with your fellow students which ecosystems might include scavengers that could perturb plant detection of human remains: 'Can the leaves of plants help us find buried human remains?', Science Alert, 4 Sept 2020: **https://tinyurl.com/y2t9ynw8**

Get involved in a citizen science project: **www.citizenscience.org**
For example, 41 165 people in 244 cities took part in the City Nature Challenge despite the pandemic this year. Don't worry if you aren't good at identifying organisms — download a free app (e.g. iNaturalist seek: **www.inaturalist.org/pages/seek_app** — which can give you all seven taxonomic ranks of an animal, plant or fungus from kingdom to species from a photo on your mobile).



what is...?

Oceanography

Some of the tiniest organisms on our planet have a huge influence on our global climate. Oceanographer Jonathan Sharples brings biology, chemistry, maths and physics together to explain how this works

Plants form the base of food chains that support almost all animal life. They are also important for removing carbon dioxide from our atmosphere, and for generating oxygen. If you were asked which plants are the most important players in these processes, you might suggest trees, and describe the role played by the tropical and northern forests. However, of the total amount of photosynthesis happening on our planet, only half of it happens on land. The other half takes place in the ocean.

Key words

- Carbon dioxide
- Nutrients
- Photosynthesis
- Zooplankton
- Phytoplankton

Photosynthesis at sea

What is an important plant that grows in the ocean? When asked that question, knowing what terrestrial plants are like, you might think of things with similar structure and scale — seaweeds. But while kelp forests such as that shown above are important ecosystems in some parts of the world, they do not add much to the total amount of photosynthesis that goes on in the sea — seaweeds are responsible for only about 2–3% of the ocean's photosynthesis. The most important players in the ocean are the microscopic single-celled plants, the free-living members of which are called phytoplankton (from the Greek *phyton*, meaning plant and *planktos*, meaning drifter).

Phytoplankton are tiny. The smallest is a photosynthetic bacterium called *Prochlorococcus*. This single-celled plant is less than 1 μm in diameter, but it is the most numerous photosynthetic organism on Earth (see Figure 1). It is the dominant plant in most of the open ocean.

Somewhat bigger than these bacteria are the many species of flagellates and dinoflagellates (see centrespread). These eukaryotes are typically a few thousandths to a few hundredths of a millimetre in size. At a similar size there are coccolithophores (see Figure 2 and the centrespread). These single-celled marine plants are encased in chalk plates. Their name reflects these plates — *cocco-* comes from the Greek word for berry, used to denote objects that are spherical, *lith-* comes from the Greek for stone, and *-phore* is Greek for 'bearing'. Over millions of years, as the coccolithophores sink to the seabed, they become compressed into rock and form features such as the white cliffs of Dover.

At the top end of the size range is a group of phytoplankton called the diatoms (see centrespread). These reach sizes of a few hundredths to a tenth of a millimetre. Diatoms are encased in intricate, tough, silica shells. Their name comes

BiologicalSciencesReview*Extras*

Go to the extra resources for issue 1 of this volume to find out why oceanographers consider photosynthetic bacteria and algae to be plants: www.hoddereducation.co.uk/bioreviewextras from the Greek word for 'cut in two' as they are all formed in two halves (see the junction running around the cell in A in the centrespread). Over millions of years, as diatoms build up on the seabed they form deep deposits. Under some conditions these deposits form oil; under others, the build-up forms diatomaceous earth. Both commodities are harvested and used in a wide range of applications. The uses of diatomaceous earth include use as a filtration aid, mild abrasive (metal polishes and toothpaste), porous support (cat litter) and a stabilising component of dynamite.

Phytoplankton may be small, but they are very numerous. If you scoop up a mug full of seawater next time you are at the beach, you've caught about half a million phytoplankton. They are so abundant we can visualise them from space, using satellite-mounted sensors that can detect chlorophyll (see Figure 3). The sensors measure the amount of light from the ocean (or land) in several wavebands (or colours). The concentration of chlorophyll is estimated by looking at the ratios between the different colours. For instance, the light reflected from the ocean shifts from blue to green as the amount of chlorophyll increases. These satellite methods are tested and calibrated against samples collected by oceanographers working on ships at sea.

The challenges of plant growth at sea

Phytoplankton growing in the ocean have problems that terrestrial plants don't face. In order to grow, all plants need sunlight, nutrients (such as nitrates and phosphates) and carbon dioxide. On land, most plants have leaves in the air, where there is plenty of sunlight and CO_2, and roots in the soil, where there are nutrients. When they die, their organic material decays in the soil and is recycled into nutrients that can be used by other plants.

In the ocean, life for a plant is trickier. Sunlight is absorbed very effectively by water — at a depth of 50 m or so below the sea surface, the amount of light available is less than 1% of the light that hits the sea surface. So phytoplankton can only photosynthesise and grow in the surface few tens of metres of ocean. But the average depth of the ocean is roughly 3.5 km. When phytoplankton die, they sink to great depths. So the recycling of dead organic material occurs hundreds or even thousands of metres away from the sunlit surface waters. Indeed, when we measure nutrients in the ocean (see Figure 4) we find that there are hardly any in the surface water, but a lot much deeper.

Growing roots to reach hundreds of metres, perhaps over a kilometre, down into the ocean bed is physically unfeasible. So how do phytoplankton grow in the surface sunlit ocean, and at the same time acquire the nutrients they need? The answer lies in how the water circulates and mixes. When you pour milk into a cup of coffee, you might stir the drink to get the milk evenly mixed through it. In the ocean, water currents and turbulence stir up the water, which brings the nutrients from the depths up to the sea surface. Without this, nutrients would become concentrated in the bottom of the ocean and plant life in the surface ocean would cease.

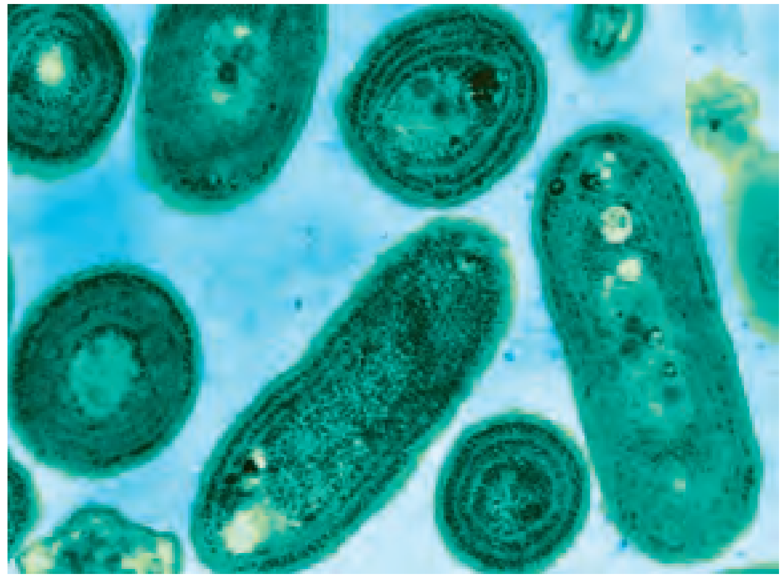


Figure 1 Coloured transmission electron micrograph of the cyanobacterium *Prochlorococcus*. The membranes coloured green are thylakoids — similar to the photosynthetic membranes in chloroplasts ×40 000

Winds and waves at the sea surface, along with tides, can cause turbulence. This is why, in satellite images showing chlorophyll, much of the ocean's chlorophyll is in the northern Pacific and Atlantic and in the Southern Ocean — places where we frequently get storms (see Figure 3). Along the equator, deep currents bring inorganic ions up to the surface and provide nutrients for the phytoplankton. So phytoplankton growth is intricately linked to the physics of the ocean.

So what about the carbon that plants need to grow? There is plenty of carbon dioxide dissolved in seawater — there is about 50 times more carbon in the ocean than there is in the atmosphere. When phytoplankton grow in the surface sunlit waters, they absorb dissolved carbon from the sea (in the same way that land plants absorb CO_2 from the air). As the ocean surface loses carbon to the phytoplankton it absorbs more from the CO_2 in the atmosphere.

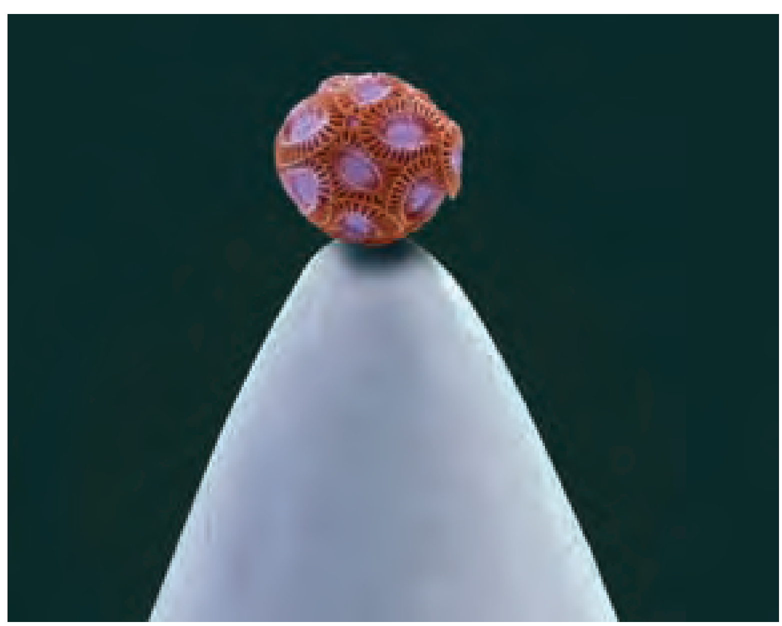


Figure 2 Coloured scanning electron micrograph of a coccolithophore on the tip of a pin ×400

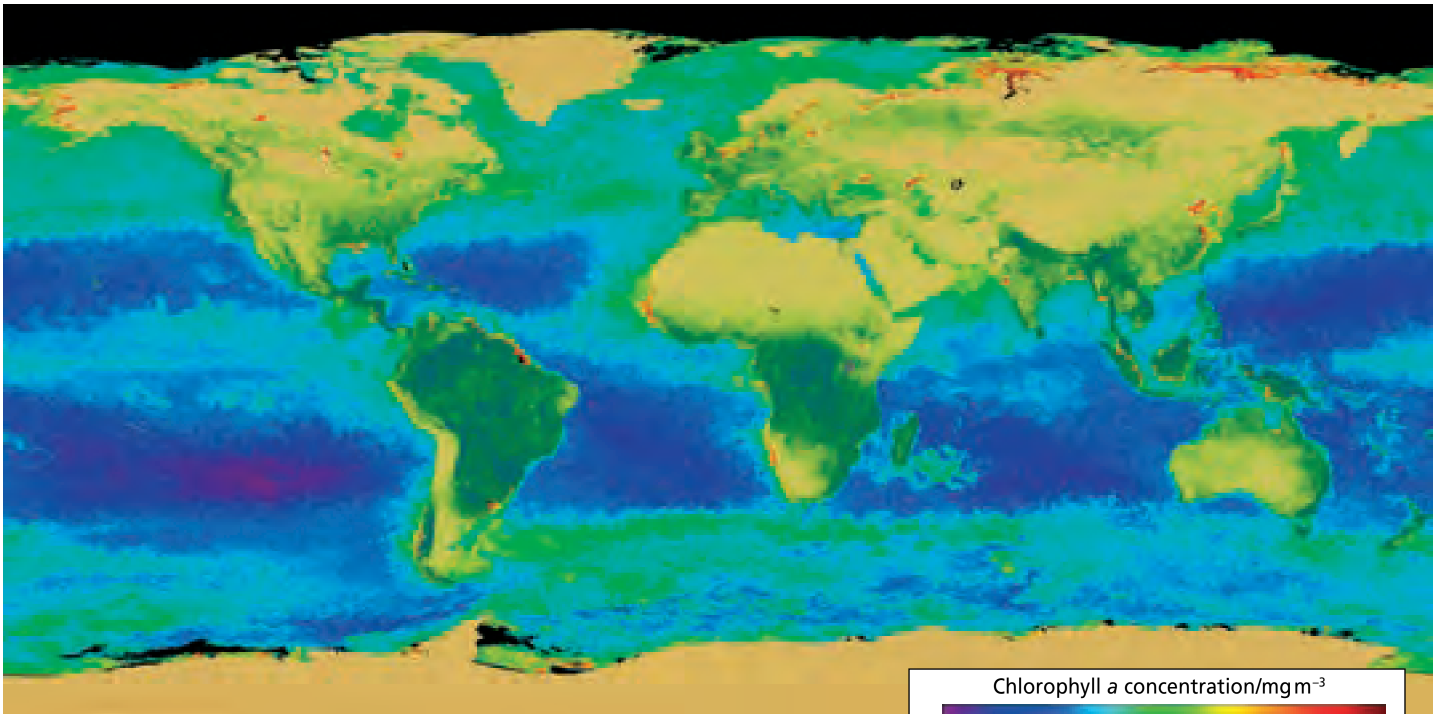


Figure 3 Satellite image showing chlorophyll. On the land, the tropical and temperate forests are clearly visible in dark green. In the ocean there is abundant chlorophyll in the northern Atlantic and Pacific, in the Southern Ocean near Antarctica, and along the equator — almost all of this ocean chlorophyll is inside microscopic phytoplankton

Figure 4 Left: an instrument package being deployed into the ocean to collect information. The package is lowered down to the seabed, sending back data including temperature, salt concentration and the amount of chlorophyll in the water. The grey bottles can be snapped shut at different depths, trapping seawater that is then analysed for phytoplankton and nutrient concentrations back aboard the research vessel (right)

Further reading

Miller, C. D. (2003) *Biological Oceanography*, Blackwell Publishing.

The Monterey Bay Aquarium Research Institute: **www.mbari.org**

Earth Observatory, 'Chlorophyll': **https://tinyurl.com/ybopemn8**

'From tiny plankton to massive tuna: how climate change will affect energy flows in ocean ecosystems': **https://tinyurl.com/ydcefzov**

Plankton and our climate

The great depths of the ocean are an advantage to us when it comes to the fate of all that carbon absorbed by the phytoplankton. As with the nutrients used by the phytoplankton, the recycling of the carbon contained in phytoplankton happens deep in the ocean. This means that the organic carbon taken downwards by the sinking phytoplankton will not see the atmosphere again for the length of time it takes the ocean circulation to bring that deep water back up to the surface. This is typically a few hundred to a thousand years. So phytoplankton growth causes the ocean to take CO_2 out of the atmosphere, and the sinking dead phytoplankton export that carbon downward and away from the atmosphere. This carbon sink is a key part of how our climate works (see Box 1).

There is one more important player in this story of how microbes in the ocean affect our climate. The phytoplankton are eaten by tiny marine animals called zooplankton (see Figure 5). The zooplankton play two important roles. First, they themselves are eaten by plankton-eating fish (e.g. anchovies, sardines, mackerel, basking sharks) and so they provide a way of getting all that plant material into the rest of the food chain (see Box 2 and the centrespread). Second, and linked to our climate story, the zooplankton are important because they defecate. The faecal pellets released by these tiny animals are made up of densely packaged waste carbon — carbon that was originally part of phytoplankton cells. These dense pellets sink to the deep ocean very quickly — an efficient pathway exporting the carbon away from the atmosphere, as the high speed of sinking means that most of the recycling of the carbon occurs deep in the ocean, well away from the atmosphere.

Understanding how microscopic plants grow in the ocean and how they affect Earth's climate is one of the big topics that biological oceanographers investigate. What makes oceanography so interesting is that dealing with such big questions is not just biology. To fully understand the plankton and what they do you also need to include the chemistry of ocean nutrient distributions and the physics of ocean circulation and mixing. When we go to sea on our research voyages we work in multi-disciplinary teams, bringing experts in ocean biology, chemistry and physics together to answer some of the most important questions about how our planet works.

Figure 5 One of the most important groups of animals in the ocean — a member of the zooplankton. This is a copepod — vital food for fish larvae and plankton-eating fish (see pp. 20–21) ×10

Box 2 How much phytoplankton does a fish need?

The answer to this question depends on how many trophic levels there are between the phytoplankton and the fish. For an anchovy, which eats zooplankton, there are two trophic jumps — phytoplankton to zooplankton, and zooplankton to the fish. For a larger predatory fish (such as tuna or shark) there might be four or five trophic jumps as the smaller fish eat the zooplankton, and then themselves get eaten by progressively larger fish (see centrespread). Very roughly, each trophic jump is 10% efficient in transferring organic fuel up to the next level. So an anchovy will need to have consumed about 10 times its mass in zooplankton, which will be based on 100 times its mass in phytoplankton.

Box 1 Phytoplankton and climate change

The growth of phytoplankton is not limited by a lack of CO_2. This means that increasing CO_2 in the atmosphere, which is happening due to climate change, does not make life better for phytoplankton. Instead, their growth is limited by nutrient supply. Over much of the ocean the limiting nutrients tend to be nitrates and phosphates. However, there are significant areas, such as the Southern Ocean around Antarctica, where there is plenty of these nutrients, but iron is the factor that limits phytoplankton growth.

It has been suggested that fertilising the ocean (e.g. by dumping large amounts of iron in the Southern Ocean) could trigger extra phytoplankton growth and remove more CO_2 from the atmosphere, thus helping to solve our global warming problem. But this wouldn't work. The excess nitrates and phosphates in the Southern Ocean is part of a global circulation of nutrients. Stimulating the use of these nutrients by adding iron simply means that they are not available for phytoplankton growth in other parts of the world. In other words, fertilising one part of the ocean might increase phytoplankton growth there, but the net effect over the entire global ocean will be zero.

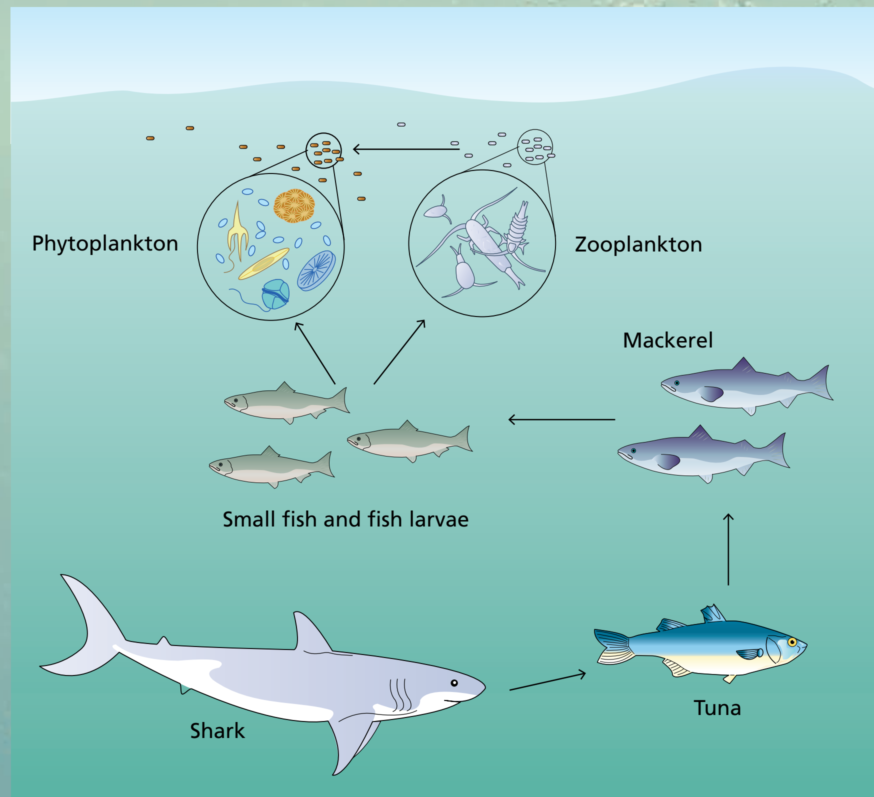
Professor Jonathan Sharples is an oceanographer at the University of Liverpool. His research focuses on ocean circulation in the large sub-tropical regions of the oceans. At the University of Liverpool he uses his research findings to teach undergraduate students of oceanography about how the ocean supports the life of microbial plankton and how they affect Earth's climate.

Biological Sciences review

Ocean food chains

Trophic levels

Most of the life in our oceans relies on energy from the sun. The primary producers — the organisms at the first trophic level — include some of the microscopic aquatic organisms (plankton) shown here in coloured scanning electron micrographs. These photosynthetic members of the plankton are called phytoplankton.



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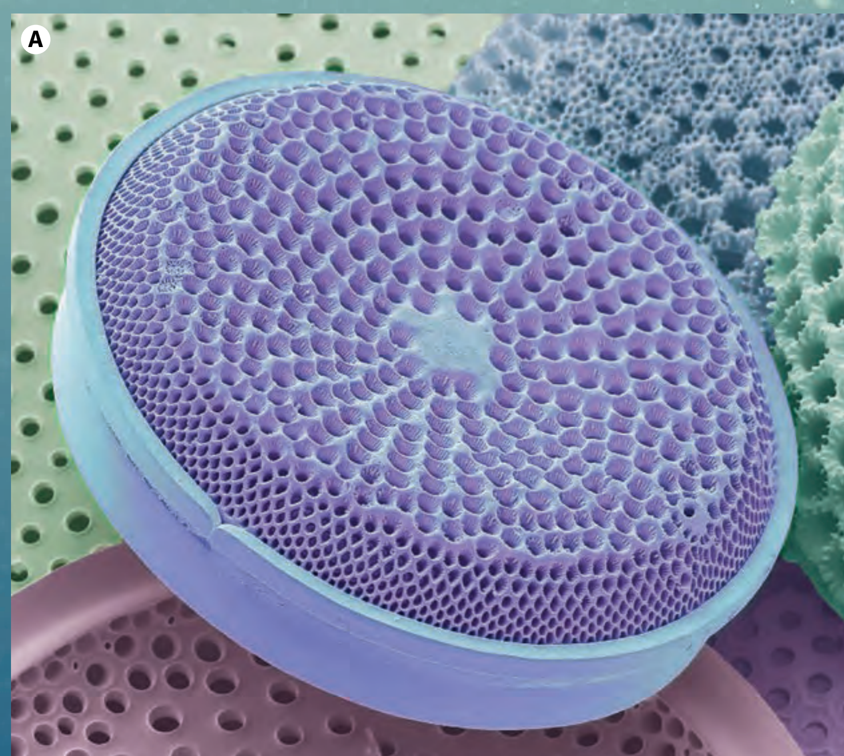
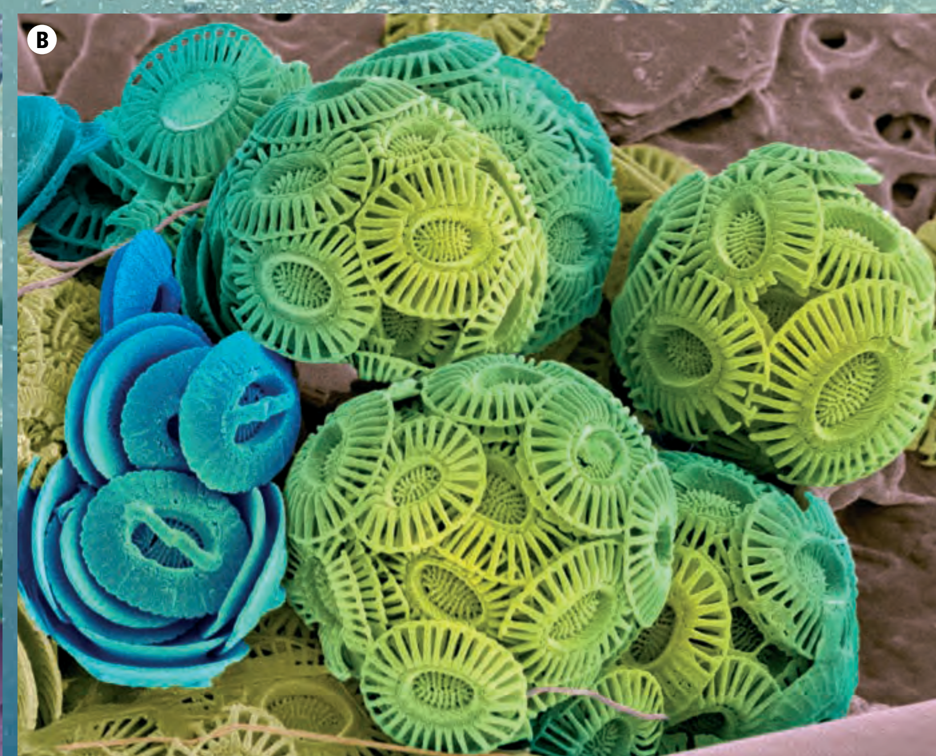
Zooplankton

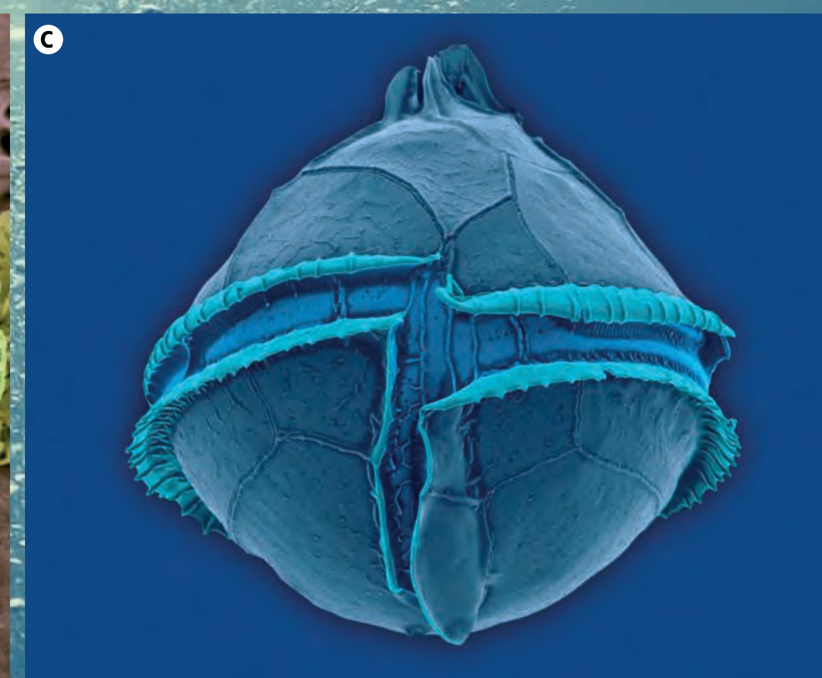
D is a copepod (×300) — a tiny crustacean animal — a member of the zooplankton. These organisms form the second trophic level — first consumers — which are in turn consumed by larger consumers further along the food chain.

Phytoplankton

A–C are all single-celled phytoplankton and one thing that distinguishes them from each other is their cell coverings. A is a diatom (×1400). The intricate, tough covering of diatom cells is primarily silica. B shows coccolithophores (×1200)— their cells are encased by chalk plates. C shows a dinoflagellate (×665)— protected by plates of armour made of cellulose (when alive, the cell had one flagellum encircling it and another in the groove running from the middle to the posterior). The posterior flagellum drives the cell forward, the girdle flagellum causes the cell to spin on its axis. The net result is that these organisms spin through the water very efficiently — the aquadynamic equivalent of the aerodynamic efficiency of a bullet travelling out of a rifle barrel.







Professors Jonathan Sharples and **Liz Sheffield**, University of Liverpool

Starfish supper

Crown of thorns sea stars are voracious consumers of coral. What can we do to protect coral reefs from these predators?

Figure A Crown of thorns sea star on coral. The animal has grazed the living topmost layer of the coral, leaving behind empty skeletons of calcium carbonate

Coral feeders

Coral reefs around the world face many challenges. Coral bleaching (linked to climate change), pollution and hurricanes all take their toll. Many reef systems in the Indo-Pacific region, including Australia's Great Barrier Reef, face an additional, biological threat. Each adult crown of thorns sea star – COTS – can consume its own body area of living coral every night (see Figure A). These nocturnal animals can grow to a width of up to a metre, and on average each individual destroys 13 square metres of coral per year.

In an ecosystem in balance, these coral predators would pose little problem, but humans have overfished their predators (see Box 1) and agricultural runoff has provided rich nutrients for their larvae. Booming numbers of COTS have become the major cause of coral death for the already-struggling Great Barrier Reef and recent research has revealed a sinister twist to the story. While corals can recover, it takes time for them to establish – but the COTS can wait. The juvenile stage of COTS is herbivorous. Normally, the juveniles switch from eating algae to consuming coral when around 4 months old. But if coral is not plentiful, the juveniles can survive on algae until they are up to 6.5 years old, and then switch to eating coral – thwarting coral recovery.

Figure B Diver bagging a crown of thorns sea star. Subsequent immersion of the animals in fresh water can then be employed to kill them

Combating COTS

Until recently, the only sure way to eliminate COTS was physical removal and destruction of the animals (see Figure B). Trials of computerised recognition systems combined with robotic devices to deliver toxic solutions started to show promise in 2005. However, recognition accuracy of less than 70%, the need to inject a toxin into every arm of each animal (to prevent regeneration), and the risks posed by toxins to other life forms impeded progress.

In 2014, research showed that a single injection of bovine bile salts – a readily available commercial product obtained from the meat industry – killed COTS. Bile is secreted by the gall bladder of mammals, and assists with the emulsification of lipids in the small intestine. When injected into a sea star, these salts cause tissue damage, which in turn triggers a rapid and powerful immune response. The wave of tissue destruction that follows kills every part of even large sea stars in less than a day. And crucially, extensive research on a range of animals fed on bile-injected COTS showed no ill effects.

Advances in artificial intelligence and robotics have generated a robot than can recognise COTS 99.4% of the time, so we now have a means to tackle this voracious coral enemy that benefits other organisms in the ecosystem.

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Figure C Harlequin shrimp feeding on detached sea star arm

Box 1 Biological control

Reefs closed to commercial fishing have fewer COTS than those where fishing is allowed. Research shows that a wider range of fish feed on COTS than previously suspected. The development of a genetic marker for COTS allowed researchers to detect COTS DNA in the faeces of a range of reef fish and invertebrates. So, allowing the natural predators of COTS to thrive could help efforts to control outbreaks.

One species suggested as a key predator in the biological control armoury is the harlequin shrimp (see Figure C). These colourful crustaceans are well known for their gruesome sea star 'farming' habits. When a harlequin encounters a sea star, it starts by eating the tube feet (which sea stars use to move around, prise open prey, and 'right' themselves if flipped over). This immobilises the sea star, which means the shrimp can continue to dine at its leisure. If the sea star detaches a limb, it can regenerate the limb but the shrimp still gets a good meal, and there are reports of harlequins keeping immobilised sea stars alive for several weeks by feeding them, thus maintaining a living larder.

RESOURCES

'Hidden army: How starfish could build up numbers to attack coral reefs: crown of thorns starfish lie in wait as algae-eating young before attacking coral', *ScienceDaily*, 8 April 2020: **https://tinyurl.com/y4a4b4cr**

'"Love hormone" has stomach-turning effect in starfish', *ScienceDaily*, 31 July 2019: **https://tinyurl.com/y4hgcfv9**

'Fish feces reveals which species eat crown-of-thorns: Great Barrier Reef research finds the destructive starfish is eaten more often than thought', *ScienceDaily*, 18 May 2020: **https://tinyurl.com/yxoha696**

'Sea-star murdering robots are deployed in the Great Barrier Reef', smithsonianmag.com, 31 August 2018: **https://tinyurl.com/yy7nqd2x**

Are starfish really fish? National Ocean Service: **https://tinyurl.com/y5u23ee4**

Professor Liz Sheffield, University of Liverpool

EVALUATING EXPERIMENTS

Some anemones like it hot

Problems with design are not the death of an experiment

Environmental scientist Daniel Maskrey investigated how sea anemones change their behaviour in response to laboratory-simulated heatwaves. Here he explains the methods he used, how they could have been improved and the conclusions that can (and cannot) be drawn from the experiments

If you put two animals of the same species in identical environments, they may behave differently. If they do, the differences are usually maintained over time. This is the result of animal personality. By taking many individuals of a single species and repeatedly testing certain behaviours, we can make quantitative measurements of differences in personality.

Personality can drive different individuals to change their behaviour in different ways in response to changes in their environment. These changes in behaviour are called behavioural plasticity. By repeatedly testing the behaviour of animals in many environments, we can obtain measurements of differences in behavioural plasticity. Plasticity is important for animals to reduce the negative effects of environmental change, so differences in personality should have important implications for the survival and reproduction (fitness) of different individuals faced with climate change.

Beadlet anemones (*Actinia equina*)

Beadlet anemones inhabit almost every British seashore and show a range of well-characterised behaviours. They are helpful for investigating the effects of climate change on behavioural plasticity because they live at different heights on the intertidal seashore. Animals living higher up the seashore experience harsher conditions and higher temperatures than those living lower down. Beadlet anemones also have different morphotypes (genetically and visually different groups – see Box 1). The more aggressive red-underside morphotype lives higher up the shore than the less aggressive green-underside morphotype. Researchers can tell the different morphotypes apart by sight, allowing for straightforward investigations of genetically distinct individuals without costly laboratory work.

Aims

I wanted to investigate whether some anemones change their behaviour differently than others under increasing environmental temperatures

Actinia equina beadlet anemones: left, green underside; right, red underside

as some changes might improve their survival chances. I had several hypotheses, but for this article we will focus on just one. I hypothesised that the red-underside morphotype would:

- take more risks than the green at all temperatures, because aggression is often correlated with risk-taking
- be better at changing its behaviour in response to higher temperatures than the green, because it tolerates a harsher environment (see Box 1)

Box 1 Identifying anemone morphotypes

We can determine which morphotype is which by looking directly at the undersides of anemones or, if that is not practical, looking for a blue ring around the edge of their underside. The green-underside morphotype has a blue ring; the red does not (see photo above). The red-underside morphotype is able to displace the green as it is more aggressive and better at fighting, but it tends to live higher up the shore. Although it is a more challenging environment than the low-shore, red-underside anemones must have a genetically determined preference for the high-shore, otherwise they would displace green-underside individuals and move lower.

Box 2 Temperature as the key experimental variable

At first glance, changing the temperature in a short-term climate change study might seem obvious, but is it really investigating the effects of climate change? The short answer is 'sort of'. Most climate change happens over a period of decades, so exposing animals to 2 weeks of rising temperatures does not allow us to draw any conclusions about the effects of a generally warming climate. What it does allow us to do is to draw conclusions about the effects of extreme heatwaves, which are becoming more frequent.

The methods

I subjected anemones to 5 days at each of three temperatures (see Box 2). The normal range of temperatures these anemones experience through a year is 7.5–17.5°C, so I subjected anemones first to a normal temperature, then to a temperature at the top of the normal range, and finally to a near-lethal temperature well above the normal range (see Figure 1). When I increased the temperature after each 5-day period, I did so at a rate of 1°C per hour. I measured two behaviours, and each set of measurements was repeated three times at each temperature. This allowed me to measure the individual consistency and variability of those behaviours across temperatures. Experimental and control groups, each containing over 100 individuals, were split evenly between anemones of different morphotypes collected from different intertidal shore-heights.

Why these behaviours?

Both behaviours I investigated involved measuring how long it took for anemones to re-extend their feeding tentacles after reaction to a stimulus (see Figure 1). The startle response happens when anemones are threatened – they

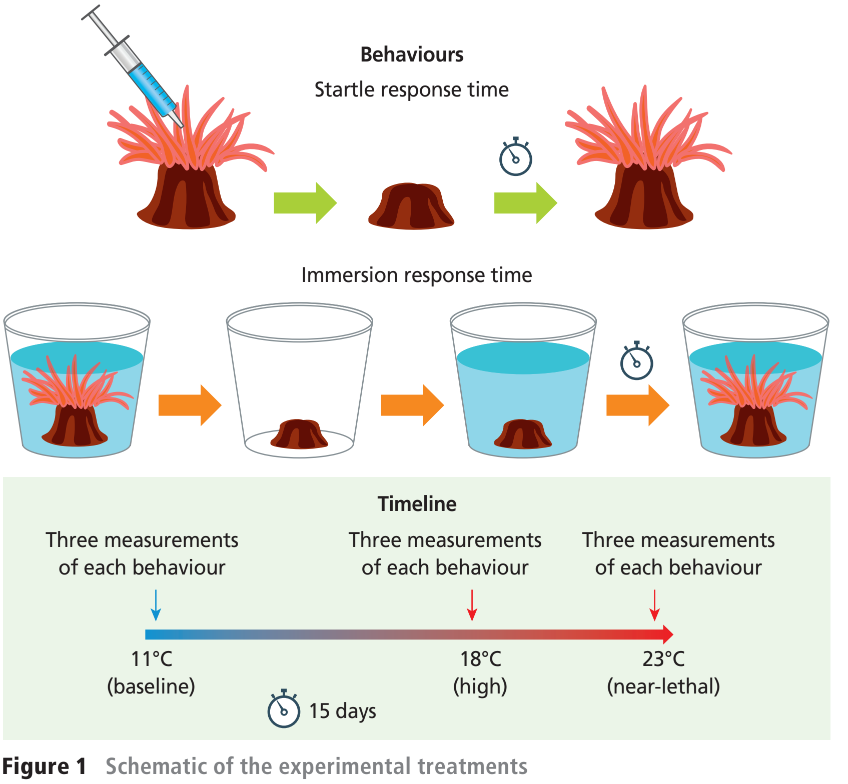
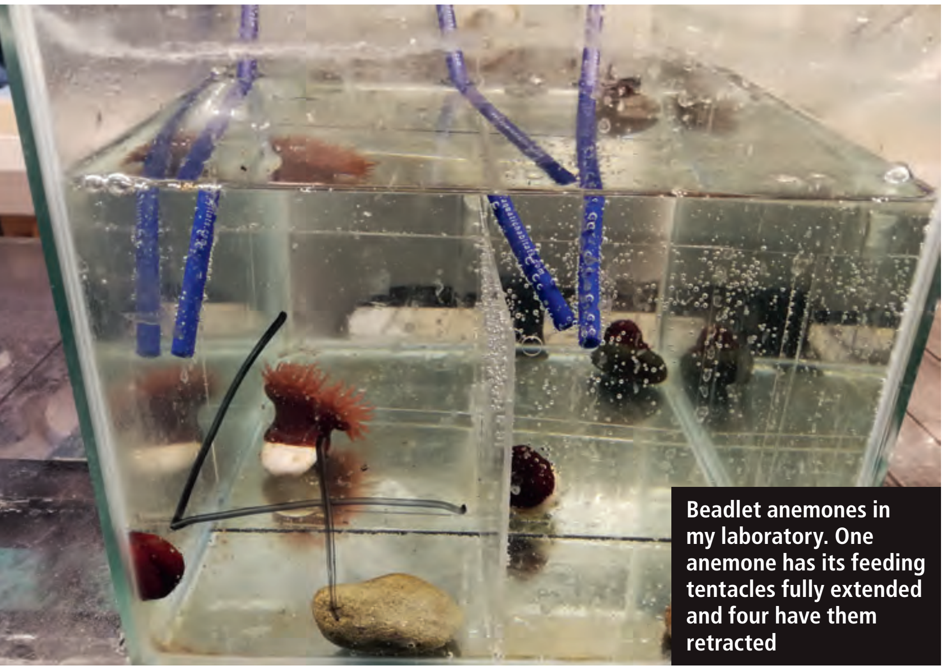


Figure 1 Schematic of the experimental treatments



Beadlet anemones in my laboratory. One anemone has its feeding tentacles fully extended and four have them retracted

retract their tentacles. The immersion response occurs when they have been reimmersed (e.g. when the tide comes in) after they have been exposed (e.g. at low tide). I measured animals along an axis of risk-taking, or 'boldness', where animals that took less time to extend their tentacles were bolder and those that took longer were shyer. I knew that these behaviours would affect anemone survival and reproduction based on previous studies, which showed that both represent an evolutionary trade-off between protecting anemones from harm and allowing them to feed. It was crucial that I provided proof that my response measurements were indeed related to the aims I wanted to achieve.

My first problem was that neither of these behaviours proved easy to measure. The startle response, especially, was a serious challenge. Previous research indicated to me that startle response time should be defined as the time it takes an anemone to 'fully re-extend' its tentacles after a fright. However, many anemones did not start with their tentacles fully extended and these animals never recovered in the way previous research described. Instead, they only recovered to the same tentacle extension that they started with. In the end, I had to use two separate definitions for startle response, one where anemones recovered to full extension and another where they recovered to their own, anemone-specific pre-startle extension. This meant that the reliability and reproducibility of my measurements needed careful verification, in case the two definitions were actually measuring different things.

Because most anemones showed some examples of both types of startle response, I was able to run an advanced correlation check to see whether the definitions were related to each other within each anemone. We would expect strong correlations between the two if they explained the same part of anemone personality, so that is what I was looking for (see Figure 2). When designing this experiment, my startle response method had appeared well-founded on previous research, so I did not do as much preliminary (pilot) work as I certainly should have done. I was fortunate here that a solution was possible and that this method generated robust outcomes, but it made me realise the importance of pilot work.

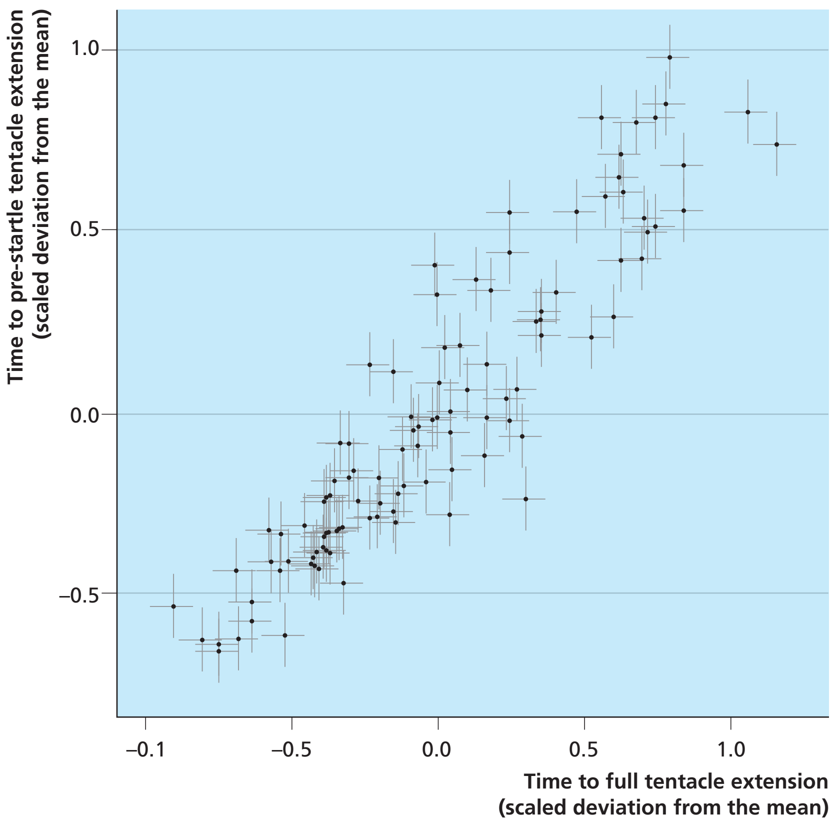


Figure 2 The tight correlation between two measures of startle response

The controls

I exposed control animals to the same schedule of testing as experimental animals but with no temperature change. This allowed me to account for time-related variables, which might themselves drive behavioural change. Ideally, I would have run control groups at the same time as experimental groups to avoid external changes, such as the seasons, potentially throwing the validity of the controls into question. Sadly, our laboratory was too small to do this. I used advanced statistical models to account for changes in the seasons but it is always better to address problems using your experimental design if you can. This becomes particularly important when using analyses like *t*-tests or chi-squared tests (as complicated as you will need to go at A-level), which cannot account for extra variables such as seasonal variations.

My design also meant that I could not know whether the observed differences in behaviour were the effect of the different temperatures themselves or the effect of the direction of temperature change (in this case, rapid heating). If I could run this study again in a larger laboratory, I would run three treatments in a crossed-over design, incorporating a control, a heating treatment and a cooling treatment. This would allow me to separate:

- the effects of time

- the effects of the direction of temperature change
- the effects of a given temperature

Evaluating the data

If we look at one of my results, we can work out what conclusions it allows us to draw, and what conclusions it does not. Using Figure 3, we can see that green-underside anemones, on average, recovered more quickly after immersion (were bolder) than reds at 11°C. This pattern was stable over the time period of our control treatment but not our experimental treatment. For experimental animals, as the temperature increased the pattern flipped, with red-underside anemones becoming bolder, shown by the purple bars being lower, than greens at 23°C.

What can we conclude?

The results do not support my first hypothesis, as green anemones were bolder at low temperatures, but they do support my second. Research is collaborative and it is cumulative. Previous research provides evidence that the metabolic rate of anemones increases with temperature and that anemones need their tentacles extended to improve their metabolic efficiency. This allows us to say with confidence that by maximising the time they spent with their tentacles extended, red-underside anemones showed a more beneficial behavioural change than greens at increased temperature. This is likely to improve red-underside survival during heatwaves and is in line with my second prediction.

What can't we conclude?

While this is a great result, we cannot say it applies to all heatwave scenarios. An important caveat with all laboratory research is that it only tests variables under a specific set of conditions, so more studies will be critical to making sure that this is a real pattern. This experiment also does not give us the tools to make any suggestions about the underlying reasons why red-undersides coped better, but it does point the way for further studies to do so.

Take-home message: turn problems into solutions

Even with some methodological shortcomings, this study provided interesting results and allowed me to draw conclusions. I have also now run a follow-up study in a much larger laboratory, where I addressed and resolved almost all these shortcomings, so it was a crucial experience for me to continue to learn and grow as a scientist.

No experimental design is perfect. Problems are a part of every scientific study, with no exceptions. Adapting to them, coming up with solutions, and avoiding unwarranted speculation about results are invaluable scientific skills. They are essential to making great contributions in any field and are as crucial to science as being able to design effective experiments in the first place.

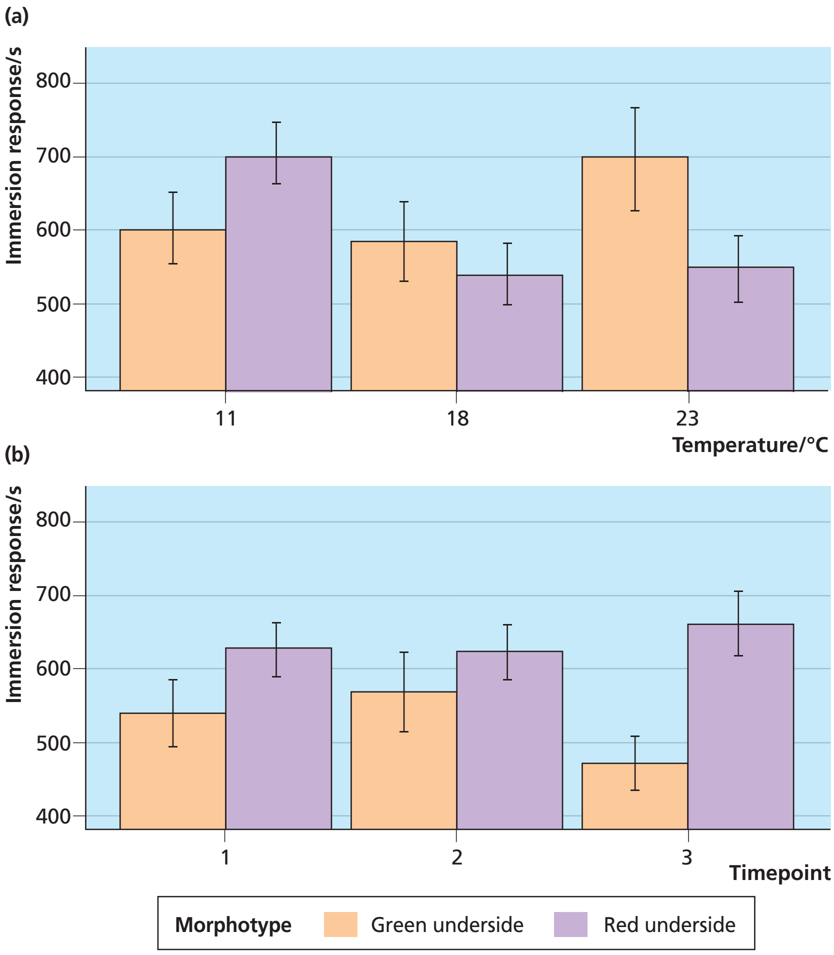


Figure 3 The relationship between morphotype and immersion response time across (a) experimental temperatures and (b) control timepoints

Things to do

- Temperature is not the only thing that is being affected by climate change. Discuss with your classmates what other environmental variables might be changing and how you think they might affect marine wildlife.
- In an answer to an A-level experimental question it is not enough to simply suggest that the researchers should 'do more studies' to verify their results. Discuss with your classmates exactly what these could be to investigate the variables involved in this research, and suggest what further studies could be conducted to elucidate the responses of anemones to climate change.

RESOURCES

Find out more about beadlet anemones from the team at *BBC Wildlife Magazine*: **https://tinyurl.com/rnden6wz**

Video showing another beadlet anemone behaviour – aggression: **https://youtube.com/watch?v=r8CE8sM01wo**

See the full study in *Journal of Animal Ecology*: **https://tinyurl.com/5b2vhktf**

Daniel Maskrey has an MSc in evolution and behaviour from the University of Exeter and is currently a PhD student in the University of Liverpool's School of Environmental Sciences.

Biological Sciences update
DECEMBER 2021
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Foul freight

Transporting freight via waterways is one of the least environmentally damaging options. But biological hitchhikers on vessels can dramatically increase the damage. **Liz Sheffield** reviews what's being done about them

International shipping currently accounts for only a small proportion of annual greenhouse gas (GHG) emissions. But emissions have risen by 70% since 1990 and some projections hold that they will grow by a further 250% by 2050. Any structure that becomes submerged is likely to be colonised, first by small and then larger organisms, described as biofouling. Anything that adds roughness to a vessel's hull will increase drag and add to the weight of the vessel, increasing fuel consumption and therefore GHG emissions. But the problems caused by fouling organisms don't stop there. Shipping is the most common pathway for the introduction of invasive species, which threaten aquatic ecosystems worldwide.

Alien invaders

Aquatic invasives damage biodiversity by displacing native species, altering community structure, disrupting food webs and impacting ecological processes. In the Hawaiian Islands, for example, 90% of 343 marine species identified as non-native are thought to have been introduced from hull fouling.

In 2011 the International Maritime Organization (IMO) issued biofouling guidelines. These provided a globally consistent approach to how biofouling should be managed to minimise the transfer of invasive aquatic species via the hulls of ships. In 2019, a global alliance of stakeholders – The GloFouling Project partnership – was formed to drive actions to implement the IMO guidelines. The partners recognised the impact of fouling on GHG emissions and in 2020 launched an initiative. The aims were:

1. To address the poor understanding among the shipping industry of the relationship between ships' biofouling and fuel consumption, and resulting GHG emissions.
2. To analyse the sustainable solutions currently available to ship owners to reduce GHG emissions through the minimisation of biofouling.

The preliminary results were presented to those of us fortunate enough to be in the audience at COP26 last month.

No foul no harm

The presentation began with some startling statistics. Figure 1 shows a compilation of data collected from

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a variety of maritime vessels. The lower end starkly demonstrates that biofouling as thin as 0.5 mm covering only 50% of a hull surface can generate an increase of GHGs of almost 25%. At the top end – e.g. vessels with 5 mm barnacles or weed – increases in GHGs of more than 50% have been recorded. Given that most aquatic vessels are currently powered by fossil fuels, clearly there are huge benefits to be gained from preventing or removing biofouling.

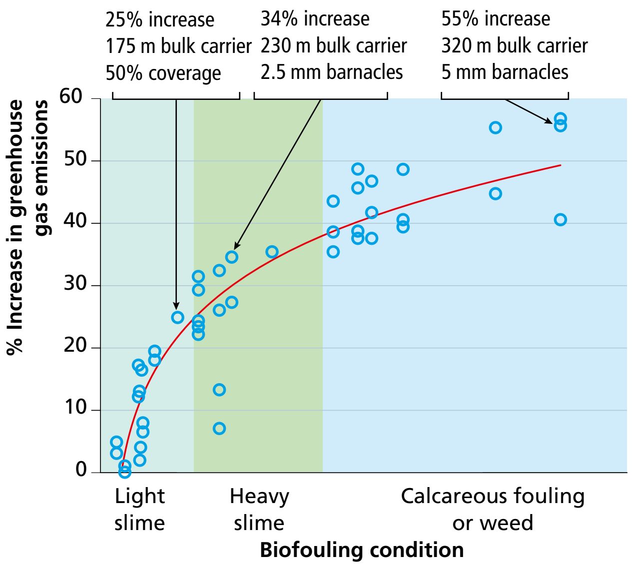

Figure 1 Compendium of results obtained from research studies on greenhouse gas emissions from light to heavily biofouled vessels

While there are costs associated with both prevention and cure of biofouling, it should be easy to convince vessel owners to invest in avoidance strategies. Even if owners are unconcerned with climate change, the saving on fuel costs would be significant over the lifetime of a freighter.

Remoras and whale sharks

Paints and coatings to deter attachment of fouling organisms are available, but most are effective for only a limited period. When they start to fail, the vessel owner has three choices.

1. Bring the boat into dry dock, strip off the fouling and start again.
2. Use ultrasonics to drive off the fouling.
3. Employ in-water cleaning systems.

In-water cleaning means less interruption to trade but has traditionally been based on ropes or abrasive devices which detach biofouling organisms (and paint debris) into the water. Recently a better system has been developed, inspired by remoras. These are fish that latch on to larger host fish with a sucker, removing parasites and loose skin. The diver-controlled Remora unit is equipped with rotating brushes that remove the fouling, creating a turbulent flow under a shroud which enters an impeller system. The removed debris and water is forced up through a hose to the Whale Shark surface processing system. This, just like a whale shark (see Biological Sciences Review, Vol. 34, No. 1, pp. 20–21), filters out particles (down to 5 µm) which can be safely disposed of.

So, such 'greenwashing' could provide a more positive meaning for that term and contribute to the reduction of both alien invaders and GHG.

Weblinks

Biofouling and the GloFouling project explained: **https://tinyurl.com/ywth92vn**

Kerala introduces the world's first solar-powered ferry: **https://tinyurl.com/2zytk2kk**

Activities

1. Think about your contribution to sustainability. Read '10 ways to reduce food miles', by EcoStreet: **https://tinyurl.com/3w2tyhwp**
2. Make sure you never introduce alien species into waterways! e.g. see: **https://tinyurl.com/377n5p4x**
3. Research ultrasonic hull cleaning and discuss the pros and cons with your classmates (consider frequencies in communication between marine organisms).