A child-centric microbiology education framework

Red and Green Tides

Hey bro: I wanted to go surfing next week but there is a red tide warning: what is that?

‘Red tide’ (toxic *Karenia brevis* bloom) off La Jolla, California. Photo credit: Alejandro Diaz

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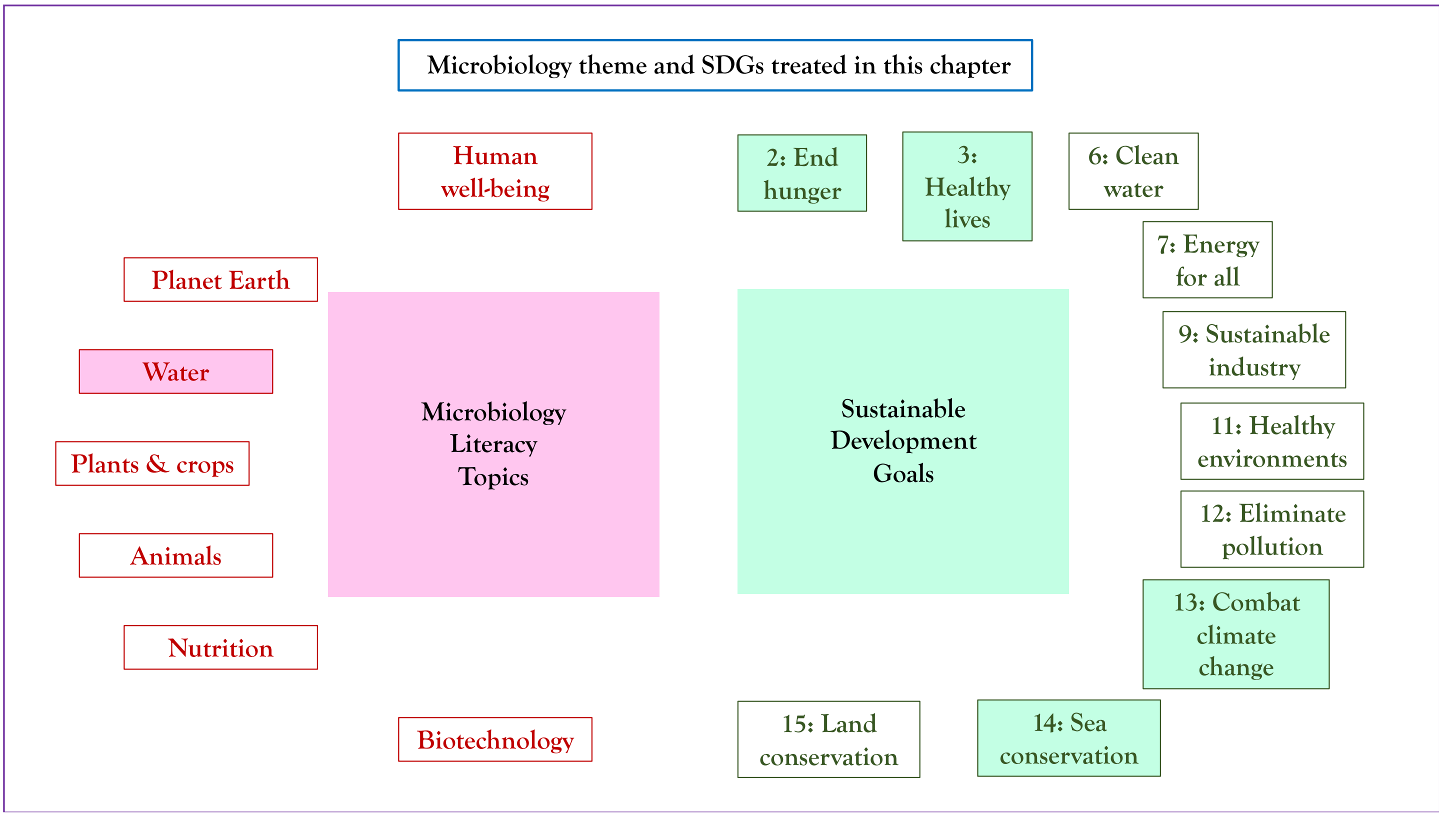
Red and Green Tides

Storyline

Marine harmful algal blooms (HABs), sometimes known colloquially as ‘red-’ or ‘green tides’, occur when populations of microbes in the water become so dense that they pose a risk to human health or the environment. These blooms are comprised of microscopic algae or cyanobacteria (also known as ‘blue-green algae’). Their characteristic red, brown or green colour comes from a combination of light-harvesting pigments, known as chlorophylls and carotenoids, which allow them to photosynthesize. HABs are a natural phenomenon, that often results when storms or currents stir up sediments from the ocean floor, providing nutrients to the algae and allowing them to grow rapidly and for a prolonged period. However, research suggests that their incidence and severity is increasing due to human activity and climate change. Vast HABs can severely disrupt the balance of marine ecosystems particularly when the algal cells die, which depletes the water of oxygen, killing fish and other organisms. More alarmingly, some species of marine microalgae produce potent toxins, which can accumulate in molluscs and fish, poisoning the animals who consume their flesh, including humans. HABs are a significant burden on the global economy, impacting heavily on aquaculture, fishing and tourism. While we do not yet have the means to eradicate HABs, monitoring and proper management of coastal systems can significantly reduce their detrimental effects.

The Microbiology and Societal Context

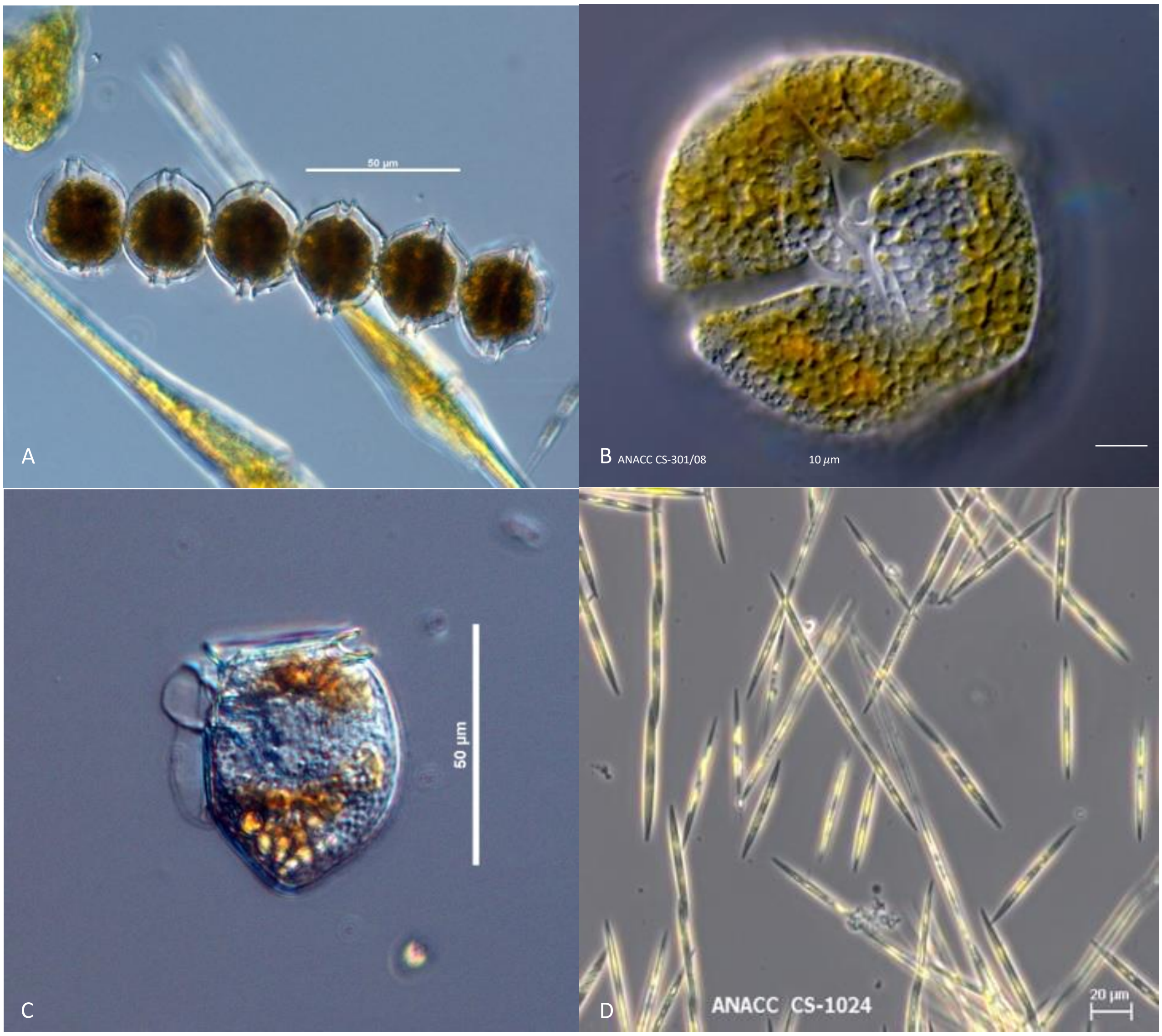
The microbiology: diversity and distribution of marine microalgae; marine microalgal toxins; environmental factors that cause microalgal blooms; impacts of harmful algal blooms; monitoring harmful algal blooms; biotechnological applications of marine algal toxins. *Sustainability issues:* food; health; oceans; climate change.



BOX 1. Microbiology themes and Strategic Development Goals treated in this chapter

Red and Green Tides: The Microbiology

1. ***Diverse species of microalgae are found in our oceans, but only a few cause harmful algal blooms.***
   a. *Around 4000 species of microalgae live in our oceans.* These unicellular plant-like organisms, also known as phycoplankton, are capable of converting carbon dioxide and energy from the sun into oxygen and chemical energy via photosynthesis. They are the most abundant and widespread primary producers on Earth and a critical part of the marine food web. They also outperform the rainforests in terms of global carbon storage and oxygen production. However, only about 200 species are known to form harmful blooms (around 80 of which are toxic), including certain eukaryotic dinoflagellate species, so-named for their whirling whip-like flagella; eukaryotic diatoms, with their jewel-like silica coats; and prokaryotic cyanobacteria, which are also problematic in freshwater systems (see Eutrophication: algal blooms, this Section). HAB-forming microalgae are morphologically, physiologically and ecologically diverse and thrive in a wide range of marine habitats, from the Equator to the Arctic and Southern oceans, but they are most problematic in the temperate and sub-tropical coastal regions.



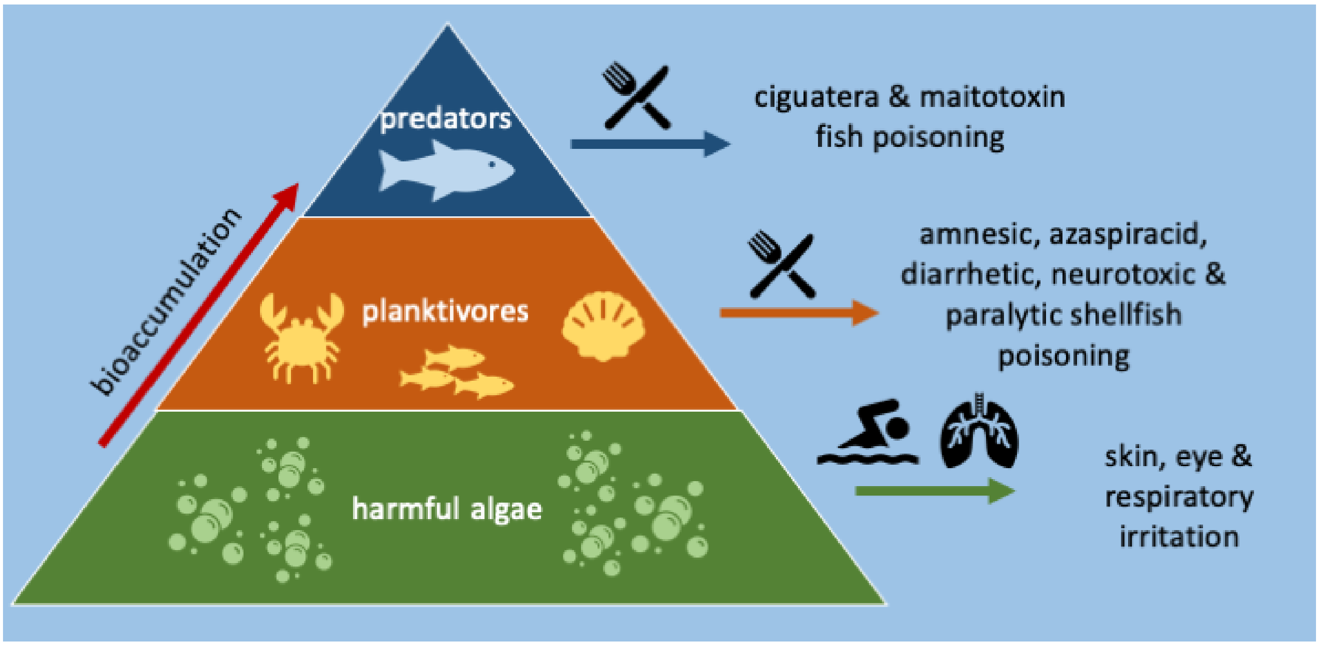
BOX 2. Morphology of different harmful phycoplankton species. Micrograph of dinoflagellates *Alexandrium catenella* (A), *Gymnodinium catenatum* (B), and *Dinophysis acuta* (C), and diatom *Pseudo-nitzschia cuspidata* (D). Photo credit: A and C sourced from Phyto'pedia (https://www.eoas.ubc.ca/research/phytoplankton/), B and D provided by Anusuya Willis and Ian Jameson, the Australian National Algae Culture Collection, Hobart.

b. *Certain species of marine microalgae produce potent toxins.* Around 80 species of marine microalgae (mostly dinoflagellates) produce potent toxins known collectively as phycotoxins (fýkos meaning algae in Greek). This may provide them with an ecological advantage by inhibiting the growth of competing phycoplankton (allelopathy) or deterring grazers. The chemistry and biological effects of phycotoxins are diverse. Some of the most problematic include brevetoxins, azaspiracids, ciguatoxins, maitotoxin, domoic acid, okadaic acid, saxitoxins, and dinophysistoxins.

Toxin	Saxitoxins	Okadaic acid/Dinophysistoxins	Domoic acid	Brevetoxins	Azaspiracids	Ciguatoxin & Maitotoxin
Producer	dinoflagellates, cyanobacteria	dinoflagellates	diatoms	dinoflagellates	dinoflagellates	dinoflagellates
Seafood	bivalve molluscs, gastropods, crabs	bivalve molluscs, gastropods, crabs	bivalve molluscs, gastropods, crabs	bivalve molluscs, gastropods, crabs	bivalve molluscs, gastropods, crabs	large tropical fish
Syndrome	paralytic shellfish poisoning	diarrhetic shellfish poisoning	amnesic shellfish poisoning	neurotoxic shellfish poisoning	azaspiracid shellfish poisoning	ciguatera fish poisoning

BOX 3. Common phycotoxin producers, seafood sources and syndromes

Phycotoxins are usually stable in the environment and are sometimes taken up and stored (bioaccumulated) in the tissues of non-susceptible organisms, particularly filter-feeders, such as mussels and clams. Human exposure usually occurs through the ingestion of molluscs, or tropical fish, and to a lesser extent via inhalation of aerosols or direct skin contact. Other marine organisms, such as whales, dolphins, and seabirds can additionally be poisoned via the direct ingestion of algal cells and contaminated water. Some phycotoxins (e.g. maitotoxin and saxitoxins) are so potent that consumption of just a small serving of contaminated seafood can cause severe illness or death. The symptoms of poisoning are often specific for the toxin ingested and have given rise to the names of several associated syndromes. For example, saxitoxin poisoning or 'paralytic shellfish poisoning', is characterised by respiratory paralysis; domoic acid poisoning or 'amnesic shellfish poisoning', is characterised by memory loss; okadaic acid poisoning or 'diarrhetic shellfish poisoning', is characterised by severe diarrhea, and so on. More generalised symptoms, including respiratory and digestive tract problems, lesions, and skin and eye irritation may also occur as a result of exposure to phycotoxins.



BOX 4. Routes of human exposure to phycotoxins. Human exposure to marine phycotoxins can occur directly through skin contact or aerosols, or indirectly through the consumption of shellfish, which feed on toxic algae (planktivores) and larger fish, which prey on planktivores.

2. ***HABs are a natural phenomenon that may be exacerbated by human activities.*** HABs occur seasonally in response to nutrient upwelling caused by storms and currents, along with natural sediment discharges from rivers. While different microalgal species have different nutrient requirements, HABs are often associated with elevated levels of phosphorous (P), nitrogen (N), and silicates. N and P are required by all phycoplankton for building proteins and for general metabolic functions. Silicates on the other hand, are a special requirement of diatoms, which use it to manufacture their unique cell walls. Trace metals, vitamins, temperature and salinity can also influence the composition and severity of blooms. While HABs have been recorded since around 1000 BC, there is strong evidence linking more recent human activity to the increasing incidence and severity of bloom events, particularly those in the coastal zones of populous cities. Nutrient pollution in the form of fertilizers, animal manure, fish food and faeces, and discharge of domestic sewerage and wastewater into the ocean has led to a sharp rise in P and N levels in coastal waters, with a parallel increase in reports of bloom events. Human activity has also been linked to the spread of HAB species around the globe, as algal cysts are frequently collected, transported and discharged via the ballast water of ships. There is mounting evidence that climate change will exacerbate the incidence and severity of HABs, with rising ocean temperatures, enhanced surface stratification, altered currents, elevated carbon dioxide levels and ocean acidification, altered nutrient availability, and a decrease in the number of algal grazers, leading to changes in the geographical range and growing season of many species. It is also interesting to note that while blooms can occur in many environments, those found near human populations are more often toxic. Whether this is due to a concentration of monitoring efforts around human habitats or the type of nutrients entering urban waterways is not clear.

3. ***HABs and their toxins have a significant impact on marine wildlife, human health, and the global economy.*** Both toxic and non-toxic phycoplankton blooms can have catastrophic effects on marine ecosystems. Active blooms shade other phycoplankton and seagrass, including *Posedonia*, resulting in the reduced growth of key species, while bloom collapse, followed by degradation of the biomass by oxygen-consuming microbes, can deplete the water of oxygen resulting in ‘dead-zones’. Even diffuse populations of only a few hundred toxic cells per litre can lead to mass poisonings of fish, turtles, sea birds, and marine mammals. Fish caged in aquaculture farms are particularly vulnerable to HABs as they can’t escape the irritating, gill-clogging, and sometimes toxic, algae. While molluscs are usually unharmed by HABs, even minor toxic blooms can mean catastrophe for aquaculture farms due to the bioaccumulation of phycotoxins in shellfish meat. Thankfully, human loss of life due to phycotoxin poisoning is a rare occurrence in most parts of the world, owing to stringent seafood monitoring regimes. However, recreational fishers should exercise extreme caution when harvesting wild molluscs and large tropical fish. The costs associated with monitoring, reporting and treating phycotoxin poisoning are an ongoing and significant burden to the economy. Likewise, financial losses from reduced tourism may result from the closure of beaches due to toxic blooms, unsightly algal scums and foul odours.

BOX 5. Environmental impacts of harmful algal blooms. A menhaden fish-kill in August 2003 due severe hypoxia (near anoxia) in Greenwich Bay, Rhode Island, following collapse of an algal bloom. Photo Credit: Chris Deacutis.

4. ***A variety of methods have been developed to monitor HABs and reduce their impact*.** Monitoring HABs is a complex problem due to large numbers of microalgal species and phycotoxins in our oceans. Morphological observations made with a microscope can help narrow down potentially toxic species, but are rarely definitive as toxic and non-toxic strains are often indistinguishable. Measuring photosynthetic pigments, directly or via satellite imaging (Box 6), can give a general indication of the bloom size and density, however, regularly monitoring the toxins themselves is the best method to minimise the potential health impacts of HABs. This was traditionally achieved by feeding or injecting laboratory mice with shellfish and their extracts, but now a range of more ethically desirable methods have been developed, including analytical chemistry techniques and diagnostic kits based on anti-phycotoxin antibodies. Molecular diagnostic tests targeting saxitoxin-biosynthesis genes in dinoflagellates and saxitoxin, microcystin and cylindrospermopsin genes in cyanobacteria have also been developed; however, most marine phycotoxin genes have yet to be discovered. HAB monitoring is becoming increasingly more sophisticated with robots and remote sensors deployed off the coast to record algal cell numbers and photosynthetic pigments, as well as nutrient levels and physical parameters in real-time. Public education and awareness campaigns also play a crucial role in minimising the human health impacts of HABs. Likewise, proper training of medical practitioners to recognise and treat phycotoxin poisoning are essential for reducing fatalities, particularly in bloom-prone coastal fishery regions.

BOX 6. Satellite image of cyanobacterial bloom in the Baltic Sea off Gotland, Sweden. Photo Credit the European Space Agency

5. ***Some marine phycotoxins could be developed into useful clinical drugs.*** Because of their potent and often very specific biological effects, some marine phycotoxins (e.g. saxitoxins) are being explored as potential drug leads. The saxitoxins, produced by certain strains of dinoflagellates and cyanobacteria, are a family of deadly neurotoxins. When ingested, saxitoxins cause paralytic shellfish poisoning, which is characterised by breathing difficulty and paralysis. This occurs because saxitoxins bind very tightly to, and inhibit, protein channels in cardiac and skeletal muscle known as voltage-gated sodium channels. However, when injected subcutaneously and at the correct dose,

some saxitoxin variants (e.g. neosaxitoxin) are very effective and long-lasting local anaesthetics. This is because they also inhibit pain-signalling sodium channels in nerve cells. As the adage goes: '*the dose makes the poison*'. In fact, numerous so-called 'microbial toxins' have been developed as clinical drugs (See Applications of microbial toxins and virulence factors, Section 9).

Relevance for Sustainable Development Goals and Grand Challenges

Harmful algal blooms in the marine environment relate to several sustainable development goals (SDGs), including:

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture** (*end hunger and malnutrition, increase agricultural productivity*). Agriculture and aquaculture are essential industries for securing global food supplies. However, they generate a significant amount of nutrient pollution, which enters the ocean via effluent discharge, rivers, and groundwater. This leads to the eutrophication of coastal systems and the promotion of harmful algal blooms. There is debate about restricting the use of N and P on crops, but the need to supply adequate quantities of food at affordable prices, are confounding factors. Farmers, marine environmental protection agencies and policymakers must work together to strike a balance between fertilizer use, crop productivity and marine ecosystem impacts. Ironically, eutrophication from agricultural runoff and aquaculture and subsequent harmful algal blooms can lead to the closure of fisheries and the reduced availability of seafood, thereby negatively impacting on global food protein security.

- **Goal 3. Ensure healthy lives and promote well-being for all, at all ages** (*improve health, reduce preventable disease and premature deaths*). Harmful algal blooms pose a significant risk to the health and well-being of humans around the globe, particularly those in the developing regions of the world. Phycotoxins can cause irritation, illness or death, depending on the exposure route, toxin type and dose. Prolonged exposure to subacute doses has also been associated with chronic illness such as asthma, allergies and even cancer. Low and middle income nations of Central America and South East Asia, which lack comprehensive HAB monitoring programs and adequate public healthcare systems, are particularly vulnerable to phycotoxin poisoning. HAB monitoring, regulation of fisheries, public awareness campaigns and early warning systems, and appropriate training of medical staff, are all critical factors in reducing the human health impacts of HABs. The economic burden of such preventative measures must be weighed against the potential loss of life from phycotoxin poisoning, the cost of treating acute and chronic illness, and the personal and national economic consequences of lost time in school and the workplace.

- **Goal 13. Take urgent action to combat climate change and its impacts** (*reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming*). Climate change is expected to result in an increase in the incidence and severity of harmful algal blooms in marine and freshwater systems. Human activities have resulted in significant increases in the concentrations of 'greenhouse gases', including carbon dioxide, methane, nitrous oxide and chlorofluorocarbons. While marine algae are natural carbon sinks, and therefore mitigators of climate change, the overgrowth of harmful species is also problematic. Climate change is projected to alter ocean currents, temperatures, surface stratification, pH, and nutrient upwelling. These changes will likely result in shifts in the geographical range and growing season of marine microalgae, including harmful and toxic species, with subsequent impacts on organisms at higher levels of the aquatic food web. It is therefore vital to monitor the diversity, distribution and abundance of these key primary producers, which can be considered sentinel organisms for the health of our oceans and Planet Earth, in general.

- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** (*reduce pollution of marine systems by toxic chemicals/agricultural nutrients/wastes like plastics, develop mitigation measures for acidification, enhance sustainable use of oceans and their resources*). Aquatic nutrient pollution as a result of agriculture, aquaculture, urban and industrial activity, is one of the key contributors to coastal harmful algal blooms.

Likewise, overfishing can perturb food webs, reduce the numbers of species that would usually feed on algae, and thus result in their proliferation. While phycotoxins are naturally occurring compounds, their overproduction can have catastrophic effects on marine ecosystems at all trophic levels.

Potential Implications for Decisions

1. ***Individual***
    a. Check local HAB alerts before swimming or fishing (staying informed reduces the risk of poisoning)
    b. Know the symptoms of poisoning (recognizing symptoms and seeking immediate medical attention leads to better patient outcomes)
    c. Eat less meat (this reduces the demand on fertilizers and the production of manure)
    d. Use cleaning products sparingly (this reduces phosphate levels in wastewater)
    e. Coastal stormwater drainage systems are not for rubbish disposal
    f. Reduce your carbon footprint to help slow climate change

2. ***Community policies***
    a. Regular monitoring of coastal waters
    b. Reliable HAB public awareness campaigns and alert systems
    c. Closure of beaches, if HABs are detected
    d. Proper management of local wastewater runoff
    e. Community action against climate change (e.g. planting trees on the banks of waterways, encouraging renewable energy etc.)

3. ***National policies***
    a. Healthcare, diagnosis and treatment of patients
    b. National HAB monitoring regimes
    c. Regulation of fisheries
    d. Regulation of tourism and recreation
    e. Protection of marine wildlife and seabirds
    f. Regulation of the use of phosphates and nitrates
    g. Regulation of agricultural, industrial and urban run-off
    h. Regulation of ballast water discharge
    i. Climate change policy

Pupil participation

1. ***Class discussion of the issues associated with HABs***

2. ***Pupil stakeholder awareness***
    a. The use of fertilizers and other nitrogen and phosphate-containing chemicals has positive and negative consequences for the Strategic Development Goals. Which of these are most important to you personally/as a class? (e.g. fertilizer use provides greater food security, but also promotes HABs).
    b. Can you think of anything that might be done to reduce the incidence and severity of HABs? (see Potential Implications for Decisions above e.g. Individual c-f; Community d, e; National f-i).
    c. Can you think of anything you could personally do to protect yourself and your family/friends/pets from marine phycotoxins? (see Potential Implications for Decisions above e.g. Individual a, b).

3. ***Exercises***

- a. Climate change is impacting our oceans. Discuss some of the anthropogenic causes of climate change and their potential impacts on marine microalgae.
- b. Create a poster illustrating some of the different routes of phycotoxin poisoning for humans and wildlife. (use Box 4 for inspiration).
- c. Why do you think harmful algal blooms are generally more problematic in coastal areas? (e.g. human activity near coastlines results in increased nutrient run-off, which promotes blooms; The impacts of blooms in densely populated areas is generally worse from a health and economical perspective because more people and industries are affected).

4. ***Class experiments***
   - a. Phycoplankton are incredibly diverse. Look at some seawater under a microscope. How many different types of phycoplankton can you identify? Draw a few examples (this is a good resource for identifying some common species KEY. You may also need to familiarise yourself with local species by checking the websites of marine research groups in your area).
   - b. Eutrophic conditions are commonly associated with HABs. Design a model that uses food dye to demonstrate how nutrients get from the land or the ocean floor to the upper (epipelagic) zone of the ocean. (e.g. via agricultural/urban runoff, groundwater inputs and/or nutrient upwelling. Example).
   - c. Photosynthetic pigments give microalgal species their characteristic colour. Separate the photosynthetic pigments from some different plants or algae using solvent extraction and paper chromatography (example). How many different pigments can you see? What role do they play in photosynthesis?

The evidence base, further reading and teaching aids

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Phyto'pedia. The Phycoplankton Encyclopedia Project. Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia. https://www.eoas.ubc.ca/research/phycoplankton/

Glossary

Allelopathy. The chemical inhibition of one plant (or other organism) by another, due to the release into the environment of substances acting as germination or growth inhibitors.

Anaesthetic. A substance that induces insensitivity to pain.

Azaspiracids. Polycyclic ether marine algal toxins produced by dinoflagellates.

Ballast water. Water stored in the bottom of a ship to provide stability.

Bioaccumulation. When a particular substance becomes concentrated in the tissue/s or organ/s of an organism.

Bioactivity. A biological effect.

Blue-green algae. A colloquial term for cyanobacteria.

Brevetoxins. Cyclic polyether compounds produced by dinoflagellates.

Carotenoids. Any of a class of mainly yellow, orange, or red fat-soluble pigments, including carotene, which give colour to plant parts.

Chlorophyll. Green pigment present in all green plants and in cyanobacteria, which is responsible for the absorption of light to provide energy for photosynthesis.

Ciguatoxins. Toxic polycyclic polyethers produced by dinoflagellates that cause ciguatera fish poisoning.

Cyanobacteria. A phylum of Gram-negative, photosynthetic bacteria.

Diatom. A single-celled alga, which has a wall of silica.

Dinoflagellate. A single-celled alga with two flagella, occurring in large numbers in marine plankton and also found in freshwater.

Dinophysistoxins. Lipophilic and thermostable polyether toxins produced by dinoflagellates.

Domoic acid. Kainic acid-type neurotoxin produced by diatoms.

Eutrophication. The excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant/microbial life.

Filter-Feeder. An aquatic animal that feeds by filtering out plankton or nutrients suspended in the water.

Flagella. Microscopic appendages that allow microorganisms to swim.

Gastropod. A mollusc of the large class Gastropoda, such as a snail, slug, or whelk.

Greenhouse gases. A gas that contributes to the greenhouse effect by absorbing infrared radiation. Carbon dioxide and chlorofluorocarbons are examples of greenhouse gases.

Harmful algal bloom. A population of microalgae that poses a threat to other organisms due to its density or toxicity.

Maitotoxin. A toxin produced by dinoflagellates composed of 32 rings, resembling a fatty acid chain.

Microalgae. Microscopic algae (also known as phycoplankton, phytoplankton or microphytes), including eukaryotic phyla and cyanobacteria.

Mollusc. An invertebrate of a large phylum which includes snails, slugs, mussels, and octopuses.

Nutrient upwelling. wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface, replacing the warmer, usually nutrient-depleted surface water.

Okadaic acid. Lipophilic and thermostable polyether toxin produced by dinoflagellates.

Phycotoxins. Toxic chemicals synthesized by photosynthetic organisms.

Phycoplankton. Microscopic algae (also known as phytoplankton or microphytes), including eukaryotic phyla and cyanobacteria.

Photosynthesis. The process by which green plants and certain other organisms transform light energy into chemical energy.

Red tide. A colloquial term for a red coloured harmful algal bloom.

Saxitoxins. A family of alkaloid neurotoxins produced by dinoflagellates and cyanobacteria.

Sentinel organism. An organism used to detect risks to humans by providing advance warning of a danger. The terms primarily apply in the context of environmental hazards rather than those from other sources.

Stratification (of water). When water masses with different properties (e.g. salinity, oxygenation, density, temperature) form layers that act as barriers to water mixing.

Trophic level. The position an organism occupies in the food web.