

# Microalgae and Human Affairs: Massive Increase in Knowledge Drives Changes in Perceptions of Good and Bad Blooms

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## Abstract

Algal blooms have been utilised by humans as nutritious food, inspired naturalists with bioluminescent dinoflagellate spectacles, but remain much undervalued by the public as the source of fossil fuels, every second breath of oxygen we inhale, and even the origin of eukaryotic life on our planet. Instead, algal blooms have been increasingly associated by human society with beach health danger and seafood poisoning, signs of nutrient pollution or impending climate change. While the impacts of harmful algal blooms on human society have been increasing, this trend is largely driven by intensified monitoring associated with enhanced aquaculture. Satellite imagery has visualised the global scale of algal bloom phenomena, and newly highlighted their role in driving climate. We demonstrate how our massive increase in knowledge of microalgae has been driving ever changing perceptions of good and bad algal blooms, and recognition of the central role microalgae play on our planet, as well as for our human future.

## Keywords

harmful algal blooms – red tides – fish kills – algal biotechnology – climate change – origin of life – artforms in nature

## 1 Introduction

While macroscopic seaweeds have been celebrated as sea vegetables for more than 2,000 years in Asian countries such as China and Japan (see Chapter 5), the detection of their microscopic counterparts had to wait until Van Leeuwenhoek (1673) used his first newly designed microscopes to study microalgae in Dutch pond water. Van Leeuwenhoek excitedly wrote to the

Royal Society of the United Kingdom: “Some of these [animalcules] are so exceedingly small that millions might be contained in a single drop of water. I was much surprised at this wonderful spectacle, having never seen any living creature comparable to these for smallness; nor could I indeed imagine that nature had afforded instances of so exceedingly minute animal proportions”. It was the German scientist Haeckel (1866) who first recognised that algae (without roots, flowers, and stems) were distinct from the better known kingdoms of Plantae and Animalia, and to accommodate them in his tree of life created the separate kingdom Protista. It had long been recognised by mariners that the land is green and the open ocean is blue. With massive increases in knowledge using algal culturing techniques, electron microscopes, molecular genetics and satellite imagery, we now know how this difference is underpinned by the existence of very distinct ecosystems (sometimes referred to as the paradox of the plankton; Hutchinson 1961) and varying abundances of phylogenetically divergent forms of plant life on the land and in the water. It is not surprising that human relationships with macroscopic land plants, aquatic seaweeds and microscopic algae are strikingly different. While seaweed farming practices have existed in East Asia for thousands of years, cultivation or harvesting of microalgae has been rare in the past (e.g. the Aztecs in Mexico). Water discolorations by microalgal blooms at various times instead have inspired awe and wonder, but more commonly in ancient times have generated fear of the unknown (e.g. the river Nile turning to blood; Exodus 1,000 BC). Starting in the 1990s with public concerns of our planet running out of fossil fuels, and in the 2000s with human-made climate change and the critical role of plants and algae in carbon sequestration being recognised, we started to see an increased public awareness of the role of microscopic algae for planetary health (e.g. James Lovelock’s Gaia hypothesis inspired by the microalga *Emiliana huxleyi*; Lovelock 1991). Current public interests in the gut microbiome for human health and the science of viral pandemics similarly are not something that early explorers of microscopic life, such as Van Leeuwenhoek (1632–1723), Pasteur (1822–1895), Haeckel (1834–1919), could have foreseen. Similarly, the continuing exploration of life forms elsewhere in the universe has a strong microbial focus, which at the same time draws us back to the microbial origin of life on our own planet. I here review examples of microalgal bloom phenomena, both good and bad, which have been part of the microbial engine of our blue planet for billions of years, but which are either newly recognised or subject to significantly changing public perceptions. From a human-centric perspective, moral judgements of which algae are good or bad are continuously shifting over time, but also vary according to whether one desires clean water

for tourism or algal rich water for fisheries productivity or aquaculture feed, biofuel production, or climate mitigation and carbon sequestration. From an algal-centric perspective, the question of whether humans are good or bad for algae (e.g. by fertilising oceans with waste nutrients, global ship ballast water transport, climate warming) will also be raised.

## 2 Algal Blooms: The Bad



FIGURE 8.1 Harmful algal blooms. 1a. *Noctiluca* dinoflagellate “red tide” responsible for beach closures in Sydney, Australia; 1b. *Noctiluca* slicks threatening salmon farms in Tasmania, Australia; 1c. Toxic *Microcystis* cyanobacterial surface bloom in a Dutch canal; 1d. Harmful bloom of *Chattonella marina* golden-brown flagellates responsible for USD71M mortality of finfish aquaculture in the Seto Inland Sea, Japan

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### 2.1 *The River Nile Turned to Blood*

One of the first written references (1,000 years BC) to a harmful algal bloom appears in the Christian Bible: '*all the waters that were in the river were turned to blood. And the fish that was in the river died; and the river stank, and the Egyptians could not drink of the water of the river*' (Exodus 7: 20–21). There have been various suggestions as to the identity of the causative organism, including the freshwater flagellates *Euglena sanguinea* or *Haematococcus pluvialis* being carried downstream by torrential waters to overflow onto the flood plain of the Nile Delta (Hort 1957). In that case, a non-toxic bloom-forming alga became so densely concentrated that it generated anoxic conditions resulting in indiscriminate kills of both fish and invertebrates. Oxygen depletion can be due to high respiration by the algae (at night or in dim light during the day) but more commonly is caused by bacterial respiration during decay of the bloom. A more insidious red-water forming organism known from the area is the brackish water toxigenic dinoflagellate *Alexandrium minutum* (described by Halim 1960 from Egypt), which kills fish and can contaminate seafood with paralytic shellfish toxins dangerous to human beings.

### 2.2 *Noctiluca Dinoflagellate Red Tides*

Japanese archives reported coastal 'red waters' ('akashiwo') as early as the year 731, putatively thought to be due by the dinoflagellate *Noctiluca scintillans*. These single celled, bubble-shaped forms, 0.5 to 1 mm in diameter, carry a sticky tentacle used to snare away other plankton that come too close. When this organism was first described (as *Medusa scintillans* Macartney 1810) this caused them to be mistaken for small jellyfish. *Noctiluca* have no means of locomotion but can adjust their buoyancy to forage through the water column. When the food is finished, billions float to the surface in the hope of being carried by wind or currents to richer waters. If they end up washed ashore by onshore winds, the death throes of billions of stranded cells become visible as pink or tomato-soup red slicks but unlike other types of algal blooms this organism is essentially harmless to humans. As a precaution in November 2012 this organism triggered the temporary closure of ten Sydney beaches including iconic Bondi Beach (Fig. 8.1a). When *Noctiluca* slicks move through salmon farm pens in Southern Tasmania, Australia, this irritates the fishes' gills and causes them to stop surfacing and feeding (Hallegraeff et al. 2019; Fig. 8.1b).

### 2.3 *Cattle Deaths from Contaminated Drinking Water*

Toxic microalgae equally occur in marine and freshwater environments, and the latter can have serious implications for human drinking water reservoirs. The earliest written record dates back to 1878 when cattle deaths were

associated with cyanobacterial toxins from the brackish water *Nodularia spumigena* from Lake Alexandrina in Australia (see Chapter 2 for *Nodularia* in the Baltic). Francis (1878) reported that “a ‘conferva’ that is indigenous and confined to the lakes has been produced in excessive quantities, so much as to render the water unwholesome. It is swallowed by cattle when drinking. This acts poisonously and rapidly causes death. Sheep from 1 to 6 or 8 hours, horses 8 to 24 hours, dogs 4 to 5 hours, pigs 3 or 4 hours”. A much more serious problem occurred in central Australia in November–December 1991 when a bloom of the cyanobacterium (blue-green alga) *Anabaena (Dolichospermum) circinalis* covered 1000 km of the Darling-Barwon river system and killed an estimated 10,000 live stock and required emergency water supplies for several towns. The cyanobacterium *Microcystis* (Fig. 8.1c) causes widespread surface scums tainted with liver-damaging toxins, responsible for 55 human deaths in a dialysis clinic in Brasil that used water from a neighbouring freshwater lake (Jochimsen et al. 1998).

#### 2.4 *Harmful Algal Blooms and Finfish Farms*

Algal blooms can cause devastating mortalities to finfish aquaculture operations. Finfish held captive in intensive aquaculture are extremely vulnerable to algal blooms (e.g. USD71M loss in Japan in 1972 (Fig.8.1d), USD800M in Chile in 2016; Mardones et al. 2021). Fish mortality can be caused by mechanical damage or clogging of fishes’ gills, oxygen depletion during algal bloom collapse, but more commonly is caused by exudate chemicals (reactive oxygen radicals, free fatty acids) which usually are of no human health significance (Hallegraeff et al. 2017). On a global scale, the economic impacts of algal blooms on finfish aquaculture far exceed impacts on shellfish farms or tourism. While wild fish can avoid and swim away from algal bloom, captive fish cannot, hence this is largely a human generated problem but on the increase.

#### 2.5 *Human Seafood Poisonings from Toxic Dinoflagellates*

One of the first recorded fatal cases of human poisoning after eating shellfish contaminated with dinoflagellate toxins happened in 1793, when Captain George Vancouver and his crew landed in British Columbia in an area now known as Poison Cove. He noted that for local Indian tribes it was taboo to eat shellfish when the seawater became bioluminescent due to algal blooms (Dale and Yentsch 1978). The identification of the causative organism, the dinoflagellate *Alexandrium catenella*, was not achieved until 1936 and the alkaloid toxins, now called paralytic shellfish poisons (PSP), were not chemically characterised until 1975. These toxins are so potent that a pinhead-size quantity (about 500 microgram), which can easily accumulate in just one 100 g serving

of shellfish, could be fatal to humans. During the 1960s the United States Central Intelligence Agency (CIA) used saxitoxin in suicide capsules (Tester et al. 2020). To date, every year globally some 2000 human shellfish poisonings are reported, with approximately 15% fatalities, but ever increasing monitoring efforts to test water samples for the causative organisms and seafood for toxins are reducing human illnesses. Another precautionary approach is to instigate blank shellfish harvesting bans in particular areas (e.g. Alaska), or instigate seasonal bans (Fig. 8.2a). In the Netherlands, historically it was recommended to only eat mussels in months with the letter “r” in it (now known to be due to diarrhetic shellfish poisoning by *Dinophysis* dinoflagellates; a syndrome newly described by Yasumoto et al. 1978).

Even more insidiously, in 1774 Captain Cook and his crew suffered from the symptoms of Ciguatera Poisoning after consumption of red bass from the New Hebrides (Vanuatu). It was not until 1979 that the link with causative species of the dinoflagellate *Gambierdiscus* was established (Adachi and Fukuyo 1979). Ciguatera poisoning is a worldwide problem associated with ingestion of certain toxin-containing fish. The disease was initially named after a turban-shelled snail known as “cigua” in the Spanish Antilles, which was thought to be the cause of this disease. More than 200 species of fish have been implicated, the most common of which include grouper, red snapper, barracuda, amberjack, and less commonly mackerel, surgeonfish, and sea bass. In ciguatera endemic areas, including the Caribbean and the South Pacific islands, the incidence of ciguatera poisoning ranges from 50–500 cases annually per 10,000 population, making it one of the commonest illnesses in those areas. The causative microalgae are bottom-dwelling species attached to seaweeds and coral rubble but never cause water discolorations. Unfortunately, because of the migratory behaviour of fish and the lack analytical ciguatoxin standards no global monitoring programs are in place for these seafood toxins. Global warming is predicted to drive a range expansion of ciguatera into new areas (Hallegraeff 2010).

## 2.6 Toxic *Pseudo-nitzschia* Diatoms and Hitchcock’s “The Birds”

On August 18, 1961, a local California newspaper reported that thousands of crazed seabirds were sighted on the shores of North Monterey Bay. The sooty shearwaters did regurgitate anchovies, flew into objects and died on the streets. This helped inspire Hitchcock’s 1963 thriller “The Birds” (Fig. 8.2b). Then, 30 years later, disorientation and death struck brown pelicans and sealions in the same area. But this time, scientists were able to demonstrate that the birds had ingested a toxin, domoic acid, produced by the diatom species of *Pseudo-nitzschia australis* (Garrison et al. 1992; see also Chapter 1, section 2.1). Humans can also be impacted when shellfish ingested the diatoms and can



FIGURE 8.2 Harmful algal blooms. 2a. Warning sign posts in Tasmania, Australia, not to collect shellfish because of contamination with paralytic shellfish poisons from seasonal dinoflagellate blooms; 2b. Hitchcock’s movie “The Birds” was based on a real event whereby toxic diatom blooms led to contaminated anchovies and seabird mortalities in California; 2c,d. “Rocksnot” in the Buller River, New Zealand, caused by the invasive diatom *Didymosphenia geminata*  
 PHOTO CREDITS: 2A. TASMANIAN GOVERNMENT DEPARTMENT OF HEALTH AND HUMAN SERVICES. 2B. THEATRICAL POSTER RELEASED BY UNIVERSAL PICTURES; 2 C, D. G.HALLEGRAEFF

suffer from a toxin syndrome called amnesic shellfish poisoning, first coined in 1987 when in Prince Edwards Island, Canada, 105 people consuming blue mussels had to be hospitalised, causing 3 fatalities. It should be noted that the harmful effects from algal toxins almost exclusively impact on mammals and birds with highly evolved nervous systems, while shellfish themselves can in fact benefit from having access to more food.

### 2.7 “Rock Snot” and Ship Hull Fouling

Whenever one immerses a boat, anchor chain, buoy or pylon in the water, it rapidly attracts a coat of fouling bacteria and microalgae, notably diatoms (see Chapter 3 for more on diatoms). Ship hull fouling costs the shipping industry billions of dollars every year in excess fuel bills. Similarly, once crystal clear trout fishing streams in the South Island of New Zealand since 2004 have been suffering from unsightly “rock snot” (Fig. 8.2c, d). The causative diatom *Didymosphenia geminata* is thought to have been accidentally introduced from the Northern Hemisphere via moist fishing waders or equipment. These blooms that smother a stream or lake bed may adversely affect water quality, ecology and fish stocks, and also can become a hazard for hydro-electric generation, agricultural irrigation and recreational pursuits (Killroy et al. 2009). The introduction of dedicated custom quarantine regulations to prevent further spreading of *Didymosphenia* as well as new International Maritime Organisation (IMO) protocols to stop spreading of microorganisms via ship’s ballast water are driven by new scientific awareness (www.imo.org; Hallegraeff and Bolch 1992).

## 3 Algal Blooms: The Good

### 3.1 Microalgal Scums as Human Food: Spirulina and the Aztecs

The Aztecs living along the shores of Lake Texcoco in Mexico in the 13th century collected *Spirulina* cyanobacterial scums, called ‘techuitlatl’, by draining the water through bags of cloth (Fig. 8.3a) and spreading out the algae on the sandy shore for sun drying. The semi-dried algae were then cut into small squares and taken to the villages, where drying was completed. Women took these algal cakes, called ‘dihé’, for sale to the local market. Dihé was crumbled and mixed with tomatoes and peppers, and poured over millet, beans, fish or meat and eaten in 70% of meals (www.spirulinaresource.com). Pregnant women ate dihé cakes because they believed its dark colour would protect their unborn baby from the eyes of sorcerers. It was not until 1967 that the nutritional properties of *Spirulina* were fully recognised by western science (60% of dry weight is protein) and this triggered many research projects for industrial purposes to establish large-scale production plants. Today, *Spirulina* (now reclassified as *Arthrospira*) is being produced in more than 22 countries and used in over 77 countries in nutritional supplements, high end cosmetics, for water purification but newly also algal biofuels (Fig. 8.3b).

Ever since Beyerinck (1890) first succeeded in culturing from Delft pond water microalgae such as *Chlorella* and *Scenedesmus*, people have proposed algal biomass production for animal and human food and biofuel. To cite from



FIGURE 8.3 Good algal blooms. 3a. Aztecs in Mexico harvesting *Spirulina* to produce algal cakes; 3b. Massive outdoor pond culture of *Spirulina* in the New Mexico desert for biofuel production; 3c. Lagoon production of *Dunaliella salina* in Western Australia for  $\beta$ -carotene biotechnology.

PHOTO CREDITS: 1A. DRAWING IN HUMAN NATURE, MARCH 1978, BY PETER T. FURST; WWW.SPIRULINASOURCE.COM; 3B. A2BE CARBON CAPTURE LLC, USA. [HTTPS://WWW.ALGAEATWORK.COM/INDEX.HTML](https://www.algaeatwork.com/index.html); 3C. BETATENE (COGNIS), W. AUSTRALIA; [HTTPS://ALCOPHARMA.COM/](https://alcepharma.com/)

early attempts of algal mass cultivation by Burlew (1953) “*In regions of the world where population is especially dense, and fertile land is limited, it is entirely possible that process-industry methods of producing food may furnish a respite from the threat of famine and so contribute toward more salutary conditions for civilized living. If algal culture can serve such a purpose, it is well worth development for that reason alone*”. This potential was rediscovered in the late 1980s and experienced a revival in the 2000, largely triggered by the prediction of

fossil fuel peak oil production. While efforts using land plant biomass (sugar cane, maize, rape seed) are competing with using agricultural land for human food, mass production of microalgae in outdoor ponds or race ways (e.g. *Chlorella*, *Botryococcus*, *Arthrospira*; up to 70% oil by weight) can produce 13x higher biomass (liters of oil per hectare) from a significantly (49–132 times) smaller area (Benemann 2013). Harvesting microalgae and extracting and refining algal biofuels currently render such ventures uneconomical, unless biofuels are a by-product of high-value pharmaceuticals or nutraceuticals (Borowitzka et al. 1984).

### 3.2 *Microalgal Biomass Culture for Biotechnology: Dunaliella salina for $\beta$ -carotene*

The green alga *Dunaliella salina* was named after its original discoverer, Michel Felix Dunal, who first reported in 1838 sighting the organism in saltern evaporation ponds in Montpellier, France. Under high light and hypersaline conditions, this green alga produces up to 5% of its dry weight as  $\beta$ -carotene (market price is \$600/kg) to protect the organism from long-term UV radiation. From a first pilot plant established in the USSR in 1966, the commercial cultivation of *D. salina* has been pursued in Australia (since 1980), Israel and the USA. Grown in 5 ha open air ponds (Fig. 8.3c), Western Biotechnology in Australia produces \$5M/yr. Similar ventures in the US focus on astaxanthin production from *Haematococcus* (valued at \$2000–\$3000/kg) to be used as a supplement in feed pellets for salmon aquaculture (Borowitzka et al. 1984) to maintain their pink flesh.

### 3.3 *Microalgal Blooms: The Green Pastures of the Sea*

Usually we think of the macroscopic algae or seaweeds, as the 'grass' of the sea, but microscopic diatoms, and more generally, phytoplankton, are the equivalent of green pastures on the land. There are diatoms in soil and other places, but diatoms represent the bulk of oceanic primary production. In the ocean, the microscopic organisms convert sunlight and nutrients through photosynthesis into the bottom of the food pyramid. These organisms form the basis of all marine foodwebs leading to edible fish. Only since 1978 satellites have been able to detect the amount of chlorophyll in the oceans. The SeaWiFS image in Fig. 8.4a represents the northern hemisphere spring with diatom spring blooms in the North Sea, supporting e.g. the rich herring and cod fisheries. Other phytoplankton rich areas are upwelling areas such as off Peru supporting sardine and anchovy fisheries, and polar regions supporting dense krill stocks being fed on by whales. As the ocean waters heat up, tropical waters tend to become more nutrient and plankton poor, but there are signs that polar waters may become more productive in near future (Doney 2006).

### 3.4 *The Breathing Lungs of Our Planet: The View from Space*

Land plants and algae help the planet breathe by turning carbon dioxide into oxygen. More and more, we are now becoming aware of the quantitative contribution by marine phytoplankton, because they account for 50% of global primary productivity (Longhurst et al. 1995). That means that every first breath of oxygen we humans take in derives from microscopic algae, and the second breath from land plants, which after all are only newcomers dating back to 400M years ago. The power of this microbial algal engine is well demonstrated by Fig. 8.4b. All the microalgal cells in the world oceans could be packed in a plank, 386,000 km long, 7 cm thick, and 30 cm wide, that is, stretching from the earth to the moon (Andersen 2005). On average this plank divides once per

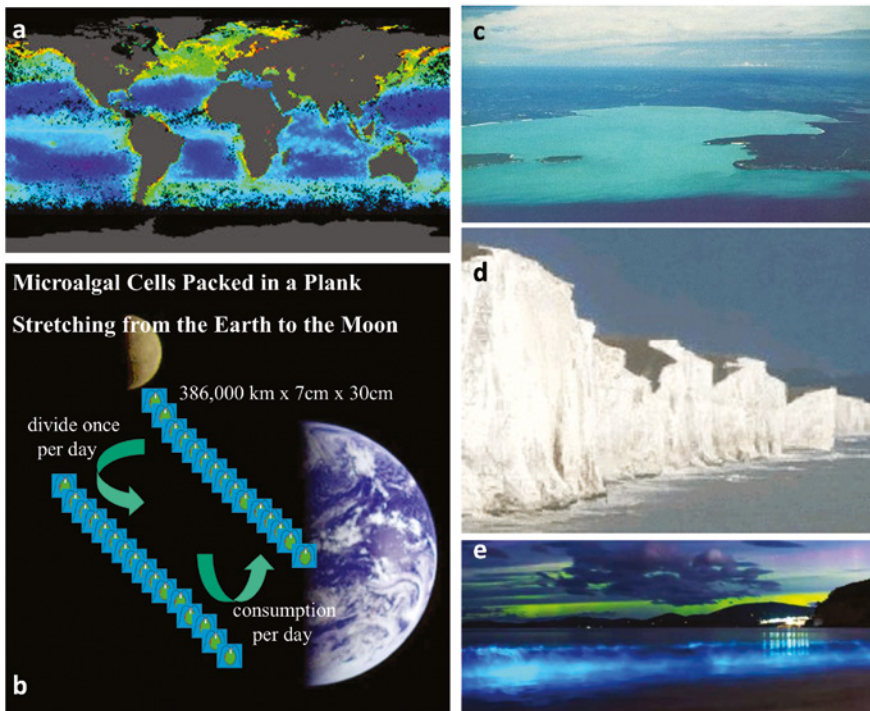


FIGURE 8.4 Good algal blooms. 4a. SeaWiFS chlorophyll satellite image showing Northern Hemisphere spring diatom blooms (red orange); 4b. The power of the microbial algal engine; 4c. Coccolithophorid bloom of *Gephyrocapsa oceanica* in Jervis Bay, Australia; 4d. White Cliffs of Dover made up of coccolithophorid chalk; 4e. *Noctiluca* bioluminescent spectacle in Tasmania, Australia

PHOTO CREDITS: 4A. NASA [HTTPS://OCEANCOLOR.GSFC.NASA.GOV/ATBD/CHLOR\\_A/](https://oceancolor.gsfc.nasa.gov/atbd/chlor_a/); 4B. ORIGINAL, BASED ON DATA IN ANDERSON 2005; 4C. COURTESY FORD KRISTO, AUSTRALIAN NATIONAL PARKS AND WILDLIFE SERVICE; 4D. GEOLOGICAL SOCIETY OF THE UNITED KINGDOM; 4E. COURTESY KELLI MILLER, TASMANIA

day, but the reason the oceans are not becoming greener or browner, is because of rapid consumption by zooplankton and larval fish. Large milky-white coccolithophorid (*Emiliania huxleyi*) blooms, visible from space, once a source of concern (e.g. Fig. 8.4c, mistaken for pollution from the milk industry in Jervis Bay, Australia; Blackburn and Cresswell 1993) are now be viewed as carbon sequestering blooms which are good for planetary health (Lovelock 1991). Realization of this crucial ecosystem activity also translated in a revived interest in understanding coccolithophorid calcareous deposits (150M years old) such as the white cliffs of Dover in England (Fig. 8.4d). In the past, massive algal blooms removing the greenhouse gas carbon dioxide from the atmosphere have been speculated to have triggered cooling periods leading to an ice age (Martin 1990). The nutrient input from both climate-driven dust storms and bushfires has been demonstrated to generate massive ocean algal blooms (Tang et al. 2021). Such scenarios have inspired ill-conceived geo-engineering plans to fertilise significant parts of our oceans to generate dense algal-blooms with the dual benefits of carbon sequestration (climate mitigation) as well as increased food production (Glibert et al. 2008).

### 3.5 *Algal Photosynthesis: The Source of Iron Ore*

The advent of cyanobacterial photosynthesis on our planet 3.5B years ago is prominently carved in the geological record in the form of banded iron formations deposited around 2.4B years ago. Early oceans contained high concentrations of dissolved iron which oxidised (the equivalent of rust formation) and then precipitated in parallel with the rise in oxygen concentrations in seawater. Proposals to name our current epoch “Anthropocene” to mark the time of humans having a substantial impact on the planet, using fossil fingerprints such as plastic or nuclear debris, fade in comparison with the huge impact of algal photosynthesis. Oxygen is highly toxic to life forms preceding cyanobacteria such as methane and sulphur bacteria which therefore were driven to exile in anoxic sediments or the deep-sea. Few people stand still today to realise that the success of the Australian, South African and Brazilian economies is almost entirely built upon the mining and export of iron ore deposits that mark this “microalgal” event.

### 3.6 *Bioluminescent Spectacles*

Charles Darwin (1839) already described bioluminescence in the sea:

*While sailing in these latitudes on one very dark night, the sea presented a wonderful and most beautiful spectacle. There was a fresh breeze, and every part of the surface, which during the day is seen as foam, now glowed with a pale light. The vessel drove before her bows two billows of liquid phosphorus,*

*and in her wake she was followed by a milky train. As far as the eye reached, the crest of every wave was bright, and the sky above the horizon, from the reflected glare of these livid flames, was not so utterly obscure, as over the rest of the heavens.” Darwin almost certainly observed a dinoflagellate bloom such as *Noctiluca* (meaning “night-light”) (Fig. 8.4e).*

These fireworks have nothing to do with the chemical element phosphorus but use a molecule luciferin, an enzyme called luciferase, which combined with oxygen generates neon blue light. This biochemical strategy was first invented by the bacteria (Aristotle already described how damp wood can glow), but from there was borrowed by numerous other creatures to serve very different purposes such as with mushrooms to attract flies that spread spores, for glow worms to attract prey, and the well-known fireflies that use it to attract a mate. For sea creatures such as *Noctiluca*, the use of bioluminescence is thought to act as a burglar alarm to scare off predators. Ironically, almost everything we know about bioluminescence dates from Navy funded research during World War 1 when a stealth German submarine tried to sneak through the Strait of Gibraltar, but lit up like a Christmas tree and was sunk by Allied forces. Despite all the research, these neon blue spectacles are tough to forecast with precision. Climate-driven bioluminescent blooms in southern Australian waters are turning into a tourist attraction (Hallegraeff et al. 2019). Similarly, a small tourism industry based on *Pyrodinium* bioluminescence in Baha Phosphorescente is based in Puerto Rico (Zahl 1960).

### 3.7 *Coral Reefs or Dinoflagellate Reefs*

Coral reefs are large underwater structures composed of the calcareous skeletons of colonial marine invertebrates called coral polyps belonging to the phylum cnidaria that includes jellyfish and anemones. Globally coral reefs generate tourism worth \$36B per year. It was not until the 1960s that it was discovered that most corals have a symbiotic relationship with zooxanthellae in their tissues. These mostly dinoflagellate microalgae (the first genus to be described was aptly named *Symbiodinium*; Freudenthal 1962) live inside the coral polyp's body where they photosynthesize to produce energy for themselves and the polyps. The polyps, in turn, provide a home and carbon dioxide for the algae. Additionally, the zooxanthellae provide the coral with their lively colors – most coral polyp bodies are clear and colorless without zooxanthellae. Essentially, the entire productivity of coral reef systems can thus be credited to microalgae, but early suggestions to rename “coral reefs” to be termed “dinoflagellate reefs” were never taken seriously. A key threat to coral reefs from climate change is coral bleaching, when high water temperatures (as little as 1°C above the long term average) causes the corals to expel their zooxanthellae.

If this lasts too long they will not return and corals die. Different species of zooxanthellae impart lesser or better protection for their coral hosts, which is now being explored as a new bioengineering approach for coral conservation (Van Oppen et al. 2017).

### 3.8 *Algae: Living Fossils of the Origin of Multicellular Life*

The recognition of the importance of water in the genesis of life, and the fact that life started with microbial forms has never been doubted. “Where did life come from?” remains one of the biggest questions in biology, that has preoccupied scientists for hundreds of years. How did a cosmic soup of inanimate matter eventually give rise to a diverse multitude of lifeforms? Charles Darwin

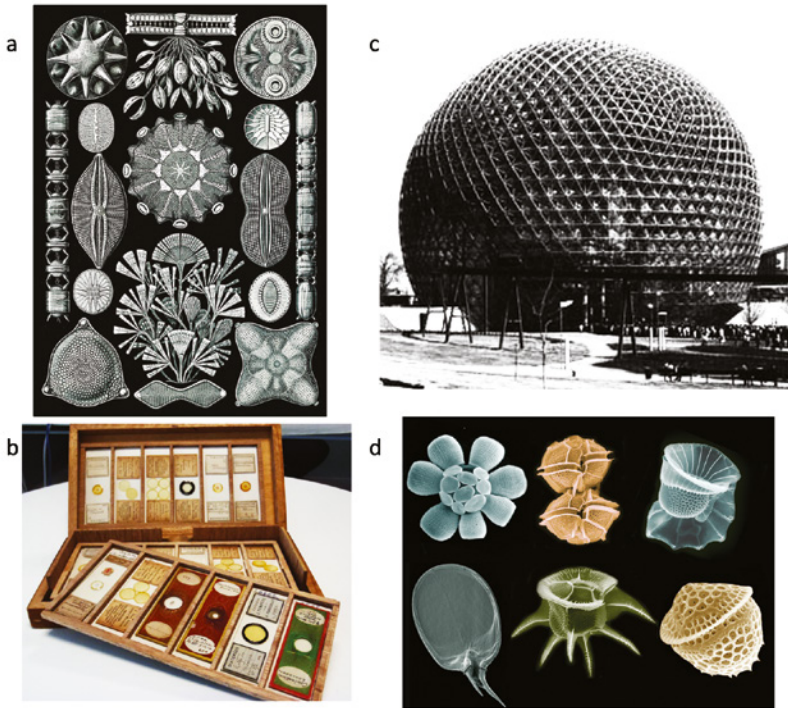


FIGURE 8.5 5a. Diatom drawings by Ernest Haeckel from his “Artforms of Nature” 1889; 5b. Permanent diatom slide mounts from the Victorian early 1900s; 5c. The design of the geodesic dome by Buckminster Fuller bears a strong resemblance to a scanning electron micrograph of the diatom *Pyxidicula* (the resting spore of *Stephanopyxis*); 5d. Tropical coccolithophorids and dinoflagellates from Australian waters

PHOTO CREDITS: 5A. HAECKEL 1889; 5B. ORIGINAL; 5C. MICHAEL ROUGIER, LIFE MAGAZINE; 5D. G. HALLEGRAEFF

(1871) already speculated “*But if ... we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity etcetera present, that a protein compound was chemically formed, ready to undergo still more complex changes ...*”. In the 1950’s, Miller & Urey (1959) conducted an experiment which demonstrated that organic compounds (aminoacids) could be formed spontaneously by simulating the conditions of Earth’s early atmosphere of methane, hydrogen and ammonia.

To date, Earth is the only place in the universe where we know for sure that life exists, but this may well change in the near future with spacecrafts busily attempting to retrieve soil samples from Mars and meteorites and return them to Earth. That life on Earth may have an extraterrestrial origin is an enticing idea, first promoted by British astrophysicist Fred Hoyle. How would organics have formed in space in the first place? And even if these organics could survive in space, would they be able to withstand entry through Earth’s atmosphere?

The recent realisation that most of the water in the oceans of our planet is older the age of our immediate solar system (Cleeves et al. 2014) significantly raised the spectre of extraterrestrial watery life. Microscopic algae which evolved on our Planet around 1B years ago, with many forms essentially remaining unchanged, represent living fossils of our watery past. It perhaps is no coincidence that the salt content of the blood running through human veins matches that of seawater, and that our red and white blood cells bear an uncanny resemblance to unicellular algae?

#### 4 Conclusions

Starting with Van Leeuwenhoek (1673), who first observed microalgae in pond water, early observers of microalgae were fascinated by their intricate designs and the possibilities these newly discovered creatures could offer. The German zoologist Ernst Haeckel (1866) enthusiastically exclaimed “*Nature has created an inexhaustable wealth of wondrous forms whose beauty and diversity way exceed anything that has been created by man*”. “*Never will I forget the delight with which I (...) first observed (...) myriad animal forms, (...) and attempted to render with my paintbrush their splendid forms and colours*”. His “Artforms in Nature” illustrations which include microscopic diatoms (Fig. 8.5a) and dinoflagellates continue to inspire artists even today. In Victorian times, it was a popular pastime to painstakingly mount cleaned diatom frustules in so-called “arranged” slides – made out of individually placed diatom shells (Fig. 8.5b). Even architects such as Buckminster Fuller, credited with the design of the geodesic dome (Fig. 8.5c), is thought to have used early scanning electron

micrographs of a diatom for inspiration. Architects and diatoms struggle with the same problem to create the strongest possible structure using the least amount of building material.

Regrettably much of the early human perceptions of awe and wonder about microalgae gave way during the 1980s to 2000s to the predominantly negative perceptions of adverse impacts from harmful algal blooms (HABS). Carried over from historic beliefs (the red river Nile, cattle deaths from contaminated drinking water, Captain Vancouver and Captain Cook seafood poisonings), globally increasing investments in shellfish and finfish farming as well as tourism focused on the human-centric view of algal blooms as being harmful and unwanted. One of the most frequently asked questions about Harmful Algal Blooms has been whether they were increasing and expanding and what is the role of nutrient pollution, climate change, shipping and aquaculture. A statistical analysis on a global dataset extracted from the Harmful Algae Event Database (9,500 events) and Ocean Biodiversity Information System (7 M microalgal records) was recently conducted for the period 1985 to 2018 to investigate temporal trends in the frequency and distribution of marine harmful algal blooms (Hallegraeff et al. 2021). The authors found no uniform global trend in the number of harmful algal events and their distribution over time, once data were adjusted for regional variations in monitoring effort. Instead, the 16-fold global increase in aquaculture production was identified as one of the key drivers of increased concerns and reports of HABS, demonstrating how perceptions and moral judgements may eclipse scientific reality. An algal bloom commonly only becomes harmful to society once you put a shellfish farm or fish farm in the middle of it, hence this is largely a human generated problem.

Citing the algal poet Ralph Lewin (1987):

*The biology of algae is a virtue, or a vice, that entails some tricky searching of the soul.*

*It involves the growth of fishes, and the harvesting of rice, And pollution, and the origins of coal. It may get us into trouble; it may get us into space; Its dilemmas are as long as they are wide. It involves some moral judgements on the future of our race – And a little bit of science on the side.*

With massive increases in knowledge using algal culturing techniques, electron microscopes, molecular genetics and satellite imagery, we now recognise the critical role that microalgae play as the basis of all food chains leading to edible fish, the source of fossil fuels, iron ore deposits, the basis of coral reef tourism and planetary atmospheric health. Mass cultivation for aquaculture

feeds, biotechnology and biofuels are attracting new interest. Bioengineering prospects of ocean fertilisation for increased fish production and carbon sequestration are on the horizon. Dedicated quarantine regulations to curb the spreading of unwanted species, for example via ship's ballast water, could never have been foreseen. It is now abundantly clear that most microalgal blooms are beneficial for humans. In turn, microalgae are stimulated by waste nutrients from human activities, the creation of artificial structures for attachment, the geographic spreading via ship's ballast water, enhanced growth by increased carbon dioxide and warming seawaters, and even nutrient inputs from climate-driven dust storms and bushfire ash. These fast-growing microorganisms represent a tremendous genetic diversity. In general they tend to be highly adaptable and, with the exception perhaps of tropical ocean plankton and coral zooxanthellae, are remarkably tolerant towards environmental change. The microbial engine of plankton algae plays a key role in our planet's ability to adapt and survive. It is perilous for our own human survival to ignore this critical creation.

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