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Harmful Algae 1 (2002) 1–4

HARMFUL ALGAE

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Comment

Harmful algae—a perspective

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Received 1 October 2001; accepted 13 March 2002

When Virgil (70–19 B.C.) wrote the words *Nihil vilior alga*—there is nothing fouler than an alga—he presumably had the stench of decaying seaweed in mind. Macroscopic algae can indeed be a nuisance, as when they get tangled around a boat's propeller or when an alien species invades and destroys native littoral communities, but many are of economic value, many are quite elegant, and none are particularly toxic. Now it is the micro-algae that attract approbium as potentially harmful nuisances. Virgil would not have known these as algae, of course, but no doubt was familiar with the scums and slimes for which they are responsible, as were Giraldus Cambrensis (1188) and Shakespeare (1598). It has been known for a long time that some water-blooms, as dense growths of these micro-organisms in freshwater are called, and red tides, which are analogous populations in the sea, may be harmful. The account in the Bible of the first plague of Egypt is a convincing description of a dinoflagellate bloom killing fish in the Nile. Fossil cysts of a toxic species of dinoflagellate, now extinct in Scandinavian waters, indicate harmful blooms between 2000 and 500 B.P. in the Kattegat-Skagerrak area. Indian tribes in the Pacific northwest seem to have had a long-established awareness of a connection between bioluminescence in the sea during hot weather, probably produced by dinoflagellates, and mussel poisoning. Over the past century reports of blooms of toxic algae, both in freshwaters and the sea, have become more frequent. This may be in part attributable to greater awareness of the public, greater attention from the media, and the attraction of scientists for interesting chemical and biological problems which may be perchance fund-worthy. However, although it is difficult to produce unequivocal evidence, it seems that the increase is real and that increasing eutrophication by human agencies is the main cause.

Micro-algae play the outstanding role of primary producers in aquatic habitats. The vast majority of the species are not only harmless and essential components of these ecosystems but are of exquisite beauty when viewed down the microscope. They can nevertheless be nuisances, even if not toxic, in some circumstances; their populations may overwhelm other forms of aquatic life, filters may be clogged, and drinking waters acquire unwelcome odours or tastes. If such algae occur in dense concentrations and die, their decomposition consumes oxygen and liberates toxic substances, such as hydrogen sulphide so that fish may be killed, but almost any other dead material may do the same. Some may be troublesome without being directly or indirectly poisonous. The 'brown tide' picoplanktonic chrysophycean *Aureococcus anophagefferens* seems to be one such. It can occur in dense populations (CirCa 10^6 cells ml^{-1}) which interfere with the ingestion of flagellates by shellfish. How is not clear, but it does not appear to be due to inhibitors produced by the *Aureococcus*. A few are harmful parasites. Among the Chlorophyta the colourless unicellular alga *Prototheca*, which lives in soil, causes the disease protothecosis in animals and humans and may lead to death by massive invasion of

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PII: S1568-9883(02)00002-1

the blood stream. The dinoflagellate *Blastodinium* is parasitic on marine pelagic copepods and freshwater copepods can be parasitized by a variety of euglenophytes. Sessile cyanobacteria have been implicated in the spread of legionnaires disease but so far planktonic algae seem to be exonerated from transmitting bacterial and viral diseases to humans.

Of the many thousands of species of micro-algae those that produce specific toxins scarcely exceed a hundred. These occur in both salt and freshwaters and whilst most are planktonic some are benthic or float at the water surface. They can attract particular attention when they cause the death of livestock that has drunk water containing them, or of fish and shellfish in the sea, or of humans that consume these. Algae which seem to be direct producers of toxic substances mostly belong to three taxonomic groups; Cyanobacteria, Dinophyta and Prymnesiophyta. As well as these, there are some groups which include one or two toxic members. Species of *Chattonella*, flagellates belonging to the Raphidophyceae, form toxic red tides in Japanese waters and a few diatoms, notably *Pseudonitzschia* species, produce domoic acid, a low molecular amino acid causing amnesic shellfish poisoning.

The Cyanobacteria (blue-green algae) have some two dozen genera including toxin-producing species. The toxins are mostly those causing acute lethal poisoning in vertebrates – neurotoxins, such as alkaloids and hepatotoxins, which nearly all seem to be peptides. Others are not so highly lethal but have more selective biochemical activity. These cytotoxins include a variety of simpler organic compounds. The Dinophyta includes about a dozen genera producing water and/or lipid soluble, non-proteinaceous, low molecular weight neuroactive secondary metabolites. Ciguatera is a tropical fish-borne disease caused by dinoflagellate neurotoxins. Paralytic shellfish toxins, also of dinoflagellate origin, are potentially lethal to man but also affect birds, fish and crabs. The Prymnesiophyta contains a few toxic species. One of them, the flagellate *Prymnesium parvum*, produces a potent toxin that causes extensive fish mortality in brackish waters. Another flagellate, *Chrysochromulina polylepis*, appeared out of the blue in blooms on eastern coasts of the North Sea, perhaps by gaining a start on competition from other species by releasing a grazer repellent. It produces an ichthyotoxic substance causing osmoregulatory failure similar to that brought about by *P. parvum*. *Phaeocystis*, a widely distributed marine flagellate, familiar to fishermen in the form of extensive blooms of mucilaginous colonies which are avoided by herring. It produces large quantities of acrylic acid, which has strong bacteriocidal properties.

There seem to be two peculiar features here. One is that the capacity to produce toxins is largely confined to three or four of the heterogeneous groups of 12 different phyla collectively known as algae. The other is that the toxins seem mostly to be harmless to the species which might be expected to compete with or prey on the organisms which produce them but are highly toxic to much larger forms of life, such as vertebrates, which are at a higher trophic level and do not occur in the same community so having little or no influence on their biological success. There appear to be no obvious explanations of these features. To speculate, one may wonder whether the reason lies in the great antiquity of these groups. The cyanobacteria are prokaryotes, lacking a nuclear envelope, the first oxygenic photosynthetic organisms to appear on earth. It has been suggested that the substantial release of polypeptides, serving no apparent biological purpose, from healthy cells of these organisms arises from ill-controlled amino acid synthesis. The Dinophyta are eukaryotes, perhaps 600 million years old, characterised by a unique type of nucleus combining both prokaryotic and eukaryotic features. The toxins they produce are endotoxins, i.e. not released into the environment while the cells are alive, so it is unlikely that they serve any useful purpose to them as toxins. No fossil remains of prymnesiophyte flagellates older than 300 million years are known but it seems likely that the group evolved at about the same time as the Dinophyta. The Prymnesiophyta are eukaryotic but have their own characteristic type of nuclear division, differing from that of the more advanced algae. Diatoms, of which very few species are toxic, are a group of comparatively recent origin—around 150 million years old—and have a nuclear organization more resembling the familiar plant type. It may be that in the more ancient groups cell organization may not be fully evolved and hence metabolic systems not fully controlled. An organism does not need to be 100% efficient in order to survive, and, if there is no selective pressure, to cease making a useless by-product (the rubber tree seems to be one of this sort). The enzyme system which produces bioluminescence in some bacteria and dinoflagellates also seems to fall under this heading and, with the toxins, to be just a relic of fruitless evolutionary experiment. On the other hand, of course, nature has its subtleties of which we are as yet unaware.

Be that as it may, the more urgent requirements are for the practical purposes of understanding, predicting, and controlling the activities of these threatening algae. So far there has been little success. The costs of analytical identification, medical treatments, lost productivity, and precautionary monitoring, amount to many million dollars per year world-wide. The first need is for accurate identification. Since many of the organisms are below 20 μm in size this calls for skilful microscopy with both the optical and electron microscopes as well as familiarity with the widely scattered and often abstruse toxonomic literature. Immunology, involving the preparation of specific monclonal antibodies, provides an alternative and more reliable method which can distinguish decisively between species and strains. This requires isolation of axenic clonal cultures of the algae. These are also necessary for determining that the toxin is actually a product of the organism under consideration. Some species have both toxic and harmless strains and there is also the possibility that toxins attributed to a particular species may not be produced by the alga itself but bacteria with which it lives in close association. The toxins themselves need to be isolated, characterised, and their chemical structures established if antidotes and possible uses in pharmacology are to be devised. The pathology of susceptible animals also needs to be studied.

If outbursts of harmful algae are to be forecast, plans made to avoid their occurrence, or controls of their impact devised, it is essential to have a broad knowledge of the behaviour of the organisms, the ecosystems in which they flourish, and the chemical, physical and biological factors which affect their abundance. Here we have to remember that human activities may play a large part in determining these factors and, in the first place, be responsible for the introduction of a harmful species; shipping ballast, for instance, has a great potential for transfer of organisms. Comprehensive understanding of life histories is needed. A species recognisable as a threat if it appears in the plankton may have a benthic phase in its life cycle, as resting spores perhaps or even as an alternating generation. *Phaeocystis* is a striking example of a planktonic species which exists in two quite different forms. The individuals are innocuous, single-celled, free-swimming members of the picoplankton, but at some stage—it is not clearly understood why—they leave the lower region of the photic zone where they can multiply rapidly, aggregate into colonies encased in mucilage of the order of a millimetre in size, and enter a slow-growing phase near the water surface. The broad geographic distribution of harmful algae is laborious rather than difficult to establish since records of outbreaks are abundant, but scattered in a wide variety of publications. Production and release of toxins by any alga may depend on the stage reached in the life cycle as well as on environmental factors, such as light, temperature and nutrient concentrations, which control its physiology. The presence of the alga is usually only noticed and harmful effects evident when it occurs in dense accumulations. What causes dense accumulations is a general problem in plankton studies, whether the algae are harmful or not. The factors involved are various. Supply of necessary nutrients is mainly dependent on transport by water movements such as upwelling of deep water, mixing of the water column by wind, and input by rivers. Vertical migration of cells in the water column depends on turbulence and on the organisms themselves. The Dinophyta, Prymnesiophyta and Raphidophyceae are flagellates, the larger ones able to swim at rates of 1–2 $\mathrm{m\,h^{-1}}$ whereas the smaller ones, of the order of 20 μm, manage around 0.05 $\mathrm{m\,h^{-1}}$. Planktonic cyanobacteria do not have flagella but move up and down in the water column by adjusting buoyancy by formation or collapse of gas vacuoles. These mechanisms allow the cells or colonies of cells to position themselves, in quiet waters, at depths at which light intensities and nutrient supplies are as favourable as possible. Sometimes they concentrate the algae at or near the water surface and a bloom is manifest. Of course, phytoplankton motility is ineffectual in the face of vigorous water movements. Red tides are most often the result of concentration of cells by onshore breezes, upwelling or convergence of currents at fronts. Some success has been achieved in predicting the development of phytoplankton growth by mathematical models based on data from laboratory experiments on growth rates, light and nutrient requirements, buoyancy and settling, together with physical data from the water body involved. Optical measurements of chlorophyll or other algal pigments from the water itself, or remote sensing, may also give some idea of the development of a bloom.

Biological factors are, however, crucial. A bloom of one species cannot develop if other species are more successful in competing for light or nutrients or if predators are present in sufficient numbers. The dense brown tides of *Aureococcus* in Narragansett Bay have been attributed to the occurrence of an ‘open niche’ allowing the organisms to exploit by rapid multiplication the comparative paucity of other phytoplankton at a time of low rate of grazing and ample nutrients. The exceptional bloom of the prymnesiophyte *Chrysochromulina polylepis*, with unexpected toxic properties which did great harm to trout and salmon farms as well as organisms in natural habitats in Scandinavian waters in 1988, seems to remain without conclusive explanation. Unusual climatic conditions or increase in nitrogen, phosphorus and trace element supplies do not seem likely causes and again it seems that the organism must have taken advantage of a lull in grazing. An algal bloom may be slowed down or ended by action of algicidal bacteria or viruses. With such inponderables, monitoring programmes are at present able to provide little or no advance warning.

An all important point is that in endeavouring to understand and manage outbreaks of harmful algal growth, it is essential to remember that these organisms are components of communities in which there are complex webs of interactions between environmental factors and the activities of a wide variety of species. These interactions involve obvious processes, such as grazing by herbivores, but also subtle effects, the nature and scope of which we are only just beginning to appreciate, such as patterns of turbulence and the release and uptake of biologically active organic metabolites in the general medium. In the course of these transfers an innocuous substance may be converted into a toxin or vice-versa. In the particular case of metabolites which are harmless to some species but not to others they may undergo a sequence of bioaccumulations, passing up a trophic chain until finally reaching a susceptible species in devastating concentration.

In attempting to manage harmful algae we cannot rely entirely on simplified and controlled experiments carried out in the laboratory but must always be aware of the complexities of the ecosystem as a whole. So often the dense bloom inflicting harm seems to arise through rare coincidences in the natural environment.

Harmful algae present problems which are unlikely to get better and may well get worse as aquaculture continues to expand. The solution calls for exploration, involving many branches of science, into diverse and intriguing avenues. This new journal will provide a stimulus for work of both practical and academic values in a challenging field.