

1 An Introduction to Harmful Algae

E. GRANÉLI and J.T. TURNER

Harmful algae have been the subjects of scientific and societal interest for centuries. Because blooms of toxic dinoflagellates were known to occasionally discolor water red or brownish red, they were, and still are known as “red tides.” Water discoloration was noted for the lower Nile in the Bible (Exodus 7:20–21), and Darwin made microscopic observations of discolored water from an apparent dinoflagellate bloom off Chile during the voyage of the HMS *Beagle* (“Some of the water placed in a glass was of a pale reddish tint and, examined under a microscope, was seen to swarm with minute animalcules darting about and often exploding. Their shape is oval and contracted in the middle by a ring of vibrating curved ciliae.”) (Galtsoff 1949, 1954).

In this book, the term “harmful algae” (HA) is used in a broad sense, referring to algae that can cause a variety of deleterious effects on aquatic ecosystems, including negative aesthetic effects such as beach fouling, oxygen deficiency, clogging of fish gills, or poisoning of various organisms. A direct effect of some HA blooms can be oxygen deficiency in deep waters, which in turn, causes mass mortality of benthic animals and fish kills (Granéli et al. 1989).

Some red-tide dinoflagellates and other harmful algae produce powerful toxins that can cause fish kills or shellfish poisoning. Included are PSP (paralytic shellfish poisoning), DSP (diarrhetic shellfish poisoning), ASP (amnesic shellfish poisoning), and NSP (neurotoxic shellfish poisoning), as well as other yet-uncharacterized toxins (see Turner and Tester 1997; Wright and Cembella 1998; Cembella 2003). Such toxicity can cause shellfish intoxication, leading to human fatalities, as well as vectorial intoxication whereby toxins are accumulated and transported through pelagic food webs by feeding interactions, leading to mortality of fish, seabirds, or marine mammals. In some cases, toxic blooms of flagellates of the genera *Chrysochromulina* or *Prymnesium* can disrupt entire ecosystems (Edwardsen and Paasche 1998).

In addition to toxicity, there are other adverse effects prompting the recent use of the more inclusive term “harmful algae.” Such additional effects include organic loading leading to anoxia, such as in the 1976 bloom of *Ceratium tripos* off New York or the 1987–88 *Ceratium* spp. blooms in the Kattegat, beach

fouling associated with massive blooms of *Phaeocystis* spp. off northern Europe, irritation of fish gills leading to suffocation by spines of *Chaetoceros* spp., or disruption of ecosystems by brown tides in Narragansett Bay, Long Island embayments, or the Laguna Madre of Texas. The economic impact of such blooms can be substantial.

Are harmful algae unique, compared to other phytoplankton? They certainly are in terms of the above-mentioned adverse effects that are of interest to humans, but other than producing toxins or other noxious chemicals, are they substantially different from other phytoplankters? Possibly they are not. Harmful algae (HA) as well as other species of phytoplankton and other organisms are all following their own autecological agendas, which together comprise community synecological dramas. Further, HA phytoplankton comprise only a small proportion of all phytoplankton species. Of the known 5,000 named living phytoplankton species (Sournia et al. 1991), known HAB species comprise some 300 species that can cause water discoloration, and only some 80 species that produce toxins that can cause human shellfish poisoning (Hallegraeff 2003).

Why are some phytoplankton toxic? It is often assumed that production of these toxins evolved to deter grazers. However, if such toxins poison primarily consumers of shellfish, or other upper-level consumers such as seabirds, marine mammals, and humans, rather than primary grazers of phytoplankton, such as bivalves and zooplankton (Turner et al. 1998), can these toxins be considered effective grazing deterrents? Other HA toxins appear to be involved primarily in allelopathy, being released in the dissolved state into seawater and causing deleterious effects on other competitor phytoplankton species (Fistarol et al. 2003, 2004; Legrand et al. 2003). HA toxins may be secondary metabolites that are only coincidentally toxic, being primarily associated with other processes such as nitrogen storage, nucleic acid biosynthesis, bioluminescence, chromosomal structural organization, ion channel transport across membranes, bacterial endosymbiosis, or pheromones inducing sexuality during bloom decline, rather than serving as grazer deterrents (Cembella 1998).

HA taxa seem to possess various attributes that enable them to form massive blooms that can dominate their ecosystems for extended periods of time. What are these attributes? Do toxins serve as deterrents that poison zooplankton grazers that might otherwise control HA blooms? Do toxins act as allelopathogens to wage chemical warfare upon other phytoplankton species that are competitors of HA species for light and nutrients? Why are toxins produced by scores of species from various microalgal groups, including dinoflagellates, diatoms, cyanobacteria, raphidophytes, pelagophytes, haptophytes, chrysophytes, and prymnesiophytes? Are HA blooms primarily due to meteorological or physical oceanographic anomalies that sporadically cause unusually high concentrations of HA species that are otherwise comparatively rare? Are HA blooms in response to anthropogenic nutrient loading

from agriculture or sewage? Questions such as these, together with suggestions that HA blooms are possibly increasing in frequency and geographic extent in response to anthropogenic activities, have prompted increased interest in HA bloom ecology over the last decade. This increased interest in HA is not just confined to the scientific community, but also extends to the general public and governments that support scientists.

The recent flowering of interest in HA blooms has prompted a renaissance in the study of phytoplankton ecology. Because it is important to know whether an algal bloom is caused by an environmentally benign species or one that can poison or kill humans or other organisms of interest to them, such as fish, seabirds, or marine mammals, the importance of “species” has returned to the study of phytoplankton. This is after several decades of banishment of taxonomy from a field that largely viewed phytoplankton cells as no more than chlorophyll containers, uptakers of radioisotopes, or as “particles” that served as food for zooplankters. Indeed, many phytoplankton ecologists appear to have recovered from the seduction in the 1960s and 70s by fluorometers, liquid scintillators, and electronic particle counters, and returned to microscopes and flow cytometers in attempts to better quantify and identify the taxa we study. Because (as students often complain), under the microscope, many different things “all look alike,” HA phytoplankton ecology has been at the forefront of prompting all phytoplankton ecology to join the recent revolution in molecular biology in order to better identify and study phytoplankton species of interest. We now know much more about not only HA phytoplankton, but all phytoplankton than we did a few short years ago.

The recent growth in HA phytoplankton ecology as a scientific discipline is evidenced by the increasing frequency and size of its international meetings. The first international conference on harmful algae was held in Boston, Massachusetts, USA in 1974, with approximately 100 coauthors of less than 50 papers listed in the table of contents. Since then, at subsequent conferences (2nd, Miami, Florida, USA, 1978), (3rd, St. Andrews, New Brunswick, Canada, 1985), (4th, Lund, Sweden, 1989), (5th, Newport, Rhode Island, USA, 1991), (6th, Nantes, France, 1993), (7th, Sendai, Japan, 1995), (8th, Vigo, Spain, 1997), (9th, Hobart, Tasmania, Australia, 2000), (10th, St. Petersburg, Florida, USA, 2002), (11th, Cape Town, South Africa, 2005), participation has steadily grown to a maximum (in St. Petersburg) of 629 published abstracts of talks or posters in the conference program with participants from 48 countries. In addition, other notable international meetings addressing HA blooms included (to name a few) the International Symposium on Red Tides in Takamatsu, Japan (1987), the “Novel Phytoplankton Blooms” meeting on Long Island, New York, USA (1988), the “Physiological Ecology of Harmful Algal Blooms” meeting in Bermuda (1996), two symposia on harmful marine algae in the United States in Woods Hole, Massachusetts, USA (2000 and 2003), nine Canadian workshops on harmful marine algae (up through 2005), the Harm-

ful Algae Management and Mitigation Conference in Subic Bay, Philippines (1999), several Gordon Conferences, at least six conferences on toxic cyanobacteria (up through 2004), and special sessions at meetings of ASLO (American Society of Limnology & Oceanography) and/or AGU (American Geophysical Union) or TOS (The Oceanography Society), EUROHAB workshops (1998 Kalmar, Sweden, 2003, Amsterdam, Netherlands), the GEOHAB Open Science Meeting on HABs and Eutrophication (Baltimore, Maryland, USA, 2005), and others. There is also a new journal, *Harmful Algae*, which began publishing in 2002. Further evidence for the growth of this discipline is the increased research funding that is being invested by governments throughout the world for the study of harmful algae.

Despite this increased activity, the last major organized published synthesis of HA ecology was the volume from the Bermuda meeting in 1996 (Anderson et al. 1998). This volume addressed most major areas of HA science, through a combination of organism-based reviews (for example, *Alexandrium* complex and related species, fish-killing taxa such as *Chattonella* spp., *Heterosigma akashiwo*, *Gymnodinium breve*, *Pfiesteria piscicida*, *Prymnesium* spp. and *Chrysochromulina* spp., and other taxa, including species of *Phaeocystis*, *Dinophysis*, *Pseudo-nitzschia*, and *Noctiluca*). Other reviews focused on subjects that applied to various HAB species such as genetic variation, chemistry and physiology of various toxins, phagotrophy, and interactions of various HAB taxa with grazers, parasites, nutrients, trace elements, turbulence, and bacteria.

Although the reviews in the volume from the Bermuda meeting were excellent and comprehensive for the time, they are now almost a decade old and somewhat dated by recent developments. Accordingly, we were approached by Springer-Verlag with a request to compile an updated synthesis of HA ecology, organized primarily around processes and questions, rather than organisms. Thus, we invited a global assemblage of active HA researchers to contribute to the chapters in this volume, and many of these same specialists had also contributed to the previous Bermuda meeting volume. All chapters in this volume were peer-reviewed, by 1–3 reviewers in addition to the editors. We hope that this volume will complement other recent reviews and syntheses in *Harmful Algae* and other journals and in international HA meeting volumes to identify gaps in our present understanding of HA ecology and to suggest areas for additional research.

Acknowledgements. We are most grateful to Christina Esplund and Roseni de Carvalho for the invaluable help they gave during the entire time this book was compiled. From the re-drawing of figures, to improving photographic resolution, text layout, etc., they have indefatigably worked with all chapters. With smiles on their faces, they took up the challenge posed by the idiosyncrasies of almost all of the scientists involved in this book. Thank you!

References

- Anderson DM, Cembella AD, Hallegraeff GM (1998) Physiological ecology of harmful algal blooms. NATO ASI Series 41. Springer, Berlin Heidelberg New York, 662 pp
- Cembella AD (1998) Ecophysiology and metabolism of paralytic shellfish toxins in marine microalgae. In: Anderson DM, Cembella AD, Hallegraeff GM (eds) Physiological ecology of harmful algal blooms. NATO ASI Series 41. Springer, Berlin Heidelberg New York, pp 381–403
- Cembella AD (2003) Chemical ecology of eukaryotic microalgae in marine ecosystems. *Phycologia* 42:420–44
- Edvardsen B, Paasche E (1998) Bloom dynamics and physiology of *Prymnesium* and *Chrysochromulina*. In: Anderson DM, Cembella AD, Hallegraeff GM (eds) Physiological ecology of harmful algal blooms. NATO ASI Series 41. Springer, Berlin Heidelberg New York, pp 193–208
- Fistarol GO, Legrand C, Granéli E (2003) Allelopathic effect of *Prymnesium parvum* on a natural plankton community. *Mar Ecol Prog Ser* 255:115–125
- Fistarol GO, Legrand C, Selander E, Hummert C, Stolte W, Granéli E (2004) Allelopathy in *Alexandrium* spp.: effect on a natural plankton community and on algal monocultures. *Aquat Microb Ecol* 35:45–56
- Galtsoff PS (1949) The mystery of the red tide. *Sci Monthly* 68:109–117
- Galtsoff PS (1954) Red tide. *US Dept Interior, Fish Wildl Serv, Spec Sci Rept* 46:1–52
- Granéli E, Carlsson P, Olsson P, Sundström B, Granéli W, Lindahl O (1989) From anoxia to fish poisoning: the last ten years of phytoplankton blooms in Swedish marine waters. In: Cosper EM, Bricelj VM, Carpenter EJ (eds) Novel phytoplankton blooms: causes and impacts of recurrent brown tides and other unusual blooms. Springer, Berlin Heidelberg New York, pp 407–427
- Hallegraeff GM (2003) Harmful algal blooms: a global overview. In: Hallegraeff GM, Anderson DM, Cembella AD (eds) *Manual on harmful marine microalgae*, vol 11, 2nd edn. IOC-UNESCO. Paris, pp 25–49
- Legrand C, Rengefors K, Fistarol GO, Granéli E (2003) Allelopathy in phytoplankton – biochemical, ecological and evolutionary aspects. *Phycologia* 42:406–419
- Sournia A, Chretiennot-Dinet MJ, Ricard M (1991) Marine phytoplankton: how many species in the world ocean? *J Plankton Res* 13:1093–1099
- Turner JT, Tester PA (1997) Toxic marine phytoplankton, zooplankton grazers, and pelagic food webs. *Limnol Oceanogr* 42:1203–1214
- Turner JT, Tester PA, Hansen PJ (1998) Interactions between toxic marine phytoplankton and metazoan and protistan grazers. In: Anderson DM, Cembella AD, Hallegraeff GM (eds) Physiological ecology of harmful algal blooms. NATO ASI Series 41. Springer, Berlin Heidelberg New York, pp 453–474
- Wright JLC, Cembella AD (1998) Ecophysiology and biosynthesis of polyether marine biotoxins. In: Anderson DM, Cembella AD, Hallegraeff GM (eds) Physiological ecology of harmful algal blooms. NATO ASI Series 41. Springer, Berlin Heidelberg New York, pp 427–451