Introduction

Algae (singular alga, Latin for "seaweed") are a large and diverse group of structurally simple organisms that range from small, unicellular species to large, multicellular forms, such as the giant kelps that grow to more than 200 feet (65 meters) in length. In fresh waters, algae typically float in the water column (planktonic algae), form mats on the bottom of the waterbody (benthic or sediment algae), or form coatings on submerged structures (periphytic or attached algae). Although the shapes and sizes of algae range widely, they are considered structurally "simple" because their cells are not organized into the distinct organs such as roots, stems, leaves, flowers, and fruits that are found in land plants. Most algae are photosynthetic and use sunlight to “fix” carbon and produce sugars, but some unicellular species are unable to photosynthesize. While cyanobacteria (commonly called “blue-green algae”) have traditionally been considered algae, recent scientific studies usually exclude them due to important structural and physiological differences. However, for purposes of this discussion, cyanobacteria will be included as algae.

Algae are at the base of the food web and are considered “primary producers” in aquatic systems because they provide sugars and chemical energy for other organisms (Chapter 1). Algae are a crucial food source for invertebrates and fish, as well as frogs and other fauna that inhabit a system. Although algae occupy a critical niche in aquatic environments, many algae can quickly grow to densities that become problematic or noxious. Noxious algal growths or “blooms” have compromised water resources throughout the world and have impeded the use of infested waters for wildlife, aquaculture, drinking, irrigation, recreation and industrial operations. Excessive growths of algae can change pH and water quality, reduce dissolved oxygen (which can kill fish and other aquatic life), and cause foul tastes and odors. In addition, several groups of algae produce potent toxins that can be deadly in even small quantities.

Tremendous economic damage can result from noxious algal growths. Annual losses of up to $2 billion in the US can arise from the inability to use a water resource for purposes such as domestic...
supply, industrial uses, irrigation, fire suppression and navigation, and can lead to declines in recreational uses and decreases in property values.

Resource managers recognize that algae must be managed in critical aquatic systems to maintain the designated uses of the water. When excessive algae growth occurs, “adaptive water resource management” is usually implemented to maintain the system and its uses. Adaptive water resource management involves careful consideration of all available options to manage or control algae and vascular aquatic plants to restore the uses of water resources. Managing noxious algal growth requires actions that may include mechanical, physical, biological, or chemical strategies, alone or in combination. Although it may be beneficial in the long run to reduce the human contributions (such as nutrient runoff) to algae blooms, many algal species can double their population size in two days or less, so immediate action is usually needed to manage infestations. In these time-sensitive situations, algaecides can serve as a first line of defense because they are cost effective, environmentally sound, socially accepted, and work quickly to control excessive populations of algae. In order to efficiently and effectively use algaecides, water resource managers must rely on their knowledge of the aquatic system (i.e., nontarget species, water quality, etc.), the algae to be controlled and the algaecides labeled for use in the system.

Algaecides are available in several different active ingredients and formulations. Algaecide active ingredients that are registered for use with the US Environmental Protection Agency (USEPA) include copper salts and formulations, synthetic organic compounds, and hydrogen peroxide (Chapter 11). Each algaecide has unique properties that should be carefully considered and evaluated prior to use in a water resource. The adoption of the National Pollutant Discharge Elimination System (NPDES) has resulted in the requirement for a permit to apply algaecides and other pesticides over or near waters of the state or nation (USEPA 2011). Materials that are not registered as algaecides by the USEPA will not be considered in this discussion.

The application of an algaecide can rapidly restore the uses of an aquatic system; adaptive water resource management should then be employed to develop strategies to prevent or mitigate future algal issues. Prevention measures such as the control of algal movement in bilge waters and bait buckets should be undertaken. Other practices, such as reduction or elimination of runoff and nutrient control in the watershed, may be helpful in the long term, but are unlikely to provide immediate relief for excessive algae problems.

**Algal toxins in freshwater systems**

This section will focus on toxin-producing species of freshwater algae, which can adversely affect other algae, invertebrates, fish and mammals. Algal toxins are problematic in fresh waters when they are produced in sufficient quantities with sufficient potency to cause direct toxicity to organisms, decrease feeding and growth rates, and cause food safety issues. Production of algal toxins may be associated with a “bloom” or exceptionally dense growth or accumulation of algae. The term “Harmful Algal Bloom” (HAB) has been used to describe a proliferation, or “bloom,” usually of phytoplankton. Because phytoplankton serves as the base of most aquatic food webs, the impact of these blooms can be devastating for consumers throughout the food web and for other flora or fauna in the affected ecosystem. Even severe blooms of non-toxic algal species can spell disaster for animals in freshwater aquatic systems since massive quantities of phytoplankton deplete oxygen in the shallow waters of many systems. Recently, the world’s coastal and inland
waters have experienced an increase in the number and type of HAB events or the observation of those events has become more intense. Scientists are unsure of the causes for this trend. Possibilities range from natural causes such as species dispersal to human-related causes like nutrient enrichment, shifts in global climate and transport of algal species by ship ballast water.

The species of freshwater algae that cause HABs, as well as their effects, vary widely. While some are toxic only when they achieve high densities, others can be toxic at very low densities (only a few cells per liter). Whereas some blooms discolor the water (thus the terms “green scum”, “red tide” and “brown tide”), others are almost undetectable by unaided visual observation. The effects of HABs generally fall into two major categories: 1) public health and ecosystem effects, and 2) economic impacts. Broadly, public health and ecosystem effects can include factors such as:

1. Filter feeding shellfish (e.g. clams, mussels) may accumulate algal toxins by feeding on the toxic phytoplankton, sometimes at levels potentially lethal to humans or other consumers;
2. Potential fish, shellfish, and bird kills, occasionally invertebrate and mammal kills;
3. Decreased light penetration can alter ecosystem function and structure;
4. Discoloration of water can be aesthetically unpleasant;
5. Toxins or other compounds released by the algae can kill fauna directly or result in low oxygen conditions as the bloom biomass decays (especially critical where fauna cannot escape);
6. Blooms can be harmful to other algae or primary producers and the food webs that are dependent on them; and
7. The effects of long-term or chronic exposures to algal toxins on shoreline residents.

Direct economic impacts caused by HABs include loss of income for commercial fishermen, loss of food for subsistence fishermen, and consumer concerns regarding food safety, as well as declines in property values.

This chapter is focused on algal toxins in freshwater systems in the US. The chapter is limited to toxins produced by cyanobacteria, golden algae and euglenoids. Other algae (e.g., *Chrysochromulina*, etc.) that produce both toxins and/or taste-and-odor compounds can be important, but are not included in this discussion. Also, some more recent discoveries, such as the *Stigonematales*-like cyanobacterium that has been implicated in avian vacuolar myelinopathy, are not included since sufficient information for management has not been developed at this time.

**Cyanobacteria: the blue-green algae**

Cyanobacteria (blue-green algae) are geologically ancient, broadly distributed inhabitants of fresh, brackish, marine and hypersaline waters, as well as terrestrial environments, and grow in diverse habitats ranging from thermal springs to the arctic. Although cyanobacteria are classified as bacteria as opposed to algae, they are photosynthetic in aquatic systems. In fact, cyanobacteria are much larger than other bacteria and are major contributors to global photosynthesis and nitrogen fixation. Cyanobacteria occur in unicellular, colonial and filamentous forms; they grow under a wide variety of conditions and can become the dominant algae in nutrient-rich water bodies. Cyanobacteria can form blooms so thick that the surface of the water appears to be covered with blue-green paint. Several cyanobacteria in the US produce substances that cause taste and odor problems in water supplies and aquaculture. Some species of blue-green algae, particularly
Anabaena and Microcystis, are widely distributed in the US and can produce toxins that are poisonous to fish and wildlife that drink toxin-contaminated water. In other parts of the world, there are documented cases of blue-green algal toxins harming humans that have consumed toxin-tainted waters.

Cyanobacterial ecology in freshwater systems
Cyanobacteria are most abundant in eutrophic conditions, but they can readily colonize most freshwater systems and can rapidly grow to great masses. Cyanobacteria can rapidly overtake a system and cause “blooms” that render the water resource unstable or unusable. The occurrence and abundance of particular cyanobacteria in a freshwater system depend on a variety of ecological factors, including nutrient status, salinity, light conditions, turbulence and mixing, temperature and herbivory. In most freshwater systems, true algae may grow faster than cyanobacteria. However, cyanobacteria can seize the advantage in eutrophic situations by out-competing algae for nutrients, thriving in low dissolved oxygen and photosynthesizing more efficiently at lower light levels. Cyanobacteria are also less affected by turbidity, high concentrations of ammonia and warmer temperatures than are algae; in addition, they may produce chemicals that inhibit the growth of competing algae and reduce grazing by invertebrates.

Cyanobacterial toxins in freshwater systems
A number of types of cyanobacterial toxins are produced by various species of blue-green algae, but most cyanotoxins are classified as either neurotoxins or hepatotoxins. Neurotoxins attack the nervous systems of vertebrates and invertebrates; symptoms of neurotoxin poisoning include loss of coordination, twitching, irregular gill movement, tremors, altered swimming, and convulsions before death by respiratory arrest. Neurotoxins are produced by several genera of cyanobacteria including Anabaena, Aphanizomenon, Microcystis, Planktothrix, Raphidiopsis, Arthrospira, Cylindrospermum, Phormidium and Oscillatoria. Neurotoxins produced by Anabaena spp., Oscillatoria spp. and Aphanizomenon flos-aquae are responsible for animal poisonings around the world. Hepatotoxins ultimately lead to liver failure; symptoms in fish include flared gills (due to difficulty breathing) and weakness or inability to swim, which can result in mortality within 24 hours of exposure. Cyanobacterial hepatotoxins are produced by many genera of cyanobacteria, including Microcystis, Anabaena, Planktothrix and Cylindrospermopsis. Hepatotoxins have been implicated in deaths of fish, birds, wild animals, and agricultural livestock, and are responsible for human illness and death in India, China, Australia and Brazil.
Management of toxic cyanobacteria

Toxin production does not always occur in a bloom of toxin-producing cyanobacteria, but it is likely that toxins will quickly be produced in toxic amounts by high-density blooms of cyanobacteria. The decision to treat cyanobacteria with an algaecide is prompted by a variety of factors, including the size of the affected water resource, the number and type of organisms (e.g., fish, mammals) in the system, the age and condition of the organisms that will be potentially affected, the sensitivity of the target cyanobacterium to treatment, and the cost of treatment. Most toxin-producing cyanobacteria are susceptible to algaecide treatments, but some experimentation may be needed to identify the best treatment for a specific strain at a site. Occasionally, the idea that algal cells may leak toxins is proposed as a consideration for initiating – or choosing not to initiate – an algaecide treatment, but the idea that all algaecides cause toxin leakage in all situations is not supported by existing data. Also, algae can double their population densities in two to three days, and toxin production may be proportional to density, so choosing not to treat suggests that the risks associated with further production of toxin are acceptable. There is no way that treatment can increase the concentration of total toxin; however, failure to treat toxin-producing algae can result in increased exposure to toxins and associated risks. Management techniques other than algaecides may be considered as well. Tactics that have been tried include physical mixing and aeration, increasing flow rate or flushing to decrease hydraulic retention time, and decreasing or altering nutrient content and composition. Some of these options are site-dependent and therefore may or may not be viable, depending upon the site and situation.

Prymnesiophytes: the golden-brown algae

Most toxin-producing species in the genus Prymnesium form harmful blooms in brackish water, but strains are expanding into freshwaters, especially during droughts. Blooms of *P. parvum* have been responsible for mass mortalities of fish and significant economic losses in Europe, North America and other continents. Species of Prymnesium have spread to several freshwater systems in the US, possibly due to exceptional drought. Texas has been impacted with recurrent blooms in several reservoirs and rivers and Texas Parks and Wildlife has offered some detailed advice regarding management options (Sager et al. 2007).

Prymnesiophyte ecology

*Prymnesium parvum* is a relatively small (~10 microns), saltwater-loving organism that is commonly referred to as “golden algae.” Golden algae are widely distributed and have been implicated in numerous and extensive fish kills in brackish waters and inland waters with relatively high mineral content on five continents. The species is capable of photosynthesis, but also feeds on bacteria and microorganisms. Dense growths of golden algae may color the water yellow to copper-brown or rust and the water may foam if aerated or agitated.
Prymnesium toxins
Golden algae produces at least three toxins, which alter cell membrane permeability and are collectively known as prymnesins. The toxin produced by *Prymnesium* causes fish to behave erratically, and young fish are more sensitive than their elders. Affected fish may have blood in gills, fins and scales and they may be covered with mucus. Fish may move to the shallows of tainted waters and leap from the water in an attempt to escape exposure to the toxins. Gill repair can occur within hours if fish are moved to uncontaminated water during the early stages of intoxication, but moving affected fish to other systems may also spread golden algae to previously uninfected systems. Mammals and birds often eat dead fish and drink water in the area, but aquatic insects, birds and mammals are reportedly not affected by prymnesin toxins. The golden alga is not known to harm humans, but dead or dying fish should not be used for human consumption as a precautionary measure.

Management of toxic *Prymnesium*
Texas Parks and Wildlife has offered detailed advice regarding management options for *Prymnesium parvum* (Sager et al. 2007), but the reader is cautioned that some methods used to control algae in aquaculture and private pond settings may be illegal elsewhere. Control methods that have been used in isolated pond culture include treatment of *P. parvum* with ammonium sulfate and copper sulfate; however, the concentration of ammonium sulfate required to control *P. parvum* (~0.17 mg /L of unionized ammonia) may adversely affect some fish, and copper sulfate may kill desirable algae along with golden algae, thus decreasing food resources for zooplankton and disrupting fish feeding. In Chinese aquaculture of carp, suspended solids (mud), organic fertilizer (manure) and decreased salinity have been used to control *P. parvum* (Guo et al. 1996), with the best results from decreased salinity and ammonium sulfate. In addition, Rodgers et al. (2010) found that *Prymnesium* from several locations were controlled by 200 ug/L of chelated copper.

Euglenoids
*Euglena* is a genus of widely distributed algae found in many shallow, relatively calm, eutrophic freshwater systems throughout the US. Toxin-producing *Euglena* can cause fish mortalities in fresh waters; for example, a number of outbreaks of toxic *E. sanguinea* have occurred since 1991 in hybrid striped bass production ponds in North Carolina and have resulted in the loss of more than 20,000 pounds of fish due to complete kill in affected ponds.

Euglenoid toxins
Species of *Euglena* are sources of ichthyotoxin (a suspected neurotoxin) in freshwater aquaculture and have caused mortalities in striped bass, channel catfish, tilapia and sheepshead minnows. Symptoms of exposure to *Euglena* toxins begin with the fish going off its feed for no apparent reason. Within 24 hours of cessation of feeding, gills become reddened, fish swim at or near the surface in an agitated or disorientated state (often with...
the dorsal fin extending out of the water), swim on their sides, or even swim upside down. If steps are not taken immediately after observing this state, the fish will be dead within 24 hours.

Management of toxic *Euglena*

If a toxic *Euglena* bloom is suspected, do not aerate the pond, as this will disperse the bloom throughout the pond. Species of *Euglena* are exceptionally mobile, and as the toxicity event progresses to the point where exposed fish are disorientated, the highest concentration of toxins seems to occur in the downwind side of the pond. Euglenoids should be sensitive to several of the commercially available algaecides, particularly those with labels that specify that euglenoid algae are susceptible. In the past, species of *Euglena* have responded to treatments with chelated copper formulations at 0.12 – 0.5 mg/L, as well as to peroxide formulations at or below the maximum label rate.

**Best management practices for noxious algae**

As adaptive water resource management is practiced today, adhering to Best Management Practices for noxious algae involves the following:

1. **Accurate diagnosis of the problem in a water resource**, which requires representative samples of water or benthic material containing the potential noxious alga(e).
2. **Identification of the targeted alga(e) and distribution** by microscopic confirmation of the density or toxin or taste-and-odor compound production. Algae are not usually uniformly distributed in aquatic systems; they may be “layered” in the water column or blown by the wind, or may be in benthic patches.
3. **Measurement of water characteristics for the site**, which can influence algal growth as well as compatibility and performance of a treatment option (e.g., algaecide). The minimum data set needed typically includes temperature, pH, hardness, conductivity and alkalinity. Other information such as nutrient concentrations and suspended solids may be useful as well.
4. **Site characteristics**, which are important for discerning an appropriate and compatible approach based on water depth and area, as well as the designated uses for the water resource (e.g. drinking water supply, swimming, fishing, etc.). Site history such as previous use of algaecides and the frequency and intensity of noxious algal blooms would be useful.
5. **Evaluation of potential options**; as mentioned above, all options should be considered in terms of their compatibility with the site and situation, as well as their ability to achieve the desired outcomes. For example, a dye to block sunlight may be appropriate for a fountain or contained water body where the entire system can be treated, but may not very useful or efficient in systems where considerable water exchange occurs. As another example, NSF-certified algaecides may be required for drinking water resources.
6. **Selection of an option or options**, which may require some experimentation to select an appropriate option. Responses of target algae to algaecide exposures can differ due to formulation or application technique.

7. **Application of the selected option** to achieve the required exposure (often called “dose”, “treatment” or “rate”), which is crucial to the success of a treatment [achieving the desired response from the target alga(e)]. The goal is to treat the target alga(e), not necessarily the water.

8. **Monitoring results** is an important step in adaptive water resource management that provides information to guide future decisions.

**Summary**
As more water resources are impacted by noxious algae and as these resources are increasingly utilized for critical purposes such as drinking water supply, irrigation and habitat for fish and wildlife, management of these crucial freshwater resources will become more prevalent. The need to constantly innovate and improve our approaches is clear and that is the goal of adaptive water resource management and BMPs.

**NOTE: If an algaecide application is indicated, all regulatory approvals and permits must be obtained. Following label instructions and restrictions is necessary to comply with federal law. Mention of a control tactic for toxin-producing algae does not constitute endorsement of an algaecide or any other tactic for your specific situation. Check with your local extension agent regarding site-specific permit requirements and restrictions.**

**Literature cited**

**Photo and illustration credits:**
- Page 105: Floating mats of *Lyngbya wollei* at Kings Bay/Crystal River, FL; John Rodgers, Clemson University
- Page 108: *Microcystis aeruginosa* along the shoreline of Pawnee Lake, NE; John Rodgers, Clemson University
- Page 109: Photomicrograph of *Prymnesium parvum* from Dunkard Creek, WV; John Rodgers, Clemson University
- Page 110: Photomicrograph of *Euglena sanguinea* from a pond in SC; John Rodgers, Clemson University
- Page 111: *Euglena sanguinea* bloom on a pond in SC; John Rodgers, Clemson University