2.18 Ecology and Management of Algae and Harmful Algal Blooms

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In contrast to the largely nonnative species of vascular aquatic plants in the preceding sections, most of the algal species featured in this section would be considered native to the United States or North America. Importantly, both native and non-native species of algae can develop nuisance-level populations and for some toxin producers, the density of algae that is problematic (dead fish or other animals) may not be discernable with unaided eyes.

Introduction

Algae (singular *alga*, Latin for "seaweed") are a large and diverse group of organisms that appear to be structurally simple, but range from small, unicellular species to large, multicellular forms, such as the giant kelps that grow to more than 200 feet 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 associated algae) or form coatings on submersed structures (periphytic or attached algae). Relatively large freshwater macroalgae such as *Chara* and *Nitella* are often mistaken for vascular plants and can form rhizoids or root-like structures to anchor themselves in the sediments. 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 vascular plants. Algae are at the base of the food web and most are considered “primary producers” in aquatic systems because they provide sugars and chemical energy for other organisms (Section 1.1). Most algae are photosynthetic and use sunlight to “fix” carbon and produce sugars, but some unicellular species are unable to photosynthesize. Some algae live solely in fresh water while others live in salt water or marine systems. About 44,000 species of algae have been described by algal taxonomists, but more than 72,000 species of algae are thought to exist on earth, so many await discovery and description. 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. In this section, approaches for intervention in harmful algal blooms (HABs), noxious growths of planktonic and filamentous cyanobacteria as well as some eukaryotic algae (species with distinct nuclei and chromosomes within a membrane) are reviewed.

Cyanobacteria or blue-green algae

Cyanobacteria are unicellular organisms that evolved billions of years ago and can be found in almost any aquatic habitat on the planet. Ancient blooms have been identified through sediment cores, suggesting that blue-green algae are

normal features of some lakes and have been for quite some time. Cyanobacteria perform three critical tasks: photosynthesis, respiration and nitrogen fixation. They can also control their buoyancy, allowing them to sink from the photic (upper) zone to the bottom of the lake and then back to the surface. Cyanobacteria can be particularly problematic because they may have a competitive advantage over most other phytoplankton. For example, some cyanobacteria can access pools of nitrogen and phosphorus that are not readily available to eukaryotic phytoplankton. Also, they can "hibernate" over winter and are rarely eaten by zooplankton, which allows populations to grow quickly. Blooms are not necessarily dependent on or caused by anthropogenic actions such as nutrient runoff but may be exacerbated by human activities. Limiting phosphorus inputs to water resources may reduce algal blooms in some cases but some cyanobacteria do not need high levels of phosphorus and nitrogen and can inhabit low-nutrient lakes.

Eukaryotes

Eukaryotic algae include green, red and brown algae, diatoms and dinoflagellates. Green algae, the basic components of the aquatic food chain, are commonly found in fresh water and may be inadvertently spread by humans; some – including *Cladophora*, *Codium*, *Caulerpa* and *Nitellopsis* – are invasive and can cause HABs. In contrast, most red and brown algae are marine. Some red algae are of commercial value and are harvested for pharmaceuticals and other products. For example, carrageenan (a common ingredient in lotions and food products) is from red algae and *Porphya* is a red alga used in sushi wrappers. Like green algae, most red algae are large, but some are coralline and provide important structural components in coral reefs. Brown algae include the "giant kelps", which contain important pharmaceutical compounds and are commercially harvested for alginic acid. Diatoms are single-celled algae with "frustule", or an outer cell wall made of silica, and about 20,000 species of diatoms that have been identified. Some diatoms are potent producers of secondary compounds, such as taste-and-odor compounds and toxins. Dinoflagellates have flagella (singular: flagellum), lash-like appendages that assist in propelling them through the water. They can grow in nutrient-poor waters and blooms are often stimulated without anthropogenic nutrient inputs. There are few reports of harmful freshwater dinoflagellates and the only species known to cause fish mortality is *Naiadinium polonicum* (formerly known as *Peridiniopsis polonica* or *P. polonicum*), a common and widespread species. Allelopathic effects (toxins produced by an alga that adversely affect another alga) by freshwater dinoflagellates are also rarely reported. Some dinoflagellates produce potent toxins at low population densities and do not discolor the water.

What causes algae blooms?

Algae are a critical part of a healthy aquatic ecosystem, but their normal presence and function in a water resource can cause problems when they grow out of control and form "blooms" or overgrowths of algae. Algae blooms have increased in recent decades and can occur due to increased sunlight, slow-moving waters and nutrient run-off. Eutrophication (the increase of nutrients in a water resource) is thought to be a leading contributor to bloom formation. Although eutrophication is a natural process, cultural eutrophication (the increase of nutrients to a lake from human causes such as agriculture and maintenance of lawns and landscapes) can also release phosphorus and nitrogen into watersheds and water resources. These excess nutrients can accumulate in lakes and reservoirs, resulting in increased frequency or intensity of algal blooms. Some noxious algae respond favorably to nutrients, while others (e.g., *Prymnesium*, *Didymosphenia geminata*) bloom as nutrient supplies are depleted.

Another factor that contributes to increasing algal blooms is the changing global climate. Climate change may affect algae growth because some species respond rapidly to changing conditions (warmer or colder temperatures, storms), which may contribute to their success in competing with other types of algae. For example, some species of cyanobacteria grow more rapidly in warmer temperatures. Noxious algae are also opportunistic and respond to episodic environmental events and upsets such as hurricanes and fires. In addition, we are moving algae around the planet at an unprecedented rate and transferring contaminated water (such as ship ballast water or from boat live wells) inadvertently spreads algal cells, fragments or spores. Finally, heightened awareness of algal blooms may also explain some of their apparent increase.

Problems associated with algae

Although algae occupy a critical niche in aquatic environments, many algae can rapidly grow to densities that become problematic or noxious. Noxious algal growths and HABs have compromised water resources throughout the world and have impeded the use of infested waters for wildlife, aquaculture, drinking, irrigation, recreation, navigation and industrial operations. Traditionally, HABs have involved high densities of algae and toxin production. However, density alone can be problematic even if toxins are not produced. Some algae may not achieve densities that are visible to casual observers and still produce sufficient toxins to kill most of the fish in the vicinity of a population growth or “bloom” (e.g., *Prymnesium* – see below). Other noxious algae can live on or adjacent to sediments and may not always be visible from the surface in waters that are not clear [e.g., *Lyngbya*, starry stonewort (Section 2.7), diatoms].

Excessive growths of algae change pH and water quality, reduce sunlight (which leads to low dissolved oxygen levels that 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 relatively small quantities. Left unmanaged, these algae can prevent the use of critical water resources for designated uses, thereby causing severe economic impacts. 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.

When do algae become problematic?

Although algae are critical components of aquatic ecosystems, their excessive growth allows them to outcompete native plants for sunlight, which can impair the habitat for fish and aquatic life. From a human perspective, algae maybe considered problematic when they become visible blooms or turn the water a pea-soup color. For example, Lake Okeechobee in Florida has received much attention for its green water. Some species of filamentous cyanobacteria may form mats along the surface of the water that are unattractive (as well as irritating for those unable to enjoy fishing, swimming or recreating due to limited mobility through the dense mats).

Many times, algae are considered problematic when population densities or production of toxins or other compounds interfere with the use of a water resource. Recreational activities such as fishing, boating and swimming can be impeded by algae forming mats along the surface of the water and dense stands below the water’s surface. Cyanobacteria produce a variety of taste and odor compounds that result in musty, sulfur, grassy or earthy odors in potable water but these are not known to be toxic. However, the negative effects of HABs go beyond aesthetics, taste and odor problems and pose severe risks to ecosystems and humans. For example, *Lyngbya wollei* is a mat-forming cyanobacterium that is native to North America but it is expanding its range from the southeastern US to the north, where it was recently detected in a lake near Detroit and in Lake Erie. Its thick mats prevent sunlight and oxygen from reaching other aquatic species, creating anoxic conditions and changing habitats and trophic networks. The increased occurrence of *Lyngbya wollei* has also been troubling for shoreline aesthetics. Rakes and other equipment have been used to remove *Lyngbya* mats from limited areas of shorelines. The loss of recreational activities has negative effects on property values and businesses (e.g., King’s Bay, Crystal River, Florida). Beyond unsightly mats, neurotoxins, hepatotoxins, and dermatotoxins have been identified in the mats. Toxins from *Lyngbya* have also been identified as tumor promoters, anti-fungal toxins, antiprotozoan toxins and mammal and fish toxins. Clearly, managing this alga when it blooms is important for human and ecosystem health!

Finally, and perhaps most importantly, HABs threaten human health. There are about 50 confirmed toxin-producing cyanobacteria and 100 known cyanotoxins, including neurotoxins, hepatotoxins, dermatotoxins, and endotoxin lipopolysaccharides (e.g., saxitoxins, anatoxin, cylindrospermopsins, lyngbyatoxins, hepatotoxins, and microcystins). One of these neurotoxins is beta-N-methyl-amino-L-alanine (BMAA), which has been linked to development of amyotrophic lateral sclerosis (ALS) and neurodegenerative disease. There are regions in New England where ALS cases are concentrated and higher than expected. Recent research using satellite remote sensing suggests that these ALS "hot spots" are concentrated in areas of poorer water quality, further suggesting linkages between water quality, cyanobacteria and high ALS incidence.

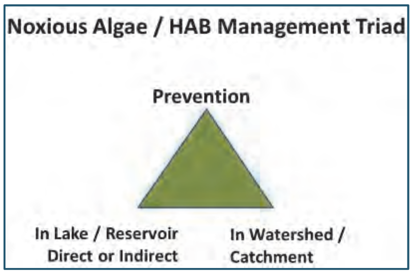
Animals as large as cattle and horses have died from exposures to cyanotoxins. Dogs swimming in water infested with cyanobacteria have died from anatoxin poisoning in California. In 2010, five dogs died and two people were hospitalized after swimming or water skiing in Milford Lake, Kansas. The only confirmed human deaths from exposure to cyanotoxins occurred in Caruaru, Brazil in 1996, when patients were inadvertently exposed to cyanobacterial toxin (microcystins) in the water used in dialysis treatment.

The effects of chronic cyanobacteria exposure on human health are largely unknown and the long-term effects are difficult to adequately study or quantify. Recent scientific studies suggest that exposure to cyanotoxins is not limited to direct exposure through activities like swimming, swallowing water or coming in contact with infested water, but people are also exposed to cyanobacteria through the air, known as aerosolization. Research is underway to understand exposures and health effects of cyanobacteria toxins and it is promising that these health conditions are receiving more attention from scientists and medical researchers.

Algae management

When noxious algae infest water resources, aquatic managers are faced with a decision to intervene or not. Unprepared, a manager may decide to take no immediate action but to monitor the situation and hope for better days. The decision to **not** intervene implies that the economic, human health and ecological risks and consequences due to algal blooms are acceptable. And "no decision" is a decision – ignoring the problem will not make it go away! It should be emphasized that taking no action is a decision and has consequences. For example, an unabated HAB will not wait on a decision and will continue to grow and spread. A few days or weeks of indecision can be very costly in terms of damage caused and increased costs for subsequent intervention or management. The time to plan is prior to arrival of the HAB.

There are a variety of options to manage algae but a decision to intervene usually requires a plan to be implemented in a timely fashion. It is important to note that the goal of modern algal management is not to remove all algae from impacted water resources, but to target the offending algae (called "targeted algal management"). As previously stated, algae are important in healthy aquatic ecosystems and some algal species are found in every water resource. Thus, a management goal is to restore uses of the water resource that are prohibited or limited by the noxious, harmful algae. Following a risk assessment, intervention involves altering the environment of the algae so the bloom is suppressed and the uses of the water resource are restored. An important point to emphasize initially is that algae are not uniformly distributed spatially or temporally. A lake may contain algae in certain locations and not in others, and at some times and not others. For example, some algae may be present at the surface of the lake. Other algae will hang out along the shoreline of the lake. Still other algae may live on one side of the lake, while the other side of the lake is relatively free from algae blooms. It is important to keep in mind that algae are not uniformly distributed as we discuss management strategies because different management strategies can be appropriate for different distributions of algae. In addition, if invasive algae have been detected in another water resource near your lake or water body, you can take measures to prevent the spread of algae to your lake.



Intervention should include both short-term and long-term solutions. Some short-term solutions may include tactics like algaecides, raking and aeration. The benefits of short-term solutions include seeing rapid results, which may include the extirpation of algae from the lake and restoration of water resources and uses. One common concern about implementing short-term solutions is that the underlying causes or "real" problem causing HABs, often presumed to be the buildup of phosphorus or other nutrients or climate change, is not addressed. Some options for intervention in growths of noxious algae are reviewed and contrasted below. When considering available tactics and developing a strategy that is specific for your situation, it can be helpful to be mindful of the HAB Management Triad.

There are two fundamental approaches for managing HABs: indirect and direct. Indirect approaches alter factors such as nutrients and light that can cause or promote algal growth, while direct approaches target specific problematic algae in the water resource or attempt to prevent the entry or spread of noxious algae into uninfested water resources. Indirect approaches involve tactics such as nutrient control in the water resource and watershed or catchment as well as management of littoral zones during construction of impoundments such as stormwater ponds and reservoirs. Indirect approaches generally do not focus on a particular species of algae or HAB. Direct approaches target specific problematic or recurring algae. No management option is a "silver bullet"; therefore, water resource and HAB management is necessarily adaptive and requires consideration of and use of all options as appropriate.

Resource managers recognize that algae must be managed in critical aquatic systems to maintain the designated uses of the water resource. When excessive algae growth occurs, adaptive water resource management is usually implemented to maintain the system and its uses. This involves careful consideration of all available options to manage or control algae and vascular aquatic plants to restore the uses of water resources. The unique characteristics of each water resource (including depth, latitude, altitude, shoreline, littoral zone, watershed, nutrients in sediments, etc.) also need to be considered in development of management strategy. Managing noxious algal growth requires actions that may include physical and cultural (Section 3.4), mechanical (Section 3.5), biological (Section 3.6) or chemical (Section 3.7.1) strategies alone or in combination.

Cultural and physical control

A popular notion is that algae can be controlled by controlling nutrient inputs to water resources. This idea perhaps originated from laboratory studies that showed that adding phosphorus and nitrogen resulted in proportional or incremental algal growth and was supported by addition of nutrients and observation of subsequent algal blooms in field studies. The time scale in these "experiments" was a few days to weeks (not centuries or thousands of years). The notion that followed was that removal of phosphorus from the water resource by decreasing inputs to the watershed or applying a binding agent such as alum or lanthanum to the water could control algal growth. And indeed that was the case in the simple laboratory studies using beakers or jars for testing. But aquatic systems store phosphorus in sediments and this phosphorus can be mobilized and made available for algal growth by winds, fires, turbulence, storm events, oxygen depletion in the hypolimnion and sediment feeding fish. This approach is not specific and targets algal production, so fisheries would also be generally impacted. Although watershed nutrient control is a popular notion and should be encouraged to slow cultural eutrophication, there is little scientific evidence that this is a successful approach for controlling noxious algal blooms.

This is not intended to discourage attempts to decrease nutrient loading to water resources, but outcomes of expensive and protracted efforts and expectations should be realistically considered. Unfortunately, preventing new phosphorus from reaching the water does not immediately reverse algal blooms because (as mentioned earlier) phosphorus is often stored in sediments. At best, nutrient reduction in inflows may initially slow algae growth; also, when developing management strategies for HABs in water resources, it is critical to consider not only management of nutrient loading from the watershed or catchment, but also how existing nutrients in the sediment of a water resource can be harnessed by cyanobacteria. Eutrophication emerges over time, so reducing inputs of nutrients into a lake will likely not reduce algae growth to a point where the uses of a water resource are restored until decades or hundreds of years have passed.

To summarize, long-term reduction of nutrient inputs to the water has been suggested as the “best” solution for harmful algal blooms and there is undoubtedly benefit to exploring the long-term causes and sources of HABs. In the meantime, there are concrete steps that can be taken immediately to address HABs and mitigate their harmful effects. These short-term solutions have benefits, even if they are not addressing the deeper causes of algal blooms, such as nutrient run-off from agricultural, suburban or urban areas. Individually or in combination, physical, mechanical, biological, chemical and preventative tactics can be used to reduce algal blooms and restore the water for recreational and other activities in a shorter time period than the long-term strategy of reducing nutrient inputs.

Light availability can have a significant effect on algae growth and new aquatic systems can be designed before construction to limit algal growth; for example, littoral zones can be limited by increasing water storage with deeper depths. These concepts are useful for stormwater impoundments but other factors such as access and recreation may take precedence over the algae and light consideration. Several dyes that have been registered by the United States Environmental Protection Agency (EPA) control algal growth by absorbing wavelengths of light that are needed for photosynthesis, but dyes are generally not used in flowing waters and larger aquatic ecosystems. The application of clays may flocculate and thereby remove algal cells from the water column may be a viable control tactic under some circumstances, but it is important to remember that clays and other flocculants are not registered as algaecides in the US. Also, rates of removal of cells due to clay flocculation, degree and rate of release of toxins from flocculated cells, physical and toxic effects on benthic organisms, and the consequences of organic loading from settled blooms on benthic oxygen conditions also need further evaluation. Benthic barriers have been used to control benthic HABs by blocking sunlight algae need to survive. These are challenging projects that require skilled divers and are used on relatively small areas such as around boat dock and marinas).

Raking or hand removal can be used to control small amounts of noxious algae growing in benthic areas or floating on the water’s surface, but this is a laborious process. Water manipulation (adjusting water flow and depth) is impractical for most systems and are only as reliable as the weather (if you need extreme drought or cold temperatures).

Biological control

There are very limited options available for biological control of algae despite their being impacted by bacteria, fungi, viruses and being eaten by zooplankton, fish, mollusks and snails. The addition of biological products to increase bacterial and fungal populations that compete with algae for available nutrients has been evaluated but the effectiveness of this strategy is not reliable or predictable. Aquatic habitat manipulation using tactics to increase zooplankton or other herbivore populations to reduce algae has long been studied. Larger herbivorous fish, crayfish, mollusks and snails consume algae in home aquaria but are subject to predation in natural systems; adding these aquatic animals is also site-specific, unpredictable and rarely feasible. Since each system is unique, efforts to use these types of bio-manipulation for algae control remain unpredictable and are the subject of considerable research.

Barley straw or straw from other cereal grains reportedly controls some algal species but results have been mixed. Some studies indicate that the straw releases anti-algal agents but these agents have not been positively identified; also, the addition of large amounts of organic matter to lakes and ponds has several deleterious effects. Any straw product that claims to control algae is violating the law administered by EPA regulations. This is not because straw is particularly dangerous, but rather because selling any product for algae, weed or insect control – even if that product is “natural” – when it is not registered as a pesticide with the EPA is illegal (Section 3.7).

Mechanical control

A variety of mechanical management tactics have been developed for HABs. The discussion in this section is limited to devices requiring external power (fossil fuel or solar) to function. These devices and approaches are not registered by the EPA and collateral damage associated with their use has not been thoroughly evaluated.

Harvesters range widely in size and design and are used mostly for filamentous algae such as *Lyngbya* and starry stonewort. Efficacy depends on the water resource, mobilization costs, access to the algae, access to remove harvested algae from the system, distance to disposal, design of the harvester and skill of the operator. Harvesters may be used in conjunction with algaecides to control areas not accessible to harvesting or to decrease biomass of algae prior to treatment. Rototilling or rotovating can be useful to manage HABs that grow as extensive mats on the sediment of lakes and reservoirs. Floating machinery can be used to "rototill" the sediments to depths of 7 to 9 inches, which dislodges algae and allows its collection and disposal. Similar to harvesting, this method does not discriminate between desirable and undesirable algae or plants and is limited to lakes and reservoirs with unobstructed areas and suitable sediments. Dragging chains attached to tractors on both sides of a canal is a common and effective technique for aquatic plant and benthic algae removal in canals if the canal banks are accessible. The dislodged algae and plant material are usually removed from the canal or the dislodged fragments will infest downstream areas. As with many control techniques, timing of the treatment influences efficacy. Like other harvesting operations, rapid regrowth necessitates repeat treatment. Dredging or excavating removes benthic algae from lakes, reservoirs and canals with a backhoe, dragline or similar excavating equipment. Significant drawbacks in using excavation equipment for algae control in canals include damage to the sediments and water resource profile and production of fragments or propagules and turbidity. Many noxious algae respond positively to disturbance like excavation, so rapid recolonization and regrowth means that ongoing management will likely be necessary and mechanical removal would have to be repeated frequently. The use of rototillers, chains, dredging or any other tactic that disturbs the sediments usually requires a Section 404 permit obtained from the Army Corps of Engineers as well as any permit required by the state.

Aeration may alter aqueous nutrient (phosphorus) concentrations or limit the time that algal cells spend in the upper photic zone on the water. By oxygenating the sediment-water interface, phosphorus release from sediments may be limited; also, aeration may disrupt the buoyancy and mobility of cyanobacteria. Scaling aeration to water resources of appropriate size and configuration is important to achieve success with this approach. Sonication or ultrasound can surely disrupt algal growth in the laboratory at a small scale, but implementation of this tactic in the field involves critical spatial and temporal scaling parameters. Sonication is advertised as effective, cost effective and environmentally sound for algal management. However, there have been reports of adverse impacts to nontarget species such as invertebrates (particularly zooplankton). The type and growth habit of algae appear to strongly affect efficacy. Considerable recent research has been ongoing regarding filtering or collecting algae for biomass and biofuel but isolating the algae from water has been a rate-limiting step. New technology involves dissolved gas floatation units, microstrainers, belt filters and settling ponds, while other approaches involve chemical coagulation and settling of algae. These approaches have not been successfully field-tested and operational data for filters and allied approaches for HAB management are not available.

Algaecides

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 within 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 their system.

Algaecides can be selective or non-selective against algae and range widely in their mechanisms of action. Selectivity depends on targeted algal species, location in the water resource, treatment and timing of application, product formulation and water chemistry. Algaecides must come in contact with algae (since there is little or no cell-to-cell movement of algaecides) and must enter algal cells to be effective. Algaecides differ in type of algae controlled, active ingredient, use sites, formulation, application rate, water use restrictions, dilution requirements and permit requirements. Algaecide active ingredients that are registered for use with the EPA include copper salts and formulations, organic compounds and peroxides (Section 3.7.1). Each algaecide has unique properties that should be carefully considered and evaluated prior to use in a water resource and some algaecides with the same active ingredients can differ in efficacy. Not all products are registered or available in all areas of the US. Always read and follow label instructions. The National Pollutant Discharge Elimination System (NPDES) requires a permit to apply algaecides and other pesticides over or near waters of the state or nation. For more information on which products are currently registered for control of algae in your state, check with your state regulatory authorities for product registration information and to determine which (if any) permits are required.

Algaecides are used primarily to control algal growth in impounded waters, lakes, ponds, reservoirs, stock tanks and irrigation conveyance systems. They can be applied as a spray directed onto an algal mat, sprayed or injected directly into the water column or applied as granular crystals or pellets. For successful treatments, it is important to get the algaecide to the targeted algae. Once a body of water becomes infested with algae, it is unlikely that algaecides will eliminate all algae or their spores (algae reproduce by cell division and/or by formation of spores). Due to their ability to reproduce quickly, however, algae are difficult to control in the long term and one treatment will rarely suffice. The efficacy of algaecides is short-lived in water and regrowth almost always occurs; as a result, re-treatment with algaecides is usually required.

One concern with any chemical control method is potential oxygen depletion after a treatment caused by the decomposition of the dead algae. Oxygen depletion can kill fish. If the water resource is heavily infested with algae it may be possible (depending on the algaecide chosen) to treat the algae in sections and let the algae in each section decompose for about two weeks before treating another section.

Applications 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 of boats and bait buckets could 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 near-term relief for excessive algae problems.

Algal toxins in freshwater systems

This section will focus on some toxin-producing species of freshwater algae as well as other noxious algae which can adversely affect other algae, vascular plants, 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 and 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 can deplete oxygen in shallow waters.

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 to 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 the area);

6. Blooms can be harmful to other algae or primary producers and the food webs that are dependent on them; and
7. The effects on shoreline residents of long-term or chronic exposures to algal toxins.

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. Some examples of management of algae producing toxins and noxious algae in freshwater systems in the US would perhaps be useful. The chapter is limited to toxins produced by cyanobacteria, golden algae and euglenoids. Other algae (e.g., *Chrysochromulina* and others) 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 (*Aetokthonos hydrillicola*) 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 in a wide variety of conditions and can rapidly 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 blue-green algae, particularly *Anabaena, Planktothrix* and *Microcystis*, are widely distributed in the US and can produce toxins that are poisonous to fish and wildlife that drink toxin-contaminated water. There are documented cases of blue-green algal toxins harming humans that have consumed or inhaled 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 readily visible masses or “blooms” that render the water resource unstable, unreliable 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 some 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 (toxins) that inhibit the growth of competing algae and reduce grazing by invertebrates.

Cyanobacterial toxins in freshwater systems

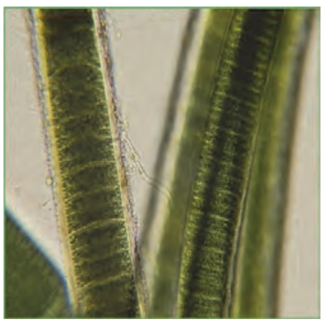
Several types of cyanobacterial toxins are produced by various species of blue-green algae, but most cyanotoxins are classified as either neurotoxins or hepatotoxins. Neurotoxins attack the nervous systems of vertebrates and invertebrates; symptoms of neurotoxin poisoning in fish include loss of coordination, 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, Nostoc, Oscillatoria, Anabaenopsis, Dolichospermum, Aphanizomenon, Phormidium* and *Cylindrospermopsis*. Hepatotoxins such as microcystins, have been implicated in deaths of fish, birds, wild animals, and agricultural livestock, and are responsible for human illness and deaths in India, China, Australia and Brazil.

Management of toxic cyanobacteria

Toxin production does not always occur in a bloom of toxin-producing cyanobacteria but toxins can 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 is often 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 of water, 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.

Lyngbya wollei

Lyngbya wollei (lyngbya) is a filamentous, mat-forming cyanobacterium that occurs in a variety of fresh waters. Based on modern genetic techniques, *L. wollei* has recently been assigned a new name (*Microseira wollei*) that may be accepted with time. It can grow in waters with low nitrogen concentrations due to its ability to fix atmospheric nitrogen, thrives at extreme temperatures ranging from melt-water lakes and streams to hot springs and contains photosynthetic accessory pigments (i.e., phycobilins) that permit growth in extremely low light conditions. Unlike other algae, lyngbya persists throughout the year and infestations are becoming more common throughout the southeastern United States. For example, it is a nuisance in the Everglades as well as Rainbow and Crystal Rivers in Florida, Guntersville Reservoir in Alabama and the lower Rio Grande, Texas. Lyngbya filaments are usually not branched and are covered by a polysaccharide sheath. Lyngbya forms dark blue to black benthic mats that range in thickness from several inches to several feet thick and may cover small ponds and entire coves. These mats, which are composed of entangled filaments and can achieve dry weights of up to 4.5 tons per acre, can trap gasses and float to the water's surface where they impede navigation and recreation, cover and smother submersed plants and clog water intakes. In addition, lyngbya releases a strong and unpleasant earthy or musk-like odor. Lyngbya also produces several toxins including paralytic shellfish poisons. If benthic algae such as lyngbya interfere with critical water resource usages and problems become severe, water resource managers often are compelled to intervene with management techniques.

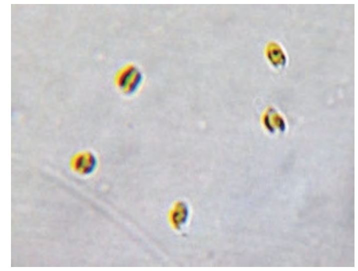


Several approaches have been used to manage excessive growths of lyngbya, including chemical (algaecides), harvesting and benthic barriers. Control efforts for this species have often been hampered by the thick sheath of mucilage that surrounds the algal cells and the presence of both surface and benthic mats in the spring and summer. Based on economic and environmental considerations, copper-based algaecide formulations are often used. For copper-containing algaecides, water characteristics and other site parameters influence the speciation of copper and thus the bioavailability and efficacy of an algaecide application. Some control success has been achieved using copper-based algaecides combined with penetrants.

Prymnesiophytes: the golden-brown algae

Most toxin-producing species in the genus *Pymnesium* form harmful blooms in brackish water, but strains are expanding into freshwaters, especially during droughts. *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 blooms in brackish and inland waters have been responsible for mass die-offs of fish and significant economic losses in Europe, North

America and other 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* has spread to several freshwater systems in the US, possibly due to drought conditions.



Golden algae produces at least three toxins which alter cell membrane permeability and are collectively known as prymnesins. The toxins produced by *Prymnesium* cause 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 exposure 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.

Texas has been impacted by recurrent golden algae blooms in several reservoirs and rivers and Texas Parks and Wildlife has offered some detailed advice regarding management options (Sager et al. 2007), but the reader is cautioned that some methods used in aquaculture and private pond settings may be illegal elsewhere. Algaecides that have been used to manage golden algae in isolated pond culture include 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* (although these are not EPA registered algaecides), with the best results from decreased salinity and ammonium sulfate. In addition, Rodgers et al. (2010) found that *Prymnesium* from several locations was 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. 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. 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. 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.

If a toxic *Euglena* bloom is suspected, the pond should not be aerated because 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 are sensitive to several 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 to 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. <u>Accurate diagnosis of the problem in a water resource</u> 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, mixed by the wind or may be in benthic patches.
3. Measurement of water characteristics for the site 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 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 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 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

Algae are a large, diverse group of organisms that range from small, unicellular species to large, multicellular forms. They may float in the water column, form mats on the bottom of the waterbody, form coatings on submersed structures or appear similar to vascular plants. Algae form the base of the food web and most are considered primary producers in aquatic systems, so they play an important role in the ecosystem. However, the overgrowth of algae can result in blooms that can be noxious and may interfere with ecosystem services and human uses of the affected water. Some species of algae produce toxins that can be harmful to fish, wildlife and humans and must be managed to reduce or prevent these problems. There are a number of tactics that can be employed for algae management but the use of algaecides is typically the most effective and economical method to control noxious and harmful algae blooms. 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.

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Page 101: *Euglena sanguinea* bloom on a pond in SC; John Rodgers, Clemson University
Page 102: *Microcystis aeruginosa* along the shoreline of Pawnee Lake, NE; John Rodgers, Clemson University
Page 104: Floating mats of *Lyngbya wollei* at Kings Bay/Crystal River, FL; John Rodgers, Clemson University
Page 105: HAB Management Triad; John Rodgers, Clemson University
Page 107: Aerator; William Haller, University of Florida
Page 109: *Planktothrix*; John Rodgers, Clemson University
Page 110: *Lyngbya wollei*; John Rodgers, Clemson University
Page 111 upper: Photomicrograph of *Prymnesium parvum* from Dunkard Creek, WV; John Rodgers, Clemson University
Page 111 lower: Photomicrograph of *Euglena sanguinea* from a pond in SC; John Rodgers, Clemson University