Eutrophication and Algal Blooms

Little girl looking out of window of plane: daddy why is that lake so green?

Hans W. Paerl

University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, NC 28557 USA

Eutrophication and Algal Blooms

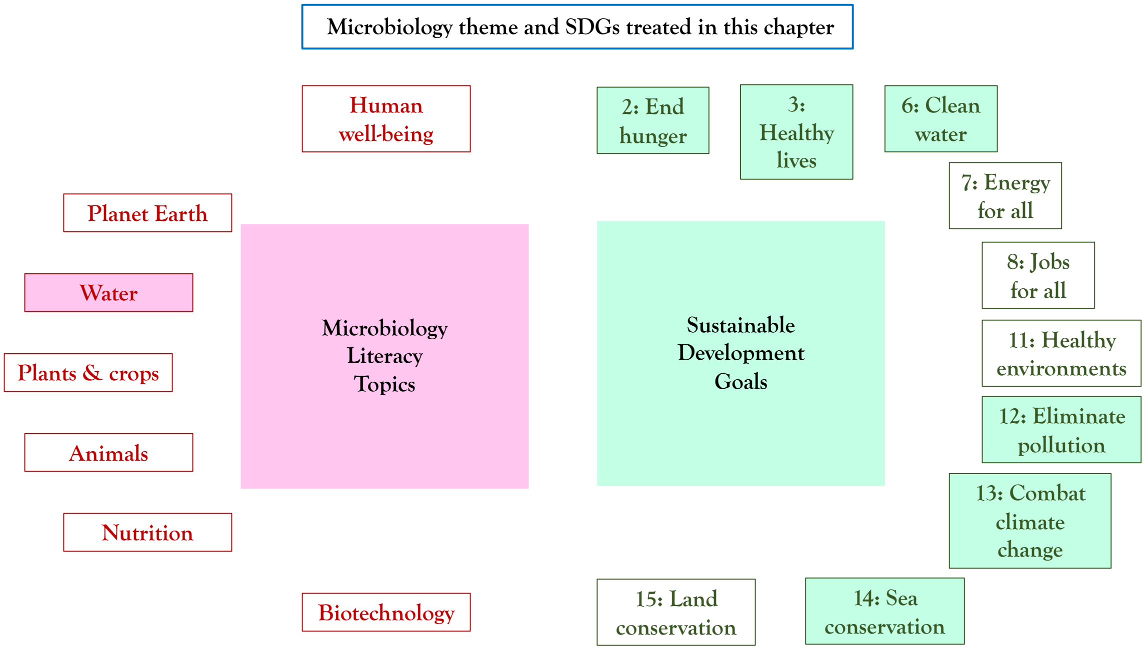
Storyline

We all like clean water for drinking, swimming, fishing and enjoying in our everyday lives. Maintaining clean water and sustainable aquatic ecosystems has become an increasing challenge as agricultural production, urbanization and industrial activities are all increasing to support the world's burgeoning population. More people to feed, house, transport and employ means more waste that is generated from all these activities. Human activities on land generate wastes containing the plant nutrients nitrogen (N) and phosphorus (P). These nutrients are essential for supporting plant growth on land and in our waterways. The use of chemical fertilizers containing these nutrients is increasing exponentially in support of agricultural and aquacultural food production. N- and P-rich human waste, discharged as sewage and from septic systems as well wastes from animal operations also find their way into waterways, either via surface runoff, groundwater or atmospheric transport. Excessive inputs of these N and P sources have led to over-fertilization of algal growth in our waterways, leading to a condition called eutrophication. Accelerating eutrophication has led to a rash of water quality problems, including massive accumulations of algae as "blooms", which can discolor affected waters. Moreover, some harmful bloom-forming algae or HABs produce toxins that can affect biota ranging from invertebrates that normally feed on algae, to fish, shellfish, birds, amphibians, reptiles and mammals, including man. Furthermore, when blooms die and are decomposed by microbes, the resultant consumption of oxygen can lead to stressful and uninhabitable low oxygen or "dead zones".

Reducing the inputs of nutrients is a "bottom line" step that needs to be urgently implemented in watersheds and airsheds surrounding our waterways to reverse eutrophication and proliferating HABs. A major challenge is to ensure adequate agricultural production without overfertilizing, so that nutrients end up benefiting food production while minimizing pollution of down-stream waterways. There are other steps that can be taken to help mitigate the eutrophication and HAB problem, but without parallel nutrient reduction strategies, these steps are only temporary "fixes". Furthermore, climatic changes taking place, including global warming and more extreme storms, rainfall and flooding events, exacerbate these problems. This further emphasizes the need to take action to reduce the nutrient overfertilization problem. In this Topic Framework, we discuss the causes, consequences and cures for the global eutrophication and HAB threats to sustainable aquatic ecosystems.

The Microbiology and Societal Context

The microbiology: Nutrients; rate-/process-limiting/controlling factors; harmful algal blooms; cyanobacteria, red tides, microbial toxins; oxygen depletion and oxygen dead zones and fish die-off; food webs and their perturbation. *Sustainability issues:* end hunger; health; food and energy, economy and employment; sustainable consumption; environmental pollution; global warming; oceans.



Eutrophication and Algal Blooms: The Microbiology

1. ***What turns water bodies turbid, discolored (green, brown, red) and often undesirable from a human use perspective?*** Eutrophication is the process by which water bodies become enriched with organic matter and discolored (green, brown and even red) through photosynthesis or chemosynthesis activities of actively-growing microbes and higher plants, and via the input of organic matter from surrounding lands or watersheds. Photosynthetic conversion of carbon dioxide (CO_2) into organic matter is called primary production, which is carried out by a diverse set of microorganisms, including bacteria, cyanobacteria (blue green algae), microscopic algae and higher plants. The availability of light and nutrients control the production of organic matter or primary production. In a water column, light availability is controlled by the amount of sunlight striking the water surface, and the transparency of the water body. Nutrient availability is controlled by nutrients entering from the land and air surrounding the water body. Much of the nutrient input is controlled by natural processes such as freshwater inflow carrying nutrients from the decomposition of land-based organic matter, solubilization of rocks and soils, weather events such as lightening and storms, and geological processes, including volcanic activity. Humans play a critical role with regard to nutrient supply in water and airsheds by increasing the production and release of nutrients through agricultural, industrial, urban and rural activities. For example, applications of chemical fertilizers, wastewater discharge and industrial pollution are major sources of human or "anthropogenic" nutrients.

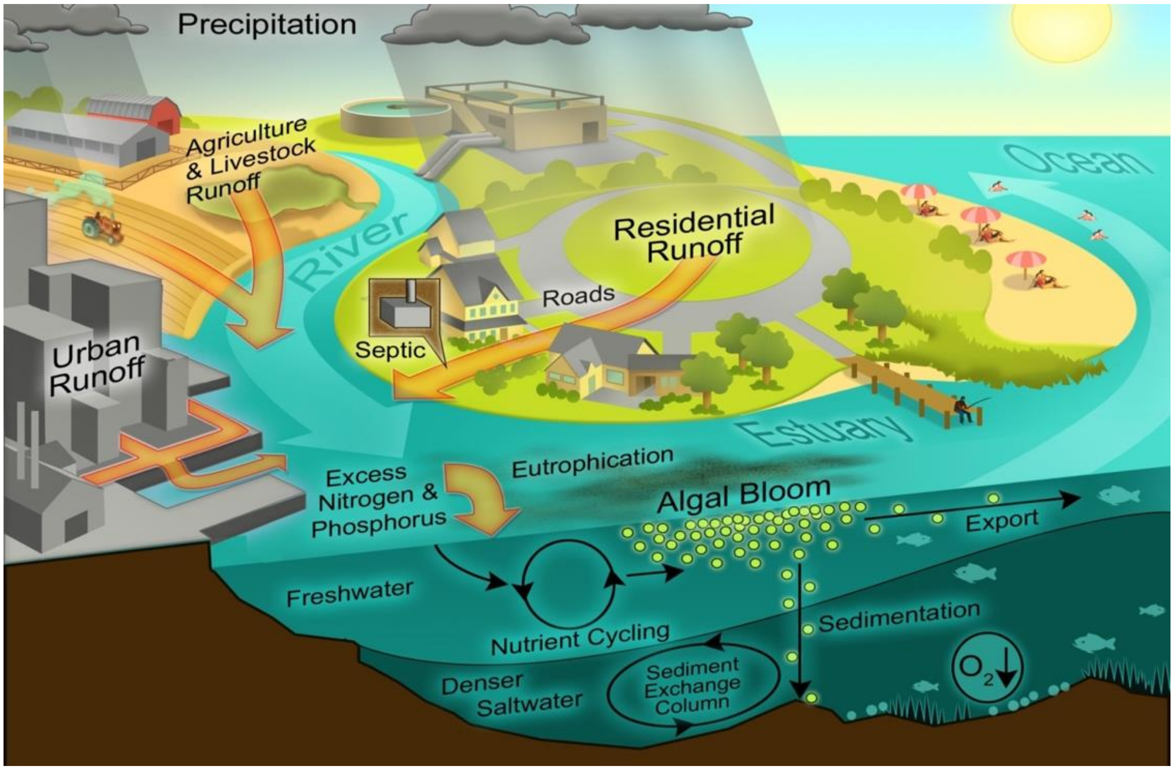


Fig. 1. Human nutrient inputs and impacts on eutrophication in aquatic ecosystems.

2. ***What are nutrients?*** All organisms in the biosphere consist of cells which, in turn, consist mostly of water and complex organic molecules comprised of carbon, oxygen and hydrogen, and other elements, like nitrogen, phosphorus, iron, and others. Whereas carbon is ultimately derived from atmospheric carbon dioxide, and oxygen and hydrogen are also plentiful (e.g. in water: H_2O), the other elements are in some circumstances in short supply. When an essential component of a process runs out, it becomes rate or process limiting. In the case of a component of cells, they stop growing, and the component is said to control primary production. The nutrients most commonly controlling primary production are nitrogen (N) and phosphorus (P), because relative to other major structural elements such as potassium, sodium, calcium, silicon and even carbon, these elements are often in shortest supply relative to plant needs. Therefore, when a water body receives N and P, for example as run-off fertilizer from agricultural operations and wastewater discharge, they are no longer process limiting and primary production and cell numbers can increase, often massively, as green, yellow, brown or red surface scums and sub-surface cloudy suspensions, or ***blooms***. The waters experiencing an algal bloom are said to be ***eutrophic.*** N- and P-enriched water bodies from riverine headwaters to the coastal ocean often exhibit high rates of eutrophication, with much of that enrichment coming from human activities (Fig. 1).

3. ***What are harmful algal blooms?*** Aquatic ecosystems require nutrients to support primary producers and the food web that relies on them. However, there is a fine balance between enough nutrients to support a "healthy" food web and ecosystem, and excessive nutrient inputs leading to accelerating eutrophication and its negative consequences, including accumulations of algal biomass as ***harmful algal blooms***, or "HABs" (Fig. 2). HABs can occur across the freshwater to marine

"continuum", depending on where nutrients are discharged and accumulate, and how fast they move downstream due to rainfall and freshwater runoff (Fig. 2). Typically, HABs are comprised of filamentous nuisance groups (cyanobacteria and green algae, or *chlorophytes*), free-floating or colonial cyanobacteria in freshwater, and toxic dinoflagellates (including red tide species) in downstream estuarine and coastal waters. Cyanobacteria are particularly problematic, because they are environmentally and physiologically harmful. They often form noxious, odoriferous surface scums and produce compounds that can be toxic to wide variety of higher-ranked organisms, including small crustacean plankton, fish, mammals, and humans. In mammals and humans, cyanotoxins can impair liver and digestive functions, and there is increasing evidence that long-term use of contaminated drinking water can lead to serious liver disease, including cancer. Other cyanotoxins can affect the nervous system. Increasingly, drinking water reservoirs and lakes have been put "off limits" to consumers because of the threat of contamination from cyanobacterial blooms. In estuarine and coastal ecosystems, dinoflagellate blooms can produce toxins affecting fish, shellfish, mammals and humans. The infamous red tide, which often originates in off-shore waters, can pose serious water quality and health problems when it moves into nutrient-enriched coastal waters.

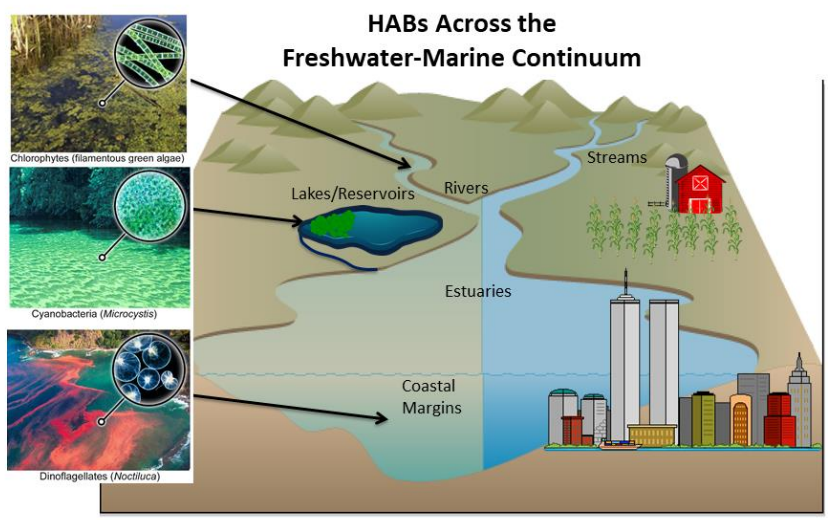


Fig. 2. Examples of HAB habitats along the freshwater to marine "continuum". Figure courtesy of American Chemical Society, Paerl et al. Environmental Science & Technology 52: 5519—5529 (2018).

4. ***How may harmful algal blooms impact food webs and create dead zones?*** Excessive human nutrient inputs can lead to accumulation of blooms, especially in stagnant, slow-flowing waters (Fig. 3, upper left hand element). If the suspended algae or phytoplankton are toxic, and/or form large aggregates that cannot be filtered by the grazing animal plankton or zooplankton that consume phytoplankton and constitute the next link in the food chain supporting finfish and shellfish, then the ungrazed phytoplankton eventually die and accumulate as organic matter that is then rapidly decomposed by organic matter-decomposing microbes, leading to high rates of oxygen consumption. If the impacted water body is not readily mixed from top to bottom and remains stagnant, it cannot

be replenished with atmospheric oxygen. As a result, bottom waters can become oxygen-deprived or 'hypoxic" (dangerously low oxygen levels), or in severe cases oxygen-deplete (no detectable oxygen) or "anoxic", conditions – "dead zones" – that lead to changes in microbial and higher plant and animal life, such as fish kills, depending on their tolerance to and preference for specific dissolved oxygen regimes.

Microbial decomposition of dead algae from blooms, and low oxygen conditions, lead to the release of inorganic forms of nitrogen and phosphorus. This constitutes "nutrient regeneration" and can support further algal blooms, especially during warm summertime stagnant, slow flow conditions (Fig. 3, lower left hand segment). In this manner, blooms are a self-fulfilling prophecy, sustaining future blooms, even in a single season.

Therefore, whether or not HABs occur, due to excessive nutrient inputs combined with appropriate flow conditions, has a major impact on whether we have a "healthy" ecosystem, where food produced by primary producers moves up the food web, leading to high rates of finfish and shellfish production, or a "unhealthy" system, where primary producers are not effectively consumed, leading to excess organic matter, high rates of oxygen consumption and poor habitat for finfish and shellfish species (Fig. 3, lower right hand segment).

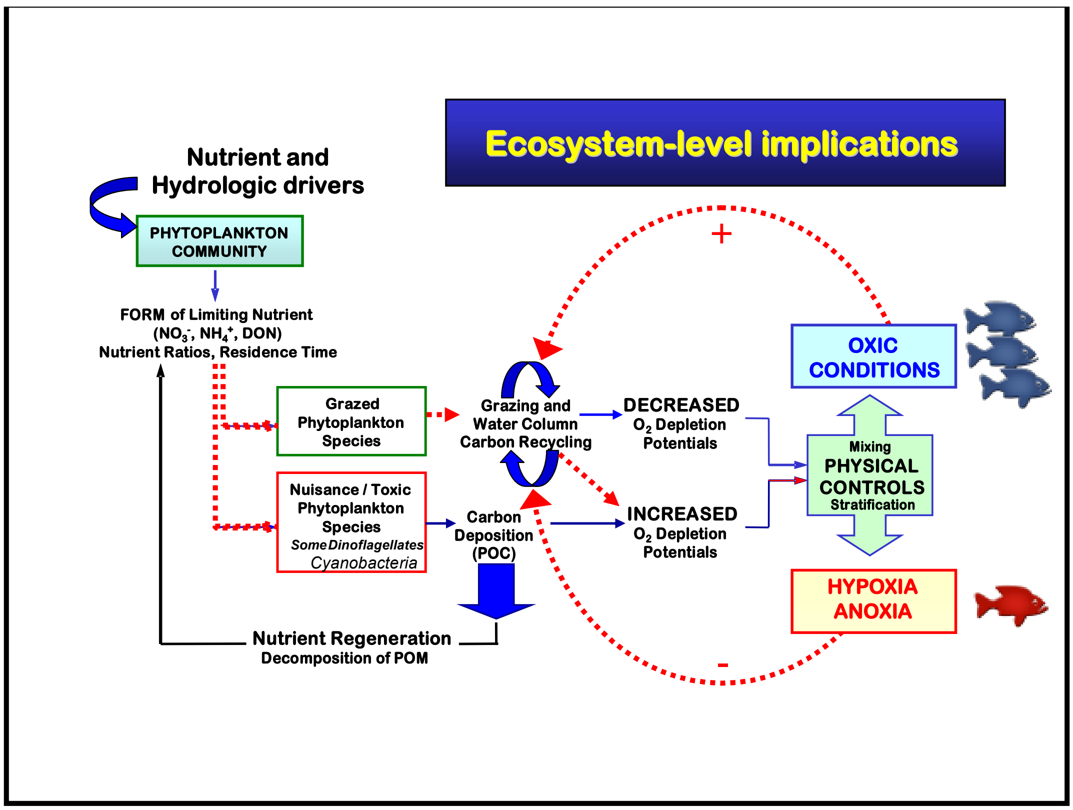


Fig. 3. Drivers and ecosystem-scale food web/biogeochemical impacts of HABs. DON is dissolved organic nitrogen. POM is particulate organic matter. POC is particulate organic carbon.

The watershed is also a major source of organic matter (OM) entering waterbodies. This OM serves as an additional carbon source for decomposers and supplements the OM produced by primary producers and it can also serve as a major source of oxygen consumption. In coastal systems, such as the Mississippi River Delta in the Northern Gulf of Mexico and the Po River Delta in the Northern Adriatic Sea, riverine organic matter combined with nutrient-enhanced primary production is a major driver of bottom water oxygen consumption, leading to oxygen-devoid dead zones inhospitable for finfish and shellfish.

5. ***How can we manage harmful algal blooms?*** Globally, a major symptom of eutrophication is the increased frequency and intensity of algal blooms in freshwater systems dominated by cyanobacteria, in estuarine and coastal systems by eukaryotic algae, including "red tide" flagellated algae, called dinoflagellates (Fig. 2). Controlling the outbreaks and proliferation of harmful algal blooms is a major eutrophication issue and water quality management challenge. Ecosystem level physical, chemical and biotic regulatory variables often co-occur and interact synergistically and antagonistically to modulate and control the activities (e.g., N_2 fixation, photosynthesis) and growth of HABs. Achievable controls that break this synergism are desirable.

Means of controlling blooms (in the order of most effective and achievable) include 1) nutrient (most often nitrogen and phosphorus) input reduction, 2) reducing water retention time and eliminating stagnant conditions, by increasing flushing of bloom-impacted waters, 3) disrupting vertical stratification, through either mechanically- or hydrologically-induced vertical mixing, 4) dredging bottom sediments, where nutrients accumulate, 5) applications of algaecides, including copper sulfate and more environmentally-friendly hydrogen peroxide, and 6) biological manipulation.

Option 1 is a "must", either on its own or in conjunction with other control strategies. Without a realistic, long-term nutrient input reduction strategy, there is not much hope for a long-term solution to the eutrophication of HAB problems plaguing aquatic ecosystems. If abundant low nutrient water supplies (i.e., upstream reservoirs) are available for flushing purposes, option (2) may be feasible. If the bloom-affected water body is small and accessible enough for installing destratification equipment, option (3) may be feasible. Dredging (4) may be an option in relatively small water bodies, but dredge spoils must be moved out of the watershed or they will leach nutrients back into these systems. Application of algaecides (5) has been used in small water bodies, such as ponds and small lakes/reservoirs. This approach is not advised for larger systems, or waters to be used for fishing, drinking water and other animal and human use purposes. Finally, biological manipulation (6) includes a number of approaches to change the aquatic food web. Biomanipulation approaches can include introducing fish and bottom filter feeders capable of consuming cyanobacteria, or introduction of lytic bacteria and viruses. The most common biomanipulation approaches are intended to increase the abundance of algae-consuming zooplankton by removing zooplankton-consuming fish or introducing carnivorous fish that prey on those fish species. Alternatively, removal of bottom-dwelling fish can reduce resuspension of nutrients from the bottom sediments.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.** Adequate human and animal nutrition through efficient, cost effective and environmentally-friendly food production is a "bottom-line" priority for the worlds burgeoning human population. While nitrogen and phosphorus fertilizers have been the mainstay of modern high production agriculture, there is a price we are paying (i.e. eutrophication and HABs) with regard to the loss of fertilizers to our waterways. Therefore, we must strive to apply fertilizers in what is termed "agronomic amounts": enough to support production on land but formulating applications so that losses from the land are minimized. In addition, wastes from animal operations (cattle, swine, poultry, finfish and shellfish aquaculture) must be retained and recycled on land, again, minimizing losses to waterways. There are technologies available to achieve these goals, but it takes investment and will to install and successfully implement these technologies. This is the price we have to pay for benefiting from optimal agricultural and aquacultural production.

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages**. There are multiple benefits to good water quality, starting with drinkable, swimmable and fishable waters. All age groups benefit from these resources and activities. In addition, "healthy aquatic ecosystems" are a prerequisite for healthy users, whether we are talking about food safety, minimizing pathogens, including bacteria, or HABs.
- **Goal 6. Ensure availability and sustainable management of water and sanitation for all** (*assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems, improve water and sanitation management)*. See above.
- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all** (*ensure access to clean, renewable and sustainable energy, and increase energy use efficiency)*. Sustainability requires the increasing use of renewables and recycling resources, including nutrients, organic wastes, which can be composted and support the growth of crops instead of exclusive use of chemical fertilizers. This optimizes food production <u>and ensures acceptable water quality.</u>
- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all** (*promote economic growth, productivity and innovation, enterprise and employment creation)*. Good water quality makes economic and social sense. Whether it is safe drinking water supplies, recreational use, tourism, fisheries, residential value and aesthetics, it all adds to the economic value and employment potentials of our waterways, lakes, reservoirs, estuarine and coastal waters, not to mention the global ocean!
- **Goal 12. Ensure sustainable consumption and production patterns** *(achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices)*. See above.
- **Goal 13. Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming)*. While appropriately managing our nutrients is of critical importance to ensuring acceptable water quality, climatic changes taking place play an interactive role in modulating water quality. Current trends in warming favor the growth and proliferation of HABs, especially toxic cyanobacteria. Furthermore, increasing intensity and frequency of storms and tropical cyclones is accelerating the loss of nutrients from land into nutrient-sensitive waterways. Therefore, steps that are being taken to reduce these unwanted climatic changes (reduce greenhouse gas emissions) will also benefit our water resources and make socio-economic sense. In particular, reducing the "glut" of biologically reactive forms of nitrogen in aquatic ecosystems will reduce eutrophication and the potential emission of intermediate N compounds like N_2O, which is a powerful greenhouse gas.
- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** *(reduce pollution of marine systems by toxic chemicals/agricultural*

nutrients/wastes like plastics, develop mitigation measures for acidification, enhance sustainable use of oceans and their resources). N, P, pesticide and growth promoter inputs associated with food production, where they occur near coastal waters, may run into marine systems.

Potential Implications for Decisions

1. ***Individual***
   a. is the local lake/river safe to swim/fish in?
   b. which leads to more eutrophication: meat or vegetables? How does this affect my decision to eat hamburger or a veggieburger? And if I decide on a hamburger, should it be with or without cheese?
   c. If I install a fishpond in the garden, do I need to stop fertilizing the roses/grass next to it? (hint: how is the water in the pond prevented from running away?)
   d. How can I learn how much fertilizer to use in my garden (hint: there may be guidelines on the fertilizer bag, but fertilizer manufacturers earn their living by selling fertilizer…)?

2. ***Community policies***
   a. Develop a monitoring system (voluntary reporting?) for fertilizer use/animal waste handling on local farms
   b. Mount an information campaign on the link between fertilizer use/animal waste handling and eutrophication
   c. encourage practices to minimize activities favour eutrophication
   d. Take actions, like aeration of water bodies, to increase oxygen levels of water bodies prone to develop oxygen-deficient dead zones
   e. Consider introduction of new biota that can help reduce blooms or their failure to enter the food chain

3. ***National policies***
   a. Consider developing a national plan for protection of water bodies, including where relevant, coastal waters, from pollution with agricultural materials, and guidelines for farmers
   b. Consider publishing an annual report on agriculture-related N and P environmental inputs (which would require annual reporting by farmers, local authorities)
   c. Promote fertilizer reduction efforts, such as crop rotation involving legumes or other nitrogen-fixing crops, and P-mobilizing symbiotic microbes
   d. Engage governments of other countries to develop regional and global policies to protect water and reduce eutrophication

Pupil Participation

1. ***Class discussion of the issues associated with modern agriculture and the quality of water bodies***

2. ***Pupil stakeholder awareness***

a. We love hamburgers/cheeseburgers, but the cattle grown for these are often fed on grain produced by intensive farming, involving the use of N and P fertilisers. The cattle themselves produce much waste containing N and P, some of which enters the soil and drains into waterways. This is equally true of dairy cattle that provide milk for cheese production. So hamburgers and other meat dishes come with an environmental cost that is higher than that of vegetables. So: should we eat fewer hamburgers?

b. When we eat hamburgers, should we have cheese or not?

c. We love to barbecue in the summer: what can we grill that has a lower N and P footprint for the environment?

The Evidence Base, Further Reading and Teaching Aids

Chislock, M. F., Doster, E., Zitomer, R. A., Wilson, A. E. 2013. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature Education Knowledge* 4(4):10

Diaz, R. J., Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926–929.

Ghadouani, A., Pinel-Alloul, B., Prepas, E.E. 2003. Effects of experimentally induced cyanobacterial blooms on crustacean zooplankton communities. *Freshwater Biology* 48: 363-38.

Honjo, M.; Matsui, K.; Ueki, M.; Nakamura, R.; Fuhrman, J.A.; Kawabata, Z. 2006. Diversity of virus-like agents killing *Microcystis aeruginosa* in a hyper-eutrophic pond. *Journal of Plankton Research* 28: 407-412.

Huisman, J., Codd, G., Paerl, H., Ibelings, B., Verspagen, J., Visser, P. 2018. Cyanobacterial blooms. *Nature Reviews Microbiology* https://doi.org/10.1038/s41579-018-0040-1.

Jeppesen, E., Meerhoff, M., Jacobsen, B.A., Hansen, R.S., Søndergaard, M., Jensen J.P., Lauridsen, T.L., Mazzeo, N., Branco, C.W.C. 2007. Restoration of shallow lakes by nutrient control and biomanipulation: the successful strategy varies with lake size and climate. *Hydrobiologia* 581: 269-285.

McQueen, D.J. 1990. Manipulating lake community structure: where do we go from here? *Freshwater Biology* 23: 613-620.

Nixon, S.W. 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. *Ophelia* 41:199-219

Paerl, H.W. 1988. Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnology and Oceanography* 33:823–847.

Paerl, H.W., Otten, T.G. 2013. Harmful Cyanobacterial Blooms: Causes, Consequences and Controls. *Microbial Ecology* 65: 995-1010.

Paerl, H.W., W.S. Gardner, K.E. Havens, A.R. Joyner, M.J. McCarthy, S.E. Newell, B. Qin, and J.T. Scott. 2016. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. Harmful Algae 54:213-222.

Paerl, H.W., T.G. Otten and R. Kudela. 2018. Mitigating the expansion of harmful algal blooms across the freshwater-to-marine continuum. Environmental Science & Technology 52: 5519−5529. DOI: 10.1021/acs.est.7b05950

Paerl, H.W., Havens, K.E., Hall, N.S., Otten, T.G., Zhu, M., Xu, H., Zhu, G., Qin, B. 2019. Mitigating a global expansion of toxic cyanobacterial blooms: confounding effects and challenges posed by climate change. *Marine and Freshwater Research* https://doi.org/10.1071/MF18392

Watson, S.B., Whitton, B.A., Higgins, S.B., Paerl, H.W., Brooks, B.W., Wehr, J.D. 2014. Harmful Algal Blooms pp. 873-920, In: J.D. Wehr, R.G. Sheath, and J. P. Kociolek, Eds. Freshwater Algae of North America. Academic Press, San Diego, CA. ISBN: 978-0-12-385876-4.

Wurtsbaugh, W.A., Paerl, H.W., Dodds, W.K. 2019. Nutrients, Eutrophication and Harmful Algal Blooms Along the Freshwater to Marine Continuum. Wiley Interdisciplinary Reviews 6(5) https://doi.org/10.1002/wat2.1373

Glossary

Chemical fertilizers: Material of natural or synthetic origin that is applied to soil to supply one or more nutrients essential to the growth of plants

Chemosynthesis: Synthesis of organic compounds by bacteria or other living organisms using energy derived from reactions involving inorganic chemicals, typically in the absence of sunlight.

Cyanobacteria: Microorganisms that morphologically resemble bacteria but are capable of photosynthesis. They are among the earliest known form of life on the earth.

Dead zones: Oxygen-devoid areas in the world's oceans and lakes, which causes these bodies of water to fails to support oxygen-requiring life living there

Dinoflagellates: Single-celled algae with two flagella, occurring in large numbers in marine plankton and also found in fresh water. Some produce toxins.

Organic matter: Diverse carbon-based compounds found within terrestrial and aquatic environments.

Nutrient regeneration: Processes by which nutrients are recycled and become available to the primary producers in an ecosystem.

Photosynthesis: The process by which green plants and some microorganisms (e.g., algae) use sunlight to synthesize foods from carbon dioxide and water

Plankton: Microscopic organisms drifting or floating in a water body, consisting chiefly of microbes, algae, protozoans, small crustaceans, and the eggs and larval stages of larger animals.

Red tide: A discoloration of water bodies caused by a bloom of toxic red dinoflagellates.

Run-off: The draining away of water (and substances carried in it) from the surface of an area of land.

Wastewater: Used water from any combination of domestic, industrial, commercial or agricultural activities, surface runoff or stormwater, and sewer inflow.

Water column: A vertical expanse of water stretching between the surface and the floor of a body of water.

Watershed: A drainage basin where precipitation collects and drains off into a common outlet, such as into a river, bay, or other body of water.