ECOLOGICAL CONSEQUENCES OF HARMFUL ALGAL BLOOMS

Abstract

This book chapter delves into the complex dynamics of harmful algal blooms (HABs) and their far-reaching implications in marine ecosystems. Highlighting the critical role of microscopic planktonic algae as a primary food source for crustaceans, fish, and shellfish, the narrative explores the dual nature of algal blooms, oscillating between advantageous and detrimental impacts on aquaculture and wild fisheries. The chapter underscores the global prevalence of harmful algal blooms, defined by the prolific expansion of specific microalgae, macroalgae or cyanobacteria. Recognizing the escalation of HABs as intricately linked to climate change, nutrient enrichment, and habitat disturbance, the authors elucidate the diverse causes behind their occurrence. Focusing on categories of bloom-forming algae, the chapter details their distinctive characteristics, impacts on aquatic ecosystems, and associated health risks, including various toxins such as paralytic shellfish poisons and neurotoxic shellfish poisons. The discussion further delves into the environmental forces driving HABs, including eutrophication, climate change, and ocean acidification. The consequences of HABs span phycotoxin accumulation, toxin transfer, high biomass blooms, ecosystem disturbance, aerosolized toxins, and localized hazardous blooms. In advocating for a nuanced understanding of the multifaceted contributors to HABs, the chapter emphasizes the need for effective mitigation and management strategies. A holistic approach that considers both anthropogenic influences and broader ecological contexts is crucial to curtail the expanding impact of HABs and restore balance to coastal ecosystems globally.

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1. Introduction

In the expansive realm of the world's oceans, microscopic planktonic algae stand as a vital sustenance source for the early stages of economically consequential crustaceans and fish, along with serving the nutritional needs of filter-feeding bivalve shellfish, including oysters, mussels, scallops, and clams. The growth dynamics of plankton algae, colloquially referred to as "algal blooms" when reaching densities of millions of cells per liter, play a pivotal role, oscillating between being advantageous and detrimental for both aquaculture and wild fisheries operations.

Numerous scholarly sources (Hallegraeff 1993; Anderson 2012; Bresnan et al. 2013; GlobalHAB, 2017) collectively define algal blooms as the prolific expansion of specific microalgae, macroalgae, or cyanobacteria (blue/green algae). In favorable environmental conditions, these blooms can attain levels that impact aquatic life and, in turn, pose consequences for human well-being. Harmful algal blooms (HABs) have been documented globally, exerting a detrimental influence on tourism, recreation, aquaculture, and fisheries (Berdalet *et al.*, 2016; Hallegraeff, 2003). Recognizing the rich diversity of marine phytoplankton, Sournia *et al*. (1991) identified 5,000 species. However, a mere 80 species possess the capacity to produce toxic substances, affecting humans through fish and shellfish consumption. Intriguingly, non-toxic species experiencing high-biomass blooms can also serve as sources of HABs.

The aftermath of algal blooms extends beyond the proliferation phase, as the shaded benthic environment witnesses a drop in oxygen levels following the bloom's decay. The resultant accumulation of algal biomass may induce water discoloration, imparting negative impacts that reverberate across the ecosystem, ultimately leading to a reduction in biodiversity.

The escalating frequency of HABs is intricately linked to climate change, nutrient enrichment, and habitat disturbance (Hallegraeff 1993; GESAMP, 2001; Smayda 2004; Anderson 2012; Berdalet *et al*., 2016). This increase in HAB occurrences carries profound negative effects, ranging from the poisoning or asphyxiation of finfish, shellfish, and human consumers to severe consequences such as fish, bird, and mammal (including human) deaths. Afflictions of the respiratory or digestive tract, memory loss, seizures, lesions, and skin irritation are among the most pronounced and memorable impacts of HABs. Additionally, coastal resources, including submerged aquatic vegetation and benthic epi- and in-fauna, undergo significant losses. As we delve into the scientific exploration of these phenomena, this chapter aims to unravel the intricate dynamics of harmful algal blooms and their far-reaching implications.

Causes of Harmful Algal Blooms

Harmful algal blooms (HABs) represent a pervasive ecological challenge, encompassing the unchecked proliferation of autotrophic algae and heterotrophic protists, a phenomenon increasingly observed in coastal waterways across the globe. The alarming surge in HAB occurrences serves as a poignant indicator of an ecological imbalance, a consequence of the intricate interplay between the expanding global human footprint and the pervasive influence of climate change.

At the heart of this burgeoning issue lie two overarching causes: eutrophication, a by product of human activities, and a suite of natural processes, including circulation, upwelling relaxation, and river movement. Eutrophication, driven by nutrient loading from agricultural runoff, sewage discharge, and industrial activities, provides an enriched substrate for algal growth, fueling the proliferation of harmful species. Simultaneously, natural phenomena such as oceanic currents and river dynamics contribute to the spatial and temporal distribution of these blooms, creating a complex tapestry of environmental factors influencing their prevalence.

Historically, the escalation of HABs has coincided with episodes wherein environmental conditions approach those conducive to maximum algal growth. This dynamic relationship underscores the intricate interplay between climate variations and the intensification of algal blooms (Moore *et al*., 2009; Gobler *et al*., 2017; Anderson *et al*., 2012). The intricate web of interacting physical, chemical, and biological factors further complicates this scenario, influencing the blooming of specific species across diverse habitats (Zingone and Enevoldsen, 2000).

Additionally, the geographic expansion of certain algal species reflects a complex interplay of factors, including anthropogenic introductions, natural occurrences such as ocean currents, and the historical presence of species at undetectable concentrations or in the distant past. This dynamic landscape of causes underscores the imperative for a nuanced understanding of the multifaceted contributors to HABs.

In navigating this intricate web of causation, there arises a pressing need for effective mitigation and management strategies. A holistic and scientifically informed approach is vital, acknowledging the diverse factors at play and charting a course towards sustainable solutions that address both anthropogenic influences and the broader ecological context. Only through such nuanced comprehension can we hope to curtail the expanding impact of HABs and restore balance to coastal ecosystems worldwide.

Factors Affecting Harmful Algae Gains and Losses

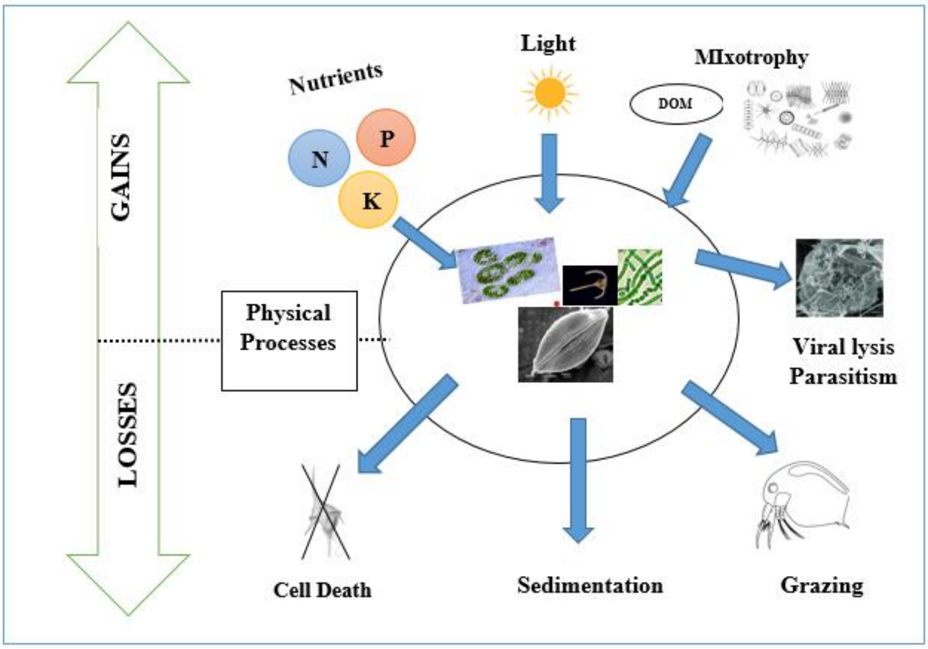

Figure 1: Factors Affecting Harmful Algae Gains and Losses

Harmful Algal Groups

In the realm of harmful algal blooms (HABs), five primary categories of bloom-forming algae take center stage, each with distinctive characteristics and impacts on aquatic ecosystems.

Dinoflagellates

Dinoflagellates, unicellular microalgae, are key contributors to the primary production of planktonic algae in water bodies and are frequently implicated in harmful algal bloom (HAB) occurrences globally (Burkholder *et al.*, 2006). Exhibiting a range of nutritional strategies, dinoflagellates can be heterotrophic, autotrophic, or mixotrophic. Reproducing primarily through asexual fission, some species engage in sexual reproduction, leading to the formation of dormant cysts capable of withstanding environmental stresses (Smayda, 1997).

Notably, dinoflagellates produce toxins that pose health risks to humans through the consumption of contaminated seafood or direct contact with HABs. Responsible for several types of seafood poisoning, including paralytic shellfish poisoning (PSP), neurotoxic shellfish poisoning (NPS), ciguatera fish poisoning (CFP), and diarrhetic shellfish poisoning (DSP), dinoflagellates exert a considerable impact on public health (Smayda, 1997; Van Dolah, 2000).

Other Flagellates

Flagellates, specifically Prymnesiophyceae and Raphidophyceae classes, contribute to harmful algal blooms with significant human impact. Prymnesiophytes, like *Prymnesium* *parvus* and *Chrysochromulina polylepis*, cause fish-kills. Phaeocystis spp., another prymnesiophyte, produces mucilaginous material, causing anoxic events that killed 10 million kg of mussels in the Oosterschelde estuary in 2001. Raphidophytes, including *Pseudochattonella verruculosa*, have triggered large-scale fish kills in northern Europe since 1998, highlighting the complex dynamics and widespread consequences of harmful flagellate blooms in marine ecosystems (Edvardsen and Imai, 2006; Smayda, 2006; Peperzak and Poelman, 2008; de Boer, 2006).

Diatoms

Diatoms, unicellular photosynthetic eukaryotes, represent approximately 100 species thriving in freshwater and marine environments globally. Playing a vital role in carbon fixation and marine ecosystem productivity, marine diatoms contribute 20% of global carbon fixation and 40% of primary productivity in marine ecosystems. Known for their siliceous cell wall, or frustule, and spines that can harm fish gills, diatoms are essential yet can be lethal to aquatic life.

Some diatoms, such as Pseudo-nitzschia species, produce domoic acid, a neurotoxin responsible for Amnesic Shellfish Poisoning (ASP) in humans. Symptoms include confusion, headaches, short-term memory loss, and, in severe cases, death (Muhseen et al., 2015).

Cyanobacteria

Cyanobacteria, often referred to as "blue-green algae," constitute a diverse group of oxygenic photosynthetic bacteria with the ability to synthesize chlorophyll-a and auxiliary pigments like phycobilins (Francis, 1878). Inhabiting various water types, cyanobacteria exhibit resilience to extreme temperatures and demonstrate a higher affinity for nitrogen and phosphorus than other photosynthetic species, capitalizing on anthropogenic changes in aquatic environments (Chorus and Bartram, 1999). Unlike other phytoplankton types, cyanobacteria, including species like Nodularia, Aphanizomenon, Anabaena, and Trichodesmium, thrive in warm, stratified conditions in both coastal and open ocean environments (Dadheech *et al*., 2013; Kleinteich *et al*., 2012). Their rapid growth in response to warming conditions sets them apart from other eukaryotic phytoplankton.

Filamentous Algae

Filamentous algae, encompassing green, red, and brown species like Cladophora, Ectocarpus, Pilayella, Ulothrix, Ulva, and Urospora, along with colonial diatoms like Melosira, trigger near-shore green tides. While non-toxic, they form dense overgrowth and drifting mats, outcompeting macrophytes, causing anoxia, and posing threats to fishing gear, boats, and tourism. Events occur notably in the Baltic Sea, Kattegat, Skagerrak, and Atlantic coast, impacting local ecosystems and tourism (Eriksson *et al.*, 2009; Eriksson *et al*., 2011; Bonsdorff *et al.*, 1997; Pihl *et al*., 1999; Vahteri *et al*., 2000; Baden *et al*., 2003; World Health Organisation, 2002). These five harmful algal groups exemplify the diverse nature of HABs, emphasizing the intricate ecological dynamics and potential health risks associated with their presence in aquatic ecosystems. Understanding the characteristics and impacts of these algal groups is crucial for developing effective management and mitigation strategies.

Harmful Algal Blooms and Toxins

In addition to the dinoflagellates, other groups such as raphid ophytes, diatoms, cyanobacteria, and several others also have species that produce toxins.
HAB toxins are mostly categorised by symptoms into the following groups:

- Paralytic shellfish poisons (PSP)
- Neurotoxic shellfish poisons (NSP)
- Amnesic shellfish poisons (ASP),
- Diarrheic shellfish poisons (DSP),
- Azaspiracid shellfish poisoning (AZP),
- Ciguatera fish poisoning (CFP) and
- Cyanobacteria toxin poisoning (CTP)

Poison	Toxin-producing organism	Toxin(s)	Foods likely to be contaminated	Symptoms
Ciguatera fish poisoning (CFP)	Dinoflagellates: *Gambierdiscustoxicus*	Ciguatoxins, Maitotoxin, Scaritoxin	Reef fish such as barracuda, grouper, red snapper, and amberjack	Nausea, Vomiting, Diarrhea, Stomach pain
Neurotoxic shellfish poisoning (NSP)	Dinoflagellates: *Kareniabrevis* and other *Karenia*	Brevetoxins	Shellfish, primarily mussels, oysters, scallops	Nausea, Vomiting, Diarrhea, Stomach pain, Numbness of lips, tongue, and throat, Dizziness
Paralytic shellfish poisoning (PSP)	Dinoflagellates: *Gymonodiniumcatenatum*, *Pyrodiniumbahamense*, *Alexandrium*	Saxitoxins	Shellfish, primarily scallops, mussels, clams, oysters, and cockles, Some fish and crabs	Nausea, Vomiting, Diarrhea, Shortness of breath, Irregular heartbeat, Numbness of mouth and lips, Weakness
Amnesiac shellfish poisoning (ASP)	Diatoms: *Pseudo-nitzchia*	Domoic acid	Shellfish, primarily scallops, mussels, clams, oysters, Possibly some fish species	Nausea, Vomiting, Diarrhea, Stomach pain, Shortness of breath, Memory loss, Disorientation, Possibly coma
Diarrheic shellfish poisoning (DSP)	Dinoflagellates: *Dinophysis*species, *Prorocentrum lima*	Okadaic acid	Shellfish, primarily scallops, mussels, clams, oysters	Nausea, Vomiting, Diarrhea, Stomach pain, Possibly chills, Headache, Fever
Azaspiracid shellfish poisoning (AZP)	Dinoflagellates: *Proroperidiunium*	Azaspiracid	Shellfish	Nausea, Vomiting, Diarrhea, Stomach pain

(https://www.cdc.gov/habs/)

Environmental Forcing of Harmful Algal Blooms

The evolution of forecasting tools and mitigation strategies has emerged from extensive research on the ecological processes governing Harmful Algal Blooms (HABs) and the identification of key factors contributing to their global proliferation, as outlined by the Ecological Risks of Harmful Algal Blooms (GEOHAB, 2003, 2006).

Eutrophication

One of the foremost environmental drivers of HABs is eutrophication, characterized by increased biomass resulting from nutrient over-enrichment in coastal waters. The ecological response to eutrophication is intricate, contingent upon macro- and micronutrient concentrations, the chemical form of nutrients (organic vs. inorganic), and nutrient supply ratios (Anderson *et al*., 2002, 2008; Heisler *et al*., 2008; Glibert and Burkholder, 2011; Kudela *et al*., 2010). Eutrophication not only poses threats to human health but also triggers fish and shellfish die-offs, sporadic deaths of marine mammals and birds, and substantial economic losses for coastal communities. These losses arise from expenses related to beach cleanup, closure of commercially significant areas, and reduced tourism and fisheries (Paerl 1988; Shumway 1990; Villac *et al.*, 1993; Horner *et al.*,1997; Turner and Tester 1997). The assessment of ecological risks is crucial for understanding the impact of harmful and toxic algae on coastal ecosystems and predicting HAB occurrences.

Climate Change

Another significant environmental force driving HABs is climate change. Changes in temperature, precipitation patterns, and ocean currents influence the distribution and intensity of algal blooms (GEOHAB, 2003, 2006; Smayda, 2008). The warming of coastal waters can create favorable conditions for the rapid growth of harmful algae, exacerbating their impact on marine ecosystems.

Ocean Acidification

Ocean acidification, resulting from increased carbon dioxide absorption by seawater, is an emerging factor influencing HAB dynamics. Altered acidity levels may affect the physiology and competitive advantage of certain algal species, potentially favoring the proliferation of harmful varieties (GEOHAB, 2003, 2006; Gobler and Sunda, 2012). In evaluating the environmental impacts of HABs, six primary categories emerge, each associated with distinctive ecological consequences and threats to human health:

1. Phycotoxin Accumulation: Leading to the accumulation of toxins in suspension-feeding organisms like bivalve shellfish.
2. Toxin Transfer and Respiratory Damage: Causing harm to fish and other marine fauna through toxin transfer and damage to respiratory processes, particularly fish gills.
3. High Biomass Blooms: Depleting oxygen levels or inducing other detrimental effects.
4. Ecosystem Disturbance: Triggering disturbances with cascading impacts on species relationships within ecosystems.
5. Aerosolized Toxins: Producing toxins that can affect human respiratory health when aerosolized.

6. Localized Hazardous Blooms: Involving benthic or epiphytic microalgae with unique habitation, processes, and severity of adverse effects distinct from planktonic HABs.
7. Understanding these environmental forces and their implications is fundamental for the development of effective mitigation and management strategies in the face of the growing challenges posed by HABs.

2. Conclusion

This comprehensive exploration of harmful algal blooms (HABs) emphasizes the intricate interplay of ecological factors driving their occurrence. The escalating frequency of HABs, linked to climate change, nutrient enrichment, and habitat disturbance, poses significant threats to marine ecosystems and human well-being. The chapter underscores the urgent need for nuanced mitigation and management strategies, acknowledging both anthropogenic influences and broader ecological contexts. By understanding the diverse causes and impacts of HABs, the scientific community is better equipped to develop sustainable solutions, mitigate adverse effects, and restore balance to coastal ecosystems on a global scale.

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