

EFFECTS OF GLOBAL WARMING ON HARMFULL ALGAL BLOOMS OCCURRENCE IN UNITED STATES OF AMERICA

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Abstract

The coastal areas of United States are heavily impacted by harmful algal blooms that have severe public health effects as well as ecological and economic impacts. Harmful algal blooms (HAB) are responsible for several types of poisoning syndromes such as paralytic shellfish poisoning (PSP), neurotoxic shellfish poisoning (NSP), amnesic shellfish poisoning (ASP), ciguatera fish poisoning (CFP), cyanobacterial poisoning and for increased marine organisms mortality. Moreover, global warming has been suggested to be associated with the harmful algal blooms dispersion along with: i) the increased sea food consumption,ii) the transportation of contaminated sea food, iii) the release of ship ballast water, d) coral reef destruction and e)eutrophication. Nevertheless, this association is not conclusively elucidated. This article aims to describe the occurrence of HAB events in United States and to outline the possible effects of global warming on HAB events manifestations.

Keywords: Harmful algal blooms, global warming, poisoning, occurrence

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Introduction

1. Harmful algal blooms: Definition and Impacts

Harmful algal blooms (HABs) occur due to the rapid increase and accumulation of algae that are causing detrimental effects on human and environmental health along with severe economic damages. They are categorized in two groups: toxic and non-toxic HABs. The toxic algae species produce various toxins that bioaccumulate and biomagnify in marine organisms and consequently cause serious health effects or even mortality both in humans and marine organisms. The most well-known type of poisonings which have been attributed to particular species are: i) paralytic shellfish poisoning- PSP (*Gymnodinium spp.*, *Pyrodinium spp.*, *Alexandrium spp.*), ii) amnesic shellfish poisoning- ASP (*Pseudo-nitzschia*), iii) neurotoxic shellfish poisoning-NSP (*Karenia spp.*), iv) diarrhetic shellfish poisoning- DSP (*Prorocentrum spp.*, *Dinophysis spp.*) and v) cyanobacterial poisoning (*Anabaena*, *Microcystis*, and *Aphanizomenon*). In addition, the causative algal species are: i) dinoflagellates (*Alexandrium spp.*, *Gymnodinium spp.*, *Pyrodinium spp.*, *Karenia spp.*, *Prorocentrum spp.*, *Dinophysis spp.*), ii) diatoms (*Pseudo-nitzschia spp.*) and iii) cyanobacteria (*Anabaena*, *Microcystis*, and *Aphanizomenon*) with the latter to be responsible for most harmful algal bloom events that are demonstrated in freshwater systems. Even though, the non-toxic species may not directly affect human and ecological health through the production of toxins, they can induce anoxic conditions as well as alteration of marine trophic chain, reduction in biodiversity, physical damages and shading of the benthos. The respective phytoplankton species are: i) dinoflagellates (*Ceratium spp.*, *Gymnodinium spp.*), ii) diatoms (*Chaetoceros spp.*, *Rhizosolenia spp.*, *Prymnesiophyte spp.*, *Phaeocystis spp.*) and iii) ciliates (*Mesodinium spp.*), etc. As we mentioned before, these “noxious” or “nuisance” species proliferate quickly and the resulting increase of their biomass leads to water discoloration (e.g. red tides) (Grandjean, Ozonoff 2008, Moore, Trainer et al. 2008, Anderson, Cembella et al. 2012, Shen, Xu et al. 2012).

2. Harmful algal Blooms: Human Health Impacts

Most of HAB toxins are dangerous neurotoxins which dramatically disrupt neurologic system and are accountable for a wide range of symptoms that make clinical evaluation of the underlying cause even more difficult (Fleming, Broad et al. 2006). The main exposure routes to these toxins are: a) ingestion of contaminated fish or shellfish, b) ingestion of contaminated water, c) inhalation of contaminated aerosols and d) dermal contact with contaminated water (Moore, Trainer et al. 2008). Nevertheless, ingestion of contaminated shellfish is the primary route of exposure and exacerbation of gastrointestinal symptoms may be observed even in minutes after the sea food consumption. With regards to paralytic shellfish poisoning (PSP), amnesiac shellfish poisoning (ASP) and ciguatera fish poisoning (CFP), acute respiratory symptoms can be lethal within minutes to hours. Additionally, amnesiac shellfish poisoning (ASP) and ciguatera fish poisoning (CFP) might induce chronic neurologic symptoms lasting from months to years. Moreover, cyanobacteria (*Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Lyngbya*, *Nodularia*, *Oscillatoria*, and *Trichodesmium*, *Microcystis* and *Planktothrix*) might cause several types of toxicity such as dermatotoxicity, hepatotoxicity, immunotoxicity, neurotoxicity, endocrine and respiratory toxicity as well as genotoxicity and cytotoxicity that are the primary mechanisms of cancer initiation (Fleming, Broad et al. 2006).

Therefore, harmful algal blooms are an important public health issue since human populations might be chronically exposed to such neurotoxic and carcinogenic agents.

Harmful algal blooms occurrence

Coastal regions throughout the world are detrimentally impacted by harmful algal blooms (Anderson, Burkholder et al. 2008, Shen, Xu et al. 2012). "Hong Kong waters, East China Sea, Korean South Sea, Japanese Sea, the Gulf of Tokin, Arabian Sea, the coast of France, the coast of Portugal, New Zealand waters, the Galician Rias, Baltic Sea, the Gulf of Mexico, Washington, the Gulf of California, the coast of Florida, the Gulf of Maine, the coast of Nova Scotia, the coast of British Columbia and the South African coast are all areas subject to HABs with bewildering tendencies of larger spatial extents and higher frequencies" (Shen, Xu et al. 2012). Harmful algal blooms occurrence and severity have increased profoundly during the last decades especially in United States coastline (Figure 1). In table 1, we demonstrate harmful algal bloom events that occurred in United States with respect to the area of the incident, the causing algal species and the consequent type of poisoning along with its effects on public health, ecosystem health and economy. The increased prevalence of harmful algal blooms has two possible explanations; either a) the harmful algal bloom events have indeed been increased or b) the current detection methods are far more sensitive than older ones. Nonetheless, the dispersion of algae and more specifically of dinoflagellates and their toxins might have been promoted due to the: a) the increased sea food consumption, b) transportation of contaminated sea food all over the world, c) release of ship ballast water, d) coral reef destruction, e) eutrophication and possibly due to our study factor g) global warming (Fleming, Broad et al. 2006, Anderson, Burkholder et al. 2008).

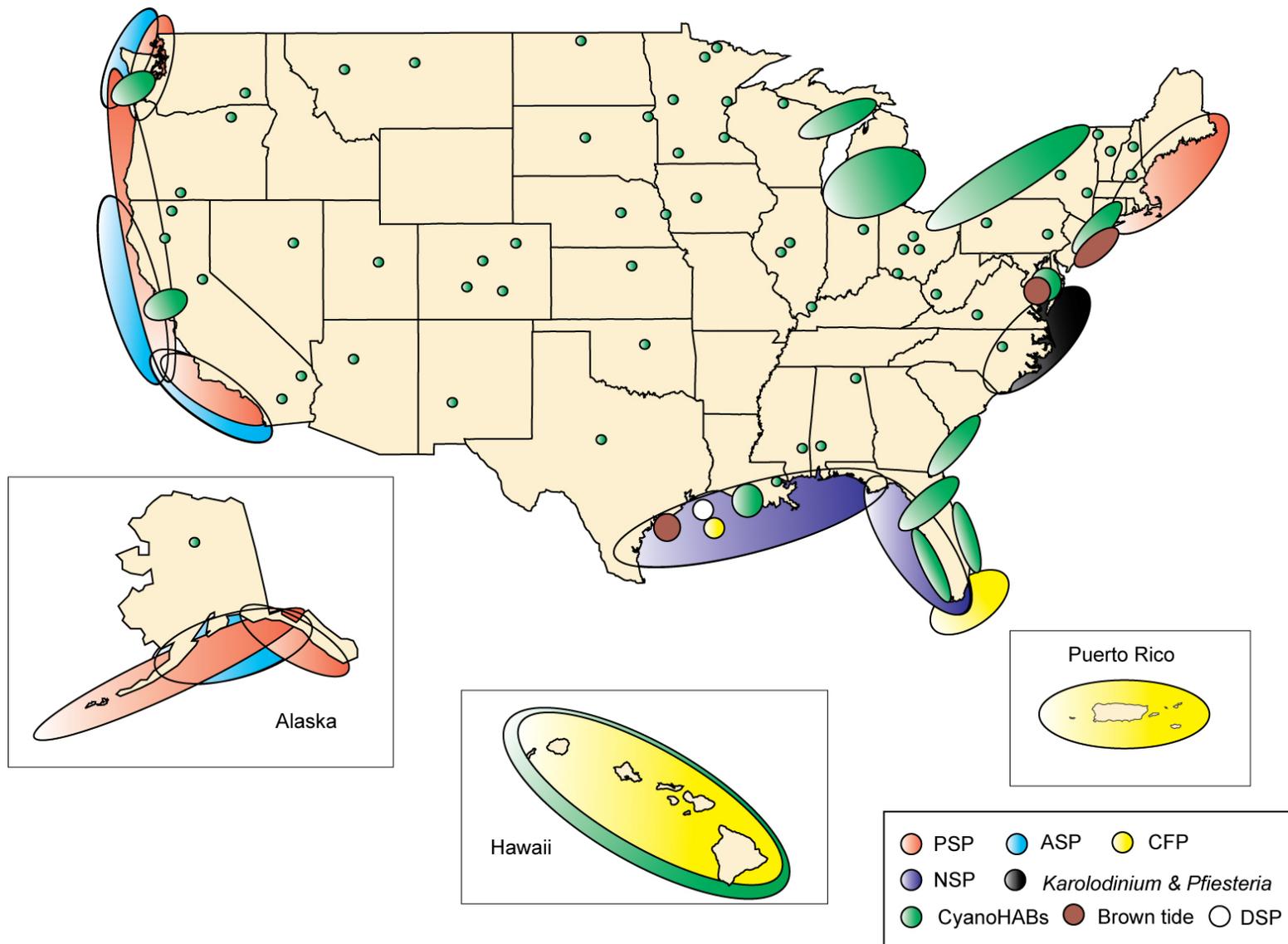


Figure 1: Occurrence of Harmful algal blooms across U.S (Grandjean, Ozonoff 2008)

Table 1: Harmful algal bloom events in U.S.A; Causing agents and impacts

Area	Type of poisoning/ Other	Respective Algal Species	Type of Toxin/Other	Human Health effects	Ecosystem impacts	Economic impacts	References
Northeastern coast (e.g Gulf of Maine-Casco Bay, Massachusetts Bay) Western coast (e.g coast of California-Drakes Bay, Oregon, Washington, Alaska, Hawaii etc) Mid-Atlantic coast	Paralytic Shellfish Poisoning (PSP)	<i>Alexandrium spp.</i> (e.g. <i>A. tamarense</i> , <i>A. acatanella</i>) <i>Gymnodinium spp.</i> (e.g. <i>G. catenatum</i>) <i>Pyrodinium spp.</i> (e.g. <i>P. bahamense var. compressum</i>)	Saxitoxin	Gastrointestinal symptoms, Acute respiratory distress Death	Alteration of marine trophic structure, Marine organisms mortality (mammals, fish seabirds, shellfish, lobster)	Loss of natural/cultured seafood resources, Decrease in tourism and recreational activities	Grandjean, Ozonoff 2008 Anderson, Burkholder et al. 2008 Lewitus, Horner et al. 2012
Western coast (e.g coast of Hawaii) Gulf of Mexico (e.g. Florida Keys) Coast of Puerto Rico, Virgin Islands, Guam, American Samoa, Northern Mariana Islands	Ciguatera Fish Poisoning (CFP)	<i>Gambierdiscus toxicus</i>	Ciguatoxin	>80 physiological disorders Gastrointestinal symptoms, Acute respiratory distress Death	Alteration of fish behavior, Alteration of immune responses, Disrupted ecosystem health	>95% of medical costs from HAB in U.S.A	Grandjean, Ozonoff 2008 Anderson, Burkholder et al. 2008 CDC 2012

Table 1: Harmful algal bloom events in U.S.A; Causing agents and impacts (continued)

Area	Type of poisoning/Other	Respective Algal Species	Type of Toxin/Other	Human Health effects	Ecosystem impacts	Economic impacts	References
Gulf of Mexico (e.g Coast of Texas, Louisiana, Mississippi, Alabama, Florida)	Neurotoxic Shellfish Poisoning (NSP)- Red tides	<i>Karenia Brevis</i>	Brevetoxins	Gastrointestinal symptoms- Gastroenteritis, Neurological symptoms- Muscle Cramps, Seizures, Paralysis Respiratory symptoms- bronchitis, pneumonia	Fish kills	Decline in commercial and recreational fish stocks	Grandjean, Ozonoff 2008 Anderson, Burkholder et al. 2008 Carvalho, Minnett et al. 2011 Frolov, Kudela et al. 2012
Western Coast (e.g. Washington- Puget Sound, California) Northeastern Coast Gulf of Mexico Mid Atlantic Coast (e.g. Chesapeake Bay- Maryland, Florida)	Amnesic Shellfish Poisoning (ASP)	<i>Pseudo-nitzschia</i> (e.g. <i>P. pseudodelicatissima</i> , <i>P. cuspidata</i> and <i>P. australis</i>)	Domoic acid	Neurological symptoms- Confusion, Gastrointestinal symptoms- vomiting, diarrhea Acute respiratory distress Death	-	Shellfish harvests closures, Prohibition of recreational, commercial, tribal harvest of clams	Grandjean, Ozonoff 2008 Anderson, Burkholder et al. 2008 De La Riva, Gretel Torres, Johnson et al. 2009 Lewitus, Horner et al. 2012

Table 1: Harmful algal bloom events in U.S.A; Causing agents and impacts (continued)

Area	Type of poisoning/ Other	Respective Microorganism	Type of Toxin/Other	Human Health effects	Ecosystem impacts	Economic impacts	References
Great Lakes (Western Lake Erie, Saginaw Bay-Lake Huron, Bay of Quinte-Lake Ontario, Lake Michigan) Lake Okeechobee (Florida), Lake Ponchartrain (Louisiana), Mid Atlantic Coast- Chesapeake Bay (Maryland, Virginia), Florida Bay (Florida)	Cyano-bacterial Poisoning- Blue tides	<i>Cyanobacteria-</i> <i>mostly Microcystis (M.aeruginosa), Anabaena, Aphanizomenon, Cylindrospermopsis, Lyngbya, Nodularia, Oscillatoria, Trichodesmium Planktothrix</i>	Mostly Hepatotoxic Microcystin	Skin irritation, Liver disease, Alteration of immune system, Allergies, Neurological symptoms, Compromised endocrine and respiratory system, Cancer	Livestock, wildlife, birds mortality	-	Grandjean, Ozonoff 2008, Michalak, Anderson et al. 2013 Hall, Paerl et al. 2012 Lewitus, Horner et al. 2012 CDC 2012
Mid Atlantic Coast- Chesapeake Bay, Maryland Coastal Bays Gulf of Mexico Western Coast (e.g. California- San Francisco Bay, Monterey Bay, Washington)	Diarrhetic Shellfish Poisoning	<i>Prorocentrum (e.g. P.minimum)</i> <i>Dinophysis spp.</i>	Okadaic acid	Diarrhea	-	-	Lewitus, Horner et al. 2012
Northeast/Mid Atlantic	Brown Tides	<i>Aureococcus anophagefferens</i>	None	-	Shading benthos	Decrease in tourism and recreational activities	Anderson, Burkholder et al. 2008

Table 1: Harmful algal bloom events in U.S.A; Causing agents and impacts (continued)

Area	Type of poisoning/ Other	Respective Algal Species	Type of Toxin/Other	Human Health effects	Ecosystem impacts	Economic impacts	References
Mid-Atlantic- Chesapeake Bay, Maryland Coastal Bays Gulf of Mexico Western Coast (e.g. California- San Francisco Bay, Monterey Bay, and Southern California, Washington)	Other	<i>Pfiesteria piscicida</i> , <i>Karlodinium spp.</i> , <i>Heterosigma spp.</i> , <i>Chattonella spp.</i> , <i>Fibrocapsa japonica</i> , <i>Cochlodinium spp.</i> <i>Protoceratium reticulatum</i>	-	-	Fish mortality	Decline in commercial and recreational fish stocks	Anderson, Burkholder et al. 2008 Anderson, Burkholder et al. 2008 Lewitus, Horner et al. 2012

Global Warming and HAB events occurrence

Global warming is the rise in the average temperature of Earth's atmosphere and oceans due to accumulation of heat energy that is trapped by greenhouse gases (e.g. CO₂) that are released by human activities like fossil fuel combustion in both stationary (e.g. industries) and mobile sources (e.g. cars). According to EPA (2013), the growth and dominance of harmful algal blooms will be promoted by global warming due to : i) warmer water temperatures, ii) changes in salinity, iii) increases in atmospheric carbon dioxide- CO₂ concentrations, iv) change in rainfall patterns, v) intensification of coastal upwelling and vi) sea level rise. Temperature, light and nutrient availability determine phytoplankton growth thus all the aforementioned consequences of global warming will definitely affect the occurrence of harmful algal blooms ((Moore, Trainer et al. 2008), (Paerl, Otten 2013). A large fraction of the trapped heat energy is stored in oceans and in other water reservoirs such as lakes. Therefore, thermal stratification is intensified thus favoring the growth of harmful algal species, namely cyanobacteria and dinoflagellates which are mobile and abundant in the upper layers of the water column. Consequently, they have an advantage over less mobile and more desirable phytoplankton species (Paerl, Hall et al. 2011). Water temperature is projected to be increased in Pacific Northwest region (e.g. Oregon, Washington, California) and it will stimulate primary growth as well as earlier and longer lasting harmful algal blooms (Gerten, Adrian 2002, Grandjean, Ozonoff 2008). In addition, it will allow the dispersion of thermophile species into new areas (Grandjean, Ozonoff 2008, Moore, Trainer et al. 2008). Furthermore, the increase in surface-water temperature is associated with more intense precipitation phenomena such as storms which increase nutrients flow. Nutrients flow along with greater residence time in case of subsequent droughts induces even more harmful algal species proliferation and more specifically cyanobacterial growth. Global warming is also expected to increase drought frequency and duration thus the occurrence of harmful algal blooms based on the aforementioned hypothesis is even more likely (Friocourt, Skogen et al. 2012, Baron, Hall et al. 2012). Salinity gradients that are directly related to salinity differentiation as a consequence of global warming, promote earlier stratification in the spring and longer persistence during winter thus temporally expanding the growth of harmful algal species. Furthermore, according to Paerl and Otten (2013) some bloom forming cyanobacteria are salt tolerant even though they usually exist in freshwater systems such as San Francisco Bay (California, USA), and Lake Ponchartrain (Louisiana, USA). Ocean and atmospheric CO₂ concentrations are in a dynamic balance. Hence, the ocean CO₂ concentrations increase due to the increase in atmospheric CO₂ concentration, resulting in ocean acidification that threatens the existence of calcifying organisms and it causes coral reefs destruction. Coral reef destruction increases the available space for algae colonization. Moreover, climate change causes stratospheric ozone depletion which allows more UV- radiation to reach the surface of Earth. Increased absorption of UV-radiation causes cell apoptosis and organisms such as cyanobacteria which are UV-resistant are more likely to survive than other sensitive organisms (Paul 2008). We ought to mention that both light and temperature affect cyanobacteria toxicity either directly through the induction of toxin production or indirectly through the stimulation of cell growth and division (Grandjean, Ozonoff 2008). Lastly, shorter ice cover periods will be observed and as a consequence algal spring blooms will develop earlier and with higher primary productivity (e.g. Lake Tahoe and Lake Castle in California) (Gerten, Adrian 2002). All in all, the range of warm water species is expected to increase whereas the range of cold water species will be reduced. In addition, some algae species with specific

characteristics such as cyanobacteria are expected to dominate over their opponents and their seasonality as well as bloom event duration will be prolonged. Furthermore, the trophic chain will be radically changed since global warming will either lead or deviate from the species-specific optimum growth conditions for algal species and marine organisms respectively (Anderson, Cembella et al. 2012). In table 2, we provide two examples of algal species and the occurrence of harmful algal blooms with respect to the projected climatic changes for specific areas in United States.

Table 2: Examples of HAB occurrence in U.S. regions and the effects of global warming

Area	Examples	Type of Poisoning	Global warming effects	Effects on HAB occurrence and severity	References
Puget Sound Washington	<i>Alexandrium catanella</i>	Paralytic Shellfish Poisoning	Higher temperatures	Expansion of growth periods due to earlier optimum temperatures	Moore, Trainer et al. 2008)
Lake Erie	Cyanobacteria	Cyanobacterial Poisoning	Higher temperatures Lake Acification More UV radiation	Expansion of growth periods due to earlier optimum temperatures Stimulation of growth over other competitors: i) normal growth in low pH conditions and ii) UV-resistant Increased hepatotoxin production	Paul 2008 Paerl, Hall et al. 2011 Moore, Trainer et al. 2008 El-Shehawy, Gorokhova et al. 2012

Discussion

United States coastline is profoundly impacted by harmful algal bloom events. The manifestation of such events has recently been boosted by various factors that are vastly determined by human activities and habits. The dispersion of harmful algal species is promoted by: i) the increased sea food consumption, ii) the transportation of contaminated sea food, iii) the release of ship ballast water, iv) coral reef destruction and v) eutrophication. In addition, global warming as a result of heat energy entrapment by greenhouse gases that are released by fossil fuel combustion has recently been speculated to be a contributing factor. According to EPA (2013) manifestation of harmful algal blooms will be induced by the following changes: i) increased water temperature, ii) salinity changes, iii) increased atmospheric carbon dioxide- CO₂ concentrations, iv) alteration of rainfall patterns, v) intensification of coastal upwelling and vi) sea level rise. If these speculations are true then the future will be ominous since global warming is inevitable. Nevertheless, prevention and monitoring of HAB exposures and illnesses must be a primary public health aim through: i) regulating the toxin levels in seafood or fishes and closing harvests when reaching extreme levels, ii) improving detection methods with regards to HAB surveillance and HAB poisonings, iii) informing public about HAB related symptoms as well as how to avoid exposure and iv) encouraging seafood industry and other industries to implement prevention programs (Grandjean, Ozonoff 2008, Anderson, Cembella et al. 2012, Shen, Xu et al. 2012, Frolov, Kudela et al. 2012, Paerl, Otten 2013). Moreover, lake- scale measures can be implemented for the reduction of cyanobacterial blooms such as nutrient input reductions, nutrients removal after their discharge in the lake, alteration of physical factors that favor cyanobacterial blooms (e.g. thermal destratification through the use of vertical mixing devices), increase of nutrients removal rate so as to reduce their residence time et cetera. However these techniques are very costly even at such small scale and the hydrological and physicochemical effects of global warming must be incorporated to achieve minimization of harmful algal blooms occurrence. Stricter limits on greenhouse emissions must be enforced as well as a radical change in our extremely polluting behavior (Paerl, Hall et al. 2011, Paerl, Otten 2013). Harmful algal blooms are an important public health issue and their manifestations will be more frequent and severe. United States have the technology and the means to implement the aforementioned prevention measures so as to safeguard their citizens' health. Our knowledge about global warming and its effects is ever increasing and we ought to prepare ourselves for this new era.

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