A Review on Harmful Algal Blooms Detection and Mitigation

March 31, 2022

1 Introduction

The most important basis of food web in the ecosystem are small microscopic single-celled organisms to large sea weeds called algae. As these microscopic organisms grow out-of-control, these algal blooms can spread toxins, which are harmful for other creatures in the ecosystem, which directly or indirectly rely on them. The Harmful Algal Blooms (HABs) are a wide growing problem in most US lakes and other water bodies across the country, which can lead to poor water quality and thereby causing serious environmental, human and aquatic health issues. Most algal species are immobile and their distributions are usually controlled by the movement of waves, currents and tides in the water bodies. These microscopic algal species are originated from the phytoplankton variety, which are different from their close relatives, called the multicellular algae or sea weeds.

Both algal varieties play an important role in the production of oxygen and thereby enabling life on earth and it also forms the base of the aquatic food chain as it provides food for human society and other living creatures on earth. Figure 1 shows the food web linkage in the ecosystem [14]. Phytoplankton or microscopic marine organisms, which sits at the bottom of the food web are the source of food for many other planktons, small fishes and even large animals like whales. Similar to plants, phytoplankton get their energy from carbon dioxide through photosynthesis. They play a significant role in the transfer of carbon from atmosphere to ocean. Phytoplankton also uses the pigment chlorophyll to harness light energy for photosynthesis[11].

The growth of phytoplanktons depends on the availability of carbon dioxide, sunlight and nutrients. Nitrate, Phosphate, silicate and calcium are the important nutrients required by phytoplanktons to survive. There are many kinds of phytoplankton like cyanobacteria, silica-encased diatoms, dinoflagellates, green algae, and chalk-coated coccolithophores. Among the many variants of phytoplankton, the most harmful species can be found in eukaryotes, dinoflagellates, raphidophytes, diatoms, euglenophytes, cryptophytes, haptophytes, pelagophytes, and chlorophytes[9]. Some of the most toxic species of phytoplanktons are shown in Table 1.

These species of phytoplankton require trace amounts of iron for their growth. Water temperature and water salinity, depth of the water, wind, and the kind of predators

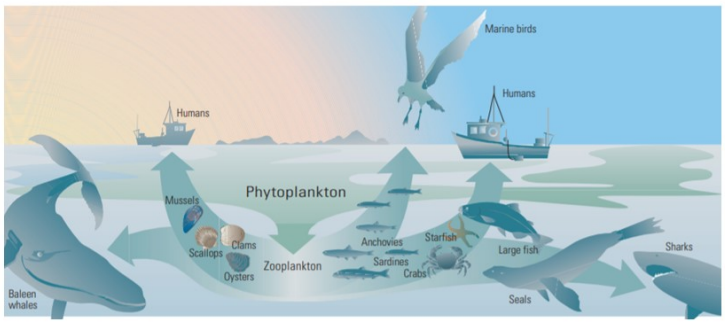

Figure 1: Food web chain [14]

grazing on the phytoplankton also contribute to the growth of phytoplanktons. When conditions are right, the phytoplanktons grow enormously, which create a condition called "bloom". Certain species of phytoplanktons like cyanobacteria produce powerful bio toxins, which can in turn create "red-tides" or harmful algal blooms. The cyanobacterial bloom can grow on rocks beneath the surface of water as well as on the surface of water, in which the water may look like foam, scum, mats and even spilled paint. It can even change the color of the water to red, orange, green, blue, brown and yellow. It has been studied that the algal blooms can be found in fresh water, salt water and brackish water, where fresh water meets salt water.

1.1 Social Economical impact of HAB

Millions of dollars are spent annually to study the HAB-related impacts world wide. The study of impacts created due to HAB events spread over public health, commercial fisheries, recreation, tourism, environmental monitoring, and bloom management.Figure 2, shows the classification of socio-economic impacts spread due to the effects of HAB.

Mostly the economic impacts of HABs are quantified by subtracting the socioeconomic measures when there is events of HAB and when there is no HAB events. Figure 3 shows various sectors that are affected due to HAB events.

According to [16], the estimated annual economic impacts from Harmful Algal Blooms in the United States, comes mostly from health sector. As shown in Figure 4, around 45% of total economic impact is from the public health across United States according to the estimate during 1987-1992 period. The second sector is in commercial fishery which had an economic impact around 37%. The remaining sectors include recreation and tourism which contribute around 13% and Monitoring and Management in turn contribute around 4% of the economic loss.

An earlier nationwide estimate (in 2000) of the average annual costs of HABs is approximately $78 million (in 2021 dollars), of which public health is the largest component (nearly $35 million), followed by the effect on commercial fisheries ($29 million),

Table 1 Toxic species of phytoplankton[10]

Image	Phytoplankton_species	Genus	Distribution	Effects
	Pseudo-nitzschia	Diatom	Widespread	Produce neurotoxins
	Alexandrium	Dinoflagellate	Coastal temperate to tropical waters	Paralytic Shellfish poisoning
	Dinophysis	Dinoflagellate	Widespread	Diarrhetic Shellfish poisoning
	Gonyaulax	Dinoflagellate	Widespread	Gonyaulax spinifera can produce toxins.
	Lingulodinium	Dinoflagellate	neritic, warm temperate to tropical waters	Bioluminescent and toxic
	Margalefidinium	Dinoflagellate	Cosmopolitan in warm and temperate waters	High density blooms can color the water brown or red
	Prorocentrum	Dinoflagellate	Oceanic, neritic, warm to artic waters worldwide	
	Protoperidinium	Dinoflagellate	Wiespread throughout oceans	
	Protoceratium	Dinoflagellate	Neritic, estuarine, cold temperate to subtropical waters	Produce yessotoxin
	Gymnodinium	Dinoflagellate	Oceanic to estuarine, warm temperate to tropical	Produce saxitoxins
	Heterosigma akashiwo	Raphidophyte	Coastal regions worldwide	Responsible for massive fish mortality
	Karenia	Dinoflagellate	Oceanic to estuarine, warm temperate to tropical	Produces brevetoxin, a potent neurotoxin
	Aphanizomenon	Cyanobacteria	eutrophic lakes, reservoirs, regulated fish ponds, and cattle ponds.	Produce saxitoxins
	Cylindrospermopsis	Cyanobacteria	Genus is tropical/ subtropical in origin, but it has expanded into temperate areas, particularly the northern hemisphere	Produce Cylindrospermopsin, a toxic compound that affects the human liver and kidneys
	Dolichospermum	Cyanobacteria	Worldwide,	Produce toxins
	Microcystis	Cyanobacteria	Cosmopolitan	Produce toxins(microcystins)
	Nodularia	Cyanobacteria	Worldwide	Produces nodularin, a potent natural toxin
	Oscillatoria	Cyanobacteria		Produce both anatoxin-a and microcystins

recreation and tourism ($10 million), and spending for monitoring and management $3 million).14 Average annual costs tend to mask the significance of individual HAB events, some of which greatly exceed the annual average for the entire country.15 Moreover, the direct effects of HABs can propagate through regional economies, causing negative impacts to other sectors.

The average public health impact during the period from 1987-1992 was mainly due to shellfish poisoning and it costs around $1 million per year. It has been identified that in Sarasota County, Florida there was an increase in hospital emergency during

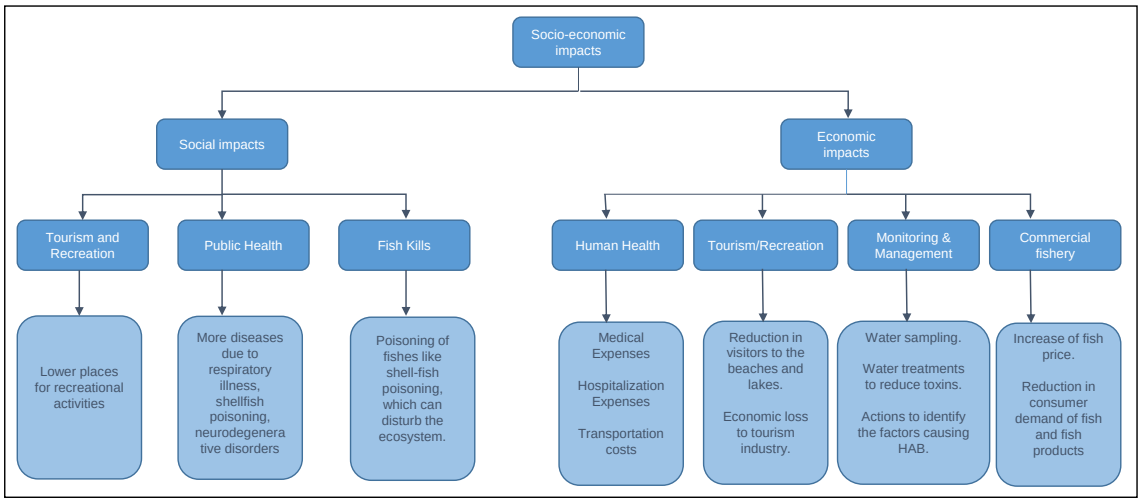

Figure 2: Socio-Economic Impacts[16]

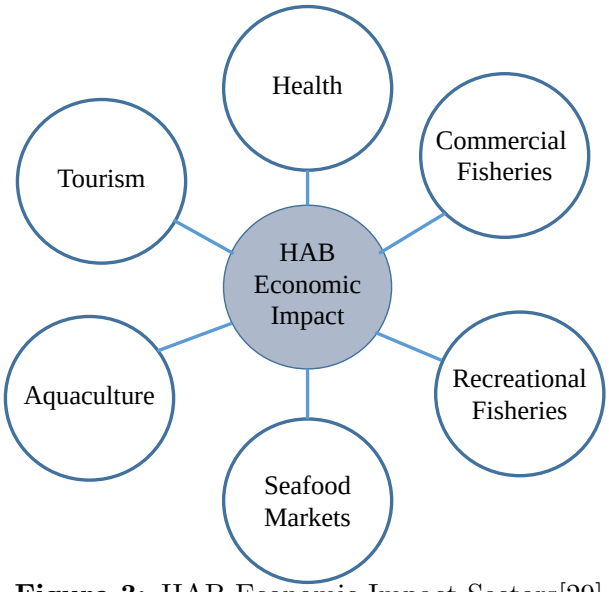

Figure 3: HAB Economic Impact Sectors[29]

the event of red tide, which has an increase of hospital emergency cases. They found that the costs due to respiratory illness alone ranged between $0.5 to $4 million dollars. The economic costs related to public health is the sum of medical expenses and lost work days and was found to be around an average cost of $22 million dollars in Florida red tide event.

Fishery is another important sector which has been affected due to HAB events. It has been studied that an economic loss of nearly $6.5 million dollars to local restaurants and hotel industries resulted in Okaloosa county, Florida due to red tide events

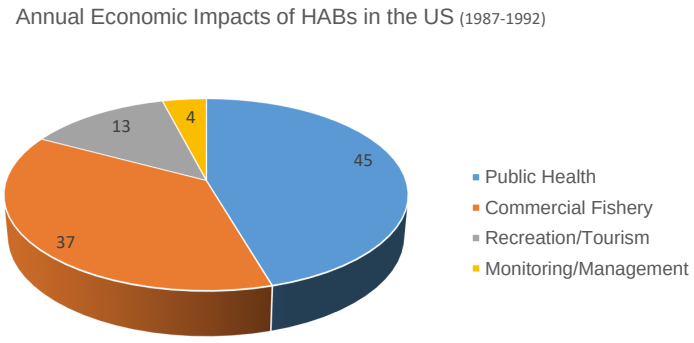

Figure 4: Sectors of Economic Impacts affected in the United States due to HAB events[16]

during 1995-2000 period.The 2015 U.S. West Coast domoic acid event [21] shattered the fisheries industries creating an economic shock for the coastal communities. It greatly created the financial, emotional and socio-cultural impacts of those employed in fishing sector than those in other industries.

The impact of HAB can also affect the recreation and tourism as massive death of fishes accumulating in beaches can diminish the quality of beaches and can in turn cause the closure of recreational fisheries. It has also been reported in [8] that the average economic cost on recreation and tourism during the period from 1987-1992 was around $7 million per year. In [8], it has also been stated that the economic loss in fisheries industry is minor when compared to the loss created in recreation and tourism industry due to HAB events. The cost incurred in monitoring and management due to HAB events is determining the amount of money spend on cleaning up the beaches, monitoring the presence and formation of HAB events and so on. It has been estimated that an annual average monitoring and management costs in US has a total of around $2million dollars. The annual monitoring and management expenditure in Florida during the red tide event was estimated to be around $170 thousand per year and most of the expenditure was applied to beach clean up activities such as cleaning beaches due to disposal of dead fishes and washed up seaweeds. Table 2 gives a summary of maximum costs incurred in each sectors due to HAB events across US.

Moreover, the economic impacts due to HAB event in one sector such as commercial or recreational fishing is estimated using a regional IO model [19]. The regional IO model will help to capture the economic impacts of related industries which are linked to one another. For example, if a HAB event affects the commercial fisheries in a particular region, which lead to a decline in the local fishing industry.

Category	Maximum Costs	Economic Effects
Shellfish Poisoning	1	Productivity losses and medical costs of illness and mortalities from poisonings.
Ciguatera Fish Poisoning	22	Productivity losses and medical costs of illness from poisonings.
Commercial Fisheries	19	Direct output impacts of fishery closures in actual fisheries.
Recreation and Tourism	29	Reduced expenditure from recreational fishery closures; slowed coastal hotel and restaurant trade and tourism.
Monitoring and Management	2	Government budgets and expenditures associated with environmental sampling, administration of closures and seafood consumption warnings and beach cleanups.

Table 2 Summary of economic effects of HABs across US(2000 $ million)[8]

- Social Impact - Economical Impact - World wide - Nation wide - International issues - Marine : Social and Economical impact

1.2 Factors influencing HAB growth

There are many factors that contribute to the growth of HAB. Many studies are already in literature which study the factors affecting harmful algal blooms. Among the many such factors, weather conditions, physical and chemical factors all contribute to the growth of the algal blooms as shown in Figure 2.

The chart in Figure 6 shows various factors contributing to the cyanobacterial concentration yearly in Buckhorn lake, Ohio State, US from 1988 to 2018. Among the plotted factors like Chlorophyll-a concentartion, Secchi depth and Total Nitrogen (TN) levels, the contribution of TN in water lead to high algal growth.

1.2.1 Presence of chlorophyll-a:

In [17], the factors influencing the formation of algal blooms were analyzed in Taihu Lake from 2000 to 2011 using MODIS. The authors found that Chlorophyll-a was an important indicator for the algal bloom presence. Chl-a continues to increase during summer months especially from June to September due to high wind speed. Moreover, nutrients like Total-Nitrogen (T-N) and Total-Phosphorous (T-P) have correlation with Chl-a and T-P 's influence on Chl-a was higher compared to T-Ns.Various physical and chemical factors such as total nitrogen, total phosphorous, chl-a content, temperature and light intensity all contribute to the formation of algal blooms[31].

1.2.2 Influence of nutrients:

According to [1], eutrophication plays an important role in the formation of HABs. Eutrophication occurs when the environment becomes enriched with nutrients and thereby increasing the amount of plant and algal growth in estuaries and coastal waters. Agricultural and industrial activities especially fish farming all causes water to runoff to lakes, estuaries and coastal water bodies carrying excessive amount of nitro-

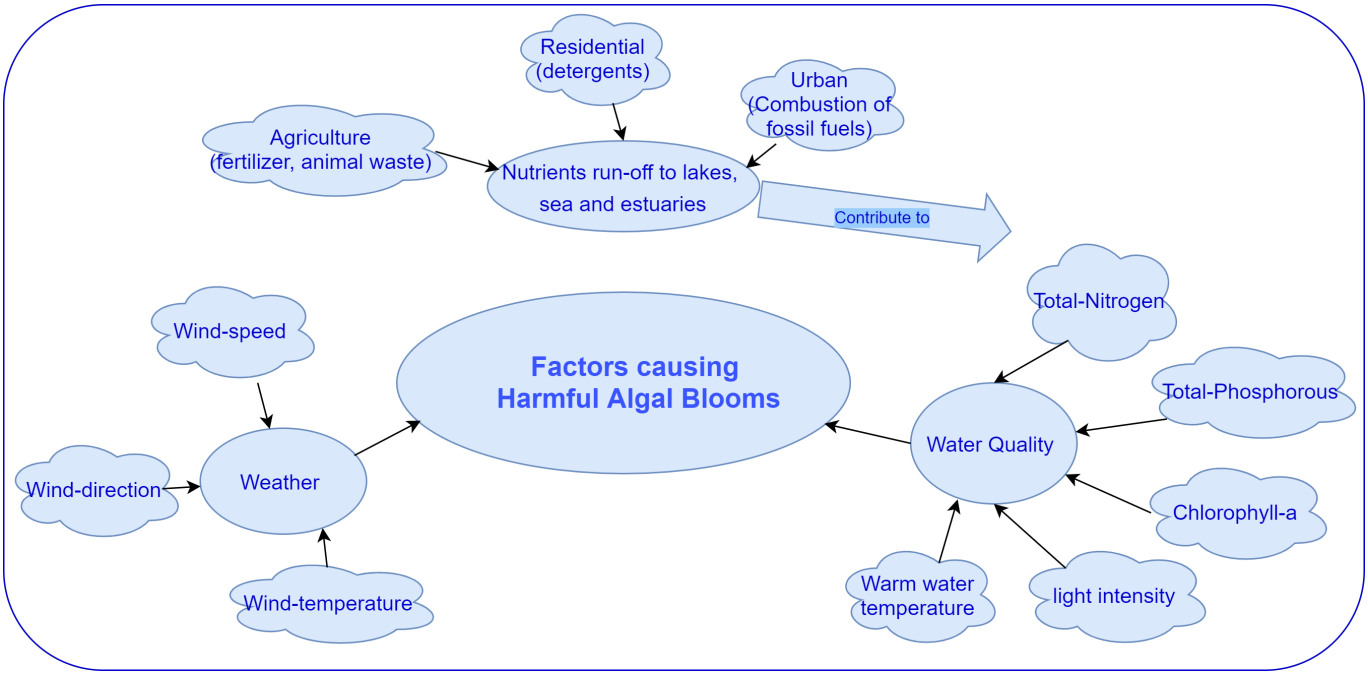

Figure 5: Factors affecting formation of HAB

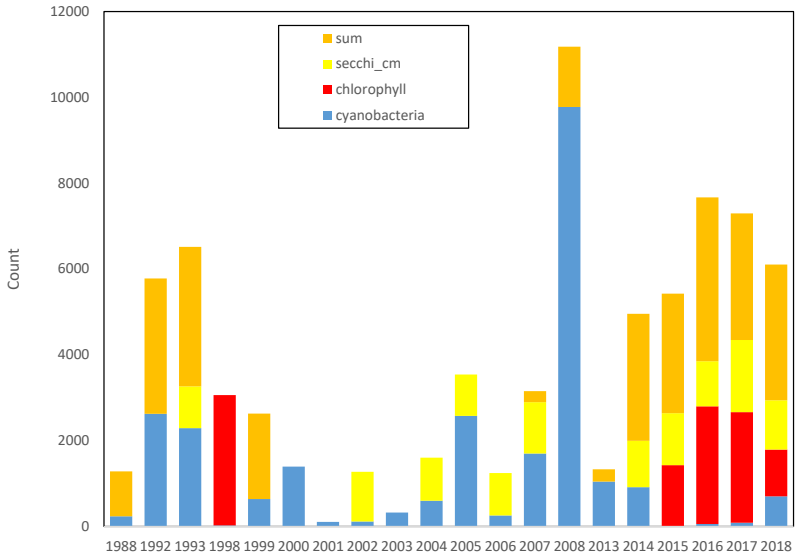

Figure 6: Factors affecting formation of HAB in Buckhorn Lake, Ohio [28]

gen, phosphorous and other nutrients which contribute to the growth of algae [24].

Another paper [20], stated that ocean acidification, which is caused by high pCO_2 and low pH and greenhouse warming also added to the factors for the formation of Harmful Algal Blooms. In addition to that elevated CO_2 levels also promoted to the growth of algal blooms.

In North Dakota state, Many of North Dakota's waterbodies are affected by nutrient pollution. It is estimated that 69of perennial streams in the State are impaired due to excessive P and 57(NDDEQ, 2015a). Furthermore, more than 24impaired for fishing and water-based recreation due to excessive nutrients (NDDEQ, 2015b). In addition, a growing number of lakes and reservoirs in the State are experiencing harmful bluegreen algae (i.e., cyanobacteria) blooms caused by excessive N and P loadings. Of concern are recent reports of blue-green algae blooms in parts of Lake Sakakawea. These blue-green algae blooms can produce harmful toxins, referred to as cyanotoxins, in the water which can pose a risk to human health in drinking water supplies and by primary contact recreational activities such as swimming, skiing, and boating.

1.2.3 Effect of weather:

Weather data is another important factor for the formation. Summer temperature drives the abundance of HAB. The longer the summer, the higher will be the abundance of cyanobacterial algae and it was noted in [7] that increased temperatures are associated with increased total phosphorous content and hence increase in algal blooms.Wind speed, direction of wind and other weather related data contribute to the frequency of occurrence of HAB. In many experiments conducted for the study of HABs it was found that when the speed of wind above the water bodies is slowed down below a particular velocity, it results in the formation of more HABs[17]. The algal bloom decreased, when the speed of wind is greater than 4m/s.

Rapid snow melts what is forested with stratification in the study of algal blooms

Environmental conditions contributing to algal blooms There are many causes for algal blooms in freshwaters and it is often difficult to pinpoint specific reasons why a bloom forms. In many cases, a set of unique environmental conditions occur in a waterbody, which can lead to a particular species dominating and triggering a bloom. While bloom formation is waterbody specific, the most common factors for bloom formation are timing, nutrients, temperature, light, and stable conditions.

Algal blooms in BC most often occur in the late-summer and early-fall. However, they can occur at any time of year, even under ice. Blooms typically last from several days to a few weeks, but can sometimes last as long as several months if environmental conditions are favourable.

In contrast to the factors contributing to the increase in algal bloom, there are factors which contribute to the bloom reduction. One such factor is the presence of turbulence in water bodies [23], [18]. Small scale turbulence resulted in an increase in algal growth compared to larger turbulence. Another factor is reduced rainfall contribute to the reduction in vertical distribution of algae. In [20], it has been proposed that UV-C irradiation suppresses the growth of algal blooms.

1.3 HAB vs Health

The harm that produced by the bloom of cyanobacteria are large and life threatening. The toxins of the cyanobacterial bloom can kill aquatic animals and even mammals and humans. Even dead cyanobacteria can sink into deep ocean floor or lake floor and get decomposed by bacteria, which in turn can deplete the oxygen levels in water, suffocating animal life inside water[13].

People that swallow or come into contact with water containing cyanotoxins can become sick with diarrhea and vomiting; experience numb lips, tingling fingers and toes, dizziness, rashes, hives, or skin blisters. Pets and livestock may also suffer adverse health effects. There are no known antidotes for the cyanotoxins produced by blue-green algae. Children and pets are at a higher risk than adults for illness because of their smaller size

In [25], several human health effects caused due to HABs were summarized. Some of the problems associated with exposure to cyanobacterial blooms are the following.

- skin diseases such as rashes, hives or skin blisters
- stomach/liver illness such as diarrhea and vomiting
- experience numb lips
- tingling fingers and toes
- dizziness
- respiratory problems
- several neurological effects

Other illness caused by consumption of seafood, which are contaminated with algal toxins include [6]:

- Ciguatera poisoning
- Paralytic shellfish poisoning
- Neurotoxic shellfish poisoning (NSP)
- Amnesic shellfish poisoning
- Diarrhetic shellfish poisoning

.

In [[22], [2]], a Harmful Algal Bloom-related Illness Surveillance System (HABISS), which is a product of Center for Disease Control and Prevention (CDC), which collects data related to human and animal illness is mentioned. It is responsible for monitoring the impact on the frequency of HAB-related illness caused due to increase contact of human and animals with HAB.

The paper [5], discuss about the Harmful Algal Blooms in the Mediterranean Sea and the Black Sea and its effect on human health. In addition to the five main poisoning caused due to the consumption of sea food toxicated by algal toxins, other toxins

from two dinoflagellate sources are air transmitted (aerosolized) to impact human health causing respiratory illness. Marine algal blooms and it's impact on human health have been discussed in [33]. In the paper, it has been cited that the illness caused by Ciguatera Poisoning is estimated to be around 251 cases per 10,000 persons per year especially among Pacific and Caribbean populations. In [32], the algal bloom poisoning in fresh water and its effect on children were discussed. According to the paper, children are more prone to illness caused due to the toxification of algal blooms than adults. There has been an incident happened in Dane county, Wisconsin in July 2002, where a group of teenagers who swam in the golf course pond covered by the scum of blue-green algae, was affected.

According to [25], ingestion of seafood contaminated with toxins produced from diatoms and dinoflagellates, respiratory exposure via aerosols, drinking contaminated water bathing in contaminated lakes etc., are some of the reasons for the human and and animal health damage. The following table 1, shows the cyanotoxins biological and human health effects.

Cyanotoxins	Symptoms	Effects
Hepatotoxins		
Microcystin	Within 4-24hrs to few days:Diarrhea, vomiting, liver hemorrhage, shock, abdominal pain, jaundice, weakness, multiple organ failure.	Can be lethal. Exposure: drinking water, contaminated dialysis fluid, recreational environments.
Nodularin	Diarrhea, vomiting, goose bumps, weakness, liver hemorrhage.	N/A
Cylindrospermopsin	Gastroenteritis abdominal pain, vomiting, diarrhea, acute liver inflammation, liver and kidney failure, hay fever, asthma.	Chronic exposure linked to cancer
Neurotoxins		
Anatoxin-a/ Homoanatoxin-a	Muscle twitching, cramping, staggering, paralysis, convulsions, gasping, respiratory failure, death by suffocation.	Can be lethal.
Saxitoxins	Paralytic shellfish poison: Nausea, vomiting drowsiness, fever, muscular paralysis, respiratory failure, death.	Death can occur 2-12 hrs after exposure.
beta-Methylamino-L-alanine (BMAA)	Implicated on chronic neurodegenerative disease	Chronic exposure linked to chronic neurodegenerative conditions: Amyotrophic Lateral Sclerosis.
Irritants and Dermatotoxins		
Aplysiatoxins	Skin irritations, asthma like symptoms	N/A
Lyngbyatoxin	Smooth muscle contraction. Skin\\ irritation	N/A

Table 3 Cyanotoxins Human Health Effects [25]

Studies further show that the presence of cyanobacteria blooms in lakes and water bodies can generate toxins like BMAA which can further cause several neurological

disorder like Motor Neuron Diseases and can even lead to death, if not controlled. Motor Neuron Diseases (MNDs) is a rare and serious condition that cause neurodegenerative disorder, in which the cells especially those which control the voluntary muscles of the body lose its structure as well as the functions and eventually leading to cell death. There are various categories of MNDs, which include Amyotrophic Lateral Sclerosis (ALS), Progressive Bulbar Palsy (PBP), Pseudobulbar Palsy, Progressive Muscular Atrophy (PMA), Primary Lateral Sclerosis (PLS), Spinal Muscular Atrophy (SMA) and Monomelic Amyotrophy (MMA) and some rare variants resembling ALS. Eventhough MNDs can affect both children and adults, varying symptoms are shown in different patients, depending on the type of MND being affected. One of the common symptom affected by MND is muscle weakness[12].

According to [15], the MNDs are classified based on whether the degeneration is inherited, sporadic(no family history) or affects the upper motor neurons, lower motor neurons, or both. The symptoms and the affected category of MNDs vary depending on the type of MND being affected. In [27], it has been stated that there has been evidence from collecting the brain and cerebro-spinal fluid samples from patients with AD (Alzheimer Disease) and ALS (Amyotrophic Lateral Scelerosis) and the samples contained the presence of neurotoxin β -N-methylamino-L-alanine (L-BMAA), which are produced by cyanobacteria and algal species. It also emphasis that L-BMAA plays an important role in slow-developing neurodegenrative diseases, including ALS/Parkinsonism Dementia Complex (ALS/PDC) found on Guam islands.

Gaum islands in 1940s first reported the high incidence of neurodegenerative disease and has found linkage to the environmental exposure to amino acid β-methylamino-L-alanine (L-BMAA)[30]. The paper confirmed the presence of BMAA and its isomers in cyanobacteria in eastern Australia freshwater systems. The paper [26], also provides sufficient evidence for the incidence of ALS due to the exposure of cyanobacteria algal blooms. It provided four major pieces of evidence link BMAA exposure to ALS. The presence of similar neuropathology in the brain of vervets, by chronically feeding them BMAA for 140 days has been demonstrated in [4]. Another paper [3], also confirms the detection of number of ALS cases among the residents of Enfield, New Hampshire, which is a town surrounded by a lake with cyanobacteria algal blooms. The paper basically done an investigation on finding the link between toxic algal cyanobacterial blooms in New Hampshire and the development of ALS.

1.4 HAB detection : Motivation

2 HAB detection Approaches

2.1 Lab based testing

2.2 Remote sensing based approaches

Remote Sensing is the method of detecting and monitoring of physical characteristics of any area by the means of measuring the reflectance of the emitted radiation from a distance using satellites or aircrafts. The cameras on the satellites or aircrafts are responsible for taking images of large areas on the earth's surface. More than a decade

has passed which began the research on detection of algal blooms using remote sensing satellites.

Many types of sensors are being used to capture the images via remote sensing. Images are captured either through multi spectral sensors or hyper spectral sensors.

2.2.1 Sensors used

Multi-spectral Camera

Hyper-spectral Camera A Hyper-spectral image is made up of reflections from hundreds of different bands in the electromagnetic spectrum. In this image each object exhibits a unique reflection characteristic. Due to this similar looking objects can be separated with different characteristics. Multiple research has been carried out to find different use cases of Machine Learning Algorithms on Hyper-Spectral Images to analyze different areas of Interests. Authors in [**gewali2018machine**] and [**ozdemir2020deep**] have also created excellent surveys to find out different areas of Deep Learning applications of Hyper-spectral Images. The uses of Hyper-Spectral Imaging and ML has been carried out across various areas of interest such as Agriculture, Food Technology, Biomedical Science.

2.2.2 Ground based sensing

2.2.3 Aerial based Sensing

2.2.4 Satellite based sensing

2.3 Other VI applications (Marine / Fresh Water)

3 Machine learning Methods used in HAB

Logistic regression

Random Forest Random Forest is a popular ensemble machine learning algorithm used for both the purposes of classification and regression [real time ml] especially in situations where the datasets have high-dimensionality [Combining UAV-based]. Random Forest tries to tackle one of the fundamental problems of Decision Trees, which is overfitting. The algorithm tries to solve this issue by creating a forest, or several decision trees, by utilizing a meta-algorithm called Bootstrap Aggregation or also called BAGGing. This algorithm utilizes a subset of features and records to train each tree within the forest in parallel. Due to the implementation of bagging, random forest is robust enough to achieve high accuracy while very little feature engineering is required. Generally speaking, the more trees utilized to create the model, the more accurate the results are [real time]. To generate a prediction, the input data is fed to each tree in parallel and each tree makes its prediction based on the subset of features and records it was trained on. At the very end, a voting scheme is utilized in which the prediction with the most number of votes is the result.

Support Vector Machine (SVM)

K-Nearest Neighbour (KNN)

LSTM

Neural Networks Neural Networks (NN) is an algorithm that is based on the fundamental understanding of how the biological neural network (BNN) is structured [Integration of high]. The network consists of layered nodes, or neurons, that accept an input and produce an output based on a specified activation function. There are three main variations of layers that are utilized within NN. These are the input layer, hidden layers, and output layer. The input layer accepts data that we wish to train the model on or predict. This information is then passed to the hidden layers. To determine which subsequent neuron is fired, weights are attached to each connection. Initially, these weights are initialized randomly based on a selected distribution. During the training process, these weights are updated through a process called backpropagation. The intensity of change is scaled using the learning rate. A higher learning rate makes more dramatic changes during the adjustment process while a small learning rate has the inverse effect. Ultimately this backpropagation method tries to minimize the loss and maximize the predictive power and accuracy.

Convolutional Neural Networks (CNN) Convolutional Neural Networks (CNN) are an architecture that falls into the category of deep learning (DL) [**areaoptimized**]. The architecture was first introduced in 1979, and subsequently, backpropagation was implemented in 1989 [**areaoptimized**]. The basic building blocks for the CNN consist of convolutional layers and pooling layers which are stacked in a hierarchy structure [**areaoptimized**], [**depth**]. One of the main differences between machine learning architecture and CNN architecture utilizes fully connected layers. This implies that every node within the network is connected to all previous and subsequent nodes [**depth**]. Due to the complexity, and size, of the network, to achieve state-of-the-art results GPU training needs to be utilized.

k-Nearest Neighbor (kNN) k-Nearest Neighbor (kNN) is one of the oldest, most popular machine learning algorithm utilized today [**comparativeknn**] [**adaptiveknn**]. kNN is a special type of machine learning algorithm called unsupervised model and is often used for classification problems [**comparativeknn**]. The algorithm tries to label unlabeled data points by selecting the majority label based on k neighboring points in the training data [**adaptiveknn**]. Generally, points are considered neighbors to the data point in question based on the euclidean distance. Due to the relatively simple steps, kNN is considered to be a simple and easy algorithm to understand and implement.

3.1 HAB related ML Application categories

3.1.1 Forecasting

. Value of HAB forecasting in a region include the following

- Identifying the potential impacts by economic sector (e.g., commercial fisheries, aquaculture, recreational fisheries, seafood markets, tourism, public health, etc.).
- Measuring the economic impacts (e.g., harvest losses) of HAB events in the absence of prediction. This step involves an economic impact analysis of the status quo.
- Characterizing the prediction itself. For example, the goal of HAB prediction

is to predict the occurrence or non-occurrence of a large-scale event within a season. The value of HAB prediction depends on the accuracy or skill of the prediction.

- Examining how decisions would be made in light of a HAB prediction. This step involves identifying a range of potential responses by public and private decision-makers and evaluating their economic consequences.
- Developing an overall measure of prediction value using the model described above.

Forecasting can help in the following

- Reduced frequencies and spatial scales of unnecessary closures of recreational and commercial fisheries;
- Increases in the daily bag limit on recreational fishing ahead of toxin outbreaks;
- Reduced HAB monitoring and management costs (e.g., due to optimization in field sampling);
- Enhanced protection of public health;
- Improved business planning and investment decisions;
- Informed private recreational trip decisions;
- Reduced adjustment cost (e.g., trip cancellations and interruptions, and product recalls);
- Increased consumer confidence; and
- Possible co-benefits in ocean research, education, and training, and others.

3.1.2 Detection

3.1.3 Instance Segmentation

3.2 ML algothims, Models

HAB related ML/Data science work done in Forecasting, Detection and Segmentaiton

4 HAB Management

4.1 Current Approaches

US West Coast - Paper: [29] -These authors also found that income diversification was an effective strategy for reducing or recovering HAB-related income losses.

-the study found that individuals who suffered greater absolute income losses were employed in the fishing industry, more dependent on shellfish as a source of income, and exposed to longer fisheries closures.

https://www.epa.gov/aboutepa/epa-region-8-mountains-and-plains

4.2 Future possibilities

5 Limitation and Research Gaps

References

[1] Donald M Anderson, Patricia M Glibert, and Joann M Burkholder. "Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences". In: *Estuaries* 25.4 (2002), pp. 704–726.

[2] Lorraine C Backer and Dennis J McGillicuddy Jr. "Harmful algal blooms: at the interface between coastal oceanography and human health". In: *Oceanography (Washington, DC)* 19.2 (2006), p. 94.

[3] Tracie A Caller et al. "A cluster of amyotrophic lateral sclerosis in New Hampshire: a possible role for toxic cyanobacteria blooms". In: *Amyotrophic Lateral Sclerosis* 10.sup2 (2009), pp. 101–108.

[4] David A Davis et al. "L-serine reduces spinal cord pathology in a vervet model of preclinical ALS/MND". In: *Journal of Neuropathology & Experimental Neurology* 79.4 (2020), pp. 393–406.

[5] Margherita Ferrante et al. "Harmful Algal Blooms in the Mediterranean Sea: Effects on Human Health." In: *EuroMediterranean Biomedical Journal* 8 (2013).

[6] Lynn M Grattan, Sailor Holobaugh, and J Glenn Morris Jr. "Harmful algal blooms and public health". In: *Harmful algae* 57 (2016), pp. 2–8.

[7] Jeff C Ho and Anna M Michalak. "Exploring temperature and precipitation impacts on harmful algal blooms across continental US lakes". In: *Limnology and Oceanography* 65.5 (2020), pp. 992–1009.

[8] PADM Hoagland et al. "The economic effects of harmful algal blooms in the United States: estimates, assessment issues, and information needs". In: *Estuaries* 25.4 (2002), pp. 819–837.

[9] "http://oceandatacenter.ucsc.edu/PhytoGallery/toxigenic.html". In: (2021).

[10] "http://oceandatacenter.ucsc.edu/PhytoGallery/toxigenic.html". In: (2021).

[11] "https://ec.europa.eu/environment/integration/research/newsalert/pdf/215na5$_e$*n.pdf*". In: (2021).

[12] "https://en.wikipedia.org/wiki/Motor$_n$*euron$_d$isease*". In: (2021).

[13] "https://en.wikipedia.org/wiki/Phytoplankton". In: (2021).

[14] "https://pubs.usgs.gov/circ/c1198/chapters/123-132$_P$*hytoplankton.pdf*". In: (2021).

[15] "https://www.ninds.nih.gov/Disorders/Patient-Caregiver-Education/Fact-Sheets/Motor-Neuron-Diseases-Fact-Sheet". In: (2021).

[16] "https://www.whoi.edu/cms/files/Economics$_r$*eport*$_1$8564$_2$3050*.pdf*". In: (2021).

[17] Changchun Huang et al. "Detection of algal bloom and factors influencing its formation in Taihu Lake from 2000 to 2011 by MODIS". In: *Environmental earth sciences* 71.8 (2014), pp. 3705–3714.

[18] H Kenneth Hudnell et al. "Freshwater harmful algal bloom (FHAB) suppression with solar powered circulation (SPC)". In: *Harmful Algae* 9.2 (2010), pp. 208–217.

[19] Wassily W Leontief. "Quantitative input and output relations in the economic systems of the United States". In: *The review of economic statistics* (1936), pp. 105–125.

[20] Shang Li et al. "UV-C irradiation for harmful algal blooms control: A literature review on effectiveness, mechanisms, influencing factors and facilities". In: *Science of The Total Environment* 723 (2020), p. 137986.

[21] Stephanie K Moore et al. "Harmful algal blooms and coastal communities: Socioeconomic impacts and actions taken to cope with the 2015 US West Coast domoic acid event". In: *Harmful Algae* 96 (2020), p. 101799.

[22] Stephanie K Moore et al. "Impacts of climate variability and future climate change on harmful algal blooms and human health". In: *Environmental health*. Vol. 7. 2. Springer. 2008, pp. 1–12.

[23] Hans Paerl. "Nutrient and other environmental controls of harmful cyanobacterial blooms along the freshwater–marine continuum". In: *Cyanobacterial harmful algal blooms: State of the science and research needs*. Springer, 2008, pp. 217–237.

[24] Jungsu Park et al. "Recent advances in ultrasonic treatment: challenges and field applications for controlling harmful algal blooms (HABs)". In: *Ultrasonics sonochemistry* 38 (2017), pp. 326–334.

[25] OM Pulido. "Phycotoxins by harmful algal blooms (HABS) and human poisoning: an overview". In: *Int. Clin. Pathol. J* 2.6 (2016), pp. 145–152.

[26] Dunlop Ra et al. "Is Exposure to BMAA a Risk Factor for Neurodegenerative Diseases? A Response to a Critical Review of the BMAA Hypothesis." In: *Neurotoxicity Research* 39.1 (2021), pp. 81–106.

[27] Paola Sini et al. "Cyanobacteria, Cyanotoxins, and Neurodegenerative Diseases: Dangerous Liaisons". In: *International Journal of Molecular Sciences* 22.16 (2021), p. 8726.

[28] Nathan J Smucker et al. "Increasingly severe cyanobacterial blooms and deep water hypoxia coincide with warming water temperatures in reservoirs". In: *Global Change Biology* 27.11 (2021), pp. 2507–2519.

[29] Vera L Trainer. "GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies." In: (2020).

[30] Jake P Violi et al. "Prevalence of β-methylamino-L-alanine (BMAA) and its isomers in freshwater cyanobacteria isolated from eastern Australia". In: *Ecotoxicology and environmental safety* 172 (2019), pp. 72–81.

[31] Chao Wang et al. "Multiple effects of environmental factors on algal growth and nutrient thresholds for harmful algal blooms: application of response surface methodology". In: *Environmental Modeling & Assessment* 21.2 (2016), pp. 247–259.

[32] Chelsea A Weirich and Todd R Miller. "Freshwater harmful algal blooms: toxins and children's health". In: *Current problems in pediatric and adolescent health care* 44.1 (2014), pp. 2–24.

[33] Nick Young et al. "Marine harmful algal blooms and human health: A systematic scoping review". In: *Harmful algae* 98 (2020), p. 101901.