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REVIEW ARTICLE

Harmful Algal Blooms (HABs) Management in Tropical Marine Food Production Areas Amidst Climate Change

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ABSTRACT

Fundamental to coastal communities is the utilization of the marine environment for food and livelihood. In tropical areas, food production depends on the harvest and/or culture of organisms on the coasts, which now have multiple uses and receive anthropogenic inputs from both the land and sea. Harmful Algal Blooms (HABs) have been recorded in many of these production sites, with observed health, socio-economic, and some environmental effects for various known or yet-to-be-understood reasons. A critical review of the management schemes/approaches of HAB events in tropical food production areas is presented, focusing on the Philippines, where HABs and their impacts have been recorded for over thirty (30) years. The affected areas are sometimes declared “disaster areas” so authorities can heighten mitigation and relief efforts. Some HAB management schemes and methods are briefly described to serve as models for reviewing and enhancing the current HAB management scheme. Although the impacts of climate change on HABs have not been substantially well-studied, it is prudent to have future-ready management of food production that considers this phenomenon as a significant factor, particularly in areas with long coastlines.

This contribution helps to achieve SDGs 1 (no poverty), 2 (zero hunger), 11 (sustainable cities and communities), 13 (climate action), and, especially, SDG 14 (life below water).

Keywords: Climate change, Harmful Algal blooms, Prevention, Control, Mitigation, Risk Management, Mariculture

Abbreviations: ASEAN, Association of Southeast Asian Nations; BFAR, Bureau of Aquatic Resources; COBSEA, Coordinating Body on the Seas of East Asia; DOH, Department of Health; DOST, Department of Science and Technology; GEOHAB, Global Ecology and Oceanography of Harmful Algae; GlobalHAB, Global Harmful Algal Bloom, HAB, Harmful Algal Bloom; IAEA, International Atomic Energy Agency; IMTA, Intergrated Multitrophic Aquaculture; IOC, Intergovernmental Oceanographic Commission; IPCC, Intergovernmental Panel on Climate Change; IPHAB, Inter-governmental Panel on Harmful Algal Blooms; ISSHA, International Society on the Study of Harmful Algae; NAST PHL, National Academy of Science and Technology Philippines; PICES, North Pacific Marine Science Organization; PCAARRD, Philippine Coucil for Agriculture, Aquatic, and Natural Resources Research and Development; PCM, Prevention, Control, and Mitigation; PSP, Paralytic Shellfish Poisoning; PST, Paralytic Shellfish Toxin; SCS SAP, Strategic Action Program for South China Sea and the Gulf of Thailand; SCOR, Scientific Committee on Ocean Research; SROCC, Special Report on the Ocean and Cryosphere in a Changing Climate; UNEP, United Nations Environmental Programme; UNESCO, United Nations Educational Scientific and Cultural Organization; UNOPS, United Nations Office for Project Services; WESTPACHAB, Sub-commission for the Western Pacific – Harmful Algal Bloom Programme

1. Introduction

The extent to which climate change affects Harmful Algal Blooms (HABs) is not sharply defined, but there has been a multitude of research on this topic in the past few decades (Gobler 2020). The 2019 United Nations' Intergovernmental Panel on Climate Change's (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) is the first IPCC report to directly link HABs to climate change. The report (Pörtner et al. 2019) highlighted the following: a) HABs display range expansion and increased frequency in coastal areas since the 1980s in response to both climatic and non-climatic drivers such as increased riverine nutrient runoff; b) Observed trends in harmful algal blooms are attributed partly to the effects of ocean warming, marine heatwaves, oxygen loss, eutrophication, and pollution; and c) HABs have had negative impacts on food security, tourism, the local economy, and human health. Well-documented global trends in HABs have been shown to be promoted by human activity; however, individual events are driven by local, regional, and global drivers, making it difficult to critically assess ecosystem conditions and responses at various scales.

It is within this frame of reference that the first Special Issue on Climate Change and Harmful Algal Blooms was published (Gobler 2020). Through ocean warming, climate change has received the most significant attention in HAB research in mid- and higher latitudes (Moore et al. 2008; Anderson et al. 2012; Glibert et al. 2014). In general, there is an outlook/scenario that increasing sea temperature could lead to possible events wherein HABs migrate poleward with progressive warming, a hypothesis affirmed by several earlier studies (Gobler 2020; Hallegraef 2010). HABs migrating to new ecosystems can pose significant risks to aquatic ecosystems and human communities. In addition to how HABs respond to climate change, scientists, managers, and the public are concerned with HABs because of the harm they can cause within the new coastal zones. Climate change may intensify certain HABs in terms of frequency and intensity in some, but not all, coastal ecosystems (IPCC 2019; Pörtner et al. 2019; Ho and Michalak 2019). However, there is a need for more data and studies to understand the nature of this threat despite the apparent certainty of the co-occurrence of HABs and climate change stressors such as increasing temperatures. Hallegraef et al. (2021) have attributed the perceived global increase in HABs and algal blooms to intensified monitoring and emerging bloom impacts. Azanza et al. (2024) presented some discussions on the apparent impacts of “anomalous“ El Niño-La Niña strong typhoons and unusually heavy rainfall on HAB occurrence in the Philippines and Malaysia.

The earliest comprehensive publication on HAB management is that of Shirota (1989), whose concept of Prevention, Control, and Mitigation (PCM) in HAB management was further used by a number of countries (Anderson, 2014). The United Nations Educational Scientific and Cultural Organization (UNESCO) Inter-governmental Panel on Harmful Algal Blooms (IPHAB, https://hab.ioc-unesco.org/) and the International Society on the Study of Harmful Algae (ISSHA, http://www.issha.org/) are the principal organizations that

Transactions NAST PHL Vol. 46: (2024)
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have dedicated activities to understand HABs in order to come up with management measures using science, technology, and innovation. Programs such as the Global Ecology and Oceanography of Harmful Algae (GEOHAB), the Global HABs of the IPHAB, and the UNESCO Scientific Committee on Ocean Research (SCOR, https://scor-int.org/cb-org/unesco/) have several publications on these issues and concerns. The SCOR and IOC/UNESCO Global Harmful Algal Blooms (GlobalHAB) Program is an international scientific program on HABs "aimed at fostering and promoting cooperative research directed toward improving the understanding and prediction of HAB events and providing scientific knowledge to manage and mitigate their impacts against the background of global changes in climate and increased anthropogenic pressures on aquatic ecosystems." Climate change is one of the major topics being investigated and supported by GlobalHAB.

A review of the available literature shows that climate change impacts are not explicitly factored into the enhancement of national HAB management schemes and systems. However, climate change has been invoked as an essential concern but not fully considered in the "business as usual management scheme/tools." Depending on scientific and technical resources (personnel, infrastructure, and funding), different countries have varying HAB management capabilities. Very related to the number of publications and dedicated services, including maintenance of websites, the following countries have advanced HAB management: Japan, USA, Australia, Canada, China, Denmark, Spain, and France (Anderson et al. 2001; Hall et al. 2001). The aforementioned list is without prejudice to the many other countries that have also made advances in their HAB management support systems.

The main objective of this paper is to review and suggest improvements on how HABs can be managed in seafood systems, particularly in areas where food sustainability is critical, e.g., in Southeast Asia, where there have been historical HAB impacts. It is not the intention of this paper to review the recorded impacts of climate change-related HABs on humans and nature (food production sites) since this topic is tackled in the aforementioned publications and several others, the most recent of which is by Tewari (2022).

2. HAB Management Schemes: Prevention, Control, and Mitigation (PCM)

2.1 Can HABs be Prevented?

Preventive actions are those taken to avert HABs from occurring or directly impacting a particular resource or environment. HABs, like other ocean and coastal phenomena, are complex, and only some of the available knowledge needed are only those that would enable managers to prevent them from happening. Substantial and sustained research on all aspects of HABs, particularly their ecology, physiology, and oceanography, is much needed, remembering the common scientific belief in the management of HABs that it should be "species-specific and site-specific" (Azanza 2013) and seriously considering the impacts of climate change on the affected environment. Managers and government officers generally think fundamental or basic science issues have little practical use in HAB management.

Challenges in preventing HABs arise because, even though we may understand the environmental factors affecting the population dynamics of a specific HAB organism, there are significant limitations and complexities in effectively modifying or controlling these factors. One example is the correspondence of an increased number of milkfish cages and pens in the mariculture site in Bolinao, Pangasinan, and the increased frequency of HABs and fish kill events (San Diego-McGlone et al. 2008; Escobar et al. 2013). Enrichment of the culture sites with fish feeds and their fecal materials caused high eutrophication during the hot summer. This led the local government to implement preventive and control measures, such as reducing the number of fish culture cages and pens. HABs causing fish kills apparently decreased in number and intensity but nevertheless persisted, particularly, during the hot season. It should be pointed out that in addition to mariculture, another important source of nutrients to coastal waters is agricultural production that contributes HAB-stimulating nutrients to its coast. Decision-makers in Bolinao are, therefore, faced with possible point and non-point sources of nutrients.

Transactions NAST PHL Vol. 46: (2024)
doi.org/10.57043/transnastphl.2024.5323

2.2 Can HABs be Controlled?

Control of HABs or their management through suppressing or destroying the bloom is challenging and questionable, as these processes interfere with bloom development, particularly in the later stages. Anderson (2014) noted the lack of research on bloom control, contrasting with efforts to control nuisance species in terrestrial agriculture. He listed the following reasons for this reticence or reluctance to explore control strategies and impacts: 1) HAB phenomena remain poorly understood – "We can't control what we don't understand"; 2) Scientific uncertainty is always present; the challenge is determining when sufficient knowledge exists to support the formulation and evaluation of treatment strategies; 3) Solutions may be worse than the HAB problem, or their impacts could be acceptable on a smaller scale to stop or prevent bloom impacts that are more widespread and long-lasting, an approach taken in agricultural pest control where there have been recorded successes.

Anderson (2014) also encouraged targeted research on HAB control, starting from the laboratory to the mesoscale before proceeding to large-scale blooms, best conducted under a HAB PCM program that supports HAB ecology and oceanography research. A recent review of strategies and methods for controlling HABs is that of Imai et al. (2021).

Clay flocculation, which uses both chemical and physical techniques to remove or control certain HABs, has been employed with success in Korean waters threatened by red tides of *Cochlodinium polykrikoides* (Choi et al. 2014; Park et al. 2013). Laboratory experiments on clay used in the immediate vicinity or coastal area where HABs often occur have been done in the Philippines (Manset et al. 2013; Orizar et al. 2013, Padilla et al. 2010) but have not yet been used as a control measure, as more studies are needed. Clay flocculation aims for target cells (which are in bloom) to be physically removed from the water with minimal environmental impacts, usually using naturally present clay and relying on clay/cell flocs settling to bottom sediments.

Other direct control mechanisms, like the removal of HAB cells through filtration or biological control (using other plankton species, parasites, viruses, or bacteria) (Manset et al. 2013; Hansen et al. 2004), have not progressed from laboratory experiments to larger-scale application. Unlike in terrestrial habitats, where these control tools can be feasible, there is considerable opposition to introducing non-indigenous or indigenous strains on a larger scale, as they could pose unknown and potentially irreversible risks.

Chemical control, which some might use to mitigate the immediate results of an ongoing HAB, involves toxic chemical release. This was attempted in 1957 against the Florida red tide organism, now called *Karenia brevis*, using copper sulfate spread over the bloom area with dusting airplanes (Anderson et al. 2012). Although the treatment appeared successful in destroying large patches of red tide bloom, it was not considered successful as the red tide bloom reappeared weeks later, after transporting offshore populations to the treated sites. There were probable but unmeasured collateral mortality/effects on co-occurring organisms during the treatment due to the broad lethality of copper. This seems to be the single reported attempt to control HABs chemically.

Genetic approaches used successfully in terrestrial agriculture, such as engineering crops capable of producing their own insecticides or herbicides, have yet to be applied to marine pests like HABs. It could be possible to engineer a HAB species to no longer produce toxins or make a particular bacterial strain more pathogenic, with more specific activity against certain HAB cells. A future decision on this type of research and testing needs government and stakeholder support.

Environmental manipulation involves physical or chemical modifications of the environment to affect the growth of target species and/or enhance that of a natural or introduced biocontrol. This could involve large-scale manipulation of nutrient levels in coastal waters through pollution or other control policies and will likely take years, even decades, to yield the expected results and impacts. Efforts could include altering water circulation or residence time, like dredging or opening channels.

Similar attention should be given to steps taken if a particularly toxic or dangerous algal species is detected in bloom near a major aquaculture center for the first time. Quick action to destroy most of the blooming organisms might prevent immediate and potential impacts in future years if that species is not allowed to colonize the area, such as with cysts.

Transactions NAST PHL Vol. 46: (2024)
doi.org/10.57043/transnastphl.2024.5323

2.3 Mitigation of the Impacts of HABs: The Most Common Management Option

Mitigating schemes in the context of HABs, particularly in cases of manageable recurrent blooms of toxic or harmful species, include harvesting produce and implementing quarantines for shellfish before the blooms start or become significant. This requires close monitoring of environmental conditions that favor the initiation, development, and termination of blooms. Forecasting and modeling tools, among others, are essential for the success of this mitigating option. The subsequent sections focus primarily on mitigating methods and systems for HAB management.

A very recent review examined regional HAB observing programs in the United States of America, the European Union, and Asia (FAO-IOC-IAEA, 2023). It concluded that there is no global "one-size-fits-all" approach and that regional responses and solutions can be achieved through integrated and coordinated advances in the scientific understanding of HABs (Anderson et al. 2012). The review authors provided the following recommendations to advance an integrative global ocean observing system optimized for HABs, building on the Global Ocean Observing System:

- "Deliver systems that are fit for the purpose, with cost-effective and sustainable HAB forecasts that meet the HAB-risk warning requirements of end-users. Use (preferably automated) near real-time information to provide advanced HAB warnings and share knowledge of best practices across regions.
- Adopt a systems approach for sustained global ocean observation incorporating earth observations/models with ecological knowledge/models. This approach will advance seasonal to decadal forecasts, allowing governments to plan and adapt to a changing marine environment while supporting and sustaining coastal industries.
- Develop interfaces that mutually benefit different sectors and address critical stakeholder needs, recognizing different priorities for regulators, industry, science, and society. Provide complementary and accessible data sets.
- Promote the transformation of data into information that serves both scientific and societal needs. This includes robust communication among stakeholders, partners, and policymakers, and leveraging regional HAB observing systems to support technology comparisons" (FAO-IOC-IAEA, 2023)".

3. HAB Management in Marine Food Production Sites in Southeast Asia: A focus on the Philippines

Since updated HAB management schemes of other Southeast Asian countries have not been available or published, the Philippine HAB management scheme will be discussed. Furio et al. (2012), Furuya et al. (2017), and Yñiguez et al. (2021) have updates on the regional occurrences of harmful algae or toxins and the potential of a HAB event that allows authorities, industries, or individuals to take actions to minimize HAB impacts.

The Philippines and Malaysia have the most reports on HABs (https://haedat.iode.org/) compared to other Southeast Asian countries and have several publications on HAB management. In a recent paper (Yñiguez et al. 2021), long-term data sets were used to report increasing HAB frequency and duration in the Philippines and Malaysia. The blooms of Paralytic Shellfish Toxin (PST)-producing species in the Philippines did increase in frequency and duration during the early to mid-1990s but have stabilized in some areas since then. The number of sites affected by these blooms continues to expand but slower than in the 1990s. Furthermore, the type of HABs and causative species have diversified for both toxic blooms and fish kill events (Yniguez et al. 2021; Azanza et al. 2024). Malaysia showed no increasing trend in the frequency of toxic blooms over the past three decades since *Pyrodinium bahamense* was reported in 1976. Similar to the Philippines, other PSP causative species, such as *Alexandrium minutum* and *Alexandrium tamiyavanichii* have become a concern in Southeast Asia, though no significant expansion within the last decade has been reported. The new sites affected and the increase in types of HABs/causative species could be attributed to various factors, such as introduction via mariculture and eutrophication, and partly to increased monitoring/research and awareness. Although the increase in *Pyrodinium* blooms seems to coincide with abnormalities of the El Niño Southern Oscillation (ENSO) as first observed by Azanza and Taylor (2001), this link should be better understood to determine how climate change plays a role in HAB occurrence.

Nutrient input management and implementing sustainable aquaculture/mariculture practices are important aspects of controlling HAB occurrences in coastal communities. Aside from the contribution of nutrients from land-based sources, mariculture produces nutrient waste primarily through the excretions of cultivated organisms and the direct addition or decomposition of external feed inputs (Bouwman et al. 2013). The predicted increase in annual maximum daily precipitation in the Philippines and more prominent heavy rainfall in the northwestern and midwestern parts and the coastal areas in the east (Hong et al. 2022) can result in increased nutrient run-off to coastal areas. Managing the watershed and improving agricultural activities and waste-management practices will be crucial to the holistic approach to HAB control. Furthermore, improving the current aquaculture/ mariculture practices should be further explored to make them more sustainable and reduce their impact on the nutrient loadings in the aquatic ecosystems. The ongoing UNEP-UNOPS project "Implementing the Strategic Action Programme for the South China Sea and the Gulf of Thailand" (SCS sAP Project) "aims to estimate effluent quantities and pollutant loadings from coastal aquaculture in the SCS marine area, and share best waste water management practices among UNEP-COBSEA member nations that include the Philippines" (https://scssap.org). One approach tested in Italy was the Integrated Multitrophic Aquaculture (IMTA), wherein a polyculture of several bioremediating organisms (e.g., mussels, tubeworms, sponges, and seaweeds) were combined with coastal fish farms which resulted in improving water (e.g., nitrogen and total coliform) and sediment quality (e.g., total coliform and zoobenthic quality indices) (Stabili et al. 2023). This approach requires understanding of the relationships and trophic interactions in the HAB-prone areas. The polyculture composition should be carefully formulated in order not to cause any more environmental issues in the HAB-prone area where the fish farming/mariculture activities are occurring.

During the late 1980s, red tide/HAB was observed to be expanding in the Philippines when red tide/HAB monitoring and information campaign programs started in the country. The management of HABs has undergone some changes from the 1980s to the present. From an interagency "Red Tide Committee," co-headed by the Director of the Bureau of Fisheries and Aquatic Resources (BFAR) and the Secretary of the Department of Health (DOH), the processes have been streamlined. At present, BFAR, assisted by Local Government Units (LGUs), leads the "Red Tide/HAB" monitoring and management. The regular monitoring reports, previously called "Red Tide Bulletins," are now under the heading "Shellfish Bulletins," which are signed by the BFAR director and made available on the BFAR Shellfish Bulletin Website (https://www.bfar.da.gov.ph/shellfish-bulletin-no-02-2022/). The bulletins report on the occurrences of Paralytic Shellfish Poisoning (PSP) toxicity (toxic values and cases not provided). Many HAB monitoring areas (about 50, mostly in sites where recurrence has been noted) are sampled at least once a month, with sampling frequency increasing when blooms happen. In several cases, areas economically affected by HABs declare a "state of calamity" to receive government financial subsidies. Depuration as a mitigating measure to reduce economic loss for HAB-affected shellfish, has not been practiced in commercially cultured and fresh harvest, although laboratory experiments have shown that this is feasible (Andres et al. 2019) as done in other countries.

Collaboration with universities and colleges in affected areas has been undertaken to facilitate data gathering and analysis. A HABs watch led by the Marine Science Institute, University of the Philippines, has been implemented recently to include more relevant environmental parameters, such as marine litter, which could serve as a vector for HAB transfer (Onda et al. 2020). Likewise, modeling of HABs, particularly those caused by *Pyrodinium*, which was started during the PhilHABs (part of the GEOHAB program of UNESCO IOC SCOR-HAB), facilitated the beginning of some form of forecasting in areas like Manila Bay and Sorsogon Bay (Villanoy et al. 2006; Azanza 2013; Yñiguez et al. 2018). Dinoflagellate cyst mapping and life cycle studies have also been conducted to understand and manage recurring HABs in highly affected areas (Azanza et al. 2004; Sombrito et al. 2004; Azanza et al. 2019). Modeling of HABs in specific areas like Manila Bay has been initiated by an interdisciplinary or multidisciplinary group of researchers to further understand the bloom dynamics of the causative species (Villanoy et al. 2006; Yñiguez et al. 2018).

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The need for forecasting, risk assessment, and early warning tools that could significantly enhance HAB management in the Philippines are being addressed more intensely by universities with the support of government agencies like the Department of Science and Technology, BFAR, Department of Interior and Local Government, and the Philippine Space Agency. Control methods have been tried in the laboratory but have yet to be applied in the field since further studies are needed (Padilla et al. 2010; Orizar et al. 2013; Manset et al. 2013; Hansen et al. 2004).

4. Some Other HAB Management Schemes as Models

4.1 The Scottish model

An online early warning system operational in Scottish coastal waters has been developed to minimize the risk to humans and aquaculture from the human health and economic impacts of HABs and their associated biotoxins, as published by Davidson et al. (2021). This system consists of a map and time-series-based visualization tools and utilizes a "traffic light" index approach to highlight elevated HAB/biotoxin risk locations. High-resolution mathematical models of cell advection and satellite remote sensing provide early warning of HABs moving from offshore waters to the coast. Expert analyses of HAB, biotoxin, and environmental data, considering recent and historical trends, are utilized to deliver a weekly forecast of the risk from HABs and their biotoxins. This scheme allows for the implementation of mitigation measures by HAB managers and aquaculture businesses in anticipation of a HAB event.

4.2 HAB Monitoring and Management in Japan

The presence and status of HABs in Japan have been reviewed by Imai et al. (2021), revealing a decrease in red tides, although toxic blooms are found to be increasing in western Japan. Environmentally friendly control strategies against HABs are also compared with integrated agricultural pest management. For instance, very high densities (105 –108 CFU/g) of algicidal and growth-inhibiting bacteria found in biofilm on seagrass and seaweed surfaces and in surrounding coastal seawater could be used to manage certain HABs. The situation in freshwater ecosystems is similar to that of coastal seas in terms of the toxic cyanobacterium, *Microcystis aeruginosa*, and aquatic plants. Recent findings offer new insights into the ecology of influential bacteria and harmful algae, suggesting that protection and restoration of native seagrasses and seaweeds in coastal marine environments should be implemented to suppress HABs. Diatom blooms were successfully induced with bottom sediment perturbation to prevent the occurrence of harmful flagellates such as *Chattonella* spp. and *Alexandrium catenella* in the Seto Inland Sea. However, the authors believe that robust and reproducible verification should be conducted. “Sato-Umi,” a Japanese concept for a total approach to ecosystem health, is helpful for HAB control in sea and freshwater ecosystems when adequately managed by people.

4.3 HAB Management in China

Phytoplankton monitoring, as in many countries, has been used as an early warning of HABs in China. HABs were traditionally seen and monitored by in-situ observations, including those from ships. The Chinese National Marine Environmental Monitoring Center database is used to develop the HAB risk index, based on the causative species' density of HABs or chlorophyll-a (Chla) concentration. Hydrological, biochemical, and meteorological factors are also utilized, including temperature, salinity, pH, and dissolved oxygen (DO). Remote sensing tools are employed in monitoring and studying HABs in Chinese seas (Guan et al. 2022). Localized algorithms have been developed to extract bloom information in the past using data from satellites and aircraft, for example, HAB algal size, microalgal bloom, and floating macroalgal bloom (the dinoflagellate *Prorocentrum donghaiense* and the green macroalga *Ulva prolifera*).

Modeling and near-term or seasonal forecasting of HAB events are prepared based on a statistical analysis of historical HAB events. Key factors are extracted and used to forecast future HAB events. Artificial intelligence, an emerging method, has now been applied. However, based on their current work, the best approach is to use data from statistical analysis to feed into an artificial neural network. Red tide forecasting using log datasets of previous events and the projection of long-term HAB events of various types in many areas in China is now being undertaken (Guan et al. 2022).

Transactions NAST PHL Vol. 46: (2024)
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4.4 HAB risk communication in Canada

Variations in the policies for monitoring HABs and communicating risks across different jurisdictions in Canada have been published (Rashidi et al. 2021), emphasizing the creation of a coherent system with consistent messaging and inter-agency communication to reduce risks. Citing the case of Ontario, the design and implementation of an integrated communication system for HABs at the provincial or local level, with close collaboration among all stakeholders, facilitates risk reduction. Modifying federal guidelines and protocols to meet the specific needs of each province or locality, mandating regular and consistent monitoring of all popular recreational sites, and regularly using an accessible and interactive HABs database across Canada are considered of primary importance. This is especially valuable for provinces with transboundary waterways, such as Manitoba and Ontario, Alberta and British Columbia. Researchers must identify HAB trends, and the program should engage meaningfully with indigenous community members and other relevant provincial and federal stakeholders. The goal is to effectively monitor and communicate HABs across all stakeholders, and to use innovations involving citizen science, emphasizing that "the realities of climate change indicate that it would be prudent to start on that path."

Countrywide, the most common approach for raising awareness of risks involves local on-site signage, which is used with varying success, and web-based communications, which are seen as the preferred method by agencies for reporting and public information access. Rashidi et al. (2021) suggest that future studies on "new risk communication technologies consider innovative and interactive apps, which will also be worthwhile to address HABs in Canada."

5. Synthesis and Ways Forward

The coasts and oceans constitute a significant part of the environment that humanity can harness for continued and sustainable existence. The utilization of these environments has become complex and sometimes conflicting. In many countries, these areas are primarily for survival and livelihood, as in Southeast Asia/Philippines, where fisheries and mariculture have significantly influenced the socio-economic conditions of coastal communities. Globally, changing nutrient inputs from the coasts/watersheds due to various human activities could greatly influence present and future coastal and marine ecosystems (Glibert et al. 2014; Glibert and Burford 2017). Regardless of whether the increase in the number of HABs in these production sites can be attributed more to increased awareness/ studies on HABs, the fact remains that these HABs have recorded escalating impacts on the coastal environment and people. Therefore, HAB management should be given enhanced and dedicated attention.

Future HABs will occur in an anthropogenically altered ocean; therefore, future occurrences and impacts will differ from what we know today. This is particularly true as climate change can have pronounced repercussions on both HAB organisms and those dwelling in the affected or potentially affected areas. It is quite encouraging that interest and efforts in HAB research and management have continued, with international networking (IOC IPHAB, IOC WESTPACHAB, ISSHA, etc.) greatly assisting students, researchers, managers, governments, and public and private organizations.

Several international workshops and conferences have considered not only HAB preventive and mitigating schemes of management but also those addressing solutions to control HABs, like the recent "International Workshop on Solutions to Control HABs in Marine and Estuarine Waters" held on October 21 and 22, 2023 (GlobalHAB/PICES Workshop). The workshop focused on HAB control methods, either by killing or removing cells and/or toxins from the water. Methods that have been field-tested and some advanced laboratory methods with strong evidence that they could be suitable for field use were highlighted. Discussions included effectiveness for use in marine systems, cost, scalability, regulatory hurdles, and approaches for communicating with the public and stakeholders.

Climate change impacts, interactions, or intensification effects on HABs have not been dealt with exhaustively. An approach to understanding HAB responses to climate change is described by Ralston and Moore (2020), who explore and compare the relative strengths and weaknesses of statistical and process-based models. They emphasize that approaches to improve modeling of HAB responses to climate change should include the use of ensemble approaches, scenario planning, and understanding the downstream effect on coastal communities. An ideal HAB management scheme

Transactions NAST PHL Vol. 46: (2024)
doi.org/10.57043/transnastphl.2024.5323

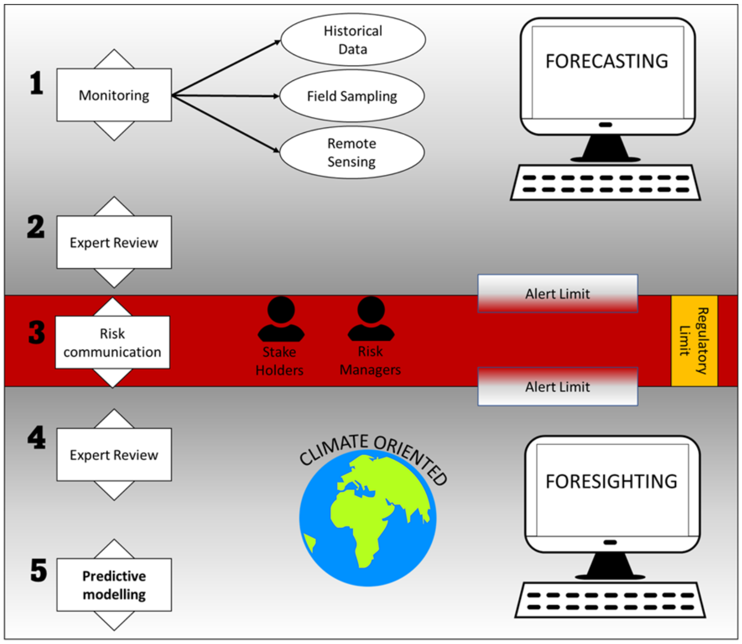

Figure 1. An ideal management strategy for HAB-affected food production sites in the face of climate change.

(Figure 1) could be developed for the Philippines, where stakeholders are involved in risk assessment and mitigation/response, and expert analyses can enhance the processes before, during, and after the blooms.

The substantial effects of climate-driven changes on coastal ecosystems, including the intensification of HABs, are becoming increasingly clear. Advances in understanding and predicting HABs in a changing world will be needed to formulate plans that minimize their impacts on coastal ecosystems, animals, and human communities.

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All authors made intellectual contribution to various parts of the paper; RV Azanza wrote the outline, and first draft of the paper; GS Jacinto, PP Rivera, LT David, V Vargas-Nguyen and IS Orizar revised/edited the text critically and provided figure (s) or additional information. All authors read and approved the final manuscript.

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