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An Overview on the Occurrences of Harmful Algal Blooms (HABs) and Mitigation Strategies in Korean Coastal Waters

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Abstract—Recent wide spread and persistent harmful algal blooms (HABs) give severe impacts on public health and fisheries economics along all coasts of Korea. As the HABs have become more widespread and caused increasing fisheries damage, Korea established an integrated monitoring system included oceanographic, environmental, and red tides observations. Both oceanographic and environmental data and remotely sensed information are available for HABs prediction. Hierarchical HABs monitoring whose observation time is based on the frequency of HABs occurrence for the last five years has been run to take appropriate response actions according to the HABs magnitude since 1996.

Korea has been employed a variety of mitigation strategies directly or indirectly to affect the size of a HAB population or its impacts. They can be classified into two categories: precautionary impact preventions, and bloom controls. To give precautionary attention to fishermen and aquaculturists, Korea has been operating an alert system. It consists of several alerts such as 'Red Tide Attention', 'Red Tide Alert' and 'Warning Lift'. As one of direct HABs controls, Korea has dispersed yellow clay on coastal aquaculture farms to remove fish killing *C. polykrikoides* blooms since 1996. The clay can flocculate the dinoflagellate cells and causes them to sink to the bottom of the water body. This can dilute the cell density of dinoflagellates in the cages thereby not killing the accommodating fish. It has so far proven not to induce significant negative impacts on water quality or benthic organisms. In addition to clay dispersal, Korea is studying other possible mitigative substances and techniques such as biological and physical controls.

Korea has joined the regional and international meeting, and continues to exchange data and information with neighboring countries such as Japan, China, South East Asian countries, and Russia through NOWPAP, PICES, APEC, and EASTHAB meetings.

Keywords: HABs monitoring, *Cochlodinium polykrikoides*, mitigation, direct control, clay dispersal, precautionary prevention

1. INTRODUCTION

Historical records of red tides are easily found as seawater discoloration in the historical documentation in Korea. The term red tides indicate all kinds of blooms that discolor water even if they cause no harm. In Korea, these events have commonly been called red tides until the 1970s. However, most scientists recently prefer the term "harmful algal blooms (HABs)", instead. Low-density blooms of toxic dinoflagellates that cause shellfish poisoning were excluded from the term red tides until the 1970s. The term HABs includes those blooms in which toxic microscopic organisms cause food poisoning syndrome at low cell density without water discoloration.

HABs cause fish kill mainly in summer, and occasional shellfish poisoning in late spring in the southern part of the South Sea of Korea. *Karenia mikimotoi* bloom caused severe damages to fisheries in 1981 for the first time in Korea, and the dominant HAB species then changed to *Cochlodinium polykrikoides* after 1995 in Korean waters. As the HABs have become more widespread and caused increasing fisheries damage, Korea established a more comprehensive and independent monitoring system. The Korean monitoring system now stands as an independent national ocean monitoring project. Active investigations of the mitigation of HABs have also been initiated since 1996 due to consecutive outbreaks of fish-killing *C. polykrikoides* blooms. Since 1996 the central and local governments have dispersed yellow clay into the water in order to remove the *C. polykrikoides* cells through flocculation. The yellow clay can help minimize the damage to fisheries and has so far proven not to induce significant negative impacts on water quality or benthic organisms. In addition to clay dispersal, Korea is studying other possible mitigative substances and techniques such as biological and physical controls to minimize economic loss from HABs.

2. RECENT PROGRESS ON THE MONITORING AND DEVELOPMENTS OF HABS

2.1. Monitoring and prediction system

Korea has carried out regular coastal and offshore water monitoring to understand the variation of oceanographic, environmental, and ecological changes in marine ecosystems. The oceanographic observation was initiated in 1921, and has compiled 88 years of oceanographic data up to 2009. It is therefore possible to clarify the relationship between the outbreaks of HABs and the increase in water temperature for the last nine decades. The coastal environmental and the HABs monitoring were carried out to secure the safety of marine food since the 1970s. The frequency and intensity of this monitoring was strengthened due to the rise in public concern about coastal eutrophication and HABs.

1) Oceanographic observations and monitoring

Oceanographic observations in Korean coastal waters have been carried out by the National Fisheries Research and Development Institute (NFRDI) since 1921. It covers all Korean coastal waters including adjacent ; the total surface area is estimated to be approximately 450,000 km^2. Annually, six parameters of regular oceanographic observations have been conducted at about 300 regular stations established parallel to the longitude. Temperature and salinity were daily measured at 33 stations established along the coast. State-of-the-art technology such as ocean remote sensing and satellite tracking drift buoys are also used, with sea surface temperature (SST) from NOAA and chlorophyll contents from SeaWiFS on service for the public. Recent moderate satellite images from Moderate Resolution Imaging

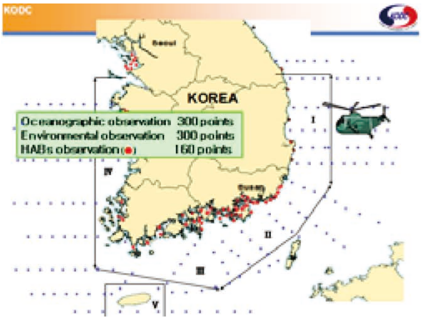

Fig.1. Locations of national oceanographic observation and environmental monitoring (left). A research vessel, *Tamgu-1*, of National Fisheries Research and Development Institute (right).

Spectro-radiometer (MODIS), Korean Arirang Satellite, and Indian Research Satellite (IRS) can provide valuable real time data and information essential to clarify the outbreaks of HABs.. The Korea Ocean Data Center (KODC) disseminates all data at real time on-line using the internet and an automated telephone response system.

2) National Marine Environmental Monitoring

Since 1972, regular coastal monitoring has been conducted by the NFRDI to assess coastal water quality and its impact on marine flora and fauna. Under this project, a suite of biological and chemical parameters are being monitored. Monitoring has been carried out on four occasions from February to November to clarify the seasonal changes in the coastal and offshore waters. This has provided metadata essential to build coastal environmental protection policy for the sustainable development, minimization of environmental impacts, and fisheries damage due to environmental constraints such as persistent organic pollutants (POPs), HABs, shellfish poisoning and summer anoxia. Now high quality assurances and quality controls for all data are being done for the regional and international cooperation.

3) Monitoring for Harmful Algal Blooms (HABs)

Hierarchical HABs monitoring

To take appropriate actions to protect the aquacultural fish from fish-killing dinoflagellates blooms, Korea is running a well-designed monitoring system in place since 1995. Now it runs biweekly or monthly at regular stations from March to November by NFRDI and local authorities. When fish-killing HABs occur, the monitoring system takes daily observation during the subsequent development of the HAB in the affected area and neighboring waters susceptible to being affected. Since 1996, another local monitoring team patrols along the coast every day to find the red tides between May and October. The main targeted phytoplankton species are *C. polykrikoides*, *K. mikimotoi* and *Gyrodinium* sp. nov. This monitoring has been based on the mechanisms illustrated for the initiation and subsequent development of *C. polykrikoides* blooms (Kim et al., 1999).

Table 1. Water quality parameters measured for marine environmental monitoring by NFRDI.

Body	Parameters	Parameters measured
Water	General	Temperature, Salinity, pH, DO, COD, Nitrite, Nitrate, Ammonium, Phosphate, Oily substances, SS, transparency, *E. coli*
	Trace metals	Cu, Pb, Zn, Cd, Cr^{+6}, Hg, As, CN
	POPs	PCBs, TBT, Dioxin
Living organisms	Productivity	Chlorophyll
	Trace metals	Cu, Pb, Zn, Cd, Cr+6, Hg, As
	POPs	POPs, TBT
Sediments	General	Sieving, Ignition-loss, Total-sulphide, COD
	Trace metals	Cu, Pb, Zn, Cd, Cr+6, Hg, As
	POPs	PCBs, TBT, PAHs, Organic-chlorine

POPs: Persistent organic pollutant; TBT: Tributyl-tin; PCBs: Polychloro-biphenyls; PAHs: Poly aromatic hydrocarbons

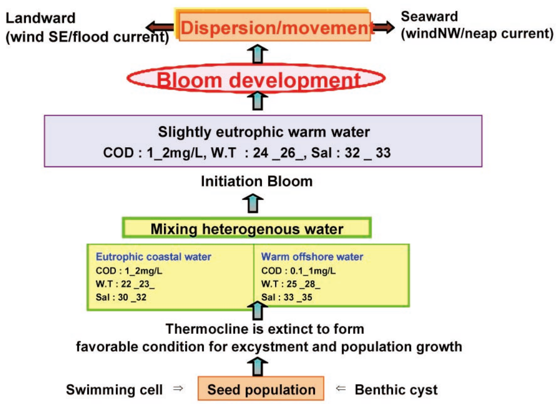

Fig. 2. Schematic diagram illustrating the initiation and subsequent development of harmful algal blooms in the South Sea of Korea. (NFRDI 2002; Kim et al., 1999).

Most of the red tide information is distributed immediately to aquaculturists, fishermen and municipal administrative authorities by facsimile telegraph, an internet website (http://www. nfrdi.re.kr) and an automated telephone response system that began to operate on 6 May 1996.

Red tide alert system and alarm facilities

To give precautionary attention to fishermen and aquaculturists, Korea has been operating an alert system. It consists of several alerts such as 'Red Tide Attention',

Table 2. The phytoplankton Genera responsible for the HABs in Korean waters (Kim, 2005).

Class (classis)	Order (ordo)	Red tide Organisms (Genus)
Cyanophyceae	*Chroococcales*	*Anabaina, Microcystis*
Cryptophyceae	*Cryptomonadales*	*Chroomonas*
Dinophyceae	*Prorocenrales*	*Prorocentrum, Cochlodinium, Karenia*
	Noctilucales	*Noctiluca*
	Peridiniales	*Alexandrium, Ceratium, Lingulodinium*
Biciflariophceae	*Centrales*	*Chaetoceros, Skeletonema,*
	Pennales	*Asterionella, Pseudonitzschia*
Raphidophyceae	*Raphidomonadales*	*Chattonella, Fibrocapsa, Heterosigma*
Chrysophyceae	*Dictyochales*	*Dictyocha*
Euglenophyceae	*Eutreptiales*	*Eutreptiella*
Protozoa	*Ciliophora*	*Mesodinium rubrum*

'Red Tide Alert' and 'Warning Lift'. The notices of attention and alert are issued when the density of *C. polykrikoides* exceeds 300 cells/mL and 1,000 cells/mL, respectively.

Bio-optical oceanography and remote sensing

In order to describe and understand the dynamics of HABs, there is a need for continuous measurements at fixed locations, with high-resolution vertical profiles, as well as synoptic measurements over broad regions of the coast and shelf. In recent times, real-time data from state-of-the-art remote sensing and drifting and fixed buoy-watches are widely used for prediction. At present, Korea and Japan exchange their new findings on bio-optic technology, to estimate the total area affected by HABs.

2.2. Recent trends of HABs

1) Spatio-temporal distribution of HABs

The outbreaks of harmful algal blooms (HABs) were rare and prevailed mostly by diatoms until the 1980s, but HABs became more frequent and widespread during the 1990s with dominant species of dinoflagellates (Kim et al., 1997). In the early 1990s, dinoflagellates species other than *C. polykrikoides* blooms have been generally observed from early spring to late autumn, with the main season from June to September. In 1995, one of the fish killing dinoflagellates, *C. polykrikoides*, formed a dense bloom in almost all of the southern coastal waters, and then persisted for about two months, resulting in the largest fish kill, with an alleged loss of US$ 1 million. Since then, *C. polykrikoides* has been one of the worst HAB species owing to its widespread, long-persistency, and subsequent massive fish kill in Korea.

Based on four decadal observations of the phytoplankton community, seasonal species changes have been observed, representing typical temperate patterns of spring diatom and mid-summer dinoflagellates. Up until the 1980s, diatoms were the prevailing species except during the hot summer season of August when dinoflagellates prevailed. Since the 1990s, the dinoflagellates have become the most important

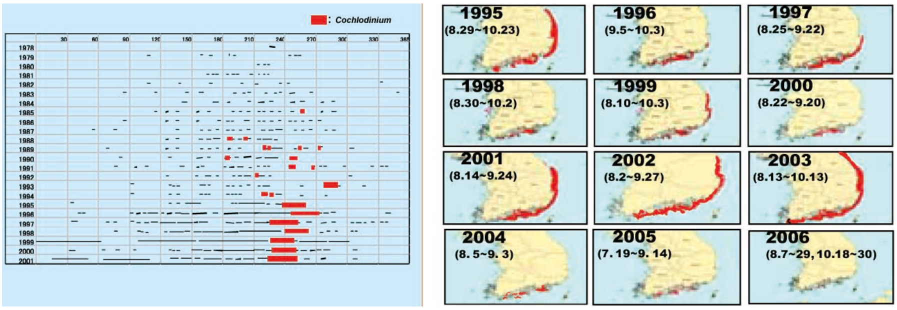

Fig. 3. Annual distribution in the periods of HABs since 1978 (left, black lines showing the periods of other HAB species), and the areas affected by fish-killing *C. polykrikoides* blooms in Korean coastal waters since 1995 (right).

Table 3. Three stages of HABs in Korean coastal waters since 1982 (Kim, 2005).

Terms	Harmless Bloom 1982–1988	Harmful Bloom 1989–1994	*Cochlodinium* Bloom 1995–2003
Area	Localized	South Sea/East Sea	Widespread
Density (cells/mL)	less than 8,700	<25,000	<43,000
Persistency	<10 days	<20 days	up to 62 days

species in the context of harmful algal blooms. Since 1995, the fishkilling dinoflagellate *C. polykrikoides* has been a dominant species of HABs. However more recently, there has been a change in the dominant species, because *C. polykrikoides* has decreased whilst other dinoflagellates of Karenia and Prorocentrum genera have increased.

2) Long-term trends of HABs in terms of distribution and intensity

Annual fluctuation of the HABs for the last two decades can be identified as 3 stages, based on the spatial distribution, and the density and duration of the bloom. The first stage is a "harmless diatom bloom period (hereafter harmless blooms)" recorded for about 7 years from 1982 to 1988. The second stage spanned from 1989 to 1994 and can be described as the "harmful dinoflagellate bloom period (hereafter harmful blooms)", and the third stage from 1995 to 2003 is the "fish-killing *C. polykrikoides* bloom period (hereafter *Cochlodinium* blooms)". During the first stage, the area affected was localized in and around Jinhae Bay, South Sea with the highest cell density of 8,700 cells/mL recorded (Table 3).

The second stage could be defined as the development stage from a localized 10-day bloom to a widespread-high density 20-day bloom. In the third stage, the HABs became widespread throughout the whole South Sea. The highest density in one blooming episode sometimes reached 48,000 cells/mL; dense enough to kill aquatic animals. In general, the duration of algal blooms was about one or two months in length, with annual fluctuation. In 2003, *C. polykrikoides* blooms recorded the highest density of 48,000 cells/mL, and the longest persistent bloom of 62 days. In recent times, some changes in the dominant species of HABs have been observed and more in-depth monitoring is needed to clarify these developments.

3.3. The impacts of HABs on sustainable fisheries

As seen in the global waters, the HABs cause substantial impacts on the growth, recruitment and mortality of fish population in Korea, especially by fish killing algal blooms that caused direct and severe damage on the coastal aquaculture industries. So far, it was proven that three fish killing species such as *C. polykrikoides* since 1989, *Gyrodinium* sp., in 1992 and *Karenia mikimotoi* since 1981 have occurred in the Korean coastal waters (Kim et al., 1997). Among them, *C. polykrikoides* was the most harmful species., followed by *Gyrodinium* sp., a new species collected from Chungmu coast in 1992 (Kim et al., 1995).

Based on the observations for the last two decades, the economic impact of HABs has been magnified partially by the widespread fish-killing HABs and partially by the expansion of shellfish and fish culture farms. In August 1981, for example, Korea experienced large economic loss due to fish mortalities caused by *K. mikimotoi* red tides in Chinhae Bay (Cho, 1981; Park, 1982). The fisheries loss was calculated to be approximately US$ 2.6 million (Kim, 2005). In 1992, other fish mortalities caused by *Gyrodinium* sp. resulted in severe fisheries damage and a loss of US$ 24.3 million. In 1995, an alleged economic loss caused by a *C. polykrikoides* bloom was US$ 95.5 million, and has been recorded as the biggest fisheries damage experienced in Korea. In addition to the direct fish kill and impacts on coastal ecosystems, the indirect effect from the HABs is unforeseen and difficult to quantify.

However recently, the fisheries damage has decreased sharply due to the low density *C. polykrikoides* blooms since 2004. There were no fisheries damages in 2008 even though the *C. polykrikoides* bloom had persisted for about two months.

3. HABS MANAGEMENT AND MITIGATION

Mitigation

1) Precautionary prevention

The ultimate goal of monitoring and mitigation of HABs is to protect public health, fisheries resources including aquacultural industries, ecosystem structure and function, and coastal aesthetics. This requires a fundamental understanding of many factors that regulate the dynamics of HABs, the environmental impacts of the practical techniques and substances to be implemented to prevent the HABs. In that case, economic aspects pertaining to diminish the HABs in field should be considered. In general, it is recommended to apply precautionary preventions rather than direct control methods, owing to relatively low costs and environmentally friendly techniques.
In Korea, when the blooms threaten fish-kill, NFRDI issues HABs alert and asks aquaculturists to take precautionary actions, for examples, to reduce fish density in

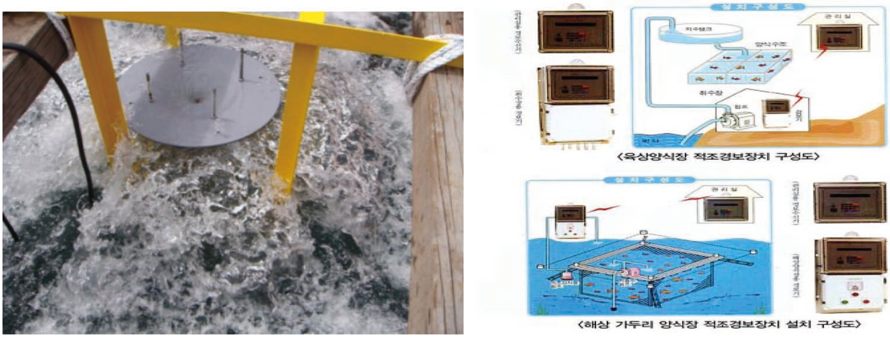

Fig. 4. Bottom water pumping in the cages (left), and red tide alarm system and schematic layout in the land-based fish tank (upper right) and fish cage(lower right) to alert aquaculture manager (NFRDI, 2002).

cages, lessen feed supply, transport fish to refuge sites, harvest fish or shellfish as early as possible. Pumping bottom water to the surface in order to circulate well is also widely applied due to its efficiency, low costs, and easy operation. Korean central and local governments recommend aquculturists to install the red tide alarm system. This system, created by the NFRDI research team in 2000, is to alert aquaculturists to the approach of red tides. Immediate actions should be taken, such as stopping red water supplies into tanks and the automatic supply of liquefied oxygen into fish tanks.

The red tide alarm system consists of sensor and alarm apparatus. The sensor can detect the chlorophyll, temperature and turbidity of the water. When HABs are detected by determinations of chlorophyll concentrations and microscopic observations, alarms are given by sound in the daytime and by light in the night or both simultaneously. It is possible to stop seawater supply into the tank automatically and supply the liquid oxygen. The best way to minimize the damages is to find the outbreaks of HABs at the initial stage and take emergency action. The present action plan consists of regular monitoring and quick announcements to alert fishermen. Recently, the HAB alarm system and shield curtain for the fish cage have been invented and are commercially available.

2) Control of HABs

Direct Control

Since 1996, Korea has dispersed yellow clay on coastal aquaculture farms to remove fish killing dinoflagellate blooms, especially to protect against *C. polykrikoides* (NFRDI, 2002; Kim, 2005). The clay can flocculate the dinoflagellate cells and causes them to sink to the bottom of the water body. This can dilute the cell density of dinoflagellates in the cages thereby not killing the accommodating fish.

Based on field and laboratory experiments, the yellow clay shows a high removal rate of dinoflagellates from the water column. The amount dispersed for these purposes won't harm fish or shellfish. Clay scattering is therefore regarded as one of

Fig. 5. Clay scattering on the area affected by HABs in Korea (Kim, 2006).

the most promising controlling agents against fish-killing *C. polykrikoides* blooms in Korea. Other countries including China, Japan, and USA have also used clay to control dinoflagellates blooms. This mitigation strategy looks promising, but considerable research is still needed to assess the impacts on the structure and function of marine ecosystems. Critical unknowns include the fate and effects of sunken cells and toxins on bottom-dwelling animals and the collateral mortality of co-occurring planktonic organisms. Decomposition of sedimented biomass and the resulting oxygen depletion are also serious concerns.

Predation and mortality of HAB species are obviously critical elements of bloom dynamics, but they also represent an avenue to explore with respect to biological control strategies. Research on predator-prey interaction is needed both to elucidate aspects of HAB dynamics and to identify opportunities for mitigation. The biological control of HABs by using grazers such as copepods, bivalves, and ciliates had been examined, but the results were minimal because of the huge scale of red tides. In Korea, it was found that some copepods and ciliates can graze the dinoflagellates such as *C. polykrikoides* and *Karenia mikimotoi*.

Viruses, parasites, and bacteria are also promising control agents, as they can be abundant in marine systems, replicate rapidly, and sometimes are host-specific. Up until now, no field trials of bloom control using viruses and bacteria have been attempted, in the large part because of uncertainties about host specificity, pathogen stability, and environmental impacts. It is clear that "microbes" of this type can have profound impacts upon HAB population dynamics, but there is no practical knowledge of underlying mechanisms, or of their impacts on bloom dynamics and on the function of marine ecosystems. Therefore, comprehensive studies on the impacts of microbial control agents on the biosphere are needed.

Indirect Control

HAB species require major and minor nutrients that can be supplied either naturally or through human activities, such as pollution. Based on recent scientific findings, the increases in pollution are linked to increases in the frequency and abundance of HABs (GEOHAB, 2006). It follows that a reduction in pollution would lead to a decrease in bloom frequency. It is possible to reduce the outbreaks of coastal HABs by decreasing terrigenous nutrients or by altering the nutrient ratios. Korea is studying these issues, in an attempt to apply regulations to terrestrial discharges.

Another techniques under research in Korea is "bio-manipulation", which is to establish "bio-remediation" to control nutrients and populations of HABs or grazers. One poly-cultural system looks at the establishment of seaweed culture in front of fish culture ground to make macro-algae absorb organic matters discharged both from fish cages and bottom sediments. Still another technique is the modification of water circulation. Artificial aeration is used to mix the water column, favoring species that thrive in well mixed waters over those requiring stratification. The design and evaluation of bio-manipulation strategies require a fundamental understanding of associated processes, such as the grazing losses, or the influence of water column mixing on species succession. These are important unknowns and thus represent promising research directions.

In enclosed or semi-enclosed areas, the outbreaqks of HABs which are initiated by eutrophication and getting worse owing to the restricted water circulation can be minimized by ameriorating the circulation of water masses to increase the exchanging rate of nutrient-rich water and HAB species with offshore waters. For example, the sea dyke dam that can control water volume of a control pond using tidal differences is one such promising application. This also requires an understanding of linkages between coastal hydrography, nutrient loadings, and bloom dynamics, of which little is known for most HAB species.

5. INTERNATIONAL AND REGIONAL COOPERATION FOR HABS RESEARCH

Exchanges on HABs data and scientific findings

Given that HAB problems are expanding and have many impacts on the marine ecosystem and public health, it is necessary to exchange HABs data and information among interested countries and international organizations to efficiently manage affected marine resources and to protect public and ecosystem health. The exchange of information can encourage and support aquaculture development, and contribute to policy decisions on coastal managements, such as waste or sewage disposal, and aquaculture development.

What is clearly needed is cooperation and collaboration to establish a coordinated domestic, regional and international scientific program on the ecology and oceanography of HABs, which incorporates full participation of numerous scientists from several countries. In late 1997, the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) agreed to form a partnership to develop such a program. Finally, a plan for co-ordinating scientific research and co-operation to develop international capabilities for assessment, prediction and mitigation entitled "Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)" has emerged as a unique international HABs project (GEOHAB, 2001, 2003). Korea has joined the regional and international meeting, and continues to exchange data and information with neighboring countries such as Japan, China, and Russia through NOWPAP, PICES, and EASTHAB meetings.

6. CONCLUSIONS

Coastal and marine resources are economically important because they generate a varying flow of services, benefits and utilities to both individuals and societies. However, HABs and the aestival anoxia, both of which have likely resulted from pollution, recently threaten sustainable productivity in most coastal areas. Over the last several decades, Korea has experienced an escalating and worrisome trend in the incidence of those problems. Their impacts include mass mortalities of farmed fish and shellfish, and sometimes human illness from intoxicated shellfish.

However, the mechanism on the initiation and subsequent development of fish-killing dinoflagellate, especially *C. polykrikoides*, is still not fully understood due to inadequate information about oceanographic properties in the western Pacific and East China Sea.

The Korean fisheries economy depends heavily upon the coastal zone for marine products, so it is especially sensitive to constraint from red tides and toxic micro-algae. Therefore, it is imperative that environmental challenges, such as HABs, are combated to maintain the sustainable productivity of the sea.

It is apparent that precise and quantified information on the management of HABs and their impacts on marine living resources should be exchanged between countries to help clarify the underlying mechanisms on the initiation and subsequent development of fish killing HABs.

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