ISBN 978 -1-927797-40-2
ISSN 1198-273X

PICES SCIENTIFIC REPORT
No. 59, 2020

GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies

NORTH PACIFIC MARINE SCIENCE ORGANIZATION

PICES Scientific Report No. 59
2020

GlobalHAB
Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies

edited by
Vera L. Trainer

November 2020

North Pacific Marine Science Organization (PICES)
P.O. Box 6000, Sidney, BC, V8L 4B2, Canada
www.pices.int

PICES Scientific Reports

Published since 1993, the PICES Scientific Report series includes final reports of PICES expert groups, proceedings of PICES workshops, data reports and reports of planning activities. Formal peer reviews of the scientific content of these publications are not generally conducted.

PICES Scientific Reports can be found at: https://meetings.pices.int/publications/scientific-reports

This report was developed under the guidance of the PICES Science Board and its Marine Environmental Quality Committee. The views expressed in this report are those of participating scientists under their responsibilities.

Front cover:
Clockwise from top left: Razor clams are canned and sold for income by Quinault Indian Nation, Washington State (Source: Vera L. Trainer, NOAA); oysters are a large commercial industry affected by harmful algae and their toxins (Source: Taylor Shellfish); microscopic images of two harmful algal genera, *Pseudo-nitzschia* and *Alexandrium*, are microscopic phytoplankton that can cause economic damage to fisheries (Source: Brian Bill, NOAA); *Pseudochattonella verruculosa* caused a massive fish kill in Seno de Reloncavi, Chile, in 2016 (Source: Servicio Nacional de Pesca, SERNAPESCA); recreational razor clamming brings thousands of diggers to the Washington State coast every year (Source: Vera L. Trainer, NOAA).

This document should be cited as follows:

Trainer, V.L. (Ed.) 2020. GlobalHAB. Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies. PICES Sci. Rep. No. 59, 107 pp.

Table of Contents

Participants of the MEQ Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms, October 17–19 2019, during PICES-2019, Victoria, British Columbia, Canada.

1 Introduction

Vera L. Trainer[1], Keith Davidson[2], Kazumi Wakita[3], Elisa Berdalet[4], Marc Suddleson[5], Geir Myre[6] and Dean Trethewey[7]

[1] Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E, Seattle, WA 98112, USA

[2] Scottish Association for Marine Science, Scottish Marine Institute, Oban, PA37 1QA, Scotland, UK

[3] School of Marine Science and Technology, Tokai University, 3-20-1 Orido, Shimizu-ku, Shizuoka, 424-8610, Japan

[4] Institute of Marine Sciences (ICM-CSIC), Pg. Marítim de la Barceloneta, 37-49, Barcelona, Catalonia, 08003, Spain

[5] National Centers for Coastal Ocean Science, NOAA, Silver Spring, MD 20910, USA

[6] Aquaculture Department, XL Catlin Norway, part of AXA XL, a division of AXA, C. Sundsgate 37, 5004 Bergen, Norway

[7] Grieg Seafood BC Ltd., #106 – 1180 Ironwood Street, Campbell River, BC, V9W 5P7, Canada

Over the last two decades, several efforts have been addressed to compile what is known about the economic impacts of harmful algal blooms (HABs; *e.g.*, Anderson *et al*., 2000; Hoagland and Scatasta 2006; Huppert and Trainer, 2014; Trainer and Yoshida, 2014; Sanseverino *et al*., 2016). One study estimated the annual cost of HABs in the European Union at 800 million USD (Hoagland and Scatasta, 2006) but most of that cost was extrapolated from very few HAB organisms. In China, a single *Karenia mikimotoi* event in 2012 caused up to 330 million USD loss to the mariculture industry, mostly cultivated abalone (Guo *et al*., 2014). Although past reports have attempted to gather comprehensive economic impact data (*e.g.*, Trainer and Yoshida, 2014), both the type and amount of information were limited, highlighting the need for collaboration between HAB scientists and economists. Furthermore, most countries have neither conducted economic analyses of HABs nor collected data that can be used to generate reliable quantitative estimates of net economic losses and impacts. The lack of data, appropriate and standardized protocols, and the dearth of peer-reviewed studies hamper efforts to quantify the societal costs of regionally frequent, intense, and long-lasting HAB events and to help evaluate the cost of various strategies being developed for HAB prevention, control, and mitigation.

To strategize how specific economic studies can be used to assess the economic impacts of HABs and mitigate their associated risks, a Marine Environmental Quality (MEQ) sponsored Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies was held on October 17–19, 2019, at the Annual Meeting of the North Pacific Marine Science Organization (PICES; Appendices 1 and 2). During this 2.5-day workshop, over 48 international experts on economics, insurance of aquaculture companies, and the science of HABs from Australia, Canada, China, Chile, France, Japan, Korea, Norway, Scotland, Spain, the United Arab Emirates, the UK, and the USA (see list of participants, Appendix 1) discussed a compendium of case studies that highlighted the economic ramifications of HABs on farmed salmon and shellfish, and on wild-caught, reef-based fisheries.

The workshop included plenary lectures summarizing the state-of-the-art knowledge, ideas and concepts about the economic consequences of HABs worldwide on wild and recreational fisheries and aquaculture, concentrating on five areas of focus:

1. An overview of methods used to evaluate the economic impacts of HABs;
2. *Cochlodinium polykrikoides* bloom impacts on wild and aquaculture fish kills in Korea;
3. Ciguatera fish poisoning with direct effects on human health and wellbeing;
4. HAB impacts on fish and shellfish aquaculture in the European Union, Canada, and Chile.
5. Impacts of HABs on salmon cage aquaculture.

The HAB-related losses faced by insurers are huge. At the workshop, a representative from a reinsurance company specified that 45% of insurance claims are now related to HABs. In fact, it was stated that the losses due to HABs are larger than any storm that insurers have ever faced. In the Republic of Korea, an insurer recently collapsed due to the frequent and enormous losses of aquacultured fish attributed to HABs.

During the workshop, breakout groups were formed to discuss strategies for mitigation, including the value of information from better or more refined forecasts. Questions addressed included: Can contingency planning reduce loss? How can areas be opened more quickly, how can closures be shorter, and what is the value of information from better forecasts? What is the cost benefit analysis of monitoring programs? How much should be spent on monitoring? For insurance purposes, how can the cost of HABs be reduced?

Several examples of HAB-related losses and mitigation costs were discussed in detail. A HAB incident in northern Norway alone resulted in the loss of 14 thousand tons of Atlantic salmon in May 2019, resulting in a total loss of at least 330 million USD, including insured losses of 45 million USD, underinsured values and deductibles of 40 million USD, losses of future salmon sales of 160 million USD, cleanup costs of 30 to 40 million USD, and loss of taxes and unemployment benefits of 50 million USD. In Brittany, France, the Laboratoire d'Economie et de Management de Nantes-Atlantique (LEMNA), University of Nantes, is conducting a detailed estimation of the impacts of shellfish trade bans caused by HABs. Researchers at LEMNA are creating a database documenting these trade bans from 2004 through 2018 at shellfish harvesting areas in four French departments (Finistère, Morbihan, Loire-Atlantique and Vendée). These four areas encompass about 700 shellfish farms representing 37,600 metric tons of products having an estimated value of €141 million (>156 million USD), *i.e*., 20% of the national shellfish harvest.

Ciguatera fish poisoning (CFP) deserved special attention at the workshop. This non-bacterial food poisoning, endemic in the South Pacific Islands and the Caribbean Sea, seems to be spreading due to climate change, globalization, and dwindling marine fishes. Poisoning results from the consumption of fish contaminated with *Gambierdiscus*-produced ciguatoxin. The main challenges to effective CFP detection are the rapid and accurate detection of the causative species and toxins in seafood. CFP has major impacts on human health which are anticipated to increase with climate change (Kidwell, 2015), with acute and chronic diseases and subsequent loss of work hours, and with changes from traditional protein sources to imported products. Appropriate strategies for intervention are urgent but difficult to implement. The workshop participants discussed recent studies that are opening new possibilities to address CFP risks in island nations (Trick *et al*., this report).

The huge HAB-related losses to industry, consumers, and governments illustrate the need for insurers, the aquaculture industry, public health professionals, economists, and HAB scientists to work together to estimate the cost of HAB events relative to the costs of mitigation and management.

There are a number of factors that directly impact the economic stability of both finfish and shellfish aquaculture, of which HABs are only one. Better economic assessment is therefore required to evaluate and prioritize responses to HAB events as appropriate to business need. It is also necessary to determine whether pre-emptive measures currently taken are the most appropriate course of action or whether investment in alternative warning or mitigation approaches is more cost effective. The “halo effects” of HAB impacts are also poorly quantified, including consumer confidence in seafood during and after HAB events. Finally, HAB impacts on aquaculture can be intermittent. While fish and shellfish kills can be massive, they may be years apart, so multi-year economic assessments are needed to better quantify changes in losses and impacts. The future changes on HAB frequency and intensity (Wells *et al*., 2020, including extreme HAB events (Trainer *et al*., 2020) cannot be ignored.

Studies of economic and social losses and their impacts need to be planned and teams need to be formed prior to HAB events to ensure that they are comprehensively studied. Toward this goal, the workshop further helped to establish greater connections between economists, industry scientists, and HAB researchers. In this report we provide a series of case studies to help guide future research and management priorities.

Acknowledgments

This workshop was sponsored by the North Pacific Marine Science Organization (PICES)[1] and the international programme IOC-SCOR GlobalHAB[2] with funds from the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC UNESCO)[3] and the Scientific Committee on Oceanic Research (SCOR)[4], through a contribution from the U.S. National Science Foundation (Grant OCE-1840868) to SCOR and by national SCOR committees. Financial support was also provided by the International Society for the Study of Harmful Algae (ISSHA)[5], Northwest Pacific Action Plan Coastal Environmental Assessment Regional Activity Centre (NOWPAP CEARAC)[6], Grieg Seafood Ltd., AXA XL Reinsurance[7], and by other funding agencies that allowed the attendance to the workshop by the scientists indicated in Appendix 1. We thank the following colleagues who provided helpful reviews: Eileen Bresnan, Veronique LeBihan, Kedong Yin, Po Teen Lim, Lincoln MacKenzie, and Bengt Karlson.

[1] https://www.pices.int/
[2] http://www.globalhab.info/
[3] https://ioc.unesco.org/
[4] https://scor-int.org/
[5] https://issha.org/
[6] http://cearac.nowpap.org/
[7] http://www.griegseafood.com/

References

Anderson, D.M., Hoagland, P., Kaoru, Y. and White, A.W. 2000. Estimated economic impacts from harmful algal blooms (HABs) in the United States. WHOI-2000-11 Technical Report. 96 pp.

Guo, H., Liu, X., Ding, D., Guan C. and Yi, X. 2014. The economic cost of red tides in China from 2008–2012, pp. 27–34 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Hoagland, P. and Scatasta, S. 2006. The economic effects of harmful algal blooms, pp. 391–402 *in:* Ecology of Harmful Algae. Ecological Studies (Analysis and Synthesis), vol. 189, *edited by* E. Granéli and J.T. Turner, Springer, Berlin, https://doi.org/10.1007/978-3-540-32210-8_30.

Huppert, D.D. and Trainer, V.L. 2014. Economics of razor clam fishery closures due to harmful algal blooms in Washington State, pp. 59–7 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Kidwell, D. 2015. Mitigation of harmful algal blooms: The way forward. PICES Press Vol. 23, No. 2. PICES, Sidney, B.C. Canada. pp. 22–24.

Sanseverino, I. Conduto, D., Pozzoli, L., Dobricic, S. and Lettieri, T. 2016. Algal bloom and its economic impact. JRC Technical Report. EUR 27905 EN, doi:10.2788/66047.

Wells, M.L., Karlson, B., Wulff, A., Kudela, R., Asnaghi, V., Berdalet, E., Cochlan, W., Davidson, K., De Rijcke, M., Dutkiewicz, S., Hallegraeff, G., Flynn, K., Paerl, H., Legrand, C., Silke, J., Suikkanen, S., Thompson, P., Trainer, V.L. and Trick, C.G. 2020. Future HAB science: directions and challenges in a changing climate. *Harmful Algae* **91**: 101632, https://doi.org/10.1016/j.hal.2019.101632.

Trainer, V.L. and Yoshida, T. (Eds.) 2014. Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture. PICES Scientific Report No. 47, 85 pp.

Trainer, V.L., Moore, S.K., Hallegraeff, G., Kudela, R., Clement, A. and Mardonez, J. 2020. Pelagic harmful algal blooms and climate change: lessons from nature's experiments. *Harmful Algae* **91**: 101591, doi:10.1016/j.hal.2019.03.009.

2 Evaluating the Economic Impacts of Harmful Algal Blooms: Issues, Methods, and Examples

Di Jin[1], Stephanie Moore[2], Dan Holland[2], Leif Anderson[2], Weol-Ae Lim[3], Dohoon Kim[4], Sunny Jardine[5], Simone Martino[6], Fatima Gianella[7,8] and Keith Davidson[8]

[1] Woods Hole Oceanographic Institution, Woods Hole, 266 Woods Hole Rd., Woods Hole, MA 02543, USA
[2] Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E, Seattle, WA 98112, USA
[3] National Institute of Fisheries Science, 216 Gijanghaean-ro, Gijang-eup, Gijang-gun, Busan, 46083, Republic of Korea
[4] Pukyong National University, 45 Yongso-ro, Nam-gu, Busan, 48513, Republic of Korea
[5] School of Marine and Environmental Affairs, University of Washington, 3707 Brooklyn Ave. NE, Seattle, WA 98105, USA
[6] Department of Environment & Geography, University of York, Wentworth Way, York, YO10 5NG, England, UK
[7] University of the Highlands and Islands, 12b Ness Walk, Inverness, IV3 5SQ, Scotland, UK
[8] Scottish Association for Marine Science, Scottish Marine Institute, Oban, PA37 1QA, Scotland, UK

Introduction

Harmful algal blooms (HABs) can cause significant economic impacts around the world. Economic sectors directly affected by HABs include commercial fisheries, recreational fisheries, aquaculture, food markets, coastal tourism, and public health (Adams *et al*., 2018). These direct effects can propagate through regional economies, causing negative impacts to other sectors.

It is important to quantify the economic impacts of HABs in order to identify and implement effective and cost-efficient mitigation strategies in the management of these coastal hazards. Mitigation strategies may be informed by or rely on HAB monitoring, management, and research and development programs that can be costly; information on the economic impacts of HABs helps managers understand the benefits of these programs (in terms of damages avoided). HAB economic impact studies also inform private investment decision-making in different sectors by improving the characterization of relevant financial risks. Finally, HAB economic impact studies are typically transdisciplinary in nature, requesting collaboration between natural and social scientists. These types of studies are of growing importance as many future challenges can only be managed with an improved understanding of coupled natural–human systems.

This section summarizes case studies of the economic impacts of HABs in regions of the US, Korea, the UK, and Canada, highlighting the use of different methods for evaluating impacts to various economic sectors. The primary objective of this section is to inspire and facilitate transdisciplinary studies of the economic impacts of HABs by developing collaborations and competencies in understanding relevant economic analyses, which will contribute to effective HAB management. First, we provide an overview of some commonly used methods for assessing the economic impacts of HABs, introducing concepts and terminology that are fundamental for economic analyses. We then summarize some of the known impacts to various economic sectors, drawing on case studies presented at the workshop. Finally, we describe mitigation strategies for reducing the economic impacts of HABs and methods for conducting cost-benefit analyses of HAB forecasts that enable dynamic ocean management.

In the section, economic impacts are broadly defined to capture a wide range of negative economic effects (*e.g.*, reductions in net benefits or revenues, increases in costs, or changes in economic activities in regional economies associated with HABs). Note, however, that the term refers only to measures of a specific type of economic analysis in the field of economic studies. Specifically, economic impacts are typically defined in the context of an economic impact analysis which examines the effect of an event on the economy in a specified area, ranging from a single neighborhood to the entire globe, using an input-output (IO) or general equilibrium model.

Methods for assessing economic impacts of HABs

A comprehensive assessment of HAB economic impacts should consider the key components and their relationships depicted in Figure 2.1. Central to any HAB impact study is an understanding of the dose–response relationship between HAB frequency and intensity and socioeconomic measures (*e.g.*, fisheries landings, number of tourists). Characterizing this relationship requires a baseline to be established. In most places, HABs are episodic, and the baseline for an economic sector is its production output in the absence of a HAB. This baseline may vary seasonally and across geographical space. An accurate description of the baseline typically requires researchers to examine multiple variables in other relevant environmental and socioeconomic data sets.

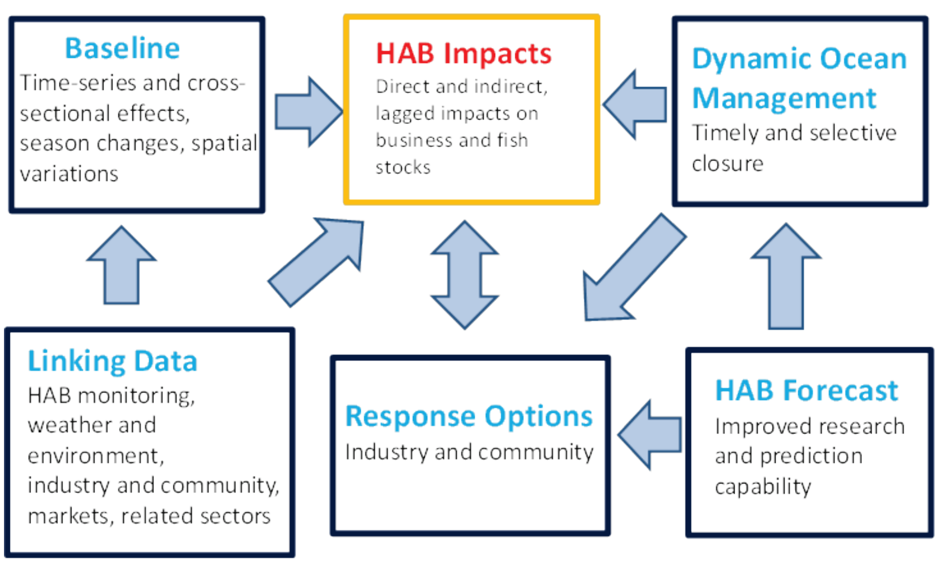

Fig. 2.1 Key components of HAB socioeconomic analysis and their relationships.

HAB impacts are investigated by a counterfactual analysis (see Table 2.1 for definition) which measures what outcomes would have been realized without HABs. Specifically, the impacts are estimated by comparing counterfactual outcomes to those observed when HABs were present. In a simple case, HAB impacts are quantified by subtracting the socioeconomic measures (*e.g*., fisheries landings) when the HAB occurred ("with HAB") from the baseline of these measures. The socioeconomic measures with the HAB are influenced by hazard mitigation and response actions taken by individuals and businesses in relevant industries and communities. These HAB response options are, in turn, affected by HAB monitoring and forecast capabilities and ocean management actions (*e.g*., fishery closures).

Most existing HAB studies focus on reductions in the economic outputs in selected sectors using a subset of variables (see below). Comprehensive assessments are the subject of future analyses. Nonetheless, the key components of HAB socioeconomic analyses and their relationships shown in Figure 2.1 will help readers understand the context of these studies. Note that many other HAB effects are not explicitly shown in the figure, such as health costs borne by individuals and lost recreational activities due to HAB closures which may not be captured at the business level.

Concepts and terminology for economic analyses of HABs

Table 2.1 summarizes concepts and terminology related to HAB economic impact analysis. According to economic theory, the effects of a HAB on an economy should be examined in terms of changes in net economic value (also referred to as economic welfare), which is the sum of consumer and producer surplus in relevant sectors, in a counterfactual analysis. This type of analysis requires additional economic data on market demand and production costs, which is often not feasible due to lack of data or limitations on project time and budget. In fact, most existing HAB economic impact studies do not measure changes in economic welfare, although their results typically capture the essence of HAB economic effects and are useful for policy purposes.

Direct economic impacts on an industry sector

A correct measure of the impact of a HAB should be based on a comparison of two scenarios: with and without the HAB event, which is the essence of a counterfactual analysis. Suppose that the net economic benefit of an industry or an individual (Π) can be measured (*e.g*., net revenue from fishing, recreational harvest, or consumption of fish products). Let A and B refer to the net economic benefits with- and without-HAB; then the economic damage of a HAB event is the difference between these benefits ($\Delta\Pi$):

$$\Delta\Pi = \Pi_A - \Pi_B.$$

In the case of commercial fishing, Π_A represents the actual harvest value (or net revenue if cost data are available) in a year with a major HAB event(s) and Π_B is the baseline harvest value. Because HABs lead to harvest losses from fishery closures, $\Delta\Pi$ is expected to be negative (Jin *et al*., 2008).

Theoretically correct measures of HAB impact should capture changes in social welfare (consumer and producer surpluses), or at least consider changes in both revenue and costs. In most cases, however, data limitations result in economic impacts often being measured in terms of reductions in gross revenues (*e.g*., price multiplied by quantity of fish landed). For example, commonly available data are aggregate regional quantity and values of landings in recent years.

The public health effects related to HABs can also be assessed in the same framework. In this case, Π is the number of relevant hospital visits or consumers who suffer from HAB-related poisonings, and $\Delta\Pi$ captures the number of patients or relevant costs attributable to HABs.

Table 2.1 Economic concepts and terminology related to economic impacts analyses of HABs.

Term	Definition
Benefits	The benefits people get from something are equal to the maximum amount they are willing to pay for it.
Catch shares	A fishery management system that allocates a secure privilege to harvest a specific area or percentage of a fishery's total catch to individuals, communities, or associations.
Consumer surplus	The difference between the price that consumers pay and the price that they are willing to pay.
Costs	The costs of something are all expenditures of productive resources or inputs required to produce it.
Counterfactual	In the case of understanding the impacts of a harmful algal bloom (HAB), the counterfactual is what outcomes would have been realized without the HAB.
Counterfactual analysis	Comparing observed outcomes to a counterfactual.
Economic impacts	Changes in economic outcomes such as income and employment. See also a narrow definition in the context of an economic impact analysis (EIA) in Table 2.2.
Economic multipliers	In an EIA, multipliers are computed in an input-output (IO) model. Typically, each economic sector's output multiplier measures the total impact on the regional economy of a $1.00 change in the final demand for that sector's output.
Net economic value	Net economic value, also referred to as economic welfare, is the sum of consumer and producer surplus.
External benefits	Benefits generated with the production or consumption of a good that are not considered by the producer or consumer, because they are not compensated for these benefits.
External costs	Costs generated with the production or consumption of a good that are not considered by the producer or consumer, because they do not pay for the costs.
Externalities	Any external costs and benefits.
Markets	Institutions in which buyers and sellers of goods and services carry out mutually agreed-upon exchanges.
Open access fisheries	Right to catch fish is free and open to all.
Opportunity costs	The maximum value we give up by doing one thing instead of something else.
Private goods	Goods must be bought in order to be consumed and whose ownership is restricted to the group or individual that purchased the good.
Producer surplus	The difference between the price that producers receive and the price that they are willing to accept.
Race to fish	Harvesters compete with each other to capture the fish first.
Variable costs	Costs that vary with the quantity produced.

Total impacts on regional or national economies

The broader economic impacts associated with HAB-related lost revenues in a sector, such as commercial or recreational fishing, can be estimated using a regional IO model (Leontief, 1936), typically comprising the coastal counties in the study area (Oh and Ditton, 2008; Dyson and Huppert, 2010). The inter-industry linkages in an IO model characterize the effects of activities in one industry on all other industries from which it purchases factors and to which it sells products. An IO model thus can be used to understand the economic "influence" of an industry in the study region on the other sectors of the economy to which they are linked. Specifically, industry influence is estimated using economic multipliers:

$$\frac{\partial \mathbf{X}}{\partial \mathbf{Y}} = (\mathbf{I} - \mathbf{A})^{-1}$$

where $(\mathbf{I} - \mathbf{A})^{-1}$ is called the Leontief inverse; $\mathbf{I}$ is an $n \cdot n$ identity matrix; $\mathbf{A}$ is an $n \cdot n$ technical coefficient (input-coefficient) matrix; $\mathbf{X}$ is a $n \cdot 1$ column vector denoting output; and $\mathbf{Y}$ is a $n \cdot 1$ column vector denoting final demand. This equation shows that a change in the final demand y_i (an element of $\mathbf{Y}$) for the output from industry i affects the output from all linked industries (n elements of $\mathbf{X}$).

All processing sectors (industries), final demand (including consumer/household purchases, private investment, government purchases, and exports), and the payments sector (value added, including labor costs, capital costs, taxes, rental payments, and profits) are incorporated into an IO table (transactions table). Total industry outlays equal the value of total industry outputs. Outlays are payments made by firms for inputs and for other purposes in the payments sector. Inputs are purchased locally (within a region) or imported from outside the region. Outputs are goods or services produced by the industry. They can be consumed directly by households and others as final demand within a region or sold to other industries as intermediate demand.

The major advantage of the IO model is its explicit capture of all the linkages in the IO table. For example, suppose a HAB event affects commercial fisheries in a region. This leads to a decline in the output of the local fishing industry. To capture the full effect of the decline of fisheries output to the regional economy, we need to quantify the economic importance of the industry to the economy of the region. Fisheries contribute to employment and to household incomes. Port buildings and equipment also provide a basis for tax revenues that support local and state government programs. In addition, as purchasers of inputs, the fishing industry supports a number of other industries, such as boat building and repairs. When all the linkages within the economy are considered, the income and employment generated by the fishing industry have ripple effects on the overall income and employment of the region.

Specifically, an industry's contribution to the overall regional economy consists of three components: direct, indirect, and induced effects. In the case of fisheries, if a vessel is laid up due to a HAB, the associated lost jobs and income are the direct effects. In this case, indirect effects are additional jobs and income lost in other industries, such as boat repairing, which can be indirectly credited to the lost vessel. The more inputs produced and purchased within the region, the greater the magnitude of the indirect effect. Finally, lost jobs mean lower household income or a smaller number of households in the region. Lower income leads to reduced spending on food, housing, and other items, such as cars. These are the induced effects.

Note that a standard IO model (a demand-side model) is based on backward-linkage analysis (which describes the interconnection of a particular sector to those sectors from which it purchases inputs), and the multipliers are output multipliers. Each sector's multiplier measures the total impact on the regional economy of a $1.00 change in the final demand for that sector's output. Alternatively, a supply-side IO model can be built to investigate forward linkages (which capture the interconnection of a particular sector to those sectors to which it sells its output). The corresponding multipliers are input multipliers. Each sector's multiplier measures the total impact on the regional economy of a $1.00 change in the primary input for that sector. To estimate the impact of changing outputs of some sectors (*e.g.*, a reduction in fishing due to HAB events), an IO model with mixed exogenous/endogenous variables can be employed (Miller and Blair, 1985). Steinback (2004) has shown that the standard IO model can be adapted to investigate output changes using an adjustment procedure.

Although linear IO models can handle a large number of industry sectors in the economy, the approach often is limited only to descriptive studies. In the IO models, technical coefficients and prices are fixed. As a result, these models do not capture some key nonlinear interactions in the relevant economy, such as the supply and demand for goods and services, and they cannot be used to examine economic welfare changes. To address these issues, computable general equilibrium (CGE) models are often used (Fig. 2.2). A CGE model can be calibrated initially using regional economic data from the IO model, calculating *status quo* quantities for production, consumption, and trade in each sector for a given baseline set of prices $\mathbf{P}_0$. To simulate the effects of lost fishing, the model is re-run with the change (reduction) in fish landings. An optimization solver is used to recalculate both a new set of equilibrium prices $\mathbf{P}_1$ and corresponding changes in quantities so that all markets are cleared (*i.e.*, supply = demand in each sector) after the simulated change in fish supply. A change (loss) of social welfare is then evaluated as an equivalent variation (EV), which measures a loss in household utility, assuming that prices remain constant:

$$EV = F_E(U_1, \mathbf{P}_0) - F_E(U_0, \mathbf{P}_0).$$

In the above equation, F_E is a household expenditure function, and U_1 and U_0 are household utility levels with and without the modeled change in commercial fishing, respectively (Jin *et al.*, 2008).

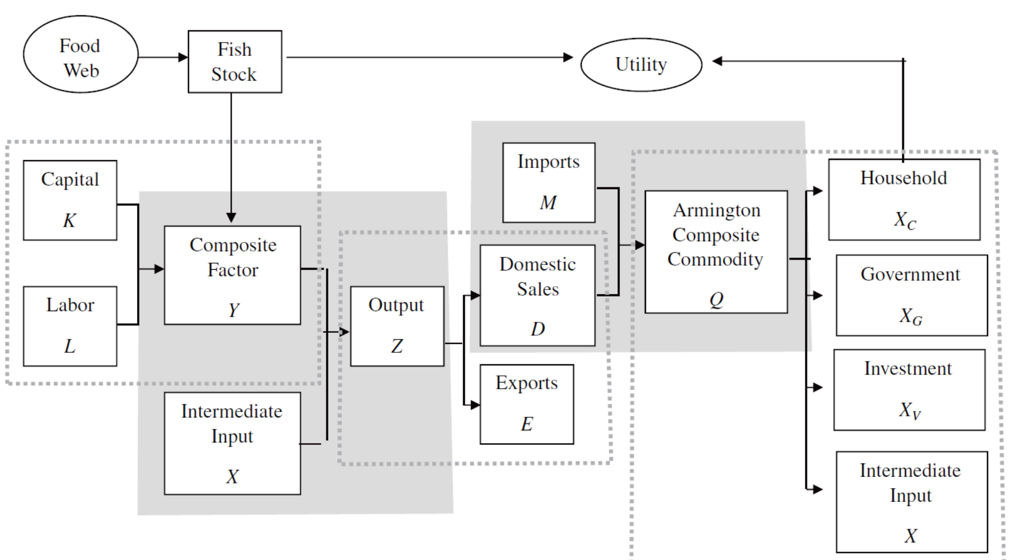

Fig. 2.2 Basic components of a computable general equilibrium (CGE) model used to assess the welfare changes associated with changes in fish stock. From Jin *et al.* (2012).

Additional concepts used in the regional economic analysis are presented in Table 2.2. According to Watson *et al*. (2007), although the terms "economic contribution", "economic impact", and "economic benefit" are often used interchangeably in some regional economic studies, these are separate terms for distinctly different metrics. Economic impacts are defined as the net changes to the economic baseline of a region that can be attributed to an industry or event. Detailed explanation of these concepts and relevant model specifications are beyond scope of this section. However, it is important to note that economic analyses should clearly define the terms used to avoid confusion and misinterpretation, which may be particularly problematic in situations that are political in nature.

Table 2.2 A definition of terminology for regional economic analysis. From Watson *et al*. (2007).

Term	Definition
Economic activity	Dollars spent within region that are attributable to a given industry, event, or policy.
Economic activity analysis	An analysis that tracks the flow of dollars spent within a region (market values). Both economic impact and economic contribution analysis are types of economic activity analysis.
Economic contribution	The gross change in economic activity associated with an industry, event, or policy in an existing regional economy.
Economic impact	The net changes in new economic activity associated with an industry, event, or policy in an existing regional economy.
Cost-benefit analysis	An economic efficiency analysis that measures net changes or levels in social welfare associated with an industry, event, or policy. This type of analysis includes both market and non-market values and accounts for opportunity costs.
Input-output model	A specific methodological framework that characterizes the financial linkages in a regional economy between industries, households, and institutions. Input-output only measures economic activity and does not include any nonmarket values.

Data needs for HAB impact studies

To develop a basic HAB economic impact analysis, one needs information on the timing, duration, and geographic scope of a HAB event, as well as time-series measures of economic activities in each affected region and sector (*e.g*., value of fishery landings). More sophisticated analyses require additional information, such as spatial data on HAB monitoring and management (*e.g*., fishery closures), detailed microdata on economic activities (*e.g*., fishing vessel trip records), and additional social survey data on markets and response actions. Regardless of complexity, all studies are grounded in the key components depicted in Figure 2.1.

Selected examples of HAB economic analyses

An overview of existing literature

There is a growing literature on the economic impacts of HABs. These studies cover different economic sectors, including *commercial fisheries* (Habas and Gilbert, 1974; Hoagland and Scatasta, 2006; Jin and Hoagland, 2008; Jin *et al*., 2008; Holland and Leonard, 2020; Jardine *et al*., 2020); *recreational fisheries* (Hoagland and Scatasta, 2006; Oh and Ditton, 2008; Dyson and Huppert, 2010; Anderson and Plummer, 2017); *aquaculture* (Rodríguez *et al*., 2011; Martino *et al*., 2020); *seafood markets* (Wessells *et al*., 1995; Whitehead *et al*., 2003; Parsons *et al*., 2006); *tourism* (Habas and Gilbert, 1974; Van Beukering and Cesar 2004; Hoagland and Scatasta, 2006; Larkin and Adams, 2007; Morgan *et al*., 2009, 2011); and *public health* (Hoagland and Scatasta, 2006; Hoagland *et al*., 2009; Nierenberg *et al*., 2010; Hoagland *et al*., 2014; Diaz *et al*., 2019). Table 2.3 summarizes the above and additional samples of HAB economic impact studies in the literature. More comprehensive reviews of relevant studies can be found in Hoagland *et al*. (2002), Landsberg (2002), Groeneveld *et al*. (2018), and Adams *et al.* (2018).

Table 2.3 Selected studies on HAB economic impacts.

Commercial fisheries Habas and Gilbert (1974) Hoagland and Scatasta (2006) Jardine *et al*. (2020) Jin and Hoagland (2008) Jin *et al*. (2008) Park *et al*. (2013) Holland and Leonard (2020) Lim and Kim (2020) presentation at the workshop* West *et al*. (2019) poster at the workshop	**Recreational fisheries** Hoagland and Scatasta (2006) Oh and Ditton (2008) Dyson and Huppert (2010) Anderson and Plummer (2017)
Aquaculture Rodríguez *et al*. (2011) Martino *et al*. (2020)	**Seafood markets** Wessells *et al*. (1995) Whitehead *et al*. (2003) Parsons *et al*. (2006)
Tourism Habas and Gilbert (1974) Beukering and Cesar (2004) Hoagland and Scatasta (2006) Larkin and Adams (2007) Morgan *et al*. (2009) Taylor and Longo (2010) Morgan *et al*. (2011)	**Health** Hoagland and Scatasta (2006) Hoagland *et al*. (2009) Nierenberg *et al*. (2010) Rongo and van Woesik (2012) Hoagland *et al*. (2014) Diaz *et al*. (2019)

* Workshop (W18) on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, October 17–19, 2019, PICES-2019, Victoria, Canada.

In the rest of this section, we summarize the HAB impact studies presented at the workshop by economic sector and geographic location.

Commercial fisheries

US Northeast

Jin *et al*. (2008) estimated the economic impacts of the 2005 bloom of *Alexandrium fundyense,* which was the most widespread and intense in New England waters in recent decades (Fig. 2.3). The estimates were based on historical data on monthly shellfish landings by species from the National Marine Fisheries Service, the Massachusetts Division of Marine Fisheries, and Maine Department of Marine Resources (Fig. 2.4). Figure 2.5 depicts the baseline and HAB year shellfish harvests.

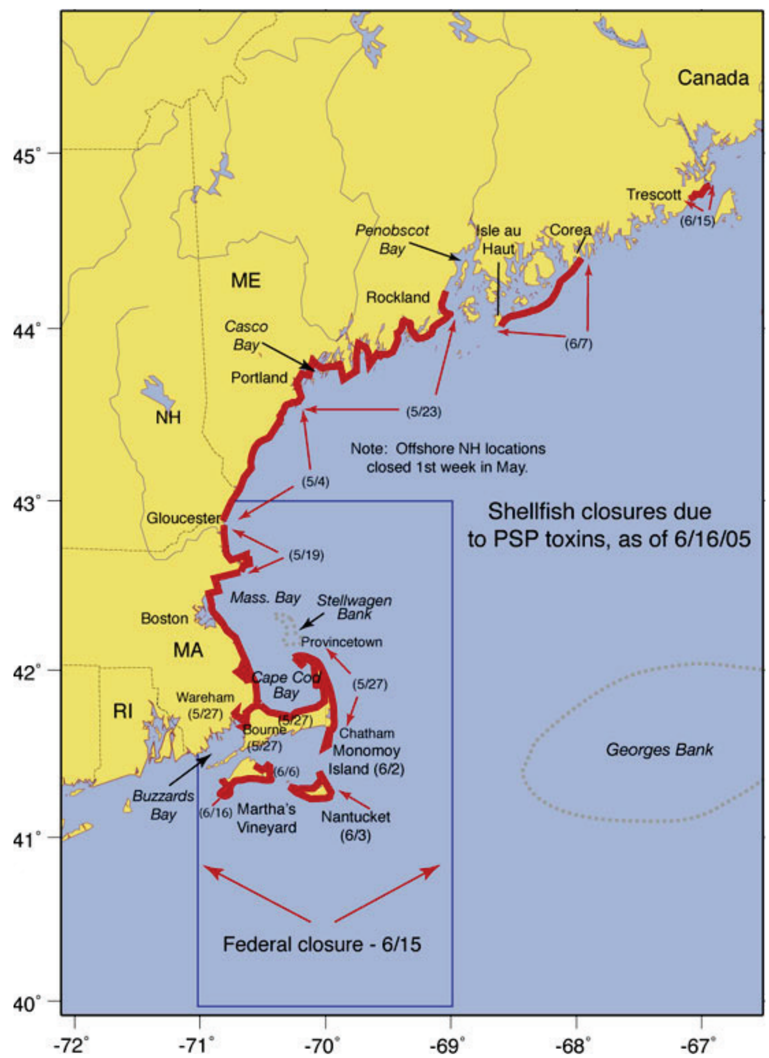

Fig. 2.3 The 2005 HAB event in New England. PSP - Paralytic Shellfish Poisoning.
Source: http://vishnu.whoi.edu/services/communications/oceanusmag.050826/v44n1/redtide-en1.html.

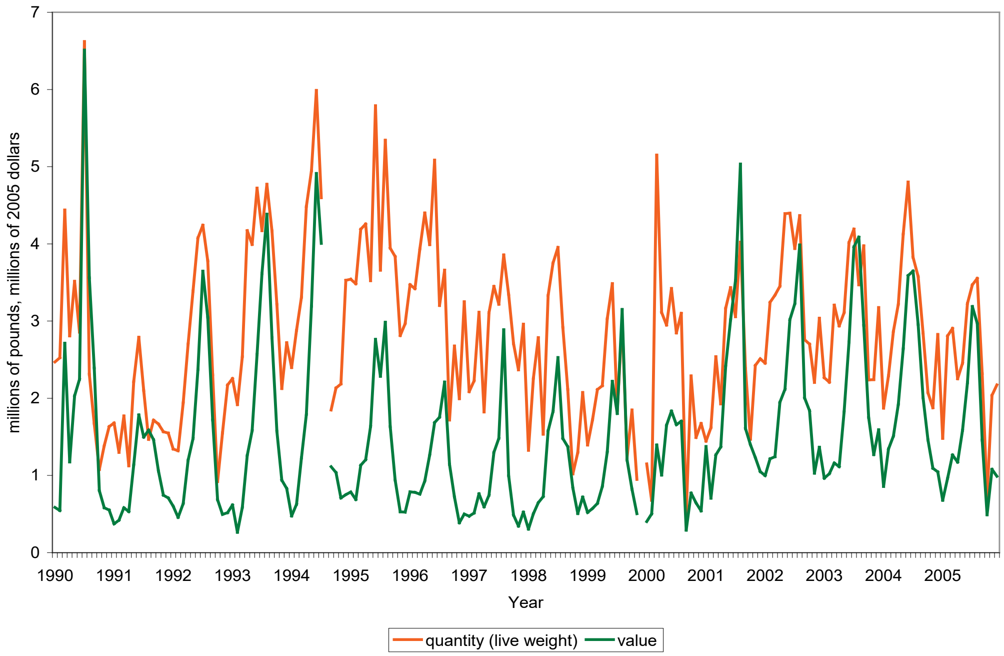

Fig. 2.4 Monthly shellfish landings in Maine 1990–2005. Landings include four shellfish species: quahog, softshell clam, mussel, and oyster.

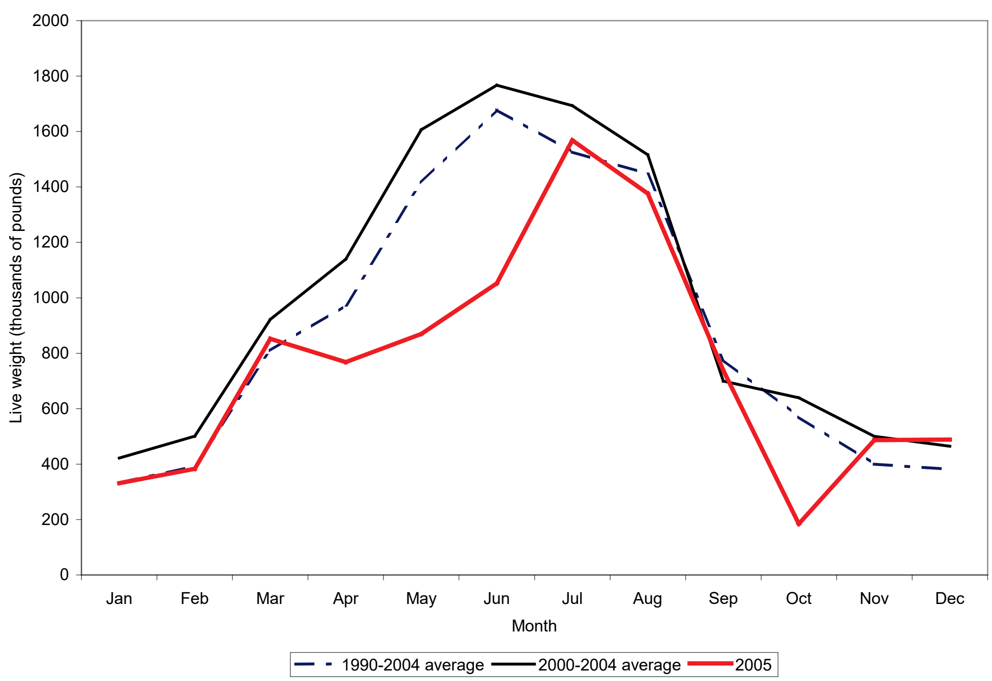

Fig. 2.5 Monthly softshell clam landings in Maine baseline *versus* 2005.

The study found that the direct economic impacts of the 2005 event on commercial shellfish fisheries, in terms of lost gross revenues, were 2.4 million USD in Maine and $16–18 million in Massachusetts. In addition, the event had broad spatial and temporal effects on the shellfish market. In response to a supply shortage resulting from local closures, there was an increase in shellfish imports to New England during the HAB event. Further, shellfish closures in Maine were the most likely cause of observable price changes on the Fulton Fish Market in New York.

Figure 2.6 depicts two baseline prices (*i.e*., 1990–2004 average and 2000–2004 average) and the wholesale price in 2005 on the Fulton Fish Market. An interesting finding was that the price was higher than normal during the early stages of the HAB event (May and June), possibly due to supply shortages from Maine, and lower than normal during the later stage of the event (August through October), possibly because of consumer concerns of seafood quality resulting from negative media publicity, as discussed in Wessells *et al*. (1995) and Whitehead *et al*. (2003). Another possible cause for the price drop is that when the New York market expected supply to be limited all summer, wholesalers switched to other sources or to other shellfish species to ensure stable supply.

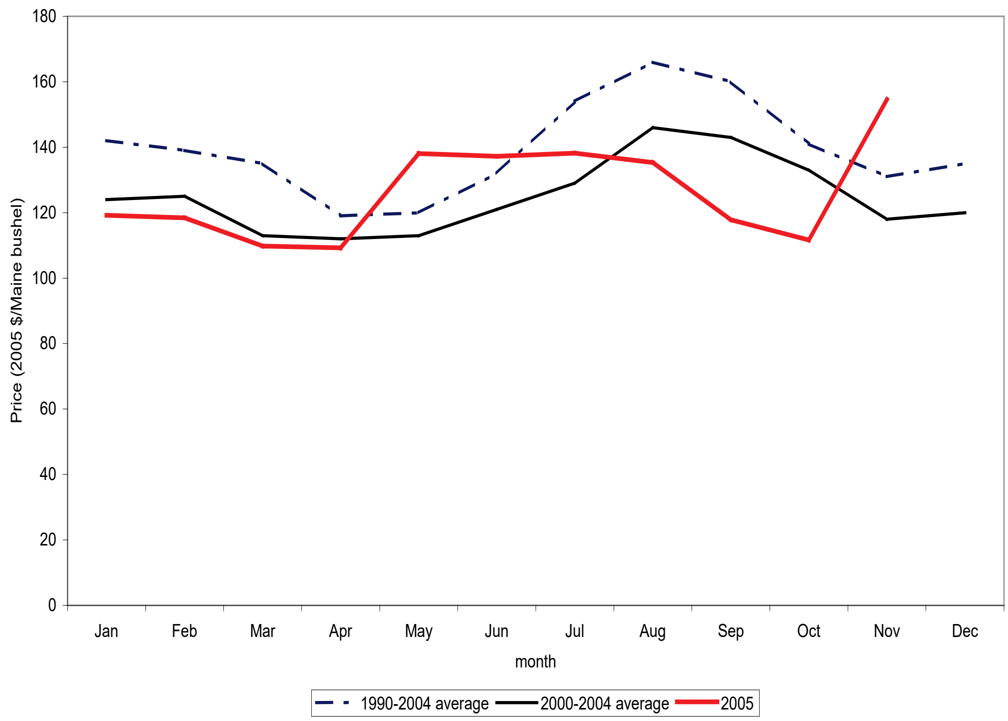

Fig. 2.6 Softshell clam wholesale prices on New York Fulton Fish Market: baseline *versus* 2005.

When time series data on the value of fish landings are available, a regression model can be constructed to estimate the effects of a HAB event. Let y be the dependent variable (value of landings), that can be modeled as:

$$y = \alpha_0 + \sum_{i=1}^{11} \alpha_i M_i + \alpha_{12} t + \alpha_{13} t^2 + \alpha_{14} HAB + \varepsilon$$

where α_0 through α_{14} are coefficients and ε is an error term. M_i is the dummy variable for month i, *HAB* is the dummy variable for the period with HAB, and t is time (*i.e*., year). A dummy variable is a binary (0 or 1) variable capturing the effect of a specific time period or an event. For example, $HAB = 1$ when HAB was present in that period, and HAB = 0 otherwise. Thus, changes in y reflect a combination of seasonal fluctuations, linear and nonlinear time trends, and the HAB event. The baseline of fisheries landings is described by setting HAB = 0.

When time-series and cross-sectional data are available, the above HAB economic impact assessment method can be improved to capture weak HAB effects resulting from frequent, small HAB events. For example, the Maine Department of Marine Resources compiles geospatial data on daily shellfish production and HAB closures (Fig. 2.7).

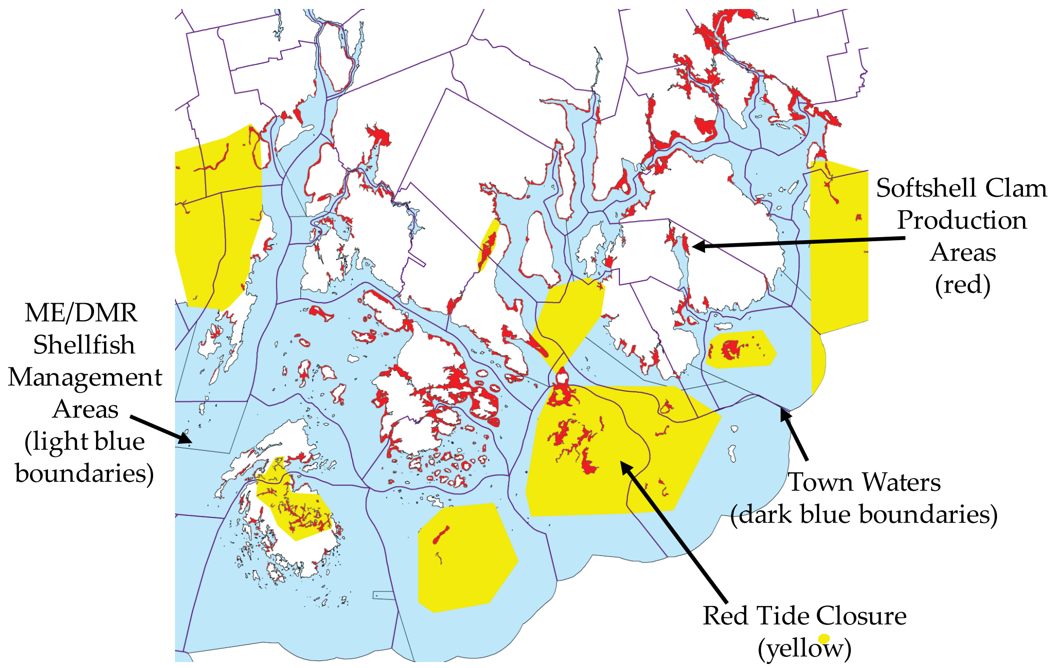

Fig. 2.7 Spatial analysis: HAB impacts on shellfish in coastal Maine. From Hoagland *et al*. (2013).

To develop an analysis of the effects of HAB-related shellfish closures on the quantity of softshell clam landings, Hoagland *et al*. (2013) constructed regression models using daily data at the town level. Let q be the dependent variable (*e.g*., harvest quantity). They model q as:

$$q_{it} = \alpha_0 + \sum_{i=1}^{N-1} \alpha_i town_i + \beta_0 pct_{it} + \sum_{i=1}^{N-1} \beta_i town_i \cdot pct_{it} + \sum_{j=1}^{J} \gamma_j M_j + \sum_{i=1}^{K} \delta_k Y_k + \varepsilon$$

where i is the index for individual town (1,2,…N), t is the index for time (a day), α_0 is the intercept, $town_i$ is the dummy variable for town i, pct_{it} is the percent clam production area closed due to HAB in town i at time t, M_j is the dummy variable for month j, Y_k is the dummy variable for year k, and ε is an error term. α, β, γ and δ are coefficients to be estimated. Thus, changes in q reflect a combination of monthly and yearly fluctuations, and percent production area closures due to the HAB (*pct*). The above formulation allows us to estimate and then calculate both the intercept and slope for individual towns. For town i, the intercept is $\alpha_0 + \alpha_i$ and the slope for *pct* is $\beta_0 + \beta_i$.

Using data from the production season (May to September) from 2008 to 2011 and the above model, Hoagland *et al*. (2013) calculated lost revenues in Maine by percent production area closure and closure length (Table 2.4). Figure 2.8 illustrates the overall framework to estimate HAB economic impacts including regional impacts using IO models.

Table 2.4 Maine softshell clam HAB closure impacts.

	Predicted economic impacts ($ million)		
	% Closure		
	25%	**50%**	**75%**
Day	0.06	0.12	0.19
Week	0.43	0.87	1.30
Month	1.73	3.47	5.20
2 months	3.47	6.94	10.40

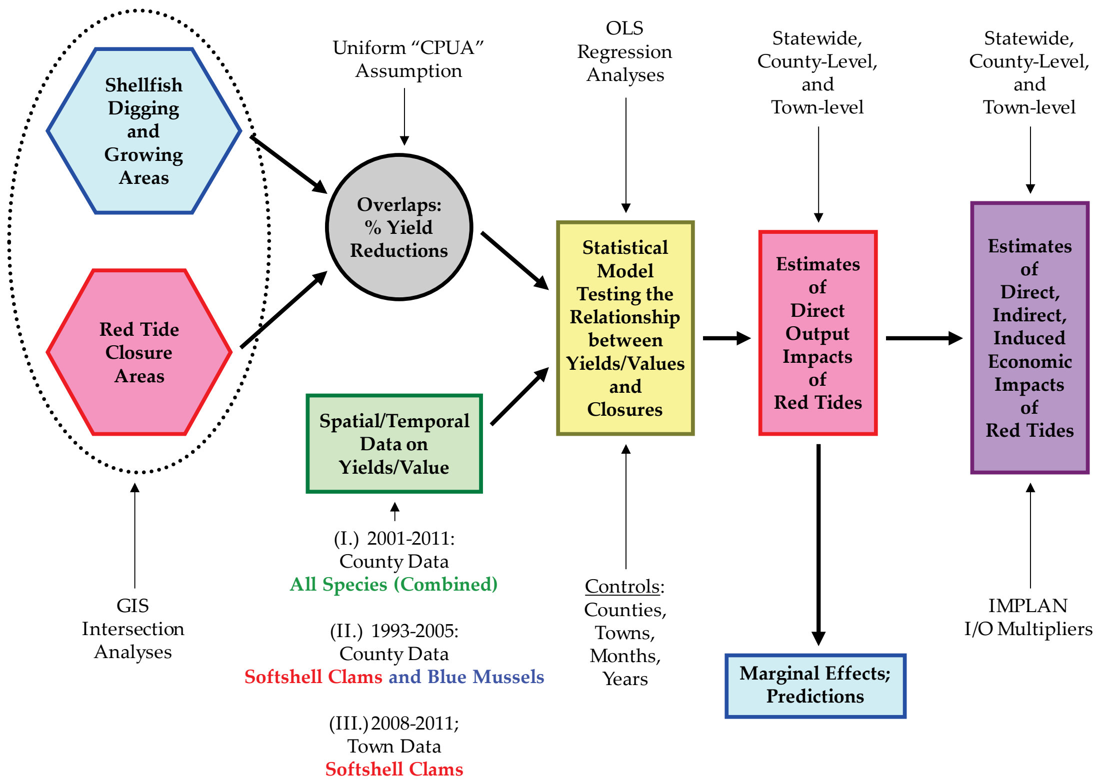

Fig. 2.8 Framework for estimating the economic impacts of shellfish closures due to HAB in Maine. From Hoagland *et al*. (2013).

US West Coast

In 2015 the North Pacific experienced a marine heatwave, nicknamed “the Blob”, with water temperatures more than 2.5 degrees Celsius above normal. The Blob led to a number of ecological disruptions and is believed to have triggered a coast-wide bloom of the diatom *Pseudo-nitzschia australis*, which in turn led to high concentrations of the toxin, domoic acid (DA), in clams and crabs (Du *et al*., 2016; McCabe *et al*., 2016; Zhu *et al*., 2017). The 2015/2016 commercial fishery seasons for Dungeness crab (*Metacarcinus magister*) were delayed in all three states due to the HAB. The California fishery was delayed almost five months which led to a Congressional appropriation of $25 million in disaster aid (Chambers, 2018).

Holland and Leonard (2020) used a statistical model of expected revenue at the vessel level to estimate what revenues for crab fishers would have been in the absence of the lengthy delay in the opening of the California Dungeness crab fishery in the 2015/2016 season. A hurdle model fit with individual vessel data from the 2009/2010 to 2014/2015 seasons was used to estimate expected revenue for the 2015/2016 season for vessels that had fished for Dungeness crab in the years preceding the closure. A linear Cragg hurdle model jointly estimates the probability of fishing and the expected revenue conditional on fishing. The analysis relied primarily on “fish ticket” data collected by California on all commercial landings, including vessel-trip level data on landings and value of landings by species. Explanatory variables for both the participation model and the latent variable (conditional expected revenue) include: indices of adult male crab abundance at the beginning of the season estimated with a depletion estimator (Richerson *et al*., 2020), vessel length, average revenue for the vessel in the prior five years, the mean latitude the vessel’s crab was landed weighted by revenue, the number of years the vessel fished in the prior five years, and an index of diversification of the vessels’ revenues across fisheries (following Kasperski and Holland, 2013).

The economic impacts of lost revenue are estimated using a regional IO model parameterized for West Coast fisheries (Leonard and Watson, 2011). Both direct and indirect income and employment effects were estimated for the harvest and the processing sector for each vessel. In aggregate, the models predict total revenue (all fished species combined) for the California crab fleet in 2016 in the absence of the delay in the season opening would have been $102.1 million rather than the observed $76 million, suggesting a loss in revenues of $26.1 million. Dungeness crab revenue for the modeled fleet would have been $50.5 million rather than the observed $37.5 million for a loss of $13 million. Thus, over half of the estimated loss in total revenues for the California Dungeness crab fleet is attributable to reduced revenues in other fisheries – from vessels that either dropped out of fishing in 2016 altogether or reduced their fishing in other fisheries in order to participate in the delayed crab fishery.

Direct income losses for the harvest sector are estimated to be $18.12 million, about half of which is associated with Dungeness crab and half with other species. Direct income losses for the processing sector are estimated at $3.29 million, again about half from crab and half from other species. Indirect losses (*i.e*., the multiplier effect through the rest of the California economy) are of similar magnitude to the direct income losses. When added to direct losses, total income losses for both the harvest and the processing sector are estimated at $43.68 million, about half of which was associated with lost crab revenue and half with other species. The model also estimates a loss of 492 jobs in the harvest sector and 111 jobs in the processing sector. Again, only about have of these employment losses are associated with reduced crab revenues – the rest are from reductions in revenues of other species.

Ritzman *et al*. (2018) examined the economic and sociocultural impacts of the closures during the 2015 event of Dungeness crab and razor clam fisheries on two fishing-dependent communities (Crescent City, California and Long Beach, Washington), using semi-structured interviews of people in the fishing, hospitality, and retail industries, and of local government officials, recreational harvesters, and others. The interview results indicated that economic hardships extended beyond fishing-related operations, permeating through to other sectors, particularly the hospitality industry. HAB-affected community members expressed a desire for clearer, more thorough, and more rapid dissemination of information regarding the management of fisheries closures and the health risks associated with HAB toxins. These themes were examined further by Moore *et al*. (2020) using a survey of people working largely in the fishing and hospitality sectors in 16 fishing-dependent communities along the US West Coast. They found that fishers experienced greater impacts compared to those working in other occupations, and they were also less likely to recover financial losses suffered as a result of the 2015 HAB.

Not all communities along the US West Coast are at equal risk for experiencing impacts related to HABs. Underlying demographic factors and socioeconomic conditions, such as poverty or high rates of unemployment, affect a community's ability to withstand impacts from multiple stressors. Moore *et al*. (2019a) used indices of community social vulnerability and fishery dependence for 17 fishing communities along the US West Coast to identify those most vulnerable to the 2015 closures of the Dungeness crab fishery. The authors also constructed an index quantifying lost fishing opportunities due to toxic HABs from 2005 through 2016. The HAB index showed that the 2015 HAB caused the longest duration and most geographically widespread fisheries closures on record.

Just as communities have unequal risk, subpopulations within communities also have different levels of risk for experiencing HAB impacts. Jardine *et al*. (2020) found that small and large fishing vessels in the commercial California Dungeness crab fishery were differentially affected by the 2015 HAB, with large vessels having a greater ability to mitigate losses. Consequently, the proportion of total revenue going to small-vessel operators and the proportion of small-vessel participation in the fishery fell in response to the 2015 HAB (as well as the 2016 HAB of *Pseudo-nitzschia* that occurred in the region). The distributional impacts of HABs have implications for the development of mitigation strategies for different ocean user groups.

Korea

Mobile fishing gear (*e.g*., trawls and dredges) used in commercial fishing makes commercial fishing possible even when HABs occur. However, fishing grounds owned by fishing communities ("Maeul") have to suspend fishing when HABs occur, resulting in a loss of income. Maeul fisheries are fishing businesses run by fishers residing in a certain locality who catch and gather shellfish, seaweed, or sedentary marine animals in a demarcated area of waters, contiguous to the shore, within a certain depth range. Maeul fisheries located on the southern and eastern coasts of Korea, are directly affected by frequent *Cochlodinium* blooms in terms of fish production. To estimate the economic effect of HABs on marine Maeul fisheries during the 2010–2018 period in the Busan, Jeonnam, Gyeongbuk, and Gyeongnam areas, data on annual fish production were compiled (Table 2.5) and the average daily production was calculated. The damage to the Maeul fisheries was estimated by multiplying the average daily production by the number of days with HABs, assuming that fisheries closed down for those days. As shown in Table 2.6, the average annual damage during the 2010–2018 period was estimated to be about US$20,000 (1 USD = 1,189 KRW). The estimate should be viewed as a lower bound, since the adverse effects of HABs on fishing villages typically last longer than the number of HAB days recorded (Lim and Kim, 2020).

Table 2.5 Fish production (in metric tons) of "Maeul" fisheries* in Korea, 2010–2018.

Area	2010	2011	2012	2013	2014	2015	2016	2017	2018
Busan	–	–	1	–	–	<1	–	–	–
Jeonnam	<1	<1	<1	<1	7	–	1	<1	66
Gyeongbuk	–	<1	–	7	–	–	–	–	–
Gyeongnam	1	–	–	<1	<1	<1	<1	<1	–

* Although fishing villages produce fish, shellfish and seaweed, only fish production, which was directly affected by HABs, was considered. In the table "<1" denotes that production is less than 1 metric ton.

Source: Statistics Korea, Fishery production statistics.

Table 2.6 Annual economic damage to marine fisheries caused by harmful HABs in Korea, 2010–2018.

Year	Estimated economic effect (1000 US$)
2010	0.3
2011	–
2012	2.4
2013	1.2
2014	13.3
2015	0.1
2016	0.4
2017	–
2018	126.9
Annual average	20

Aquaculture

Scotland

Martino *et al*. (2020) present a production approach to investigate the effects of HABs on aquaculture production. A production function describes how the output of a production process is influenced by conventional economic inputs (labor, capital, land, *etc*.) and environmental variables (temperature, climatic conditions, eutrophication, and presence of harmful algae and biotoxins). The production function approach has the advantage to capture possible modifications in the economic behavior of individuals affected by environmental changes (Hanley and Barbier, 2009). Examples of using production functions to explore the role of the environment on fishery productivity are proposed by Barbier (2000) and Sathirathai and Barbier (2001) amongst others, by modelling the habitat-fishery linkage.

In Scotland, the impact of HABs on finfish aquaculture is difficult to evaluate as there is insufficient information on the temporal and spatial occurrence of fish-killing species and associated farmed fish mortalities. In contrast, as high resolution temporal and spatial monitoring of shellfish biotoxins and their causative HABs is required by EU regulation, there is much better data to evaluate the economic impact of HABs on shellfish aquaculture. In Scottish waters four HAB genera are of greatest concern in terms of human health: *Alexandrium* which causes Paralytic Shellfish Poisoning (PSP); *Dinophysis* and *Prorocentrum* which result in Diarrheic Shellfish Poisoning (DSP); and *Pseudo-nitzschia* causing Amnesic Shellfish Poisoning (ASP). All show spatial and temporal variability within and between years (Bresnan *et al*., 2008; Whyte *et al*., 2014; Dees *et al*., 2017; Roland-Pilgrim *et al*., 2018; Parks *et al*., 2019). Of greatest health concern is *Alexandrium* due to its high toxicity (Touzet *et al*., 2010), but most prevalent, in terms of occurrences above regulatory threshold that may result in shell fishery closure, is *Dinophysis* (Parks *et al*., 2019)

The Martino *et al*. (2020) study applies a static production function approach to shellfish production in four Scottish regions (Shetland, West Highlands, Outer Hebrides and Clyde) over the period 2009–2018 to evaluate the economic impact of HABs on the Scottish shellfish industry. The authors built a panel on statistics reported in the "Scottish Shellfish Production Survey" (years 2009–2018; https://www.gov.scot/publications/). This panel was made of 40 observations, 10 observations (from 2009 to 2018) per unit (regions of production: Clyde, West Highland, Outer Hebrides and Shetlands). Variables used were annual values from production of shellfish (85% is mussel), labor (number of employees in production), number of active sites (a proxy for capital), and environmental and climatological drivers such as sea surface temperature (SST) and the North Atlantic Oscillation index (NAO). Marginal effects of toxic species and biotoxins on shellfish production were tested. Abundance values were taken from the four phytoplankton genera and biotoxins that produce illness syndromes mentioned above. The abundance was classified binarily according to values above the safety threshold compiled by the regulation (EC) No 853/2004 of the European parliament (European Union, 2004). The impact of HABs and related biotoxins on shellfish productivity is estimated using a particular form of Cobb-Douglas production function (Umar *et al*., 2017) that defines the highest level of production achievable as a function of a range of inputs, such as labor and capital, and a range of environmental variables (temperature, rainfall, eutrophication, *etc*.) supporting the economic activity. The general equation tested in this study is:

$$Production = A * K^{\beta 1} * L^{\beta 2} * e^{\beta 3SST + \beta 4NAO + \boldsymbol{\beta}\mathbf{5HAB} + \boldsymbol{\beta}\mathbf{6BTX}}$$

where *Production* is shellfish production in tons, *K* is capital, a proxy for the number of active producing sites, *L* is labor, the total number of employees, *SST* and *NAO* are the sea surface temperature in Celsius degrees and the NAO (North Atlantic Oscillation) climatic index (–1 to 1 interval), respectively. **HAB** is the vector of harmful algal bloom, and **BTX** is a vector of biotoxins produced by the **HAB**. Both are expressed in frequency, *i.e*., the fraction (interval 0–1) of algal cells and biotoxins concentration above the regulatory harmful threshold. Finally, *A* is the constant that refers to the technology or the amount of production for a unit value of *K* and *L,* assuming that the effect of *SST, NAO*, *HAB* and *BTX* is null. *Betas* are coefficients that describe the conditional change in production per unit change of each independent variable. The equation is estimated using the fixed effect estimator for panel data.

The regression analysis shows that for a 1% increase in the number of productive active sites (capital) there is a 0.99% increase in production, while a 1% increase in DSP above the threshold causes a decrease in production of 0.47%. Labor is removed because it is collinear with capital. SST is not significant, and NAO is collinear to DSP, and is also therefore removed by the model. The average fraction of DSP concentration above the threshold in the last 10 years has been 24%, thus DSP is expected to cause a yearly average reduction of approximately 11% in production. This change is equivalent to a reduction of 830 tons of shellfish per year over a total production of 7,500 tons. At the average price of £ 1,272 per ton (in 2015 constant GBP), equivalent to US$1,590 per ton, the total economic damage caused by DSP is GBP £ 1.05 million per year (equivalent to US$1.31 million).

Korea

Korean aquaculture farms are widely distributed in coastal areas where *Cochlodinium* blooms occur frequently, making these farms vulnerable to adverse effects from HABs (Lim and Kim, 2020). Damage to Korean aquaculture caused by HABs (the term HAB is used synonymously with HAB in Asia) is considerable, just as it is in Japan and China (Guo *et al*., 2014; Itakura and Imai 2014). Damage occurs when farmed fish are killed by oxygen depletion following the decomposition of massive numbers of algae.

When HABs occur, local governments and the Ministry of Oceans and Fisheries directly investigate fish kills in aquaculture farms, aggregate the results annually, and publish the statistical data. These data are a major component in the estimation of the economic damage caused by HABs (Lee *et al*., 2014).

Table 2.7 shows the economic impact of fish kills at aquaculture farms due to the occurrence of HABs during the 2010–2018 period. Although damage to aquaculture due to the occurrence of HABs does not materialize every year, the damage in the years in which HABs do occur is significant. For example, there was no damage in 2010 and 2011, but the damage in 2012 amounted to US$3.7 million, with a record-breaking US$20.8 million in 2013. From 2014–2016, damage amounted to approximately US$5 million per year, and in 2018, a relatively small amount of damage of US$0.1 million was incurred. The average annual damage to aquaculture in the 2010–2018 period was estimated at US$4.3 million.

Table 2.7 Estimated annual damages to the aquaculture sector caused by HABs in Korea, 2010–2018.

Year	Estimated economic effect (million US$)
2010	–
2011	–
2012	3.7
2013	20.8
2014	6.2
2015	4.5
2016	3.6
2017	–
2018	0.1
Annual average	4.3

Recreational fisheries

Korea

The areas that are popular for recreational fishing that attract many fisheries each year are also where HABs frequently occur. The reduction of utility (satisfaction) caused by HABs represents a very important economic effect. When the number of recreational fishing trips to fishing areas is reduced because of the occurrence of HABs, the consumer surplus is reduced.

In order to estimate the effect of HABs on recreational fisheries, it is necessary to measure the utility of fishers who visit the areas for recreational fishing. Lim and Kim (2020) use the travel cost model (TCM), which is the most widely used method to measure the utility of the area to recreational fishers (Gillig *et al*., 2000; Parsons, 2003; Lothrop *et al*., 2014). The TCM estimates recreational demand using the travel cost data for accessing and using a site as a measure of price. Consumer surplus for a recreational trip above and beyond actual expenditure can be estimated from the TCM demand equation (Ward and Beal, 2000).

In the study, face-to-face surveys were conducted with recreational fishers (260 respondents) in the 5 major coastal areas (Yeosu, Gangjin, Tongyoung, Geoje, Gijang) where HABs occur frequently, in order to investigate the costs incurred on fishing trips as well as personal details. Based on this information, the demand function was estimated and the economic value of a fishing trip was assessed. The demand function of a representative recreational angler (i) in the Yeosu area on the southern coast was specified as:

$$Trip_i = \exp(\beta_0 + \beta_1 Cost_i + \beta_2 Catch_i + \beta_3 Income_i + \beta_4 Marriage_i + \beta_5 Age_i + \varepsilon_i)$$

where *Trip* is the number of single-day recreational trips taken, *Cost* denotes travel costs including the opportunity cost of time (a quarter of daily income) to gain access to the recreational fishing region, *Catch* refers to the size of the catch (kg), *Income* is the household income, *Marriage* is a dummy variable that is equal to 1 if an angler is married, *Age* is the angler's age; and ε_i is an error term distributed as a gamma distribution with a mean of 1 and variance α (Gillig *et al*., 2000). Hellerstein and Mendelsohn (1993) show that the per-trip expected value of consumer surplus derived from such a model can be simply calculated as $1/–\beta_1$.

The above demand function was estimated using the Poisson and negative binomial regressions. Table 2.8 shows the results of the estimations.

Based on the analysis of the demand function in the negative binomial model, the economic value for each round trip taken by each recreational fisher was estimated to be approximately US$122. In order to calculate the annual economic value of the recreational fishing sector in the Yeosu region, the economic value per trip (US$122) is multiplied by the average number of trips made by each fisher i (17 trips) and the total number of recreational fishers in each year (57,010).

Table 2.8 Recreational demand function parameter estimates in the Yeosu region.

Variable	Poisson model	Negative binomial model
Constant	3.484 (0.000)[1]	2.936 (0.000)
Cost	–0.108 (0.000)	–0.069 (0.000)
Catch	0.058 (0.000)	0.072 (0.012)
Income	0.001 (0.002)	0.0004 (0.521)
Marriage	–0.307 (0.000)	–0.160 (0.292)
Age	0.013 (0.000)	0.014 (0.107)
α	–	0.957 (0.000)
Log Likelihood	–2,982.420	–983.974

[1] *p*-value in parentheses.

Table 2.9 shows the results of analyzing the economic value of the recreational fishery sector in the five major southern coastal areas in which HABs occur frequently (*i.e.*, Yeosu, Gangjin, Geoje, Tongyoung, and Gijang). For example, recreational fisher *i* visiting Gangjin makes an annual average of 13 trips, the average cost per trip is US$54.70, and the economic value per trip according to the negative binomial model is US$150.50. The average of these five regions was estimated to be 21 trips annually, the average cost was estimated at US$72.50 per trip, and the total economic value per trip was estimated at US$144.20 per person.

Table 2.9 Results of the survey of economic value of recreational fisheries in five regions in Korea.

Area	Annual average number of trips	Cost per trip (US$)	Model type	Per-trip economic value (US$)
Yeosu	17	85.80	NBM[1]	122.00
Gangjin	13	54.70	NBM	150.50
Geoje	25	80.70	NBM	150.50
Tongyoung	19	104.50	NBM	173.40
Gijang	32	37.00	PM[2]	124.50
Average	21	72.50		144.20

[1] Negative binomial model.
[2] Poisson model.

Assuming no substitution to other recreational activities, the decline in economic benefits of recreational fishers due to HABs can be calculated by multiplying the economic value per person and the number of trips lost due to HABs per year. Based on the survey results of Tongyoung (Pyo, 2009), the total number of recreational fishers visiting the regions was estimated to be 57,010 per year. Assuming that the HAB occurred in only one specific region among the five regions where HABs occur frequently, the reduction in economic benefit due to HABs was estimated to be an average of US$16.1 million per year over the 2010–2018 period (Table 2.10). However, if the HABs occur simultaneously in many regions, the decrease in utility value is expected to be even greater.

Table 2.10 Estimated annual damages to the recreational fishery sector in Korea by year caused by HABs.

Year	**Estimated economic effect (million US$)**
2010	1.4
2011	–
2012	35.8
2013	24.3
2014	37.7
2015	25.3
2016	6.7
2017	–
2018	13.4
Annual average	16.1

US West Coast

In Washington State, two studies depict the economic losses to recreational shellfish harvesters and local economies associated with HAB-related closures. Both studies used a contingent behavior approach to elicit trip-taking behavior to produce measures of net economic value and economic impacts under varying degrees of closures.

The first study examined the effect of both HAB and pollution closures on the net economic values of recreational clam and oyster harvesting in Puget Sound (Anderson and Plummer, 2017). This study used a mail survey instrument, developed with a set of focus groups and one-on-one cognitive interviews with licensed shellfish harvesters (Anderson and Plummer, 2016). Harvester response to closures was elicited through a set of four contingent behavior scenarios that were contained in each of 25 survey versions. These contingent behavior questions elicited the number of trips a recreational harvester would take conditional on closure scenarios that varied by spatiotemporal extent (additional miles to nearest fully open beach) and closure type (pollution or HAB). These trips were broken out into three types: trips to a respondent's most-used harvesting beach, non-harvesting trips to the same beach, and harvesting trips to a nearby beach that would remain open under any closure. The demand for trips was estimated using an incomplete demand system that incorporates potential substitution between trip types. Specifically, demand for trip type *i* was modeled as:

$$Trips_i = \exp\left(\theta_i + \rho Priv + \sum_n \delta_{ni}\, Closed_n + \beta_i P_i + \gamma y\right)$$

where P_i was the cost of a trip, $Closed_n$ was an indicator variable identifying a closure of type n, y was household income, and $Priv$ was an indicator for harvesters who use a private beach. Heterogeneous baseline preferences for the three trip types were incorporated by allowing the trip type demand shifters θ_i to follow a normal distribution during estimation. The negative binomial specification estimated that the average willingness-to-pay for a harvest trip was \$144, a harvest trip to an alternate beach was \$117, and a non-harvest trip was \$98. Annual measures of willingness-to-pay are provided under an example scenario of a full year closure with an additional 20 miles to reach the closest beach open to harvest. The economic loss associated with closures of different magnitudes can be estimated with the model using data on the number of harvesters originally using the beach, the number of months the beach was closed, and the distance to the nearest open beach.

The second study estimated the effect of HAB closures in the recreational razor clam fishery of the Washington coast on regional economies (Dyson and Huppert, 2010). An on-site survey distribution with a mail return was used to collect trip expenditures by category. These expenditures were used as inputs to an IO model describing the flows of goods and services in the local economies of the two counties encompassing these beaches. A contingent behavior framework elicited trip-taking behavior under a scenario of 'more beach closures' (stay home or go to the beach less frequently, go to a different beach or visit the beach without razor clamming, do a different recreational activity). These questions were used to capture potential substitution, necessary to estimate net impacts rather than simply gross contributions (Watson *et al*., 2007). Results show that an average closure (typically 2–5 days) of all four beaches would result in a loss of 67 jobs and \$2.1 million in 2008 dollars in labor income in the two local counties. A season-long closure of all four beaches would result in an estimated loss of 339 jobs and \$10.57 million in labor income. The same survey elicited willingness-to-pay to reduce beach closures to one or less per year, using a payment card contingent valuation approach. Among the 57% of harvesters who indicated they would be willing to pay more than the current price to possibly reduce the number of beach closures, the average willingness-to-pay was \$5.17. Huppert and Trainer (2014) extrapolated this value to the population of harvesters, estimating a potential annual benefit of \$662,000. These benefits were shown to exceed the \$150,000 cost of the phytoplankton monitoring system that provides early warning of HAB events, under the Olympic Region Harmful Algal Bloom partnership in Washington State.

In general, the data necessary to produce the net economic value or net economic impacts of HAB events on recreational shellfish harvesters are very similar: both require prices and quantities of trips to produce the economic demand for recreational shellfish harvesting trips. The price of a harvesting trip is composed of the travel cost to reach the site as well as any on-site harvesting costs. In both analyses, it is critical to measure the change in value that results from a particular policy, in contrast to the total economic value of harvesting. Therefore, demand models need to be able to quantify both the baseline harvesting effort as well as the harvesting effort that would result from the policy or environmental change being examined.

Seafood markets

Wessells *et al*. (1995) evaluated the impacts of a toxic algae bloom contamination event on demand for unaffected shellfish. As an empirical example of the economic losses the shellfish industry experiences for these events, demand for mussels in Montreal, Canada, was estimated using firm-level data and proxies for consumer information, during and after domoic acid contamination of Prince Edward Island mussels. In the study, consumer information regarding product quality was assumed to be a function of the number of newspaper articles. The authors found a reduction in demand following the algae contamination and calculated the losses due to the decreased demand.

Whitehead *et al*. (2003) measured the effects of information about *Pfiesteria* on three related decision processes of the consumer: risk perceptions, seafood demand, and willingness to pay for a mandatory seafood inspection program. Using responses to a survey on seafood consumption and hypothetical *Pfiesteria*-related fish kills, the authors found that announcement of a fish kill increases the perceived risks of seafood and decreases the demand for it. Information policies that assure the safety of seafood have little effect in restoring consumer confidence in it. Perceived negative information tends to decrease welfare by more than the counter effects of perceived positive information. Welfare losses are recovered through a mandatory seafood inspection program rather than safety announcements.

Tourism

A decrease in the number of marine tourists due to HAB events causes a decline in tourism-related spending in hotels, restaurants, and other businesses in the HAB-affected region. In previous studies, this tourism outcome was recognized as an important economic effect of HABs (Anderson *et al*., 2000; Hoagland *et al*., 2002; Sanseverino *et al*., 2016).

Korea

Lim and Kim (2020) estimated the effect of reductions in tourism expenditure in the five major southern coastal areas in which HABs occur frequently (*i.e*., Yeosu, Gangjin, Geoje, Tongyoung, and Gijang), using the average expenditure per trip by a tourist (*e.g*., recreational fisher), similar to the above analysis of recreational fisheries (Table 2.9). The decrease in tourism expenditure was calculated by multiplying the average trip expenditure, the annual number of trips lost due to HABs, and the total number of tourists per year. The total annual number of tourists (recreational fishers) was assumed to be 57,010 per year based on the Tongyoung survey results.

As shown in Table 2.11, assuming that the HABs occurred in only one specific region among the five regions where HABs occur frequently, the decrease in tourism expenditure due to HABs was estimated to be an average of US$8.1 million per year during the 2010–2018 period. However, if HABs occur simultaneously in many regions, the decrease in tourism expenditure is expected to be even greater.

Table 2.11 Annual decline in tourism expenditures (damage) in Korea due to HABs.

Year	Estimated economic effect (million US$)
2010	0.7
2011	–
2012	18.0
2013	12.3
2014	19.0
2015	12.7
2016	3.4
2017	–
2018	6.7
Annual average	8.1

Public health

US Southeast

An example of HAB impact estimation using spatial temporal data can be found in Diaz *et al*. (2019). The study investigated the health effects of *Karenia brevis* blooms in Florida where the Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute (FWRI) and Mote Marine Laboratory worked together to monitor *K. brevis* and maintained the Florida HAB historical database (Fig. 2.9).

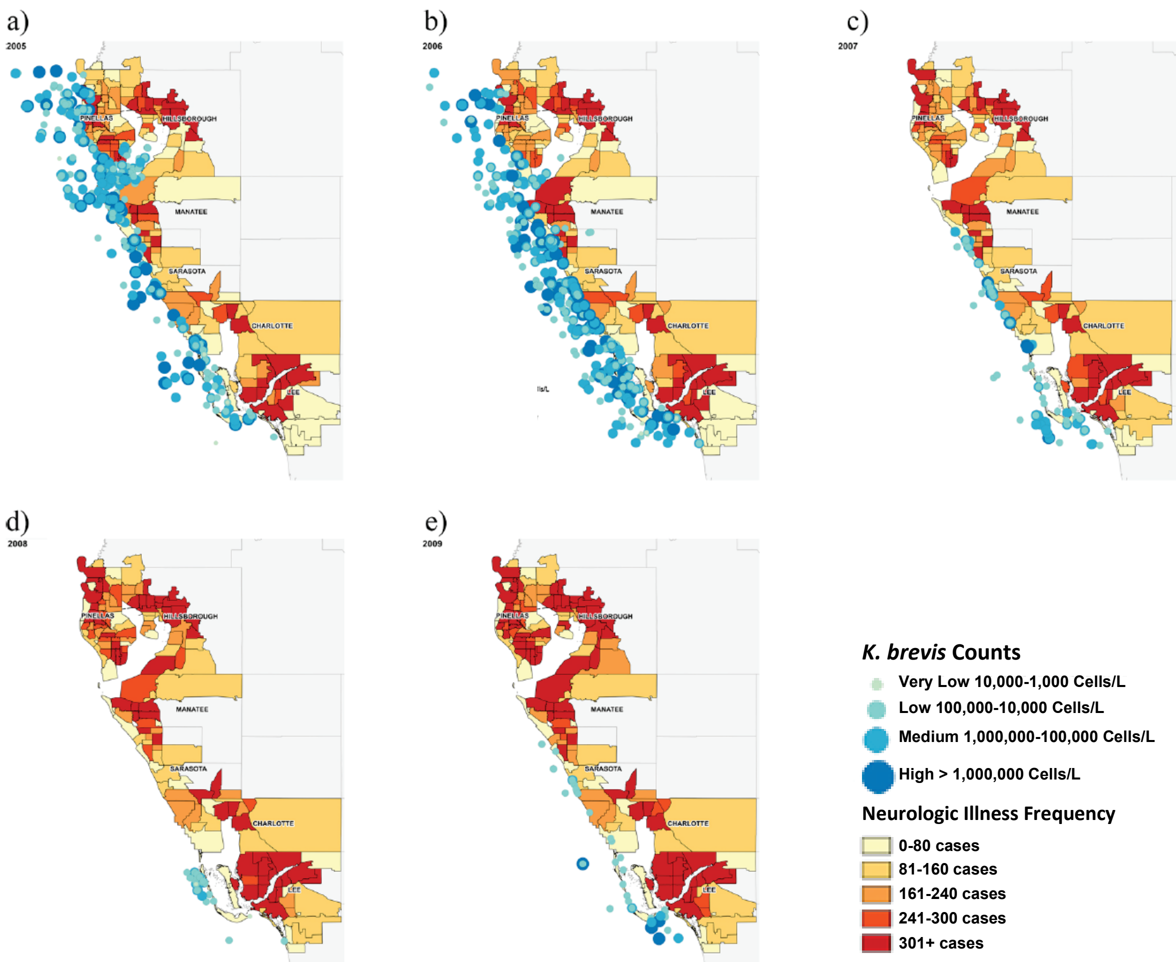

Fig. 2.9 HAB (*K. brevis*) counts and health impacts (neurological illness) in Florida in a) 2005, b) 2006, c) 2007, d), 2008, and e) 2009. Modified from Diaz *et al*. (2019).

Let V be the response (*e.g.*, the number of visits to emergency department facilities per month in a county). The relationship between the response and several covariates was modeled as follows, using a Da Silva variance-component, moving-average formulation:

$$V_{it} = \alpha_0 + \alpha_1 HAB_{it} + \alpha_2 pop_{it} + \alpha_3 tour_{it} + \sum_{j=1}^{11} \beta_j M_j + \sum_{k=1}^{K} \gamma_k Y_k + a_i + b_t + \varepsilon_{it}$$

where i is the index for each of six individual counties, t is the index for month, α_0 is the intercept, HAB_{it} is a measure of HAB occurrence and severity in county i during month t, pop_{it} is the population in county i during month t, $tour_{it}$ is a measure of tourist visits (*i.e*., number of hotel and motel rooms occupied) in county i during month t, M_j is a categorical variable for month j, Y_k is a categorical variable for year k, a_i is a month-invariant county effect, b_t is a county-invariant time effect, and ε_{it} comprises a residual unaccounted for by the explanatory variables and the specific time and cross-sectional unit effects. α, β and γ are coefficients to be estimated. Thus, changes in V were modeled to reflect a combination of monthly and yearly fluctuations, HAB occurrences, and variations in county populations and the numbers of tourist visitors. Note that the monthly categorical variables were assumed to comprise the cumulative effects of other seasonal factors influencing visitation to a medical facility, such as cooler temperatures or the prevalence of flu outbreaks in the winter or high pollen counts in the spring or fall.

In an earlier study, Hoagland *et al*. (2014) utilized a similar model and data to calculate the costs of associated adverse health impacts. When controlling for resident population, a proxy for tourism, and seasonal and annual effects, the authors found that increases in respiratory and digestive illnesses could be explained by HABs in Florida. Specifically, HABs were associated with human health and economic effects in older cohorts (≥ 55 years of age) in six southwest Florida counties. Annual aggregate costs of illness (including treatment costs and lost incomes during both treatment and recuperation) ranged from $60,000 to $700,000 annually, but these costs could exceed $1 million per year for severe, long-lasting blooms, such as the one that occurred during 2005. Assuming that the average annual illness costs of Florida Red Tide blooms persist into the future, using a discount rate of 3%, the capitalized costs of future illnesses would range between $2 million and 24 million.

Multisectoral HAB impact analysis

Korea

Lim and Kim (2020) developed estimates of HAB economic effects on the Korean national economy, using sectoral analysis described above. The overall direct impacts are estimated to be between US$32.8 and US$57.0 million per year (Table 2.12).

Table 2.12 Economic effects of harmful HABs in Korea.

Sector	Annual economic effects (million US$)
Marine commercial fisheries	0.02
Aquaculture	4.3
Recreational fisheries	16.1–32.2
Recreation and tourism	8.1–16.2
Monitoring and management	3.2
R&D projects	1.2
Total	32.8–57.0

The direct impacts can be used as inputs to an IO model to estimate broader (indirect and induced) national impacts. According to the Bank of Korea (2017), the forward linkage multiplier (input multiplier; see section on total impacts on regional or national economies, above) for a combined marine fishery and aquaculture sector is 1.465. Applying the multiplier to the reduction of US$4.32 million in marine fishery and aquaculture due to HABs, the total impacts of the two sectors are US$6.33 million on the Korean national economy. To assess the total impacts of other marine sectors (*e.g*., recreation and tourism), the individual components of those sectors will be needed to map into the corresponding sectors in the IO model by industry classification codes (*e.g*., North American Industry Classification System (NAICS) Codes).

Mitigation and value of information: Some non-exhaustive examples

HAB forecasting and mitigation: Cases of US Northeast and West Coast

US Northeast

Shellfish growers and shellfishers alike are concerned with both the timing and duration of HAB closures. Growers tend to be involved in business planning to a more significant extent than shellfishers. Therefore, growers are more likely to take advantage of HAB predictions than shellfishers. At present, however, supplies from aquaculture account for only a small fraction of the total nearshore shellfish production in Maine and Massachusetts. The ability to plan for a closure in advance of the event can make a difference. Unexpected closures are costly to both growers and shellfishers. At this time, most growers see little value in long-term annual predictions of HAB events; however, they do see some value in short-term (*i.e*., 1- to 2-week) forecasts of potential closures. Given a short-term forecast, their primary strategy would be to harvest product in advance of a closure. Because the main market is for fresh product, with a pending closure, shellfish can be harvested in advance of a bloom and kept alive for a short period of time to be sold as needed. Given a forecast of a closure, most shellfishers also are likely to try to harvest as much product as they can prior to the closure. This strategy is limited by the time of year (availability of markets), tides, and legal restrictions. In the case of a major bloom, like the 2005 event, these response measures, which are relatively small in scale, are unlikely to mitigate all of the negative impact of HABs on the shellfishing industry (Jin and Hoagland, 2008).

In both Maine and Massachusetts, the existing monitoring system for HABs involves an ongoing program of sampling and performing laboratory tests to determine the level of HAB toxins in shellfish tissues. In the event that toxins are detected in sampled shellfish at levels that exceed the regulatory limits for human consumption, by law, a portion of the intertidal and submerged lands must be closed to shellfishing until subsequent tests show that the HAB toxins have depurated. The closures relate exclusively to the protection of public health; there is no explicit consideration of the costs of closures to either commercial or recreational shellfishers or aquaculturists. This practice could be justified on economic grounds, since public health costs associated with seafood poisoning resulting from non-closure would likely be much greater than the losses from shellfishing. Monitoring in Maine takes place from April to October. Maine spends approximately $280,000 on its monitoring and management program for HABs each year. Because HAB prediction models can track a HAB event spatially and temporally, state shellfish managers can utilize model information to guide their management actions. Specifically, rather than cordoning off large areas, they may be able to close fishing areas more selectively and precisely. Thus, during a HAB year, a larger number of unaffected shellfish beds may be kept open, thereby minimizing lost landings (Jin and Hoagland, 2008).

US West Coast

Advance notices of a potential HAB event are very important to a range of ocean user groups involved in activities that depend upon marine resources. US West Coast commercial Dungeness crab fishers, their fishing crews, crab buyers, and operators of crab processing plants are independently and collectively affected by the potential for extended season closures, evisceration orders, or cancellations due to persistent levels of domoic acid impacting the crab market. The same applies to the many small businesses that cater to large numbers of recreational razor clam harvesters who descend on Washington and Oregon's small coastal communities during fall, winter and spring razor clam openers. The money spent in small hotels, campgrounds, restaurants, bars, food markets, gas stations, *etc*. are key to these businesses' survival during the otherwise very quiet winter months. Fishery closures that can cancel an entire season due to persistent levels of DA result in lost income that cannot be recovered. To make matters worse, when DA closes the recreational razor clam fishery, Dungeness crab fishers often are impacted at the same time and in the same communities.

A potential mitigation tool for these businesses may be to make adjustments in their business plans far enough in advance to lessen the impacts of these events. HAB forecasts provided can also guide fishery and human health managers to better protect human health as well as potentially inform business plans to reduce economic losses. The potential benefits of HAB forecasting (Trainer *et al*., 2020) include:

- 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.

Moore *et al*. (2019b) sought to identify effective adaptive actions used in fishery-dependent communities in response to the 2015 HAB event. Using survey data collected across 16 fishing communities, the authors identified factors affecting an individual's income loss, likelihood of income loss recovery, and severity of emotional stress. Unsurprisingly, 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. These authors also found that income diversification was an effective strategy for reducing or recovering HAB-related income losses.

HAB forecast and value of information in the Gulf of Maine

A framework for measuring the value of HAB predictions was developed by Jin and Hoagland (2008). The framework captures the effects of both private and public responses to HABs. Using data from the New England nearshore commercial shellfish fishery and impact estimates for a large-scale HAB event in 2005, the authors illustrated how the potential value of HAB forecasts can be estimated. The results indicated that the long-term value of a HAB prediction and tracking system for the Gulf of Maine was sensitive to the frequency of HAB events, the accuracy of predictions, the choice of HAB impact measures, and the effectiveness of public and private responses.

The model for assessing the value of prediction is as follows (for fuller treatments, see Berger (1985) or Clemen (1996)). Let α denote a particular action undertaken by a decision-maker and let the random variable S denote the true state of nature. Suppose that the state of nature concerns the occurrence or non-occurrence of a HAB event within a year. Thus, S can take one of two values: H (a HAB event occurs) or N (an event does not occur). Finally, let $V(\alpha|H)$ be the annual economic value to the decision-maker for action α when a HAB event occurs, and, similarly, let $V(\alpha|N)$ be the annual value for action α when an event does not occur. In the absence of a prediction of S, the expected benefit (V_0) for action α is given by:

$$E[V_0(\alpha)] = V_0(\alpha|H)prob(H) + V_0(\alpha|N)prob(N).$$

Suppose $\alpha = \{H, N\}$, that is, the decision-maker can take one of two actions: H (an alternative harvest schedule in response to HAB) or N (a normal harvest schedule for no-HAB years). The optimal action α^* (= H or N) is the one for which the expected benefit (equation above) is maximized.

$$\alpha^* = arg\ max_\alpha \{E[V_0(H)], E[V_0(N)]\}.$$

Suppose now that an annual prediction of S is issued prior to a decision time. Let the random variable X denote this prediction, which can also take only two values: H or N. Let x be the prediction in a particular year. In light of this prediction, the decision-maker updates the probability of H or N according to Bayes' Theorem:

$$prob(s|x) = \frac{prob(x|s)prob(s)}{prob(x)}$$

where $prob(s|x)$ is the posterior probability. $prob(s|x)$ is the likelihood function of x, given s, that is, the likelihood that prediction x will have been made, given that the true state of nature is s. $prob(s)$ is the prior probability reflecting the decision-maker's existing knowledge about S. In our case $S = \{H, N\}$, the posterior probabilities are:

$$prob(H|x) = \frac{prob(H)\pi}{prob(x)}\ \ and\ \ prob(N|x) = \frac{prob(x|N)(1-\pi)}{prob(x)}$$

and

$$prob(x) = \sum prob(x|s)prob(s) = prob(x|H)\pi + prob(x|N)(1-\pi)$$

is the probability of predicting x (= H or N). The likelihood function is a measure of prediction skill. For example, for a perfect prediction, $prob(x|s) = 1$ if $x = s$ and 0 otherwise for both $s = H$ and $s = N$. In contrast, for a completely non-informative prediction, $prob(x|s) = 1/2$, irrespective of x and s. Once the decision-maker updates the probabilities, she acts as before to choose the optimal action $\alpha^{**}(x)$ to maximize expected benefits (V_1):

$$\alpha^{**}(x) = arg\,max_{\alpha(x)}\{E[V_1(H|x)], E[V_1(N|x)]\}.$$

Note that V_1 is the value function with a HAB prediction (ideally capturing changes in social welfare discussed in section on methods for assessing economic impacts of HABs), which may differ from the value function without a prediction (V_0). This is because the HAB forecast system is capable of tracking HAB movement, which leads to a reduction in the total area closed for the HAB and, in turn, a reduction in economic losses.

For the decision-maker, the difference in expected benefits when the prediction is x is:

$$D(x) = E\{V_1[\alpha^{**}(x)]\} - E[V_0(\alpha^*)].$$

The idea behind the above equation is illustrated in Figures 2.10 and 2.11. Note that this difference is conditional on the prediction being x. For $X = \{H, N\}$, the unconditional difference is given by:

$$D = D(H)prob(X = H) + D(N)\big(1 - prob(X = H)\big).$$

The quantity D, which can be shown to be non-negative, is the annual value of prediction to the decision-maker. For a period of T years ($t = 1,\ldots, T$) and a discount rate of δ, the net present value (NPV) of forecasting is:

$$\sum_{t=1}^{T} \frac{D}{(1+\delta)^t}$$

It is important to point out that the value of prediction to a region, as opposed to an individual decision-maker, will be the product of decisions made by many decision-makers. In the case of HAB predictions for a commercial shellfishery, these decision-makers will include both private harvesters and shellfish managers. Estimates of the aggregated value at the regional level can be developed using results from models of regional shellfish fisheries under different management scenarios.

In summary, estimating the value of HAB forecasting in a region involves five steps:

1. Identifying the potential impacts by economic sector (*e.g.*, commercial fisheries, aquaculture, recreational fisheries, seafood markets, tourism, public health, *etc*.).
2. 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*.
3. 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.
4. 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.
5. Developing an overall measure of prediction value using the model described above.

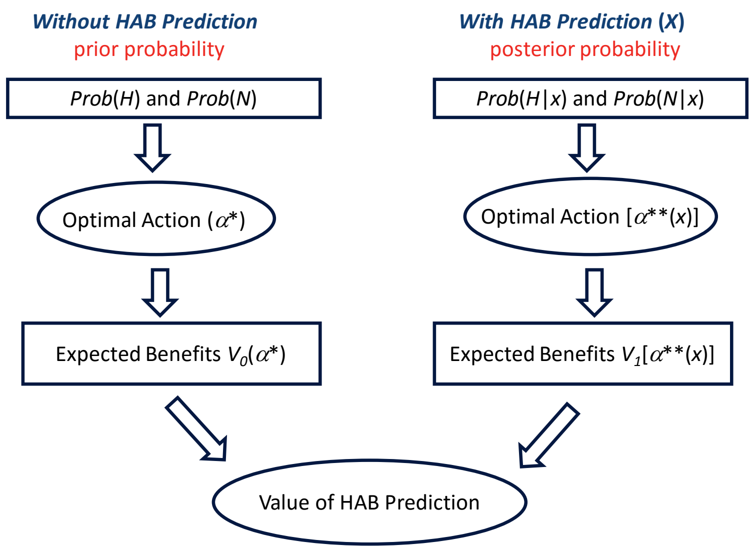

Fig. 2.10 Estimating the economic benefits of HAB forecasts.

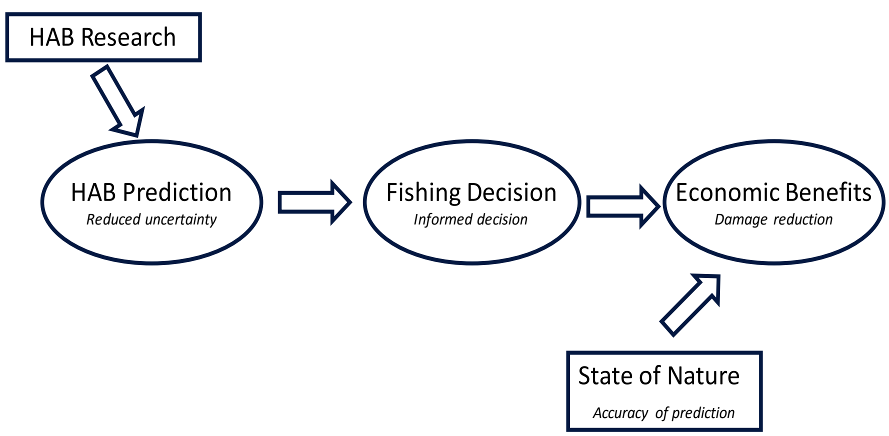

Fig. 2.11 HAB prediction and decision-making.

Additional discussions on difference approaches to estimate the value of HAB forecasting can be found in NOAA and USGS (2016) and Pearlman *et al*. (2018). These reports describe recent methodological developments in estimating the value of scientific information, as well as practical applications and solutions in the context of earth observations, including cases on flood control, HAB management, public health, and energy supply.

Insurance programs: The case of Korean aquaculture

Insurance programs have begun to play a role in HAB mitigation. The Korean aquaculture disaster insurance system was started in 2008 to compensate for damages to the aquaculture sector caused by natural disasters, including HABs. By the end of 2018, insurance products had been developed for 28 factors causing damage to aquaculture. This means that aquaculture farms will be compensated for damage caused by HABs, typhoons, strong winds, high water temperatures, low water temperatures, disease, and storms, among other environmental factors. This ensures sustainable, stable aquaculture production, thereby safeguarding the future of the aquaculture sector. By end of 2018, 4,250 (44.3%) aquaculture farms were covered by insurance. Sixty percent of the aquaculture disaster insurance premium is subsidized by the government to alleviate the burden on aquaculture farms (Lim and Kim, 2020).

Costs of HAB management and research in Korea

According to Lim and Kim (2020), both central and local governments in Korea incur costs for the monitoring and control of HAB outbreaks. This expenditure can be calculated using statistical data from the local governments and the Ministry of Oceans and Fisheries.

A monitoring system has been established in Korea to monitor and manage HAB occurrences and to minimize damage to the fishing industry. The Red Tide Monitoring and Control Office at the National Institute of Fisheries Science is responsible for prompt information collection, notification, and response. The Office monitors HABs by analyzing the results of the monthly HABs dynamics survey conducted by headquarters and regional research institutes. It also plays a role in issuing HAB warnings through breaking news. The HABs monitoring system involves ship, land, and aviation surveillance.

Table 2.13 Annual red tide monitoring and management costs in Korea.

Year	Estimated economic effect (million US$)
2010	1.7
2011	1.3
2012	0.9
2013	6.2
2014	3.6
2015	5.0
2016	3.2
2017	3.2
2018	3.2
Annual average	3.2

The annual average cost of HAB management was US$3.2 million during the 2010–2018 period (Table 2.13). The cost of monitoring and managing red tides increased significantly in 2013 after several massive HAB events.

Conclusion

This section describes the HAB economic studies presented at the Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, held during PICES-2019 in Victoria, Canada, with additional examples from the literature. The review covers different methods and different marine industry sectors at different locations. HAB research is location specific due to unique ecological and socioeconomic characteristics in each study area, and relevant economic studies have typically been designed to meet local management needs. Due to limitations of data availability, project time and budget, it is not always possible to develop a full economic analysis. Our hope is that readers of this section will find some examples and discussions which can serve as starting points for their research projects. Readers will find additional information of the studies summarized here, such as details on the frequency, duration, and intensity HAB events, specific estimation procedures, and the significance of HAB economic impacts to regional economies from the papers cited here as well as references cited in those papers.

Acknowledgments

Keith Davidson (KD), Fatima Gianella (FG), Di Jin (DJ) and Simone Martino (SM) thank PICES for travel support to attend the Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, held during PICES-2019 in Victoria, Canada. KD was funded by the UK RCUK projects OFF-AQUA and CAMPUS and the EU Atlantic Area Interreg project PRIMROSE. FG was funded by the Ocean Risk scholarship programme from AXA-XL. DJ was partially funded by the National Science Foundation Award Number: 1534054 (PFI:BIC A Smart Service System (ESPnet) for Enhanced Monitoring and Management of Toxic Algal Blooms) and benefitted from numerous discussions on relevant research topics with Porter Hoagland and Vera Trainer.

References

Adams, C.M., Larkin, S.L., Hoagland, P. and Sancewich, B. 2018. Assessing the economic consequences of harmful algal blooms: A summary of existing literature, research methods, data, and information gaps *in:* Harmful Algal Blooms: A Compendium Desk Reference *edited by* S.E. Shumway, J.M. Burkholder and S.L. Morton, John Wiley and Sons.

Anderson, D.M., Hoagland, P., Kaoru, Y. and White, A.W. 2000. Estimated annual economic impacts from Harmful Algal Blooms (HABs) in the United States. Technical Report. WHOI-2000-11.

Anderson, L.E. and Plummer, M.L. 2016. Puget Sound recreational shellfishing survey: Methodology and results. NOAA Technical Memorandum NMFS-NWFSC-132, U.S. Department of Commerce, https://doi.org/10.7289/V5/TM-NWFSC-132.

Anderson, L.E. and Plummer, M.L. 2017. Recreational demand for shellfish harvesting under environmental closures. *Marine Resource Economics* **32**: 43–57, https://doi.org/10.1086/688975.

Bank of Korea. 2017. Input-Output Statistics. Bank of Korea.

Barbier, E.B. 2000. Valuing the environment as input: application to mangrove-fishery linkages. *Ecological Economics* **35**: 7–61.

Berger, J.O. 1985. Statistical Decision Theory and Bayesian Analysis. Springer-Verlag, New York, NY.

Bresnan, E., Turrell, E. and Fraser, S. 2008. Monitoring PSP and *Alexandrium* hotspots in Scottish waters, pp. 51–54 *in:* Proceedings of the 12th International Conference on Harmful Algae, Copenhagen, Denmark, 4–8 September 2006 *edited by* Ø. Moestrup *et al*., Intergovernmental Oceanographic Commission of UNESCO.

Chambers, C. 2018. California crab industry may finally see disaster checks from 2015, mostly at $21,000 or more. Seafood News, April 30, 2018.

Clemen, R.T. 1996. Making Hard Decisions: An Introduction to Decision Analysis. Duxbury Press, Wadsworth Publishing Company, Belmont, CA.

Dees, P., Bresnan, E., Dale, A., Edwards, M., Johns, D., Mouat, B., Whyte, C. and Davidson, K. 2017. Harmful algal blooms in the Eastern North Atlantic Ocean. *Proceedings of the National Academy of Sciences* **114**: E9763–E9764, https://doi.org/10.1073/pnas.1715499114.

Diaz, R.E., Friedman, M.A., Jin, D., Beet, A., Kirkpatrick, B., Reich, A., Kirkpatrick, G., Ullmann, S.G., Fleming, L.E. and Hoagland, P. 2019. Neurological illnesses associated with Florida red tide (*Karenia brevis*) blooms. *Harmful Algae* **82**: 73–81, https://doi.org/10.1016/j.hal.2018.07.002.

Du, X., Peterson, W., Fisher, J., Hunter, M. and Peterson, J. 2016. Initiation and development of a toxic and persistent *Pseudo-nitzschia* bloom off the Oregon coast in spring/summer 2015. *PLoS ONE* **11**: e0163977, https://doi.org/10.1371/journal.pone.0163977.

Dyson, K. and Huppert, D.D. 2010. Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae* **9**: 264–271, https://doi.org/10.1016/j.hal.2009.11.003.

European Union. 2004. Regulation (EC) No 853/2004 of the European Parliament and of the Council. *Official Journal of the European Union* 30.04.2004: L139/55.

Gillig, D., Ozuna, T. and Griffin, W.L. 2000. The value of the Gulf of Mexico recreational red snapper fishery. *Marine Resource Economics* **15**: 127–139.

Groeneveld, R.A., Bartelings, H., Börger, T., Bosello, F., Buisman, E., Delpiazzo, E., Eboli, F., Fernandes, J.A., Hamon, K.G., Hattam, C., Loureiro, M., Nunes, P.A.L.D., Piwowarczyk, J., Schasfoort, F.E., Simons, S.L. and Walker, A.N. 2018. Economic impacts of marine ecological change: Review and recent contributions of the VECTORS project on European marine waters. *Estuarine, Coastal and Shelf Science* **201**: 152–163, https://doi.org/10.1016/j.ecss.2016.04.002.

Guo, H., Liu X., Ding, D., Guan, C. and Yi, X. 2014. The economic cost of red tide in China from 2008-2012, pp. 27–34 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Habas, E.J. and Gilbert, C.K. 1974. The economic effects of the 1971 Florida Red Tide and the damage it presages for future occurrences. *Environmental Letters* **6**: 139–147, https://doi.org/10.1080/00139307409437354.

Hanley, N. and Barbier, E.B. 2009. Pricing Nature. Cost Benefit Analysis of Environmental Policy. Edward Elgar, Cheltenham, UK.

Hellerstein, D. and Mendelsohn, R. 1993. A theoretical foundation for count data models. *American Journal of Agricultural Economics* **75**: 604–611, https://doi.org/10.2307/1243567.

Hoagland, P. and Scatasta, S. 2006. The economic effects of harmful algal blooms, pp. 391–402 *in:* Ecology of Harmful Algae. Ecological Studies (Analysis and Synthesis), vol. 189, *edited by* E. Granéli and J.T. Turner, Springer, Berlin, https://doi.org/10.1007/978-3-540-32210-8_30.

Hoagland, P., Anderson, D.M., Kaoru, Y. and White, A.W. 2002. The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs. *Estuaries* **25**: 819–837, https://doi.org/10.1007/BF02804908.

Hoagland, P., Jin, D., Polansky, L.Y., Kirkpatrick, B., Kirkpatrick, G. Fleming, L.E., Reich, A., Watkins, S.M., Ullmann, S.G. and Backer, L.C. 2009. The costs of respiratory illnesses arising from Florida Gulf Coast *Karenia brevis* blooms. *Environmental Health Perspectives* **117**: 1239–1243, https://doi.org/10.1289/ehp.0900645.

Hoagland, P., Jin, D., Jin, R., Ratzel, M. and Kite-Powell, H.L. 2013. A framework for estimating the economic impacts of red tide closures on yields of molluscan (bivalve) shellfish in coastal Maine. Presentation at the North American Association of Fisheries Economists (NAAFE) Forum, May 22, 2013, St. Petersburg, FL.

Hoagland, P., Jin, D., Beet, A., Kirkpatrick, B., Reich, A., Ullmann, S., Fleming, L.E. and Kirkpatrick, G. 2014. The human health effects of Florida Red Tide (FRT) blooms: An expanded analysis. *Environment International* **68**: 144–153, https://doi.org/10.1016/j.envint.2014.03.016.

Holland, D.S. and Leonard, J. 2020. Is a delay a disaster? Economic impacts of the delay of the California dungeness crab fishery due to a harmful algal bloom. *Harmful Algae* **98**: 101904, https://doi.org/10.1016/j.hal.2020.101904.

Huppert, D.D. and Trainer, V.L. 2014. Economics of razor clam fishery closures due to harmful algal blooms in Washington State, pp. 59–71 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Itakura, S. and Imai, I. 2014. Economic impacts of harmful algal blooms on fisheries and aquaculture in western Japan – An overview of interannual variability and interspecies comparison, pp. 17–26 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Jardine, S.L., Fisher, M.C., Moore, S.K. and Samhouri, J.F. 2020. Inequality in the economic impacts from climate shocks in fisheries: the case of harmful algal blooms. *Ecological Economics* **176**: 106691, https://doi.org/10.1016/j.ecolecon.2020.106691.

Jin, D. and Hoagland, P. 2008. The value of harmful algal bloom predictions to the nearshore commercial shellfish fishery in the Gulf of Maine. *Harmful Algae* **7**: 772–781, https://doi.org/10.1016/j.hal.2008.03.002.

Jin, D., Thunberg, E. and Hoagland, P. 2008. Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean and Coastal Management* **51**: 420–429, https://doi.org/10.1016/j.ocecoaman.2008.01.004.

Jin, D., Hoagland, P., Dalton, T.M. and Thunberg, E.M. 2012. Development of an integrated economic and ecological framework for ecosystem-based fisheries management in New England. *Progress in Oceanography* **102**: 93–101, http://dx.doi.org/10.1016/j.pocean.2012.03.007.

Kasperski, S. and Holland, D.S. 2013. Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences* **110**: 2076–2081.

Landsberg, J.H. 2002. The effects of harmful algal blooms on aquatic organisms. *Reviews in Fisheries Science* **10**: 113–390, https://doi.org/10.1080/20026491051695.

Larkin, S.L. and Adams, C.M. 2007. Harmful algal blooms and coastal business: Economic consequences in Florida. *Society and Natural Resources* **20**: 849–859, https://doi.org/10.1080/08941920601171683.

Lee, C., Park, Y., Park, T. and Suh, Y. 2014. Economic losses to the aquaculture industry by harmful algal blooms in Korea since 2001, pp. 35–40 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Leonard, J. and Watson, P. 2011. Description of the input-output model for Pacific coast fisheries. NOAA Technical Memorandum NMFS-NWFSC-111, U.S. Department of Commerce, 64 pp.

Leontief, W. 1936. Quantitative input and output relations in the economic system of the United States. *Review of Economics and Statistics* **18**: 105–125.

Lim, W. and Kim, D. 2020. *Cochlodinium polykrikoides* effects on wild and aquacultured fish in Asia. Presentation at the Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, October 17–19, 2019, PICES-2019, Victoria, Canada.

Lothrop, R.L., Hanson, T.R., Sammons, S.M., Hite, D. and Maceina, M.J. 2014. Economic impacts of a recreational striped bass fishery. *North American Journal of Fisheries Management* **34**: 301–310.

Martino, S., Gianella, F. and Davidson, K. 2020. An approach for evaluating the economic impacts of harmful algal blooms: The effects of blooms of toxic *Dinophysis* spp. on the productivity of Scottish shellfish farms. *Harmful Algae* **99**: 101912, https://doi.org/10.1016/j.hal.2020.101912.

McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M.D., Thomson, R.E., Cochlan, W.P. and Trainer, V.L. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophyical. Research Letters* **43**: 10,336–10,376, DOI: 10.1002/2016GL070023.

Miller, R.E. and Blair, P.D. 1985. Input-Output Analysis: Foundations and Extensions. Prentice-Hall, Englewood Cliffs, New Jersey.

Moore, S.K., Cline, M.R., Blair, K., Klinger, T., Varney, A. and Norman, K. 2019a. An index of fisheries closures due to harmful algal blooms and a framework for identifying vulnerable fishing communities on the U.S. West Coast. *Marine Policy* **110**: 103543, https://doi.org/10.1016/j.marpol.2019.103543.

Moore, K.M., Allison, E.H., Dreyer, S.J., Ekstrom, J.A., Jardine, S.L., Klinger, T., Moore, S.K. and Norman, K.C. 2019b. Harmful algal blooms: identifying effective adaptive actions used in fishery-dependent communities in response to a protracted event. *Frontiers in Marine Science* **6**: 803, https://doi.org/10.3389/fmars.2019.00803.

Moore, S.K., Dreyer, S.J., Ekstrom, J.A., Moore, K., Norman, K., Klinger, T., Allison, E.H. and Jardine, S.L. 2020. Harmful algal blooms and coastal communities: socioeconomic impacts and actions taken to cope with the 2015 U.S. West Coast domoic acid event. *Harmful Algae* **96**: 101799, https://doi.org/10.1016/j.hal.2020.101799.

Morgan, K.L., Larkin, S.L. and Adams, C.M. 2009. Firm-level economic effects of HABS: A tool for business loss assessment. *Harmful Algae* **8**: 212–218. https://doi.org/10.1016/j.hal.2008.05.002.

Morgan, K.L., Larkin, S.L. and Adams, C.M. 2011. Empirical analysis of media versus environmental impacts on park attendance. *Tourism Management* **32**: 852–859, https://doi.org/10.1016/j.tourman.2010.07.010.

Nierenberg, K., Kirner, K., Hoagland, P., Ullmann, S., LeBlanc, W.G., Kirkpatrick, G., Fleming, L.E. and Kirkpatrick, B. 2010. Changes in work habits of lifeguards in relation to Florida red tide. *Harmful Algae* **9**: 419–425, https://doi.org/10.1016/j.hal.2010.02.005.

NOAA and USGS. 2016. Report on the Value of Scientific Information Workshop. Sponsored by the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. March 3, 2016, Silver Spring, MD.

Oh, C.-O. and Ditton, R.B. 2008. A time series approach to estimating the economic impacts of exogenous events on recreational fishing. *Human Dimensions of Wildlife* **13**: 348–360. https://doi.org/10.1080/10871200802307760.

Park, T.G., Lim, W.A., Park, Y.T., Lee, C.K. and Jeong, H.J. 2013. Economic impact, management and mitigation of red tides in Korea. *Harmful Algae* **30**: S131–S143, https://doi.org/10.1016/j.hal.2013.10.012.

Parks, R., Sawn, S., Davidson, K., Turner, A., Maskery, B., Powell, A., Ford, C. and Petch, R.G. 2019. Annual report on the results of the *E. coli*, biotoxin, phytoplankton and chemical contaminants Official Control Monitoring Programmes for Scotland – 2018. Cefas Contract Reports C7711 to C7715.

Parsons, G.R. 2003. The travel cost model, pp. 269–329 *in:* A Primer on Nonmarket Valuation *edited by* P.A. Champ, K.J. Boyle and T.C. Brown, Kluwer Academic Publishers, Norwell, Massachusetts.

Parsons, G.R., Morgan, A., Whitehead, J.C. and Haab, T.C. 2006. The welfare effects of *Pfiesteria*-related fish kills: A contingent behavior analysis of seafood consumers. *Agricultural and Resource Economics Review* **35**: 348–356, https://doi.org/10.1017/S106828050000678X.

Pearlman, F., Lawrence, C.B. Pindilli, E.J., Geppi, D., Shapiro, C.D., Grasso, M., Pearlman, J., Adkins, J., Sawyer, G. and Tassa A. 2018. Demonstrating the value of earth observations: Methods, practical applications and solutions – Group on Earth Observations Side Event Proceedings. Open-File Report 2018–1054. U.S. Geological Survey, Reston, Virginia.

Pyo, H. 2009. Assessing the economic feasibility of a marine ranching project in Tongyoung. *Ocean and Polar Research* **31**: 305–318.

Richerson, K., Punt, A.E. and Holland, D.S. 2020. Nearly a half century of high but sustainable exploitation in the Dungeness crab (*Cancer magister*) fishery. *Fisheries Research* **226**: 105528, https://doi.org/10.1016/j.fishres.2020.105528.

Ritzman, J., Brodbeck, A., Brostrom, S., McGrew, S., Dreyer, S., Klinger, T. and Moore, S.K. 2018. Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae* **80**: 35–45. https://doi.org/10.1016/j.hal.2018.09.002.

Rodríguez, G.R., Villasante, S. and Carme García-Negro, M. 2011. Are red tides affecting economically the commercialization of the Galician (NW Spain) mussel farming? *Marine Policy* **35**: 252–257, https://doi.org/10.1016/j.marpol.2010.08.008.

Rongo, T. and van Woesik, R. 2012. Socioeconomic consequences of ciguatera poisoning in Rarotonga, southern Cook Islands. *Harmful Algae* **20**: 92–100, https://doi.org/10.1016/j.hal.2012.08.003.

Rowland-Pilgrim, S., Swan, S.C., O'Neill, A., Johnson, S., Coates, L., Stubbs, P., Dean, K., Harrison, K., Teixeira Alves, M., Walton, A., Davidson, K., Turner, A.D. and Maskrey, B.H. 2019. Variability of amnesic shellfish toxin and *Pseudo-nitzschia* occurrence in bivalve molluscs and water samples – Analysis of ten years of the official control monitoring programme. *Harmful Algae* **87**: 101623, https://doi.org/10.1016/j.hal.2019.101623.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic, S. and Lettieri, T. 2016. Algal bloom and its economic impact. JRC Technical Report. EUR 27905 EN. doi:10.2788/660478.

Sathirathai, S. and Barbier, E.B. 2001. Valuing mangrove conservation in southern Thailand. *Contemporary Economic Policy* **19**: 109–122.

Steinback, S.R. 2004. Using ready-made regional input-output models to estimate backward-linkage effects of exogenous output shocks. *The Review of Regional Studies* **34**: 57–71.

Statistics Korea. Fishery Production Statistics. www.kosis.kr

Taylor, T. and Longo, A. 2010. Valuing algal bloom in the Black Sea coast of Bulgaria: A choice experiments approach. *Journal of Environmental Management* **91**: 1963–1971, https://doi.org/10.1016/j.jenvman.2010.04.007.

Touzet, N., Davidson, K., Pete, R., Flanagan, K., McCoy, G.R., Amzil, Z., Maher, M., Chapelle, A. and Raine, R. 2010. Co-occurrence of the West European (Gr. III) and North American (Gr. I) ribotypes of *Alexandrium tamarense* (Dinophyceae) in Shetland, Scotland. *Protist* **161**: 370–384.

Trainer, V.L. and Yoshida, T. (Eds.) 2014. Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture. PICES Scientific Report No. 47, 85 pp.

Trainer, V.L., Kudela, R.M., Hunter, M.V., Adams, N.G. and McCabe, R.M. 2020. Climate extreme seeds a new domoic acid hotspot on the US west coast. *Frontiers in Climate*. https://www.frontiersin.org/articles/10.3389/fclim.2020.571836.

Umar, H.S., Girei, A.A. and Yakubu, D. 2017. Comparison of Cobb-Douglas and translog frontiers model in the analysis of technical efficiency in dry season tomato production. *Agrosearch* **17**: 67–77.

Van Beukering, P.J.H. and Cesar, H. 2004. Ecological economic modeling of coral reefs: Evaluating tourist overuse at Hanauma Bay and algae blooms at the Kihei coast, Hawaii. *Pacific Science* **58**: 243–260, https://doi.org/10.1353/psc.2004.0012.

Ward, F.A. and Beal, D. 2000. Valuing nature with travel cost models. Edward Elgar Publishing, Northampton, Massachusetts.

Watson, P., Wilson, J., Thilmany, D. and Winter, S. 2007. Determining economic contributions and impacts: what is the difference and why do we care? *Journal of Regional Analysis and Policy* **37**: 140–146.

Wessells, C.R., Miller, C.J. and Brooks, P.M. 1995. Toxic algae contamination and demand for shellfish: A case study of demand for mussels in Montreal. *Marine Resource Economics* **10**: 143–159, https://doi.org/10.1086/mre.10.2.42629107.

West, J.J, Travers, M., Le Bihan, V., Appere, G., Guillotreau, P., Thomas, J., Morineau, B., Pardo, S., Vulturius, G., Cusack, C. and Berdalet, E. 2019. CoCliME: Investigating the socio-economic impacts of HABs through co-development with stakeholders in European marine coastal areas. Center for International Climate Research (CICERO), Norway. Poster presentation at the Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, October 17–19, 2019, PICES-2019, Victoria, Canada.

Whitehead, J.C., Haab, T.C. and Parsons, G.R. 2003. Economic effects of *Pfiesteria*. *Ocean and Coastal Management* **46**: 845–858. https://doi.org/10.1016/S0964-5691(03)00070-X.

Whyte C., Swan, S. and Davidson K. 2014. Changing wind patterns linked to unusually high *Dinophysis* blooms around the coast of the Shetland Islands, Scotland. *Harmful Algae* **39**: 365–373.

Zhu, Z., Qu, P., Fu, F., Tennenbaum, N., Tatters, A.O. and Hutchins, D.A. 2017. Understanding the blob bloom: Warming increases toxicity and abundance of the harmful bloom diatom *Pseudo-nitzschia* in California coastal waters. *Harmful Algae* **67**: 36–43.

3 Economic Impacts and Management of *Cochlodinium* in Korea

Weol-Ae Lim[1], Do-Hoon Kim[2] and Kazumi Wakita[3]

[1] National Institute of Fisheries Science, 216 Gijanghaean-ro, Gijang-eup, Gijang-gun, Busan, 46083, Republic of Korea
[2] Marine and Fisheries Business and Economics, Pukyong National University, 45 Yongso-ro, Nam-gu Busan, 48513, Republic of Korea
[3] School of Marine Science and Technology, Tokai University, 3-20-1 Orido, Shimizu-ku, Shizuoka, 424-8610, Japan

Abstract

Cochlodinium has been the main harmful algal bloom producing marine dinoflagellate causing fish kills at aquaculture farms in Korea since the 2000s, which has also caused intense annual economic damage. To monitor and manage *Cochlodinium* bloom occurrence and minimize the damage to fisheries, various mitigation efforts, including a monitoring and notification system called "HABs Hub" and a variety of countermeasures have been established. However, the relative impacts of these efforts have not been completely estimated. Direct damage to aquaculture, the research and development budget, and various monitoring expenditures are the only economic costs that have been considered. The damage to recreational fisheries and ripple effects of the blooms through multiple industries have not yet been quantified because data availability is limited. However, because education for fishermen and public officials on controlling the blooms has been enhanced and international research cooperation has been strengthened, it is expected that more effective response efforts will be possible in the future to mitigate HABs. This summary of management and economic impacts of *Cochlodinium* blooms in Korea may serve as a reference for the development of economic impact studies and mitigation strategies for HABs in other countries. Further exchange of information to share knowledge among researchers in different disciplines is essential to develop comprehensive economic impact studies and cost-effective mitigation strategies for HABs.

Introduction

Harmful algal blooms (HABs) have become more frequent in Korean waters since the 1990s, although less dense and damaging blooms were sporadic until the 1980s. In particular, blooms of the fish-killing dinoflagellate, *Cochlodinium*, have become annual and persistent occurrences since the mid-1990s, after the first event was recorded in Jinhae Bay in 1982. The first fish kill by HABs (by *Karenia mikimotoi*) in Korea occurred in 1981, resulting in fisheries losses of 1.7 million USD (1 USD = 1,200 KRW). In

1992, *Gyrodinium* sp. caused fisheries losses of 5 million USD. Since then, *Cochlodinium* has caused fish kills in Korea with the largest losses of 7 million USD in 1993 and of 60 million USD in 1995. Throughout the 2000s and 2010s, *Cochlodinium* was the single most important fish-killing species causing damage to aquaculture farms in Korea (Lee *et al*., 2014).

Cochlodinium sp. are not known to produce a biochemical toxin; however, they cause fish to discharge a significant amount of mucilage. The main factors leading to fish kills by *Cochlodinium* blooms are associated with structural and functional changes to the gill, resulting in inactivation of enzymes, decrease of partial blood pressure and distortion of the epithelium. This results in suffocation by the decrease of oxygen exchange by the gills (Kim *et al*., 1999, 2000, 2001, 2002; Lee *et al*., 2013, 2014; Lim *et al*., 2002). *Cochlodinium* is not known to cause direct human health concerns.

Damage caused by the occurrence of Cochlodinium blooms

The occurrence of *Cochlodinium* blooms has direct detrimental effects on the aquaculture industry by causing massive mortalities of farmed fish. Local governments and the Ministry of Oceans and Fisheries have surveyed and examined the death of aquacultured fish, thereby providing useful statistical data. The annual average damage of approximately 7.7 million USD has been noted in 19 of the past 24 years (1995–2018), with the exclusion of 5 years (2008–2011, 2017), with a total amount of reported damage of 147 million USD (Table 3.1). Based on the months during which *Cochlodinium* bloom warnings have been provided, blooms occur most often in the summer (7 times in July, 12 times in August, twice in September, and once in October). The annual average duration of *Cochlodinium* blooms is over 40 days, which indicates their persistence along the southern and eastern coastlines of Korea.

Table 3.1 Annual damage and density of *Cochlodinium* blooms (NIFS, 2018a). The locations where blooms were first noted and their geographical range are shown in Figure 3.2.

Year	Warning	First observation	Geographical range	Duration (day)	Maximum density (cells/mL)	Damage (million USD)
1995	Aug 29	Goheung	Wando–Gangneung	54	30,000	63.7
1996	Sep 5	Goheung,Yeocheon	Wando–Gijang	28	23,000	1.8
1997	Aug 25	Goheung	Wando–Uljin	29	20,000	1.3
1998	Aug 3	Goheung	Wando–Geoje	34	20,000	1.3
1999	Aug 11	Goheung	Wando–Uljin	54	43,000	0.3
2000	Aug 22	Yeosu, Namhae	Goheung–Gijang	29	15,000	0.2
2001	Aug 14	Yeosu	Wando–Samcheok	42	32,000	7.0
2002	Aug 2	Yeosu	Wando–Uljin	55	30,000	4.1
2003	Aug 13	Yeosu–Namhae	Jindo–Gangneung	62	48,000	17.9
2004	Aug 5	Geoje	Wando–Geoje	30	5,800	0.1
2005	Jul 19	Goheung	Wando–Geoje	58	25,000	0.9
2006	Aug 6	Yeosu	Wando–Namhae	37	33,500	0.1
2007	Jul 31	Goheung	Wando–Uljin	50	32,500	9.6

Table 3.1 Continued.

Year	Warning	First observation	Geographical range	Duration (day)	Maximum density (cells/mL)	Damage (million USD)
2008	Jul 3	Goheung	Wando–Ulsan	62	7,300	–
2009	Oct 28	Yeosu	Yeosu–Tongyeong	20	1,660	–
2010	Sep 17	Tongyeong	Tongyeong	3	1,300	–
2011	–	–	–	–	–	–
2012	Jul 27	Goheung	Wando–Geoje, Taean	75	23,000	3.7
2013	Jul 17	Yeosu,Tongyeong	Goheung–Yangyang	51	34,800	20.6
2014	Jul 31	Goseong	Wando–Samcheok	79	20,000	6.2
2015	Aug 5	Tongyeong	Jindo–Uljin	53	32,000	4.4
2016	Aug 17	Yeosu	Goheung–Yeosu	14	2,200	3.6
	Aug 2	Jangheung	Jangheung–Goheung(Km*)	14	1,360	
2017	–	–	–	–	–	–
2018	Jul 24	Yeosu	Goheung–Busan	28	4,500	0.2
Total	–	–	–	961	–	147.0

*Km = *Karenia mikimotoi*

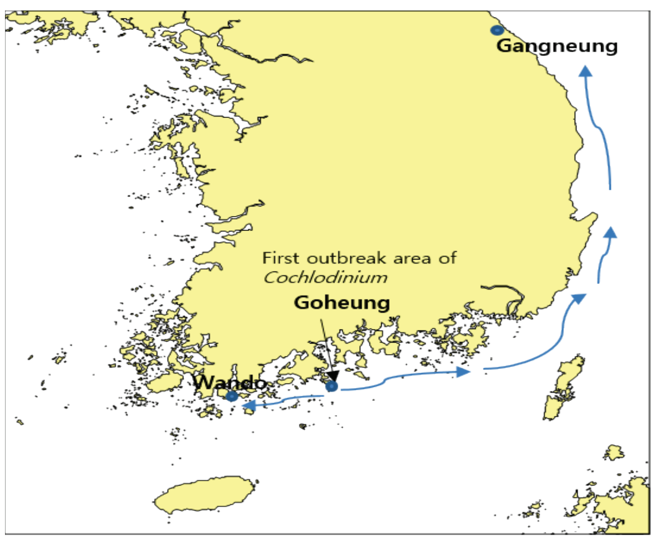

Fig. 3.1 Map of the locations where *Cochlodinium* blooms occurred in 1995 (blue arrows show the *Cochlodinium* bloom starting from Goheung in the central part of the South coast and moving eastward to Gangneung and westward to Wando along the current).

The year with the most significant damage was 1995, when there were massive *Cochlodinium* blooms which first occurred in Goheung and spread to Wando (southwestern coast) and Gangneung (eastern coast; Fig. 3.1). During that event, the *Cochlodinium* bloom lasted for 54 days and caused 63.7 million USD of damage, which accounted for approximately 43% of the total damage caused by algal blooms over a 24-year period. However, large-scale damage has been noted more recently (Fig. 3.2), totaling 17.9 million USD in 2003, 9.6 million USD in 2007, and 20.6 million USD in 2013 (NIFS, 2018a).

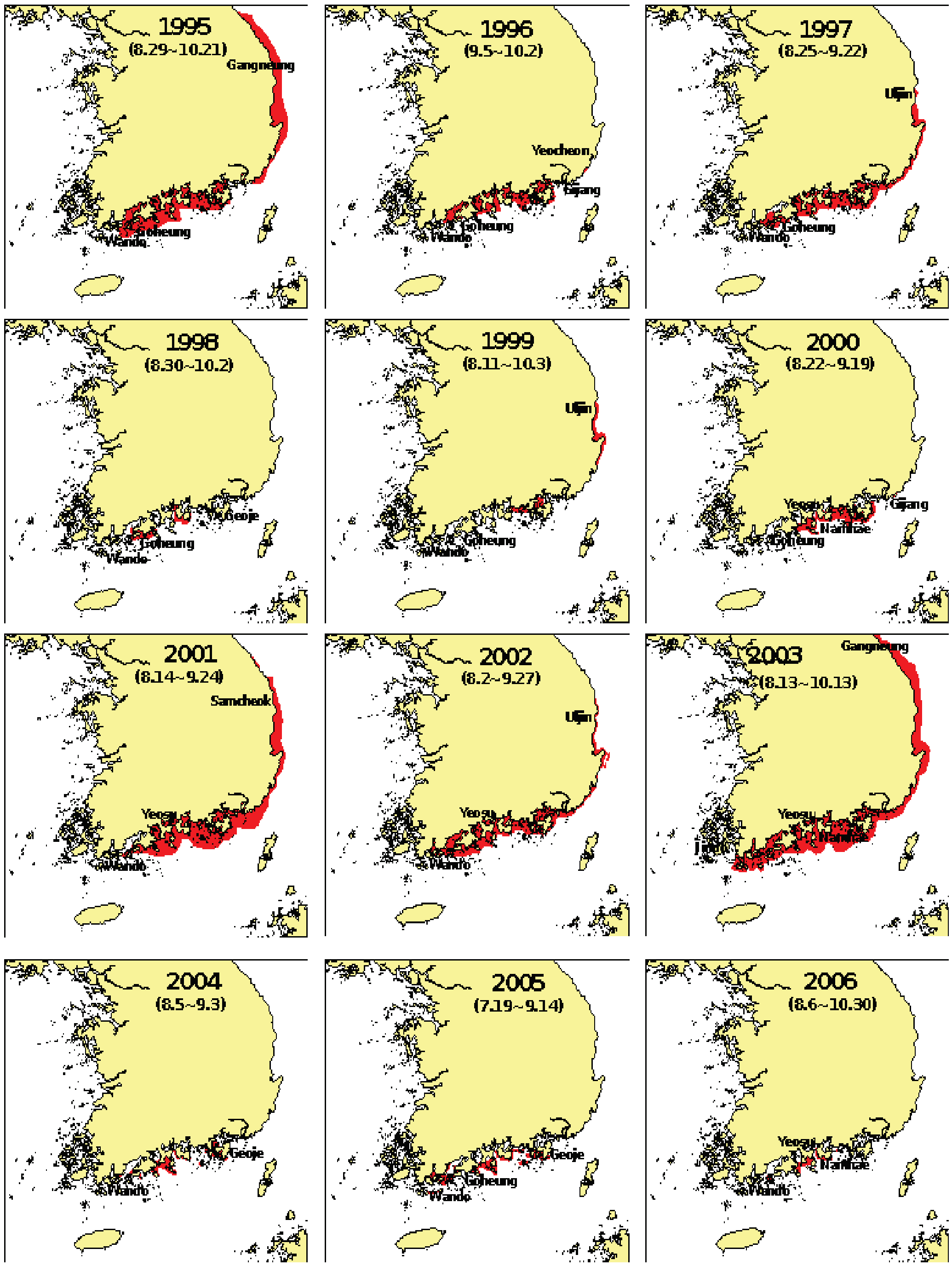

Fig. 3.2 Areas (red) where *Cochlodinium* blooms caused fisheries damage in 1995–2019 with duration (month/day) shown in parenthesis. Total economic damage accounted for ≥10 million USD in 1995, 2003, 2007, and 2013. Locations where damage was first described and geographical extent of damage is documented in Table 3.1. Source: www.nifs.go.kr/red/gallery_1.red.

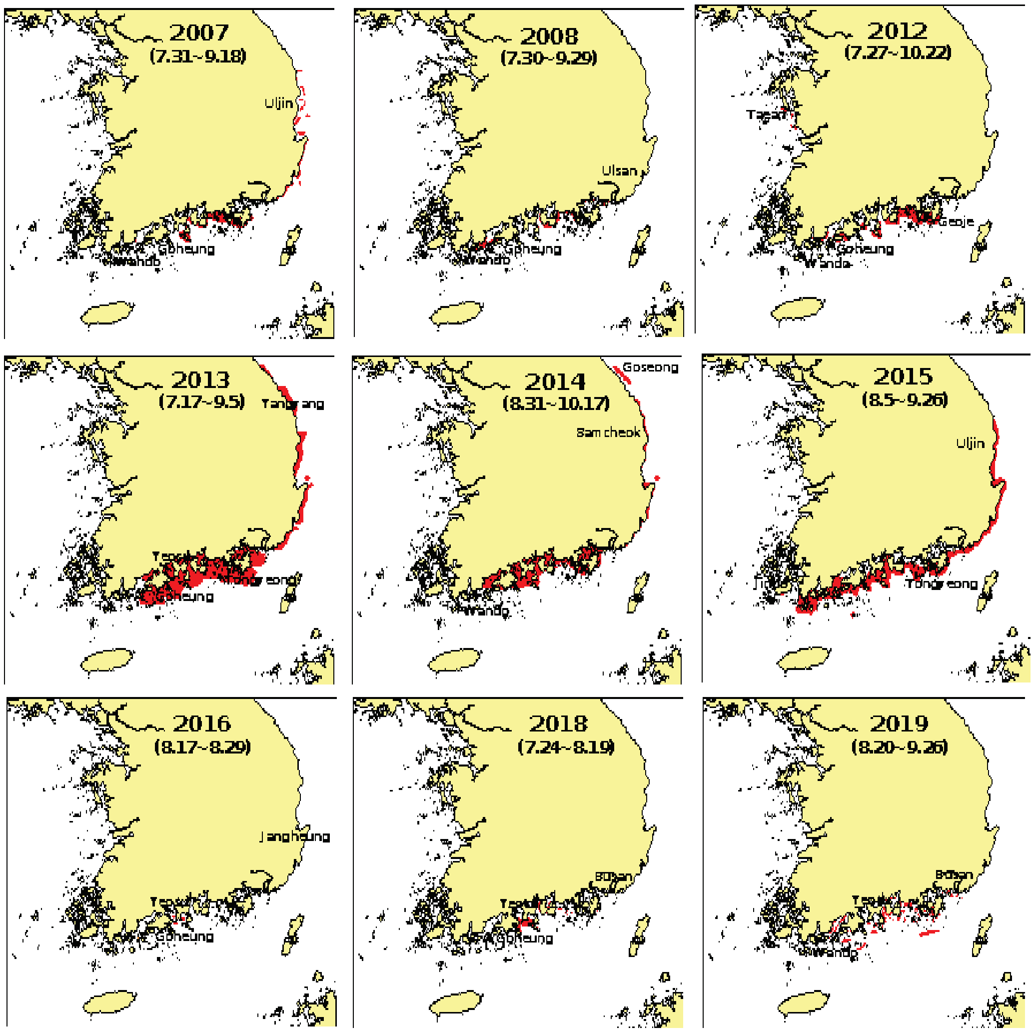

Fig. 3.2 Continued.

Example approaches for economic analysis of Cochlodinium

Recreational fisheries

The economic impact of the occurrence of *Cochlodinium* blooms thus far has been evaluated mainly on commercial fishery losses, reduced tourism sales, and monitoring and management costs (Anderson *et al*., 2000; Hoagland *et al*., 2002; Huppert and Trainer, 2014; Sanseverino *et al*., 2016). In particular, the impact on aquaculture has been intensively evaluated in Asian countries such as Japan and China (Guo *et al*., 2014; Itakura and Imai, 2014).

An important factor that has not been evaluated thus far is reduced availability of coastal regions by recreational fishermen during *Cochlodinium* blooms. Previous studies have only evaluated the effects on regional tourism due to the occurrence of the blooms. It should be noted that this occurrence also reduced the number of trips by recreational fishermen to fishing areas in the relevant regions, thus decreasing the consumer surplus (*i.e*., their utility) because the regions where the blooms frequently occur are popular for recreational fishing.

In order to estimate the effect of *Cochlodinium* blooms on recreational fisheries, it is necessary to measure the utility (satisfaction) of fishermen who visit the areas for recreational fishing. The Travel Cost Model (TCM) is the most widely used method to measure the utility of recreational fishermen (Gillig *et al*., 2000; Parsons, 2003; Lothrop *et al*., 2014). The TCM is a method used to estimate the demand for recreational uses through the collection of travel cost data that quantifies access and use of a site. Travel cost demand models use negative binomial and Poisson distributions to estimate consumer surplus for the use of a recreational site for a recreational activity. Consumer surplus or the willingness to pay (WTP) for a recreational trip above and beyond a person's actual expenditures can be estimated from the TCM demand equation (Ward and Beal, 2000).

The TCM technique was used to analyze the economic utility of fishing trips by recreational fishermen in major southern coastal regions of Korea where blooms occur frequently. In-person surveys were conducted among these fishermen to investigate the costs incurred on the trips as well as detailed personal information. For example, the demand function for a representative recreational angler in the Yeosu area on the southern coast is shown in equation (1):

$$TRIPS_i = EXP(\beta_0 + \beta_1 COST_i + \beta_2 CATCH_i + \beta_3 INCOME_i + \beta_4 MARRIAGE_i + \beta_5 AGE_i + \varepsilon_i) \tag{1}$$

where *TRIPS* is the number of single-day recreational trips taken by individual angler, *i*. *COST* denotes travel costs including the opportunity cost of time (a quarter of monthly income) incurred by the angler to gain access to the recreational fishing region, *CATCH* refers to catch amount (kg), *INCOME* is the individual's household income, *MARRIAGE* is a dummy variable that is equal to 1 if an angler is married, *AGE* is the angler's age, and ε_i is a disturbance distributed as a gamma distribution with a mean of 1 and variance α (Gillig *et al*., 2000). Hellerstein and Mendelsohn (1993) have shown that the per-trip expected value of consumer surplus, $E(CS)$, derived from count models can be simply calculated as $E(CS) = 1/{-\beta_1}$, where β_1 is the travel cost coefficient.

The demand function in equation (1) was analyzed using the Poisson and negative binomial models. The model results showed that the degree of overdispersion in the negative binomial model was significant, indicating that the Poisson model would not be inappropriate. The direction of the estimated coefficients appeared to be similar to related previous studies, and thus, it could be derived that the lower the fishing trip costs and the bigger the catch, the higher the number of trips taken.

Based on the analysis of the demand function in the negative binomial model, the economic value or utility (satisfaction) for each round trip taken by each recreational fisherman was estimated to be approximately 122 USD (1 USD = 1,189 KWD, as of January 27, 2020). In order to calculate the annual economic value of the recreational fishing sector in the Yeosu region, the economic value per trip for recreational fisherman *i* needs to be multiplied by the average number of trips made by fisherman *i* and the total number of recreational fishermen visiting annually. The decline in the utility of recreational fishermen due to the occurrence of *Cochlodinium* blooms can be calculated by multiplying the economic value per person estimated by the TCM by the reduction in the number of trips due to the number of days of *Cochlodinium* blooms per year and the total number of annual trips made by recreational fishermen to the relevant regions.

In major regions in which *Cochlodinium* blooms occur frequently (*i.e*., Yeosu, Gangjin, Tongyoung, Geoje, and Gijang), an average of 21 annual trips were taken, the average cost was estimated at 72.5 USD per trip, and the total economic value per trip was estimated at 144.2 USD per person. Assuming that *Cochlodinium* blooms occurred in only one specific region among major regions where they occur frequently, the decrease in the utility value due to *Cochlodinium* blooms was estimated to be an average of 16.1 million USD per year over the 2010–2018 period. However, if *Cochlodinium* blooms occur simultaneously in many regions, the decrease in utility value is expected to be even greater.

The impact on recreational fisheries was assessed to be much more than what was suggested by previous studies. In fact, the impact on recreational fisheries was estimated to be greater than direct damage to the aquaculture sector in Korea. Therefore, it is crucial to include this impact in the analysis of the economic damage caused by the blooms in future studies.

Ripple effects

In addition, the national economic ripple effects should be included in the analysis because marine fishery and aquaculture industry products are used as intermediate products in other industries. When harmful blooms occur and result in fish kills or the suspension/shutdown of fisheries and aquaculture activities, reductions in fisheries and aquaculture productions can adversely impact and decrease sales in other industries, in a similar way that lower tourism sales can cause a reduction in utility in recreational fisheries. Such linkage (ripple) effects can be analyzed through the Input-Output (IO), Multi-Regional Input-Output (MRIO), Social Accounting Matrix (SAM), and Computational General Equilibrium (CGE) models, using the inter-industry relation table. However, previous studies analyzing the ripple effects of the blooms (*e.g*., Dyson and Huppert, 2010) have been quite limited but confirm that assessing the economic damage for only one industry, such as marine fisheries or aquaculture, can lead to gross underestimation of its extent. Therefore, an analysis of the ripple effects, which evaluates the degree of inter-industry effect between related industries, must be considered in future economic studies.

Prevention and management of damage from Cochlodinium blooms

To reduce the detrimental effects on the fisheries caused by severe *Cochlodinium* blooms and other HAB events, a monitoring system called the "HABs Hub" was established by the National Institute of Fisheries Science (NIFS) to ensure prompt collection of samples, notification to fish farmers, and response to avoid damage when the blooms occur. Regular monitoring surveys of algal blooms are conducted monthly by NIFS headquarters and each regional fisheries institute. Forecasts are issued by NIFS to reduce damage to the fishing industry and by preventing human health costs of paralytic, diarrheic and amnesic shellfish poisoning. The HABs monitoring system is composed of vessel monitoring, land and air surveillance (Table 3.2).

The four types of bloom forecasts include pre-warning, warning, alert, and all clear. The president of NIFS, who leads the HAB effort, may issue forecasts regardless of size or density of the blooms when there are concerns that there will be fisheries damage due to the oceanic conditions or water quality. Moreover, warnings may be issued when necessary measures must be taken to mitigate fishery damage. The density of the blooms determines the forecast criteria issued for each species, and different forecasts will dictate the type of mitigation measures implemented by aquaculture farms (Table 3.3), such as environment management (*e.g*., bubbling near cages to increase oxygenation or installation of curtains) and withholding of fish food to minimize possible damage to farmed fish.

Table 3.2 HAB monitoring system.

Category	Location	Sampling period	Organization
Vessel monitoring	102 locations nationwide	Mar–Nov (monthly)	National Institute of Fisheries Science
Coastal surveillance	130 locations in 34 cities and counties nationwide	Apr–Oct (usually twice a week)	Local Governments
Air surveillance	Waters where the bloom forecasts are issued	continuously	Korea Coast Guard (in cooperation with relevant organizations)

Table 3.3 HAB forecasts issued by the National Institute of Fisheries Science (NIFS). Categories are determined by cell densities of HAB species. Source: www.nifs.go.kr/red/operation_4.red.

Category		Criteria
Pre-warning	Size	When the occurrence of the blooms is expected because the density of cells has increased.
	Density of blooms (cells/ml)	- *Chattonella* spp.: >1,000 - *Cochlodinium polykrikoides*: >10 - *Gyrodinium* sp.: >200 - *Karenia mikimotoi*: >500 - Other flagellated algae: >10,000 ○ Diatoms: >20,000 ○ Mixed: >20,000, when flagellates are > 50% of the total
Warning	Size	Phytoplankton present with radius of 2–5km (12–79 km^2) and concerns regarding the damage to fisheries.
	Density of blooms (cells/ml)	- *Chattonella* spp.: >2,500 - *Cochlodinium polykrikoides* : >100 - *Gyrodinium* sp.: >500 - *Karenia mikimotoi*: >1,000 - Other flagellated algae: >30,000 ○ Diatoms: >50,000 ○ Mixed: >40,000, when flagellates are > 50% of the total
Alert	Size	Phytoplankton present with a radius of ~5km (79 km^2) and there are expectations for considerable damage to fisheries.
	Density of blooms (cells/ml)	- *Chattonella* spp.: >5,000 - *Cochlodinium polykrikoides*: >1,000 - *Gyrodinium* sp.: >2,000 - *Karenia mikimotoi* : >3,000 - Other flagellated algae: >50,000 ○ Diatoms: >100,000 ○ Mixed: >80,000, when flagellates are > 50% of total
All clear	When the blooms have dissipated, there is no risk of fishery damage, and water quality has returned to normal state.	

The missions of several government organizations include HAB response (Fig. 3.3). However, the bloom forecast and notification system is the responsibility of NIFS, based on the detection of HABs by local governments (Table 3.3). The forecast and a specific warning level are issued by e-mail, on the NIFS website (www.nifs.go.kr/red/news_1.red), and using SMS (Short Message Service) and fax. Ultimately, a report is sent to the Ministry of Oceans and Fisheries, which is responsible for controlling the blooms by establishing appropriate mitigation measures in collaboration with other related government agencies (Ministry of Public Safety and Security, Ministry of Environment, Ministry of Science Information Communications Technologies [ICT]).

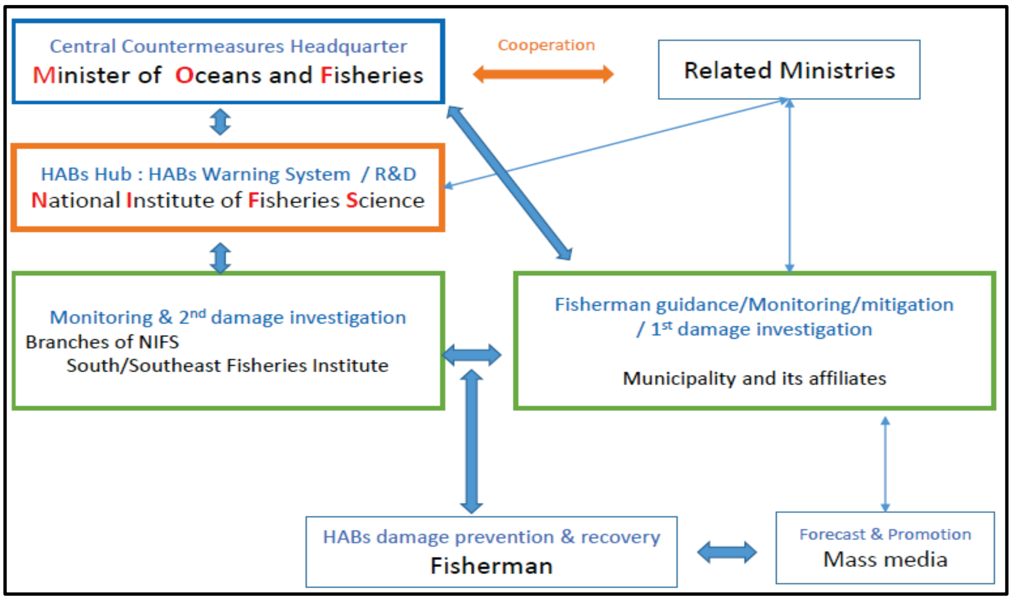

Fig. 3.3 Government organizations and their missions in HAB response (NIFS, 2019).

To reduce damages caused by the blooms, research and development activities have been conducted since 2014. The research and development funded by the Ministry of Oceans and Fisheries has cost 7.19 million USD since 2014, averaging approximately 1.8 million USD a year (Table 3.4). Research activities have included monitoring the mechanisms of occurrence, commercialization of eco-friendly mitigation measures, and reduction of damage caused by blooms at aquaculture farms.

Research and development supported by the Ministry of Science, ICT and Future Planning totaled 7.51 million USD over 5 years starting in 2013, averaging approximately 1.4 million USD a year (Table 3.5). The research focused on early prediction of the blooms, development of forecast technology, and development of a prediction and control system to reduce the spread of HABs.

The prevention and control of the blooms has been an area of great interest, receiving funding in recent years from the Ministry of Science and ICT (Table 3.5). *Cochlodinium* has thin cell walls, thus can be easily destroyed and killed when specific clay substances are sprayed into seawater containing these cells. Other methods used to control the blooms include spraying chemicals such as copper sulfate, using ultrasonic waves, or using natural competitors, such as bacteria and virus.

Yellow clay spray has been generally applied as an eco-friendly method to control blooms. When diluted in water, yellow clay forms a colloidal particles complex with bloom organisms and precipitates from surface waters. These materials effectively kill the blooms, but may also kill other beneficial microorganisms in the water. On the other hand, yellow clay is considered the most eco-friendly substance, having little effect on the marine ecosystem when it is used (Kagoshima Fisheries Technology Development Center, 2018).

Table 3.4 Research and development funded by the Ministry of Oceans and Fisheries.

Research project	Budget (million USD)				
	2014	**2015**	**2016**	**2017**	**Total**
Research on monitoring and the mechanism of bloom occurrence	0.63	0.64	0.64	0.63	2.54
Research on commercialization of eco-friendly substances for the bloom mitigation	0.50	0.53	0.53	–	1.56
Monitoring costs in waters where clay is distributed	–	–	–	0.25	0.25
Research on reducing HAB damage to aquaculture farms	0.48	0.50	0.50	–	1.48
Research on technologies for mitigation of HAB damage to aquaculture	–	–	–	0.36	0.36
Research on developing HAB prediction and mitigation methods	0.25	0.25	0.25	0.25	1.00
1. HAB monitoring using molecular probe methods	0.09	0.11	0.11	0.10	0.41
2. Research on cyst populations and life history of *Cochlodinium*	0.06	0.06	0.08	0.08	0.28
3. Research on nutrients and environmental factors impacting blooms occurrence	0.10	0.08	0.06	0.07	0.31
Total	1.86	1.92	1.92	1.49	7.19

Table 3.5 Research and development supported by the Ministry of Science and ICT.

Research project	Budget (million USD)					
	2013	**2014**	**2015**	**2016**	**2017–2018**	**Total**
Development of bloom forecast technology		0.83				0.83
Development of control system to mitigate the spread of the blooms	0.83	1.33	1.67	1.67	1.18	6.68
1. Developing nanotubes (filters) to purify seawater	0.21	0.45	0.54	0.54	0.38	2.12
2. Developing eco-friendly algicidal microorganisms to mitigate blooms	0.42	0.58	0.65	0.65	0.49	2.79
3. Developing a portable diagnosis kit to detect algal bloom organisms	0.21	0.29	0.48	0.48	0.31	1.77
Total	0.83	2.16	1.67	1.67	1.18	7.51

A government budget of approximately 44.0 million USD has been invested over the past 16 years (2003–2018) in projects to develop countermeasures. The national government provides 78% (34.2 million USD) of this budget and 22% is provided by local governments (9.8 million USD). Table 3.6 presents the annual national and local budget.

Table 3.6 Annual budget (million USD) for HAB control (NIFS, 2018b).

Expenditure	2003	2004	2005	2006	2007	2008	2009	2010
National treasury	2.13	1.43	1.19	1.30	0.61	0.48	0.74	0.86
Local expenditure	2.13	1.43	1.19	1.30	0.61	0.48	0.74	0.86
Total	4.25	2.85	2.38	2.60	1.22	0.95	1.48	1.72
Expenditure	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
National treasury	0.65	0.44	6.17	3.58	5.0	3.21	3.21	3.21
Local expenditure	0.65	0.44	–	–	–	–	–	–
Total	1.30	0.88	6.17	3.58	5.0	3.21	3.21	3.21

Outreach and education measures provide detailed information about HABs to the community. Training and education are provided for fishermen and public servants in charge of related tasks to ensure that they can take appropriate actions to control blooms and mitigate their damage. Researchers at NIFS have also been actively participating in international workshops and meetings on HABs to share information, which also assists with the establishment of more effective measures to control HABs.

Valuation of mitigation and future challenges

As explained above, various mitigation efforts including a HABs HUB and a variety of countermeasures have been established to minimize the negative impacts by HABs, especially targeted on minimizing the effects of *Cochlodinium* blooms. However, the relative impacts of these efforts have not been completely estimated. To fully understand which research and countermeasures are the most effective, further multi-disciplinary studies are needed. In Korea and Japan, together with other nations in Asia, ministries and fisheries agencies need estimates of the relative value of research, monitoring and mitigation measures to justify their support of HAB research and monitoring. Estimates of the economic impact of *Cochlodinium* blooms and evaluation of the cost of various mitigation strategies will also be helpful to countries in Southeast Asia which have observed an increasing number of fish kills associated with *Cochlodinium* blooms since the 2000s (Wakita and Iwataki, 2017).

Although a complete economic valuation of the effects of mitigation is difficult, empirical valuation is possible. Regarding the HABs Hub, it has been proven that many fishermen use it frequently, based on website access data. Fishermen in Nagasaki prefecture in Japan have stated the benefits of yellow clay to their livelihood (personal communication with Wakita and Iwataki, October 3, 2017). The value of yellow clay spray countermeasures must be estimated, considering the fact that Korea has sprayed yellow clay on HABs for many years.

The control of the blooms using yellow clay has been a strong initiative led by the Ministry of Oceans and Fisheries, National Government of Korea. This firm commitment by the Ministry of Oceans and Fisheries is partly to address persistent requests from fish farmers. This pledge to support and implement mitigation measures is important; however, it also has challenges. Frequent applications of yellow clay spray will reduce the supply of high-quality clay so that it may not be available in the future. Also, strong leadership by the government may result in a passive "wait-and-see" attitude by some fish farmers, resulting in further losses. In order to encourage active participation by farmers in controlling and mitigating damage by HABs, the Korean government has been changing major mitigation strategies to a more proactive approach of selecting for healthy, robust fish that may be resistant to HABs, rather than only reacting after HABs have been detected. The NIFS provides information on how sea farmers involved in aquaculture, such as shellfish farms, marine fish farms, and land-based farms can prevent their products from damage caused by the blooms so that they can mitigate HABs without government action.

Acknowledgments

This study was supported by a grant from the national Institute of Fisheries Science, Republic of Korea (R2020040).

References

Anderson, D.M., Kaoru, Y. and White, A.W. 2000. Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States. Technical Report. WHOI-2000-11.

Dyson, K. and Huppert, D.D. 2010. Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae* **9**: 264–271.

Gillig, D., Ozuna, T. and Griffin, W.L. 2000. The value of the Gulf of Mexico recreational Red Snapper fishery. *Marine Resource Economics* **15**: 127–139.

Guo, H., Liu X., Ding, D., Guan, C. and Yi, X. 2014. The economic cost of red tide in China from 2008–2012, pp. 27–34 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Hellerstein, D. and Mendelsohn, R. 1993. A theoretical foundation for count data models. *American Journal of Agriculture Economics* **75**: 604–611.

Hoagland, P., Anderson, D.M., Kaoru, Y. and White, A.W. 2002. The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs. *Estuaries* **25**: 819–837.

Huppert, D.D. and Trainer, V.L. 2014. Economics of razor clam fishery closures due to harmful algal blooms in Washington State, pp. 59–71 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Itakura, S. and Imai, I. 2014. Economic impacts of harmful algal blooms on fisheries and aquaculture in western Japan-An overview of interannual variability and interspecies comparison, pp. 17–26 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Kagoshima Fisheries Technology Development Center. 2018. Manual on preventing damage by red tides using improved clay. http://kagoshima.suigi.jp/akashio/newHP/2018/（最終版）散布マニュアル-2.pdf. (in Japanese)

Kim, C.S., Lee, S.G., Lee, C.K., Kim, H.G. and Jung, J. 1999. Reactive oxygen species as causative agents in the ichthyotoxicity of the red tide dinoflagellate *Cochlodinium polykrikoides*. *Journal of Plankton Research* **21**: 2105–2115.

Kim, C.S., Lee, S.G. and Kim, H.G. 2000. Biochemical responses of fish exposed to a harmful dinoflagellate *Cochlodinium polykrikoides*. *Journal of Experimental Marine Biology and Ecology* **254**: 131–141.

Kim, C.S., Lee, S.G., Kim, H.G. and Lee, J.S. 2001. Screening for toxic compounds in the red tide dinoflagellate *Cochlodinium polykrikoides*: Is it toxic plankton? *Algae* **16**: 457–462.

Kim, C.S., Jee, B.Y. and Bae, H.M. 2002. Structural alterations in the gill of the red sea bream, Pagrus major, exposed to the harmful dinoflagellate *Cochlodinium polykrikoides*. *Journal of Fisheries Science and Technology* **5**: 75–78.

Lee, C.K., Park, T.G., Park, Y.T. and Lim, W.A. 2013. Monitoring and trends in harmful algal blooms and red tides in Korean coastal waters, with emphasis on *Cochlodinium polykrikoides*. *Harmful Algae* **30S**: S3–S14.

Lee, C.K., Park, Y.T., Park, T.G. and Suh, Y.S. 2014. Economic losses to the aquaculture industry by harmful algal blooms in Korea since 2001, pp. 35-47 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture *edited by* V.L. Trainer and T. Yoshida. PICES Scientific Report. No. 47, 85 pp.

Lim, W.A., Jung, C.S., Lee, C.K., Cho, Y.C., Lee, S.G., Kim, H.G. and Chung, I.K. 2002. The outbreak, maintenance, and decline of the red tide dominated by *Cochlodinium polykrikoides* in the coastal waters off Southern Korea from August to October, 2000. *The Sea* **7**: 68–77.

Lothrop, R.L., Hanson, T.R., Sammons, S.M., Hite, D. and Maceina, M.J. 2014. Economic Impacts of a Recreational Striped Bass Fishery. *North American Journal of Fisheries Management* **34**: 301–310.

NIFS (National Institute of Fisheries Science). Algal Bloom Information System. http://www.nifs.go.kr/red/main.red.

NIFS. 2018a. 95-18 Annual Algal Bloom Occurrence and Damage.

NIFS. 2018b. Annual Budget for Algal Bloom Control Project.

NIFS. 2019. *Cochlodinium polykrikoides* effects on wild and aquacultured fish in Asia. Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, October 17–19, 2019, PICES-2019, Victoria, Canada.

Parsons, G.R. 2003. The travel cost model, pp. 269–329 *in:* A Primer on Nonmarket Valuation *edited by* P.A. Champ, K.J. Boyle and T.C. Brown, Kluwer Academic Publishers, Norwell, Massachusetts.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic, S. and Lettieri, T. 2016. Algal bloom and its economic impact. JRC Technical Report. EUR 27905 EN. doi:10.2788/660478.

Wakita, K. and Iwataki, M. 2017. Reports and trends of harmful algal blooms with fish kills in Southeast Asia. *Journal of Coastal Zone Studies* **30**: 41–52. (in Japanese with abstract in English)

Ward, F.A. and Beal, D. 2000. Valuing Nature with Travel Cost Models. Edward Elgar Publishing, Northampton, Massachusetts.

4 An Economic Assessment of Ciguatera Outbreaks – An Island Model

Charles G. Trick[1], Leif Anderson[2], Danielle Beausoleil[3], Elisa Berdalet[4], William P. Cochlan[5], Pengbin Wang[6] and Mark L. Wells[7,8]

[1] Department of Biology, University of Saskatchewan, Science Pl, Saskatoon, SK, S7N 5C8, Canada
[2] Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E, Seattle, WA 98112, USA
[3] Department of Biology, Western University, 1151 Richmond St. N, London, ON, N6A 5B7, Canada
[4] Institute of Marine Sciences (ICM-CSIC), Pg. Marítim de la Barceloneta, 37-49, Barcelona, Catalonia, 08003, Spain
[5] Estuary and Ocean Sciences Center, San Francisco State University, 3150 Paradise Dr., Tiburon, CA 94920-1205, Tiburon, USA
[6] Key Laboratory of Marine Ecosystem and Biogeochemistry, Second Institute of Oceanography, Ministry of Natural Resources, 36 Baochubei Rd., Hangzhou, Zhejiang, 310012, People's Republic of China
[7] School of Marine Science, University of Maine, Orono, ME 04469, USA
[8] Key Laboratory of Marine Ecosystem and Biogeochemistry, Second Institute of Oceanography, Ministry of Natural Resources, 36 Baochubei Rd., Hangzhou, Zhejiang, 310012, People's Republic of China

Abstract

With the nexus of climate change, globalization, and dwindling marine fishes, more attention is being paid to the increasing global burden of ciguatera fish poisoning (CFP) and the development of appropriate strategies for intervention, especially in endemic areas such as the South Pacific Islands and the Caribbean Sea. CFP is a non-bacterial food poisoning event with outbreaks around the world in which fish concentrate a potent neurotoxin (ciguatoxin) in their organs and tissues from inadvertent feeding on toxic benthic algal species. Outbreaks are frequent in endemic areas in the tropics and semi-tropics with developed corals and benthic fish fisheries. Occurrences are also present in non-endemic areas where contaminated fish are exported for consumption. Local populations on tropical or semi-tropical islands are particularly vulnerable to this poisoning through the consumption of ciguatoxin-contaminated fish. Here, we consider the pecuniary costs of population exposure to CFP using two published studies as a template for developing a case study of the eco-socio-economic cost model in island nations.

Introduction

Ciguatera fish poisoning (CFP) has likely been a health concern in the South Pacific Islands for more than a century. The logs from Captain James Cook's first voyage, and the diaries of the two naturalists aboard HMS *Resolution* (1772–1775), document fish poisonings among the crew that they linked directly to the consumption of fish caught in what is now referred to as the SPC (South Pacific Commission, also known as South Pacific Community; Doherty, 2005). As with many fish poisonings, it is uncertain if the responsible toxin was ciguatoxin (CTX), tetrodotoxin (TTX), or maitotoxin (MTX) (Doherty, 2005). The distinctions are scientifically relevant, but the clinical diagnostics (Lipkin, 1989), human health symptoms (Dickey and Plakas, 2010), and social and economic impacts (Lewis 1986a,b; Friedman *et al*., 2008) are similar. A detailed meta-analysis of CFP outbreaks has recently been published (Friedman *et al*., 2017).

Benthic-feeding reef fish accumulate ciguatoxins from the inadvertent consumption of benthic dinoflagellate phytoplankton of the genus *Gambierdiscus* that inhabits the surfaces of corals and benthic macroalgae. Although the levels of CTX are very low concentrations on a per cell basis, the toxin is fat soluble so that once consumed it is preferentially retained and concentrated in the fish organs and tissues. Toxin levels in benthic fish are a complex function of *Gambierdiscus* abundance on the substrate fish are feeding on, integrated over the fish lifetime, the age of the fish (more or less time for toxin accumulation), and the rate of toxin loss from the fish – all factors that are not well understood for any given coastal system. These toxins, in turn, are bioaccumulated in predators (*e.g*., grouper, barracuda) consuming the benthic-feeding fish, which further bioconcentrate CTX. It is often then, but not always, that these consumer-desirable reef fish are the most toxic fish in a coral system. Complicating things further is that there are no reliable, easy toxin testing methods for CTX, and fish metabolism can derivatize CTXs sufficiently to make their detection more challenging without reducing their toxicity. It is no exaggeration to say that CFP is the least understood of the major harmful algal bloom syndromes.

At present, CFP is the leading cause of seafood borne disease in tropical and sub-tropical regions and is often reported to hold this distinction globally. CTX-contaminated fish are a threat to human health at concentrations greater than 0.1 ppb (Pearn, 1996, 2001). CFP results only from consuming fish containing CTX and its close metabolic derivatives, producing a complex array of gastrointestinal, neurological, and cardiological symptoms (Château-Degat *et al*., 2007a,b). This situation, in the absence of crucial information on toxin presence, presents a serious hazard to seafood consumers. The expansion of trade in fisheries from ciguatera-endemic areas to non-endemic areas is contributing to wider distribution and increasing frequency of ciguatera among seafood consumers, in large part due to the absence of easy, routine toxin testing methods. In particular, CFP has emerged as a major and escalating global health problem in the South Pacific Islands and other tropical and sub-tropical nations, where about 400 million people live in areas where ciguatoxic fish are caught (Lehane and Lewis, 2000). The epidemiology and economic impact of these CFP outbreaks have recently been documented (Rongo and van Woesik, 2012; Morin, 2016).

Despite the wide-spread occurrence of ciguatera in the Pacific Ocean and the Caribbean Sea, there is significant uncertainty concerning factors that influence the ecology of *Gambierdiscus* species, their geographical spread, and the factors that enable them to thrive in these environments, including seawater temperature, salinity, light, anthropogenic disturbances, and other drivers linked to climate change. Recent work by Yong *et al*. (2018) (and references therein) quantified the abundance of *Gambierdiscus* at various microhabitats in healthy and destructed coral reef ecosystems. Other studies, such as Montojo *et al*. (2020), have provided evidence of the potential incident of exposure through a broad ecological survey that establishes the frequency of ciguatoxic fish within an economic region. Montojo *et al*. (2020) determined, after screening more than 500 samples, that 5% of reef fishes from three islands in the central Philippines were ciguatoxic. At this stage, obtaining this type of analytics is a valuable contribution but the interpretation into an epidemiological assessment remains undefined.

Added to the local exposure of a CFP event, there is a history of individuals exporting the toxin and associated clinical cases to locations well beyond the CFP-epicenters. This can be done through the export of contaminated fish (CDC, 2013) or through the "curious cases" of illnesses of travellers (Patel and Jutzy, 2019).

Ciguatera fish poisoning differs from other marine toxins

From an epidemiological perspective, CFP differs from many of the marine phytoplankton-produced toxins in that the primary consequence of toxin exposure is neither death nor hospitalization, but a prolonged decline in the wellness of the exposed patient. Symptoms of acute exposure are broadly expressed. CFP symptoms can occur within minutes but generally develop within 24 hours of eating contaminated fish. Initial gastrointestinal symptoms include nausea, vomiting, diarrhoea, and abdominal pain. These initial symptoms are typically followed by neurological symptoms, such as dizziness, weakness, and numbness, which may be followed by cardiovascular compromises such as low blood pressure and heart-beat abnormalities (arrhythmias) (Senthilkumaran *et al*., 2011). Although there is no specific treatment, hospitalization may be required for intravenous rehydration, cardiac monitoring, and the treatment of complications. Knowing there is no particular treatment, except in the most severe hospitalized patients, incidents are commonly unreported and the exposed individual recovers at home.

It is this latter point that differentiates this marine toxin aliment from the others. Lack of reporting and the high frequency of re-occurrence complicate the estimation of the incidence of exposure – and weakens our understanding of the connection between consuming contaminated fish and the development of symptoms (Kouakou and Poder, 2019). The effects of chronic exposure are not well understood, but anecdotal narratives indicate that many individuals become hyper-sensitive to CTX and are at risk of extensive medical intervention or death (Rongo, pers. comm.).

Environmental regulation of toxin – Exposure and incidence

The level of CTX in fish is a well-considered parameter, even though the levels in fish are not all that predictable. With accepted uncertainty of reports of ciguatera-fish poisonings, a variable acceptance of fish-avoidance strategies, variations in access by subsistence fishers, and alternative food sources, there is no reason to expect that cases of CFP should relate strongly to the presence of CTX either in benthic fish or in the dinoflagellates of the reef system that the benthic fish feed on.

The potential occurrence of CFP within coastal systems is highly variable in time and space which, combined with the difficulties of routine toxin testing, makes CFP such a challenging problem. The first factor that must be considered to estimate the potential CFP exposure remains the predominance of the benthic CTX-producing alga, such as *Gambierdiscus* species. While *Gambierdiscus* is a minor epibiont in most healthy coral systems, populations of *Gambierdiscu*s can predominate when the corals are disturbed and replaced with seagrasses or seaweed – conditions where the levels of *Gambierdiscus* in the water column also become elevated. It is believed then that surveillance of planktonic *Gambierdiscus* will be a crucial method for estimating potential CFP exposure.

Despite the observed linkages between *Gambierdiscus* abundance and disturbed corals, Rongo and van Woesik (2013) concluded from qualitative assessments that the areal extent of damaged coral is not a very good predictor of CFP, since benthic-feeding fish are not random feeders but tend to dominate where the reef has been damaged, that is, the likely location of a developing *Gambierdiscus* population. Rongo and van Woesik (2013) expanded the scale of their assessment and documented that the frequency of cyclone events that damage the corals was the best predictor. An increased frequency of storm events may have a strong impact of the human CFP incidence (Llewellyn, 2010) as these storms not only increase the benthic biogeography but may export suitable warm waters to otherwise CFP-free reefs, potentially expanding the geographical range of *Gambierdiscus* (Rhodes *et al*., 2017).

As a consequence of these combined and interactive issues, and recognizing that distributions and abundances of *Gambierdiscus* species are transitory, there presently are no clear means for forecasting times and places where CFP outbreaks will occur or how long they may last, unlike other harmful algal bloom syndromes. Further, monitoring methods to gain better knowledge of the local spatial abundances and distributions of *Gambierdiscus* species are only just being developed, so there are no well-defined relationships between cell abundance and impacts on human wellness and economies. Presently there is the development of monitoring techniques such as artificial substrate methods and initial-capture screen method (Tester *et al*., 2014, 2020). While technically laborious and pragmatically challenging, these methods represent a significant advancement in understanding benthic cell dynamics and have the advantage of being non-destructive and highly effective in benthic HAB (BHAB) sampling (reviewed in Berdalet *et al*. (2017)). In addition, Yong *et al*. (2018) showed the effectiveness of the artificial substrate method in a tropical fringing coral reef ecosystem. These types of studies will mature into predictive assays but at present we rely on case studies where post-recognition of human health impacts from CFP is available to better understand how to assess how future economic impacts may evolve.

Case studies

South Pacific Islands

Ciguatera occurrence is particularly prevalent across in coastal tropical waters of the Pacific Island Countries and Territories (Skinner *et al*., 2011). For coral reef fish that are increasingly being exported to other countries, regions, and areas, either preserved, fresh or alive, ciguatera may occur far from tropical areas, and as a result has become a worldwide health problem. Estimates of the prevalence of CTX in Oceania have ranged from 0.5/10,000 year^{-1} in Hawaii to 5,850/10,000 year^{-1} in French Polynesia (Friedman *et al*., 2008). According to the report of the Food and Agriculture Organization on CFP of South Pacific Islands (2004), the mean reported incidence rate of CFP for the South Pacific Islands during a five-year period (1979 to 1983) was 97 per 100,000 population. The South Pacific Commission reported a mean annual incidence of 217 per 100,000 population in 1987 (Glaziou and Legrand, 1994). During the years from 1985 to 1990, the Pacific Islands of Kiribati, Tokelau, and Tuvalu reported 90 to 100 cases per 10,000 population per year. In French Polynesia, Vanuatu, Marshall Islands, and Cook Islands the reported cases varied from approximately 35 to 50 per 10,000 year^{-1}. Less than 20 cases per 10,000 year^{-1} were reported for Fiji, Northern Marianas, New Caledonia, Wallis and Futuna, American and Western Samoa, Niue, Guam, Nauru, Federated States of Micronesia, Palau, Tonga, and Papua New Guinea (FAO, 2004). In French Polynesia, although a rare disease two centuries ago, CTX now has reached epidemic proportions. In the period from 1960 to 1984, more than 24,000 patients were reported from this area (Hallegraeff *et al*., 2004). In Fiji, 925 cases of CFP were reported after residents ate local snapper, barracuda, grouper and emperor in 1984, and one person died (IPCS, 1984).

Lewis (1986a,b) reviewed the earlier CFP assessments and set the stage for an epidemiological assessment of CFP in the South Pacific Islands. Using morbidity as the indicator, Lewis concluded that about 20% of the CFP cases were reported to the health units, that the incidence rates ranged from negligible to >1000 cases/100,000, and that different subregions of the South Pacific Islands had different incidence rates attributed to variations in traditional knowledge and awareness of the potential risk of CFP. Island communities without CFP incidences attribute the low fishing effort, the different levels of benthic phytoplankton, the lack of disturbance of the reef system (cyclones, construction, *etc*.), and transition away from traditional Indigenous subsistence fishing as factors leading to a low incidence rate. Lewis (1986a,b) concluded that the variance in CFP incidence was primarily a combination of the societal and environmental uncertainties.

Some 30 years later, Chinain *et al*. (2019) observed an expansion of CTX-bearing organisms throughout the South Pacific Islands, indicating that the emergence of CTX cases has a spatial and temporal pattern corresponding to invasive producers of this toxin. In addition, different marine products have been exported over the last three decades, which may have contributed to an altered risk of CFP with the new products.

Moorea Island

Morin *et al*. (2016) conducted a patient-centric assessment study of the incidence of CFP on Moorea Island (French Polynesia) using the assessment methods of Rongo and van Woesik (2012). They indicated a hospital cost of US$1613 for each reported case of CFP, while unreported cases cost US$749, as there was no hospital stay, and traditional medicines were used. The algorithm for economic costs were generated based on three components: the daily cost of the hospital stays, the cost of medication, and the costs associated with lost productivity. The community costs were calculated taking into account the rate of employment. Based on their findings, the average length of stay in the hospital was five days at approximately US$175/day for fees and medicine, which was followed by a 10-day re-cooperation at home. Each sick day carried a cost of US$17.40. Translating the costs to the island population, with an incidence rate of 8 individuals per 10,000 inhabitants, a reporting rate of 54%, and taking into account the differences between the costs of reported (hospital stay) and unreported (home care), Morin *et al*. (2016) estimated the cost to the island society of approximately US$50,000 per year during their 6-year study.

Broader socio-economic model

The full economic costs of ciguatera are composed of: 1) health costs to seafood consumers, 2) lost economic output of affected consumers, 3) lost economic profits of fishers in affected markets, 4) reduced profits of local businesses due to declining tourism, and 5) losses in economic welfare from reduced dietary choices for consumers.

Health costs to seafood consumers

Health costs to seafood consumers are the most direct component of the economic costs associated with CTX. These include costs accruing to individuals needing hospitalization as well as those opting for home treatment. Although health costs have been estimated in a few locations that could in theory be transferred to new areas, these costs are likely to be very location-specific and should be estimated using the characteristics of the affected area and population when possible.

The works of Morin *et al*. (2016) and Rongo and van Woesik (2012) dealt with two specific island situations, each with known incidence rates and exposure. They focussed on exposure and consequences, yet there are other economic costs that could be used to understand the broader impact of these CTX events. Components of aggregate CTX health costs include average length of hospital stay, length of recovery at home before returning to work, employment rate, incidence rate within the population, estimated reporting rate, and the size of the population. The cost impact to the individual is then extrapolated to the island population by relating the reporting frequency to the economic foundation of the island (% employment, GDP, *etc*.).

Multiple exposures would be common for subsistence fishers and families with limited economic means. The costs for treatment of multiple exposures would increase dramatically as the individuals become hypersensitive to the toxin, have more dramatic neurological and cardiovascular symptoms, and require a longer duration of hospital or physician care.

Lost economic output of affected consumers

In addition to health costs, seafood consumers who are exposed to CFP are unable to contribute the same level of economic output while their symptoms persist which, unlike many other seafood intoxications, in some cases can persist over weeks to months. Lost wages of these individuals are often used as a proxy for the value of this lost output (Landefeld and Seskin, 1982; Rice *et al*., 1985). However, the cost of the decline in daily performance with initial or with chronic or repeated exposure to CFP is often underappreciated in economic models. Akin to the DALY assessment (disability-adjusted life years), anecdotal reports indicate that the performance levels of exposed individuals decline with each CFP exposure. Each exposure event places the individual closer to providing no economic output and, perhaps, to higher health and chronic care costs. Repeated poisonings can lead to chronic, permanent losses in productivity (Friedman *et al*., 2017) and therefore, capturing the full reduction in economic output may require a time scale beyond the individual's return to work after poisoning incidents (*e.g*., Miller and Lestina, 1997).

Lost economic profits of fishers in affected markets

Consumers purchasing seafood products respond to information about the likelihood of adverse health effects such as CTX (Friedman *et al*., 2008). Decreased demand for seafood products from locations affected by CFP reduces the economic viability and profitability of local fishers and processors, whether these fish were bound for local consumption or export markets. This cost component can be calculated as the difference in economic profit to fishers and producers under different levels of CTX events, mindful that fishers may turn to alternative species targets if available.

In cases where CFP has become endemic, there is an economic need for fishers to shift from reef to offshore pelagic fish stocks. But this shift entails higher capital costs for vessels, fuel, and fishing gear, so the exposure of subsistent fishers to CFP would increase as they focus their fishing efforts on under-exploited reef fish populations. This situation would lead to a dramatic increase in incident rates in lower socio-economic classes or for community members wishing to maintain a traditional way-of-life.

Reduced profits of local businesses due to declining tourism

Visitation rates and spending from tourists may decrease at locations in which CTX events have been reported, even if the visitors do not intend to consume benthic fish species. This decreased visitation would reduce the economic viability and profitability of many local businesses for the following reasons:

1. Reports of CFP are associated with a loss of tourist fishing and diving activities. However, the cost of these losses is debatable, as subjective discussions indicate CFP does not reduce the tourist visits but alters the activities that tourists engage in on the islands. While this association may not have been tested, tourism researchers such as Van Doorn (1986) suggest that there is a fluid redistribution of tourist activities when economic opportunities change.

2. Reports of CFP also have been associated with establishing marine protected areas to better sustain coral reef habitats through enhancing biodiversity and complexity of the reef system, attracting more divers or observers and ostensibly benefiting human health. This apparent contradiction that CFP can become problematic in healthy coral systems stems from the fact that once *Gambierdiscus* species are present in a system, fish communities that are protected should be longer-living and larger – two attributes that correlate with a higher burden of CTX. Even in regions where fish poaching from marine protected areas is well controlled, fishing along the margins of protected areas (where fisheries success will be higher) still serves to expose communities to magnified CFP threats.

Losses in economic welfare from reduced dietary choices for consumers

Consumers in seafood markets may face reductions in net benefits (utility) if affected species are no longer available for purchase and consumption. The cost associated with this lack of consumer choice can be calculated as the difference between the net benefits of seafood consumption when reef fish are available and the net benefits to seafood consumption when only pelagic and other fly-in protein sources are available. Specific concerns include:

1. There may be a cost to supplement the food stocks of the vulnerable subsistence communities with non-fish alternatives (chicken or pork, as examples). This is a highly expensive endeavour as the imported protein must be supplied at a level corresponding to the local fish availability. The "fly in" protein needs to be prevalent, pre-cooked, and have a shelf-life or delivery system that will not increase the health risk of eating the product.

2. There may be a cost associated with secondary medical costs, primarily diabetes, associated with an altered diet to reduce the risk of CFP (Skinner *et al*., 2011). While a logical extension of the diet change, there may also be a corresponding change in socio-economic status, complicating the correlation. Ultimately, the short-term costs and long-term treatment are real costs, not normally considered in an economic assessment.

Economic costs help inform coastal policy and decision making

Estimates of the changes in net economic benefits that result from different levels of CTX incidence can help inform the likely benefits from potential prevention or mitigation options (see below). In particular, a benefit-cost analysis could be used to compare the benefits to the costs of prevention *versus* mitigation approaches. However, CTX events are stochastic and highly variable, complicating efforts to quantify the effects of different prevention or mitigation measures on the probability or frequency of an occurrence.

Prevention and mitigation

Options to reduce the severity of CFP in the community are challenging. First, we must seek options that reduce the destruction of the reef community. Fundamentally, these options must focus on those factors most detrimental to coral health, such as increased sediment loading in rivers, anthropogenic nutrient inputs associated with agriculture, domestic sewage, and physical disturbance or destruction of reef environments through land use changes, boating, or dredging. All of these factors lead to declines in coral health and a shift to macroalgal-dominated ecosystems that can enhance the presence of benthic algae such as *Gambierdiscus*. In addition, global factors (*e.g.*, climate change increasing reef water temperatures, intensification of reef damage and river runoff from cyclones and tropic storms) are all linked with an increase in CFP and should be incorporated in eco-socio-economic models. Second, socio-economic factors that change the exposure of the population to the CTX-bearing fish should be considered. While not limited to this example, as islands develop, a sub-portion of the community is economically left behind. The reasons are complex but generally are associated with lack of physical or linguistic skills to integrate into the new economy. Approaches to elevating all members of the community, with emphasis on reducing the illegal poaching of fish, is essential. Third, qualifying the consequences of CFP in exposed community members is particularly challenging.

Conclusions

CFP should be considered in the same cluster as the neglected tropical diseases – these are diseases that do not have sufficient medical consequences and, as such, do not draw the attention of either pharmaceutical companies or nongovernmental agencies. Outbreaks of CFP are usually sporadic (fish shipped to a market), hidden (treatment at home), a burden to subsistence or lower socio-economic communities, and a risk that can be avoided by more expensive alternatives (tourists and pelagic fish meals). Increased population and increased frequency of climate change-driven storm events will increase the habitat for CTX-producing cells and, as an extension, the epidemiology of CFP. The scale of impact and the pervasive reduction in wellness is leading to CFP becoming a significant non-communicable health factor in the global economy.

Acknowledgments

E.B. participation was funded by the CoCliME project, which is part of ERA4CS, an ERA-NET initiated by JPI Climate, and funded by EPA (IE), ANR (FR), BMBF (DE), UEFISCDI (RO), RCN (NO) and FORMAS (SE), with co-funding by the European Union (Grant 690462). This work was funded by an NSERC Discovery Grant 4458-2016 awarded to CGT.

References

Berdalet, E., Tester, P.A., Chinain, M., Fraga, S., Lemée, R., Litaker, W., Penna, A., Usup, G., Vila, M. and Zingone, A. 2017. Harmful algal blooms in benthic systems: Recent progress and future research. *Oceanography* **30**: 36–45, https://doi.org/10.5670/ oceanog.2017.108.

CDC (Centers for Disease Control and Prevention). 2013. Morbidity and Mortality Weekly Report (MMWR). Ciguatera Fish Poisoning – New York City, 2010–2011. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6204a1.htm.

Château-Degat, M.-L., Chinain, M., Cerf, N., Gingras, S., Hubert, B. and Dewailly, É. 2007a. Seawater temperature, *Gambierdiscus* spp. variability and incidence of ciguatera poisoning in French Polynesia. *Harmful Algae* **4**: 1053–1062.

Château-Degat, M.L., Dewailly, E., Cerf, N., Nguyen, N.L., Huin-Blondey, M.O. and Hubert, B. 2007b. Temporal trends and epidemiological aspects of ciguatera in French Polynesia: a 10-year analysis. *Tropical Medicine and International Health* **12**: 485–492.

Chinain, M., Gatti, C.M., Roué, M. and Darius, H.T. 2019. Ciguatera poisoning in French Polynesia: insights into the novel trends of an ancient disease. *New Microbes and New Infections* **31**: 100565, doi:10.1016/j.nmni.2019.100565.

Dickey, R.W. and Plakas, S.M. 2010. Ciguatera: a public health perspective. *Toxicon* **56**: 123–136.

Doherty, M.J. 2005. Captain Cook on poison fish. *Neurology* **65**: 1788–1791.

FAO. 2004. Marine Biotoxins, FAO Food and Nutrition Paper 80. Food and Agriculture Organization of the United Nations, Rome. pp. 185-218.

Friedman, M.A., Fleming, L.E., Fernandez, M., Bienfang, P., Schrank, K., Dickey, R., Bottein, M.Y., Backer, L., Ayyar, R., Weisman, R., Watkins, S., Granade, R. and Reich, A. 2008. Ciguatera fish poisoning: treatment, prevention and management. *Marine Drugs* **6**: 456–479.

Friedman, M., Fernandez, M., Backer, L., Dickey, R., Bernstein, J., Schrank, K., Kibler, S., Stephen, W., Gribble M.O., Bienfnag, P., Bowen, R.E., Degrasse, S., Flores Quintana, H.A., Loeffler, C.R., Weisman, R., Blythe, D., Berdalet, E., Ayyar, R., Clarkson-Townsend, D., Swajian, K., Benner, R., Brewer, T. and Fleming, L.E. 2017. An updated review of ciguatera fish poisoning: clinical, epidemiological, environmental, and public health management. *Marine Drugs* **15**: 72, 10.3390/md15030072.

Glaziou, P. and Legrand, A.M. 1994. Review article: The epidemiology of ciguatera fish poisoning. *Toxicon* **32**: 863–873.

Hallegraeff, G.M., Anderson, D.M., Cembella, A.D. and Enevoldsen, H. (Eds.) 2004. Manual on Harmful Marine Microalgae, 2nd revised edition. Paris, France, UNESCO, 793 pp. (Monographs on Oceanographic Methodology, 11). http://hdl.handle.net/11329/282.

IPCS (International Programme on Chemical Safety). 1984. Aquatic (Marine and Freshwater) Biotoxins. Environmental Health Criteria 37. World Health Organization. ISBN 92 4 154097 4.

Kouakou, C. and Poder, T. 2019. Economic impact of harmful algal blooms on human health: a systematic review. *Journal of Water and Health* **17**: 499–516, https://doi.org/10.2166/wh.2019.064.

Landefeld, J.G. and Seskin, E.P. 1982. The economic value of life: linking theory to practice. *American Journal of Public Health* **72**: 555–566.

Lehane, L. and Lewis, R.J. 2000. Ciguatera: recent advances but the risk remains. *International Journal of Food Microbiology* **61**: 91–125.

Lewis, N.D. 1986a. Disease and development: ciguatera fish poisoning. *Social Science and Medicine* **23**: 983–993.

Lewis, N.D. 1986b. Epidemiology and impact of ciguatera in the Pacific: a review. *Marine Fisheries Review* **48**: 6–13.

Lipkin, K.M. 1989. Ciguatera poisoning presenting as psychiatric disorder. *Archives of General Psychiatry* **46**: 384–385.

Llewellyn, L.E. 2010. Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: reassessing the link between ciguatera and climate change. *Toxicon* **56**: 691–697.

Miller, T.R. and Lestina, D.C. 1997. Costs of poisoning in the United States and savings from poison control centers: A benefit-cost analysis. *Annals of Emergency Medicine* **29**: 239–245.

Montojo, U.M., Tanyag, B.E., Perelonia, K.B.S., Cambia, F.D. and Oshiro, N. 2020. Ciguatera in the Philippines: examining reef fish vectors and its causative benthic dinoflagellates in Visayan and Sibuyan Seas. *The Philippine Journal of Fisheries* **27**: 19–29.

Morin, E., Gatti, C., Bambridge, T. and Chinain, M. 2016. Ciguatera fish poisoning: incidence, health costs and risk perception on Moorea Island (Society archipelago, French Polynesia). *Harmful Algae* **60**: 1–10.

Patel, M. and Jutzy, K. 2019. A curious case of ciguatera fish poisoning in the Midwest and a review for clinicians. *Journal of Emergency Medicine* **58**: E109–E111, https://doi.org/10.1016/j.jemermed.2019.10.017.

Pearn, J. 1996. Chronic ciguatera. *Journal of Chronic Fatigue Syndrome* **2**: 29–34.

Pearn, J. 2001. Neurology of ciguatera. *Journal of Neurology, Neurosurgery and Psychiatry* **70**: 4–8.

Rhodes, L.L., Smith, K.F., Murray, S., Harwood, D.T., Trnski, T. and Munday, R. 2017. The epiphytic genus *Gambierdiscus* (Dinophyceae) in the Kermadec Islands and Zealandia regions of the southwestern Pacific and the associated risk of ciguatera fish poisoning. *Marine Drugs* **15**: 219, https://doi.org/10.3390/md15070219.

Rice, D.P., Hodgson, T.A. and Kopstein, A.N. 1985. The economic costs of illness: a replication and update. *Health Care Financing Review* **7**: 61–80.

Rongo, T. and van Woesik, R. 2012. Socioeconomic consequences of ciguatera poisoning in Rarotonga, southern Cook Islands. *Harmful Algae* **20**: 92–100.

Rongo, T. and van Woesik, R. 2013. The effects of natural disturbances, reef state, and herbivorous fish densities on ciguatera poisoning in Rarotonga, southern Cook Islands. *Toxicon* **64**: 87–95, https://doi.org/10.1016/j.toxicon.2012.12.018.

Senthilkumaran, S., Meenakshisundaram, R., Michaels, A.D., Suresh, P. and Thirumalaikolundusubramanian, P. 2011. Cardiovascular complications in ciguatera fish poisoning: a wake-up call. *Heart Views* **12**: 166–168, https://doi.org/10.4103/1995-705X.90905.

Skinner, M.P., Brewer, T.D., Johnstone, R., Fleming, L.E. and Lewis, R.J. 2011. Ciguatera fish poisoning in the Pacific Islands (1998 to 2008). *PLoS Neglected Tropical Diseases* **5**: e1416, doi:10.1371/journal.pntd.0001416.

Tester, P.A., Kibler, S.R., Holland, W.C., Usup, G., Vandersea, M.W., Leaw, C.P., Lim, P.T., Larsen, Mohammad-Noor, J.N., Faust, M.A. and Litaker, R.W. 2014. Sampling harmful benthic dinoflagellates: comparison of artificial and natural substrate methods. *Harmful Algae* **39**: 8–25.

Tester, P.A., Litaker, R.W. and Berdalet, E. 2020. Climate change and harmful benthic microalgae. *Harmful Algae* **91**: 101655, https://doi.org/10.1016/j.hal.2019.101655.

Van Doorn, J.W.M. 1986. Scenario writing: A method for long-term tourism forecasting? *Tourism Management* **7**: 33–49.

Yong, Y., Mustapa, N.I., Lee, L.K., Lim, Z.F., Tan, T.H., Usup, G., Gu, H., Litaker, R.W., Tester, P.A., Lim, P.T. and Leaw, C.P. 2018. Habitat complexity affects benthic harmful dinoflagellate assemblages in the fringing reef of Rawa Island, Malaysia. *Harmful Algae* **78**: 56–68.

5 Estimating and Mitigating the Economic Costs of Harmful Algal Blooms on Commercial and Recreational Shellfish Harvesters

Jorge I. Mardones[1,2], Daniel S. Holland[3], Leif Anderson[3], Véronique Le Bihan[4], Fatima Gianella[5,6], Alejandro Clément[7], Keith Davidson[6], Setsuko Sakamoto[8], Takafumi Yoshida[9] and Vera L. Trainer[3]

[1] Centro de Estudios de Algas Nocivas (CREAN), Instituto de Fomento Pesquero (IFOP), Padre Harter 574, Puerto Montt, Los Lagos, 5501679, Chile
[2] Centro FONDAP de Investigación en Dinámica de Ecosistemas Marinos de Altas Latitudes (IDEAL), Valdivia, Chile
[3] Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E, Seattle, WA 98112, USA
[4] Laboratory of Economics and Management Nantes-Atlantique (LEMNA), University of Nantes, Nantes, France
[5] University of the Highlands and Islands, 12b Ness Walk, Inverness, Scotland, IV3 5SQ, UK
[6] Scottish Association for Marine Science, Scottish Marine Institute, Oban, PA37 1QA, Scotland, UK
[7] Plancton Andino SpA., Laboratorio Puerto Varas, Terraplen 869, Puerto Varas, 5550144, Chile.
[8] National Research Institute of Fisheries and Environment of Inland Sea, Japan Fisheries Research and Education Agency, 2-17-5 Maruishi, Hatsukaichi, Hiroshima, 739-0452, Japan
[9] Special Monitoring and Coastal Environmental Assessment Regional Activity Centre, Northwest Pacific Action Plan (NOWPAP), 5-5 Ushijima Shin-machi , Toyama, 930-0856, Japan

Abstract

While several studies quantify the economic costs of harmful algal blooms (HABs) on fish aquaculture, there have been few estimates of the economic costs of HABs on shellfish harvesters. Among the few economic estimates of HAB impacts on shellfish are examples from the European Union, Chile, USA, and Asia. These studies state that it is important to understand not just the overall economic costs of HABs due to shellfish toxicity, but also other losses due to a harvest delay or reduction in the value of harvest for reasons such as loss of consumer confidence in the safety or quality of the product. These different impacts suggest the potential for varied mitigation measures and economic analysis. A better understanding of how HABs impact the value of shellfish aquaculture will inform the design of monitoring and forecasting programs to make them more effective and efficient. Research on the use of economics information by farm operators or stakeholders, such as regional or national public authorities, can guide the optimal frequency and spatial resolution of monitoring to determine whether an investment in forecasting is cost effective. To quantify the economic costs of HABs on shellfish aquaculture, it is necessary to quantify the revenue, and ideally profits, that would have been realized in both the presence and the absence of the HAB. Methods and data needs for the comprehensive estimation of economic impacts of HABs on shellfish harvest are discussed.

Introduction

Shellfish production is an important industry for coastal communities, economically sustaining rural areas. Consumption of shellfish is positively perceived because the feed, additives, and antibiotics needed for most fish aquaculture operations are not required for shellfish aquaculture. The nutritional benefits and the role of shellfish in nutrient processing are valued as ecosystem services. Worldwide bivalve production increased from approximately 1 million metric tons in 1950 to approximately 16.1 million metric tons in 2015 (FAO, 2018). Most shellfish production (80%) comes from aquaculture (Smaal *et al*., 2018); international trade associated with aquaculture was valued in 2015 at US$4.4 billion (FAO and WHO, 2018).

Harmful algal blooms (HABs) present a major and growing challenge for shellfish harvesting. Under environmental conditions favorable to HABs, some species of microalgae can produce natural chemicals (biotoxins) that can persist in the water or enter the food web, leading to illness or death of aquatic organisms and/or human seafood consumers. Worldwide, more than 100 microalgae species synthesize biotoxins. The term HABs is a socio-economic and operational term because it refers to human perception of "harmfulness". Toxins produced by HABs are associated with several illness syndromes, including Paralytic Shellfish Poisoning (PSP), Diarrhetic Shellfish Poisoning (DSP), Amnesic Shellfish Poisoning (ASP), Neurotoxic Shellfish Poisoning (NSP), and Azaspiracid Shellfish Poisoning (AZP). The number of global HAB events related to illness caused by marine toxins in humans is documented from 1970 and 2019 in the Harmful Algal Events Database (HAEDAT; Fig.5.1).

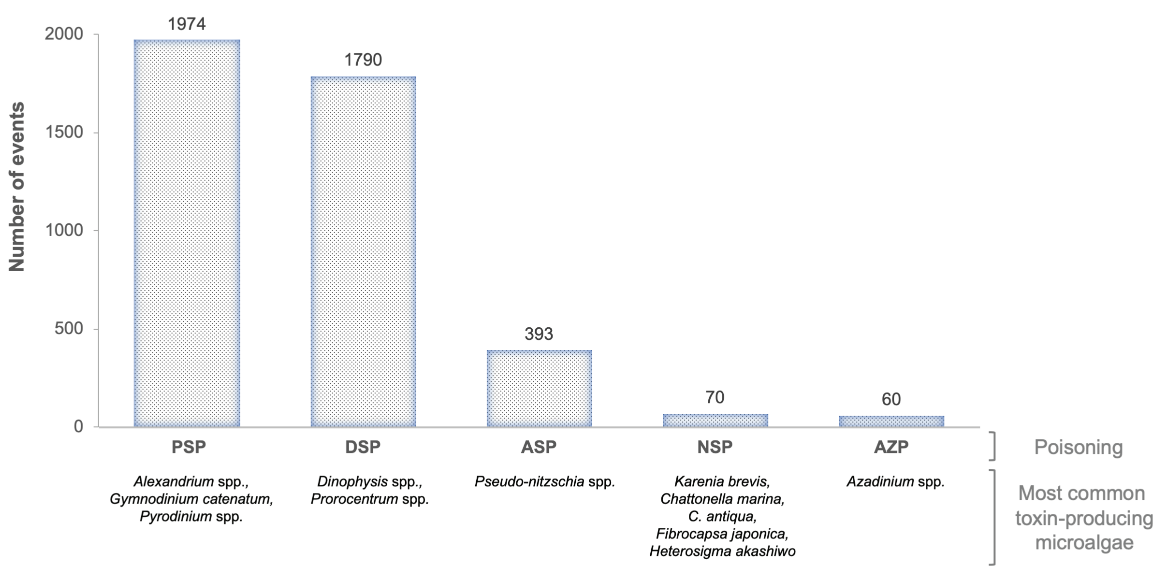

Fig. 5.1 Total number of harmful algae events by syndrome reported globally from 1970 to 2019 to the Harmful Algal Events Database (HAEDAT, www.haedat.iode.org). Only those syndromes caused by shellfish ingestion are listed here and include: PSP, Paralytic Shellfish Poisoning; DSP, Diarrhetic Shellfish Poisoning; ASP, Amnesic Shellfish Poisoning; NSP, Neurotoxic Shellfish Poisoning, and AZP, Azaspiracid Shellfish Poisoning.

To help ensure safe consumption, biotoxin-producing phytoplankton and shellfish samples are monitored and analyzed to determine whether they meet the threshold concentrations for biotoxins, which are established by governmental health institutions. In Europe, this is prescribed under regulation (EC) No 853/2004 of the EU parliament (European Union, 2004) and in the US by the Food and Drug Administration (FDA).

Mussels are one of the main cultured shellfish species at risk of contamination by HAB toxins, although oysters, scallops, and other shellfish also pose a risk to consumers. Chile is one of the world leaders in mussel farming, yielding annual revenues close to US$210 million in 2017 and 2018 (Anonymous, 2019). This industry was seriously affected by an extraordinary HAB event in 2016 due to a massive bloom of the paralytic shellfish toxin (PST) producer, *Alexandrium catenella*, that affected 200 shellfish farms (approximately 15% reduction in harvest compared to 2015) and 600 km of benthic artisanal fisheries during a 4-month closure (Trainer *et al*., 2019). The economic losses for the shellfish industry were estimated at US$2 million (190 metric tons of blue mussel could not be exported) and unemployment affected 1700 people. The loss of income in coastal communities ignited massively disruptive social protests that lasted for three weeks.

Shellfish production accounts for about 50% of European aquaculture. Production is dominated by mollusks, with over 0.63 million metric tons of bivalves produced annually (European Union, 2019), the bulk of which (almost 500,000 metric tons) is mussels. Second in importance are Pacific oysters, with production near 100,000 metric tons. The largest shellfish producers were Spain (223,000 metric tons), France (155,000 metric tons), and Italy (111,000 metric tons). The value of European shellfish at ~US$1.2 billion (European Union, 2019) is approximately 8% of the world total (Seafish, 2016).

Harmful algal bloom outbreaks responsible for DSP events, in particular, are common in Europe. Events can be large and fishery closures have lasted for up to 10 months (Berdalet *et al*., 2016 and papers therein). Most recently, a number of human poisonings were reported in 2013 following consumption of mussels harvested in the Scottish Shetland Islands. This event occurred during a time of exceptional strong westerly winds that rapidly advected an offshore *Dinophysis* population to coastal shellfish aquaculture sites. The speed of the increase in toxicity was greater than the one-week resolution of regulatory monitoring and hence contaminated product reached market (Whyte *et al*., 2014).

In contrast to the large multi-national companies that now dominate the fish farming industry, shellfish farming is carried out predominantly by (small) family enterprises (STECF, 2018) and is important for many rural areas of Europe. For example, the bulk of Scottish shellfish farming occurs in the remote rural locations of the Highlands and Islands where approximately 200 small businesses generate a gross value (turnover) of US$15.7 million (Highlands and Islands Enterprise and Marine Scotland, 2017). While small in global or even national terms, this income has a very important local social impact in remote communities that offer few other employment opportunities (Davidson *et al*., 2014).

In Europe, only few studies have been done, with considerable uncertainty in their estimation of the economic impact of HABs on shellfish production (Davidson *et al*., 2014). Between 1989 and 1998, Stolte *et al*. (2001) estimated the average yearly HAB impact on consumer welfare in the mussel sector to range between $US73 million and $US202 million, *i.e*., 18–49% of the average annual EU production. The greatest losses were in Spain and Italy. Recently, Martino *et al*. (2020) estimated the impact of HABs and their biotoxins on the Scottish shellfish industry. They found *Dinophysis* to have the greatest impact, with annual losses approximately 15% of total production.

Scotland has put mitigation measures in place to safeguard the economic sustainability of the scallop industry. In 1999, a 49,000 km^2 area in western Scotland was closed to shellfish harvesting due to domoic acid (DA), responsible for ASP (Fehling *et al.*, 2004). This prompted the largest fisheries closure ever in this country due to a HAB (Campbell *et al.*, 2001). In 2002, offshore scallop grounds continually detected ASP throughout the year, leading to further fisheries closures (Hinder *et al.*, 2011) to a level the industry found unsustainable. On a whole animal basis, toxicity was routinely found above regulatory threshold, but was not evenly distributed throughout the shellfish tissue; rather it was concentrated in the hepatopancreas. This resulted in a change of regulations that allowed harvesters and processors to remove the hepatopancreas tissue, leaving the toxin-free mussel and roe for consumption.

The appearance of novel toxins, for example, *Azadinium*-derived azaspiracids (Satake *et al*., 1998), first identified in mussels from Ireland, have had a significant effect on European shellfish aquaculture. Azaspiracids have now been found in many other European Union countries and elsewhere around the world (Tillmann, 2018). The difficulty in enumerating this species by light microscopy and the large number of toxin analogues identified (Berdalet *et al*., 2016) make the monitoring of this organism challenging.

Many other regions globally have suffered from HAB impacts to shellfish aquaculture, with notable examples including PSP outbreaks caused by the armoured dinoflagellate *Pyrodinium bahamense* var. *compressum.* For example, this species was responsible for 1995 cases with 117 deaths linked to PSP toxicity between 1983 and 1999 in the Philippines (Azanza, 1999; Azanza and Taylor, 2001). In Japan, most large-scale bivalve and abalone kills have been caused by the dinoflagellate *Heterocapsa circularisquama* (Sakamoto *et al*., 2020). The direct economic damage, calculated from the market price of lost product during the 1998 Seto Inland Sea mass mortality of oysters and clams, was calculated as 3.9 billion yen or approximately US$39 million (Sakamoto *et al*., 2020). The fishery damages caused by this species over the last 3 decades is estimated at a minimum of 10 billion yen (Matsuyama and Oda, 2020). The accumulation of PSP and DSP toxins in bivalve shellfish has become an important issue in Japan as an indirect economic loss. Since 2013, large-scale blooms of *Alexandrium* species have occurred almost every year in the North Pacific region and Seto Inland Sea. Some areas have experienced shipping bans (Fig. 5.2) for more than 200 days (*e.g*., northern part of Miyagi Prefecture in 2013, red clam shipments were stopped for 215 days). During that time, fishermen

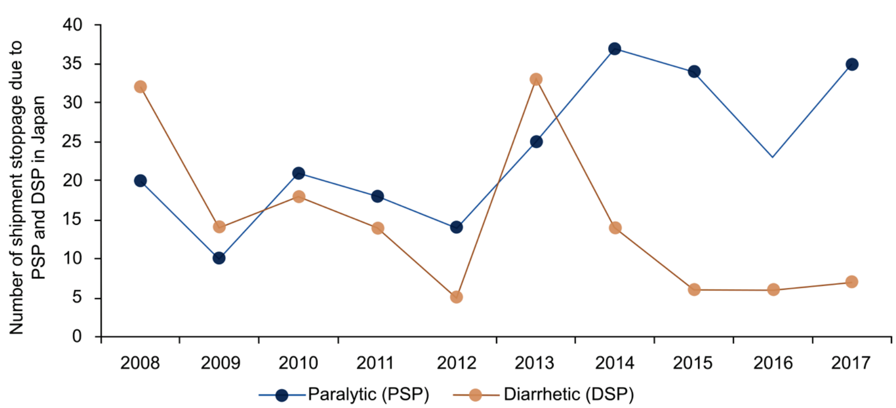

Fig. 5.2 Loss of shellfish shipments in Japan due to shellfish contamination by paralytic and diarrhetic shellfish toxins from 2008–2017. Source: Ministry of Agriculture, Forestry and Fisheries, Japan, https://www.maff.go.jp/j/syouan/tikusui/gyokai/g_kenko/busitu/01d_zyokyo.html.

suffered significant economic losses, which were not calculated. Fisheries damage due to HABs in China, Japan, Korea and Russia is discussed in a recent publication (Sakamoto *et al*., 2020), though comprehensive economic studies on HAB impacts on shellfish harvest in Asia are needed.

While the economic costs of HABs on fish aquaculture have been addressed in the literature (Skjoldal and Dundas, 1991; Yin *et al*., 1999; Anderson and Rensel, 2016), there have been few quantitative estimates of the economic costs of HABs on shellfish harvesters (Sanseverino *et al*., 2016). However, Anderson *et al*. (2000) estimated the average public heath impact due to shellfish poisoning from HABs in the U.S. to be US$1.3 million/year. This value is relatively low because of the effectiveness of HAB and biotoxin monitoring that safeguards human health. The same authors found the economic effects on commercial fisheries to be much higher (an annual average of $US18 million) but the figures included the impact of ciguatera and were provided with the caveat that data were unavailable from some states. These aggregate costs are likely to be at least as large as the cost of mitigation through improved monitoring and mitigation. A complete evaluation of the economic costs of HABs on shellfish harvesters relative to the potential benefits of mitigation measures will require the coordinated actions of an aquaculture industry that is mostly composed of local and small producers and diffuse groups of recreational harvesters.

Demands/need for economic analysis

Monitoring programs for HABs are a strategy adopted by different countries worldwide to control risks needed to protect public health and minimize ecosystem and economic losses. These programs help prevent the sale of contaminated shellfish by assessing the presence of toxic microalgae in shellfish-growing areas and phycotoxins in shellfish products. Justification of the cost of monitoring programs requires an understanding of their potential benefits. The Asia-Pacific Economic Cooperation (APEC) reported in 2001 that for annual HAB monitoring, Norway invested about US$300,000, Denmark and Portugal US$500,000, France US$800,000 and Spain (Galicia) US$1,114,000 (Anderson *et al*., 2001). Over the prior decade, Hoagland *et al*. (2002) estimated that annual average HAB monitoring and management costs in the U.S. totaled US$2 million. In 2019, an estimate of the annual cost of phytoplankton and toxin monitoring in Chile reached about US$6.9 million (Table 5.1).

A better understanding of how HABs impact the value of shellfish aquaculture can also inform the design of monitoring and forecasting programs to make them more effective and efficient. Research on use of information by farm operators or by stakeholders (regional or national public authorities) is needed to determine optimal frequency and spatial resolution of monitoring. This information will determine whether an investment in forecasting is cost effective. The value of a predictive tool increases when there is effective communication with the harvester, events are frequent, and models are highly accurate (Jin and Hoagland, 2008).

It is important to understand not just the overall economic costs of HABs, but how and why those impacts are realized. For example, losses may occur as a result of direct mortality from a HAB event, but also may be due to a harvest delay or reduction in the value of harvests. Reduced value may be due to loss of markets if harvest or sales are delayed due to HABs, making it difficult to meet demand (Jin *et al*., 2008; Rodríguez *et al*., 2011). Value may also be reduced by a loss of consumer confidence in the safety or quality of the product that undercuts demand and thus the price (Wessels *et al*., 1995; Whitehead *et al*., 2003; Garza-Gil *et al*., 2016). These different impacts suggest the potential for varied mitigation measures and economic analysis.

Table 5.1 Estimated annual cost in microalgae and toxin monitoring on the Chilean coast in 2019.

Program	Institution	Resource	Cost (US$)*
National Program for Surveillance & Control of HAB	Minister of Health	Shellfish	2,828,854
Phytoplankton Monitoring	IFOP	Shellfish	2,545,969
POAS	Plancton Andino SpA.	Salmon	339,463
PROMOFI	INTESAL	Salmon	59,406
PSMB	Univ. de Chile, UACH, Plancton Andino SpA., others	Shellfish	441,301
REPLA	SERNAPESCA	Shellfish and Salmon	67,893
REPLA	Well boat companies	Salmon	203,678
Other	Private companies	Salmon	84,866
Internal check	Fish farms	Salmon	316,800
Internal check	Mollusk producers	Shellfish	20,368
Total			**6,908,596**

* Exchange rate 1USD = 707 CLP (Mitigation and R&D not included).

POAS – Oceanographic and Environmental Program in Salmonids, PROMOFI – Phytoplankton Monitoring Program, PSMB – Bivalve Mollusk Health Program, REPLA – Hydrobiological Pest Program, IFOP – Fisheries Development Institute, INTESAL – Technological Institute of Salmon, SERNAPESCA – National Fishing Service.

One potential source of lost value of shellfish harvests associated with HABs is reduced demand by consumers due to fears about seafood safety. The obvious solution to this is to have robust, transparent, and well-regulated monitoring programs in place that ensure unsafe shellfish do not enter the food chain. The effectiveness of such a program in maintaining shellfish demand as well as protecting consumers will depend on the efficiency of information transfer and response by consumers. If consumers are confident in the information provided about shellfish safety, they may be more willing to consume it even when there are known HAB outbreaks. The willingness of consumers to pay more for extra food safety measures potentially reflects their increased confidence in the product and demand for the product (Garza-Gil *et al*., 2016). Focus groups, surveys, or empirical testing can help design communication and marketing approaches that improve health risk perception. For example, a survey in Washington State, USA, determined that consumer "willingness to pay" for reduced HAB closures was an extra $US5.00 for shellfish licenses, information that helped establish the Olympic Region HAB monitoring program through a surcharge to shellfish license fees (Huppert and Trainer, 2014).

The length of shellfish farm closures can vary with the intensity and type of HAB events. Such closures can negatively affect the value of aquaculture products in several ways, such as: 1) inability to reliably fill delivery contracts or supply during peak demand periods, 2) delay of harvest to a point where shellfish are more than their optimal size, and 3) impact on the ability to use space and gear to begin growing new cohorts. In Chile, the most intense PSP events due to *Alexandrium catenella* have resulted in high shellfish toxicities, with an extraordinary world record in 2018 of 143,130 μg STXeq. 100 g^{-1} shellfish (Chilean Ministry of Health). The problem with highly toxic blooms is that detoxification to safe levels can last several months and might become worse if the blooms reoccur. For example, an intense bloom of *A. catenella* in 1996 in the Chilean fjords reached PST concentrations as high as 28,000 μg STXeq. 100 g^{-1} in ribbed mussels (*Aulacomya atra*) that could not be detoxified before the next bloom was recorded in 1998, leading to approximately 2 years of sanitary closure (Díaz *et al.*, 2019).

Hospitalization and sickness due to intoxication incidents caused by HABs can result in high medical costs and lost wages. In Canada, a study published in 1995 revealed that the sum of medical costs and lost wages derived from 525 annual reported cases of PSP, DSP, and ciguatera poisoning was estimated at US$670,000, with many of the PSP- and DSP-related illnesses associated with the recreational harvest of shellfish (Todd, 1995). The fact that this Canadian study is more than two decades old points to the need for more recent economic assessments of HAB impacts. In Chile, the economic cost from hospitalizations due to the consumption of contaminated mussels (mainly PSP and DSP) has dramatically increased in recent years, with values that reached US$93,119 in 2018 (Table 5.2). High medical expenses show a direct relationship with highly toxic PSP events, which is of great concern since HABs are increasing in severity, frequency, and biogeographical range in southern Chile. However, these figures likely are underestimates as they do not include other impacts, such as lost wages. Given the scale of public health effects, further investigation of the economic costs in this category is a clear priority.

Table 5.2 Estimated economic impact of HABs due to hospitalizations in Chile.

		2014	2015	2016	2017	2018
Principal diagnostic	T61.2 – Other fish and shellfish poisoning	5,366	6,904	18,015	23,978	66,757
	T61.9 – Toxic effects of unspecified seafood	1,255	–	1,255	–	2,542
Secondary diagnostic	T61.2 – Other fish and shellfish poisoning	–	17,042	18,548	4,582	19,427
	T61.9 – Toxic effects of unspecified seafood	–	–	1,726	–	4,393
Total annual cost*		**6,621**	**23,946**	**39,544**	**28,560**	**93,119**

Diagnosis under the International Classification of Diseases (ICD-10) of the World Health Organization (WHO).

* Values are expressed in USD with an exchange rate 1 USD = 670 CLP used as the conversion factor.

In France, from 1996 to 2010, 561 (5%) of the 11,261 food-borne illness outbreaks (FBIOs) were attributed to the consumption of shellfish. These 561 FBIOs were the source for 4,338 patients (3% of the total number of patients reported for all of the reported FBIOs) and 179 hospitalizations (2% of the total number of hospitalizations reported for all of the declared FBIOs). The annual number of shellfish-associated FBIO outbreaks varied from 18 to 131, representing between 3% and 14% of all annual FBIOs declared (Baron *et al.*, 2012). More than half of these FBIOs (54%) came from viruses and 26% from DSP. The economic impact of these French FBIOs have not been assessed but provide insight into the potential health-related impact of HABs (Le Bihan, 2015a).

Methods and tools for economic analysis

A variety of economic methods is needed to address the different issues associated with valuing and mitigating HAB impacts on shellfish aquaculture because the impacts are diverse. Many bloom episodes have significant effects on different socio-economic systems, including: 1) human health impacts, 2) direct impacts on fishery and shellfish operations, 3) tourism and recreation impacts, 4) monitoring and management costs, and 5) loss of large investments in international marketing during supply interruption due to HABs (Adams and Larkin, 2013; Sanseverino *et al*., 2016). Impacts can also be positive, as the market values of shellfish products may increase due to limited supply during HAB episodes.

While cost estimates of some HABs events in the USA are well documented by scientific reports, many are not or are not done comprehensively, and there is a lack of reports or publicly available data on the economic impact of HABs in Europe (Sanseverino *et al*., 2016) and other parts of the world. For direct impacts on shellfish operations, it is common to simply estimate losses in gross revenues associated with HAB events as a measure of economic impacts with lost sales estimated by comparing actual sales to some average revenue over previous representative period (*e.g*., the last year or last month). However, this approach is unlikely to give an accurate estimate of actual economic losses. One reason for this is that gross revenues comprise both producer surpluses (loosely, business "profits") and the costs of supply. When shell fisheries are closed, for example, diggers or growers relinquish producer surpluses – a true economic loss – but do not incur the costs of digging or growing; therefore, there are no losses associated with the latter. If supply costs are avoided, they must be subtracted from gross revenues to determine producer surplus.

Gross revenues also do not account for lost consumer surplus (the surplus value consumers get from access to the product above and beyond what they actually have to pay for). Consumer surplus is often ignored and hard to measure but can be significant for specialty products for which there are no close substitutes (*e.g*., local markets that prize local fresh seafood). Consumer surplus can be estimated with market demand models that estimate consumer demand schedules at different prices (Holland *et al*., 2009). These analyses generally require long time series of price and quantity data, with substantial variation in quantity and price over time. If such data are unavailable, it may also be possible to estimate consumer surplus with stated preference approaches that use surveys to determine willingness to pay for products. These studies can be tailored to measure user preferences for the specific product in question or to determine attributes of the product such as health risk impact value (*e.g*., Marette *et al.*, 2008), as opposed to being constrained by available market data that may not relate to specific product of interest or attributes of it. A stated preference study might, for example, be used to determine how better information about seafood safety and better monitoring to ensure seafood is safe would impact their demand or likelihood of substituting other products.

There may also be indirect effects associated with lost production, both losses to farm suppliers and losses upstream (*e.g*., in processing or retail sectors). These are commonly estimated with an input-output (IO) model, which represents the interdependencies between different sectors of a national economy or different regional economies by a system of linear equations where outputs per industry are obtained by a fixed proportion of factors (intermediate consumptions and labor). For example, in order to either test bans on local shellfish supply or a decline in demand for shellfish products due to HABs, the Co-development of Climate Services for adaptation to changing Marine Ecosystems (CoCLiME[1]) program developed an IO model for shellfish activity based on direct, indirect, and induced effects of HABs on the regional economy of Pays de la Loire (western France) (Le Bihan *et al*., 2019). Two scenarios were simulated: 1) 30% loss of output or final demand without monetary compensation (through higher prices, or through state aid) and 2) 30% loss of output with an equivalent compensation of state aid benefiting only to the local shellfish industry. The estimation of the economic impacts of a loss of 30% of output is approximately €8 million/year (1 € = 1.20 USD), and adding an estimated indirect effect of €26 million/year in the wider economy, the total economic impact was estimated at €34 million/year (Fig. 5.3). Based on the 2012 labor/output ratios for aquaculture, a decrease of €8 million/year in output might result in the loss of 48 jobs and 152 indirect jobs in the wider economy, resulting in a total employment impact of 200 jobs (West *et al*., 2019).

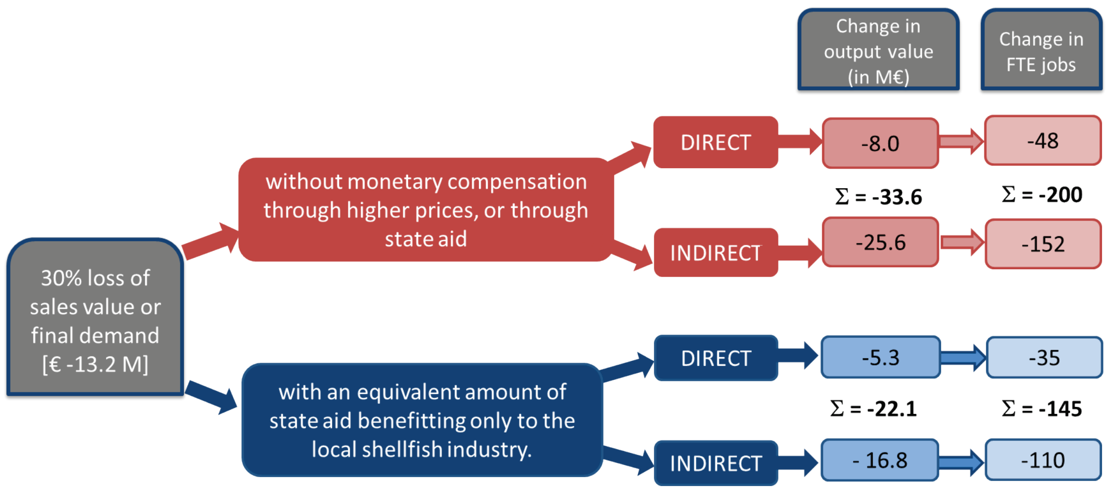

Fig. 5.3 Input-output (IO) regional model: Two scenarios with contrasted impacts for the shellfish industry. FTE – full-time equivalent.

A tailored IO model, with good information about production inputs and costs can potentially provide good estimates of both direct and indirect impacts that subtract out production input costs from lost product sales to provide net income impacts. However, the use of IO multipliers could overstate losses in upstream and supplier markets if impacts are mitigated by substitution (*e.g*., suppliers have other markets, or processors or retailers can find other suppliers of shellfish) (Adams *et al*., 2018). In such cases there may still be regional impacts but they are offset by positive impacts in other areas (one region's loss is another's gain).

To measure the costs of HABs on recreational harvesters, recreational demand models are required. These generally use revealed or stated preference approaches to model the effect of changes in HAB incidence on the demand for recreational harvesting trips. For example, two case studies in Washington State (USA) used a contingent behavior approach to elicit trip-taking behavior to produce measures of

[1] Project CoCliME is part of ERA4CS, an ERA-NET initiated by JPI Climate, and funded by EPA (IE), ANR (FR), BMBF (DE), UEFISCDI (RO), RCN (NO) and FORMAS (SE), with co-funding by the European Union (Grant 690462).

net economic value and economic impacts under varying degrees of closures. The first case study examined the effect of both HAB and pollution closures on the net economic values of Puget Sound clam and oyster harvesting (Anderson and Plummer, 2017). The behavioral response to closures was elicited through a set of four contingent behavior scenarios on each of 25 survey versions. These contingent behavior questions elicited the number of trips a respondent would take conditional on different closure scenarios. Scenarios varied by the spatiotemporal extent (additional miles to the nearest fully open beach) and type (pollution or HAB) of closures. The incomplete demand system estimated economic losses associated with closures of different magnitudes.

The second case study examined the effect of HAB closures on the economic impact of recreational razor clam harvesting on a set of four Washington ocean beaches (Dyson and Huppert, 2010). Recreational harvesting trip expenditures were used as inputs to an IO model describing the flows of goods and services in the local economies of the two counties encompassing these beaches. A contingent behavior framework elicited trip-taking behavior under different HAB scenarios. These questions were used to capture potential substitution, necessary to estimate net impacts rather than simply gross contributions (Watson *et al*., 2007).

To measure the costs of HABs on human health, the cost of illness (COI) method is most commonly used (Rice, 1967; Hodgson and Meiners, 1982). The COI method simply sums the health expenditures and lost wages from not being able to work to produce an estimate of economic costs from an illness. Although this approach is straightforward, it is known to underestimate the full economic costs associated with illnesses (Dickie, 2003; Freeman, 2014). Its primary limitation is that it fails to account for the disutility of symptoms such as pain and discomfort.

Regardless of which method is used to estimate the economic costs of HABs, it is necessary to first get a good estimate of what the reduction in value is relative to what it would have been had the HAB not occurred – the "counterfactual." If harvesting activities in the absence of the HAB were fairly stable, it may be reasonable to compare measures of net benefits with average net benefits over recent years (or months) to determine the change due to a HAB event. However, if harvesting activities are highly variable or are simply delayed, it may be necessary to develop a more sophisticated counterfactual. For example, one might develop a statistical model of expected net benefits based on historical data that accounts for other factors that impact net benefits such as environmental conditions or market conditions and seasonal factors that affect production and value. Development of a counterfactual will be specific to the particular case, and it is difficult to generalize how it should be done. The goal however, is to produce the best estimate of what both costs and benefits would have been had the HAB not occurred and compare those to actual outcomes to determine the impact of the HAB.

Mitigation

Differences in the cost of HABs to shellfish harvesters suggest a variety of potential mitigation strategies. Risk is determined by the likelihood of events and the scale of consequences. Risk management in shellfish farming depends on measures allowing professionals either to reduce the likelihood of certain events (self-protection measures) or lessen the financial consequences of the said events (self-insurance, risk transfer and solidarity (Le Bihan, 2015b)). Spatial planning for new mussel farming spots can be targeted to avoid highly frequent HAB areas, while scheduling harvesting outside peak HAB risk periods can be implemented based on existing HAB detection and forecasting systems. Geographic diversification may also reduce the likelihood of not being able to meet demand at specific times, or larger investments in gear may be required. Another indirect intervention for controlling HAB economic impacts is managing nutrient enrichment. A promising approach is Integrated Multi-Trophic Aquaculture (IMTA; Wartenberg *et al*., 2017). IMTA uses shellfish and macro-algal culturing to remove nutrients discarded from the culturing of fed species (Chopin *et al*., 2012). Cultured macroalgae can also play an important role in inhibiting the growth of toxic microalgae through competition for nutrients, inhibitory allelopathy, and/or reducing light penetration (Holdt and Edwards, 2014; Yang *et al*., 2015; Zerrifi *et al*., 2018). Decisions makers require detailed understanding of how value is impacted and how specific mitigation strategies might reduce losses or risk.

In France, Le Bihan (2015b) underlined that shellfish farmers also rely on self-insurance by setting aside contingency funds and preserving their borrowing capacity in order to deal with possible damage. It is worth noting that a French financial system, the DPA (Déduction Pour Aléas or Disaster Relief Scheme), allows shellfish farmers to build up a nest-egg fund that may be used to deal with the damage resulting from climatic, medical, family, or economic events. Shellfish farmers who can use storage and purification basins can also limit the effects of a sanitary closure.

Another way to mitigate the HAB impacts on shellfish aquaculture is through design and evaluation of insurance programs. Insurance may be a better alternative to direct subsidies paid to firms or workers during closures. Firms might wish to purchase insurance against losses due to HABs, but developing insurance products that make sense both for the insured and the insurer require detailed analysis not only of the probability of HAB events but how they impact value and how losses might be reduced. Insurance for aquaculture workers (*e.g*., unemployment insurance) may also be of interest, but again requires understanding the probability and magnitude of income losses to workers, and potential mitigation opportunities (*e.g*., alternative employment). Two key problems with all insurance productions are adverse selection and moral hazard. Adverse selection occurs when insurers cannot discern higher risk insures and charge higher insurance rates to compensate. Moral hazard occurs when insured parties reduce the actions they take to reduce the risk or magnitude of losses since they are insured against losses and have less incentive to reduce risk if it is costly to do so. Designing insurance products, whether for firms or employees, requires understanding how to identify and reduce adverse selection and moral hazard which will otherwise drive up the cost of providing insurance.

It is also important to estimate the implementation of new mitigation technologies such as outside storage (for oysters) and accelerated detoxification tanks. The practice of relaying shellfish from contaminated to clean areas may be practical in some situations for the accelerated elimination of toxins from shellfish. The viability of these new depuration methods depends on the production capacity, profitability of the farms, and the duration and intensity of the HAB event (Pérez Agúndez *et al*., 2013). Is important to estimate the costs of investment since small producers (less than 30 tons of oysters per year in France) may not have the economic capacity to invest in such strategies (Pérez Agúndez *et al*., 2013).

Effective management practices influence a business's resilience to HABs. In the case of the Galician mussel industry, HAB losses have been reduced (Rodríguez *et al*., 2011). This is because product was sold during months prior to high HAB incidence, or after the event. A rotation system for harvesting mussels was also established to alleviate the loss of profit, providing an opportunity to all farmers for equitable sales. Continued improvements to monitoring technologies (*e.g*., *in situ* autonomous instruments such as the imaging flow cytobot and environmental sample processor, as well as other methods) may enable finer-resolution harvest management and help avoid blanket closures in aquaculture regions.

Data needs, availability and gaps

To quantify the economic costs of HABs on shellfish aquaculture, it is necessary to quantify the revenue, and ideally profits, that would have been realized in the absence of the HAB. If there is a direct loss due to mortality of a shellfish crop, it may be possible to simply estimate the lost revenue using recent price data or prices from nearby areas that were not affected. Ideally, farm-level price data associated with individual sales would be collected, enabling development of an expected price for the lost sales that most closely matches the product lost, where it came from, and when it was sold. However, because sales data are proprietary and may be generated by many small firms, it is unlikely that farm transaction-level data will be available. An alternative would be to maintain a time series of prices at a regional scale with as fine a temporal and spatial time scale as feasible (*e.g.*, monthly prices by product in each county). Such data might be collected using a regular survey of producers.

In many cases, determining the aquaculture loss due to a HAB may be more complex when it involves a delay in harvest or a change in the quality of the product due to the delay. In such cases, determining the loss requires estimating what the value of production would have been had the delay not occurred. Again, applying the most appropriate prices to the production that would have occurred will require access to recent prices or contemporaneous prices from another area.

Quantifying the loss or delay in aquaculture production due to a HAB may also be complex when it is not due to a direct mortality event. In the event of a delay there may still be a loss in value if growth *in situ* does not exceed natural mortality, and the product form may change from what it would have been (*e.g.*, larger size and different grade). Data on historical production at the finest temporal and spatial scale available may be used to estimate what production would have been as compared to observed production.

In addition to losses to aquaculture producers, there may be losses to consumers of shellfish products. Estimating these losses in consumer surplus will likely require retail price data. For products that are sold on global markets, use of global price data may be feasible and consumer surplus is likely to be small for such production in any case. However, for products that are primarily consumed locally and are distinct without close substitutes, consumer surplus losses could be significant. Estimating these losses would require a time series of region- and product-specific retail prices or the use of a stated preference approach such as a discrete choice experiment.

Estimating the net economic value or net economic impacts of HABs on recreational shellfish harvesters requires prices and quantities of trips to quantify the economic demand for recreational shellfish harvesting trips. The price of a harvesting trip is composed of the travel cost to reach the site as well as any on-site harvesting costs. For both net economic value and economic impact calculations, it is critical to measure the change in value that results from a particular policy, in contrast to the total economic value of harvesting. Therefore, recreational demand models need to be able to quantify both the baseline harvesting effort as well as the harvesting effort that would result from the policy or environmental change being examined.

T61 Toxic effect of noxious substances eaten as seafood

Excl.: allergic reaction to food, such as:
- anaphylactic shock due to adverse food reaction (T78.0)
- dermatitis (L23.6, L25.4, L27.2)
- gastroenteritis (noninfective) (K52.-)

bacterial foodborne intoxications (A05.-)

toxic effect of food contaminants, such as:
- aflatoxin and other mycotoxins (T64)
- cyanides (T65.0)
- hydrogen cyanide (T57.3)
- mercury (T56.1)

T61.0 Ciguatera fish poisoning

T61.1 Scombroid fish poisoning

Histamine-like syndrome

T61.2 Other fish and shellfish poisoning

T61.8 Toxic effect of other seafoods

T61.9 Toxic effect of unspecified seafood

Fig. 5.4 Medical classification of the toxic effects of noxious substances in seafood, based on the International Classification of Diseases (ICD-10) of the World Health Organization. Highlighted in orange are the categories assigned for classification of PSP, DSP and AZP.

In order to estimate the health costs of HABs to affected consumers, it is necessary to identify the extent of illnesses that are caused by the HAB. Shellfish poisonings are reported according to the International Classification of Diseases (ICD-10) of the World Health Organization (WHO). The ICD-10, however, does not specify which ones are intoxications caused by toxic microalgae (with the exception of ciguatera fish poisoning) related to PSP, DSP and AZP. Instead, poisoning caused by HABs is classified according to the toxic effect of noxious substances eaten as seafood under items T61.2 and T61.9, which also include viral and bacterial poisonings (Fig. 5.4). These illness data would need to be combined with the cost associated with treatment, losses in worker productivity as proxied by wage rates, and the disutility of symptoms such as pain and discomfort, if available. Finally, the value of a statistical life approach (*e.g.*, Bowland and Beghin, 2001; Kniesner *et al.*, 2012) would need to be used to estimate costs due to any human fatalities caused by the HAB.

Acknowledgements

We thank the SCOR and IOC UNESCO GlobalHAB program and PICES for financial support. J.I.M. was funded by the Instituto de Fomento Pesquero (IFOP). K.D. was funded by the UK RCUK projects OFF-AQUA and CAMPUS and the EU Atlantic Area Interreg project PRIMROSE. F.G. was funded by an Ocean Risk Studentship from AXA-XL. V.L.T. was supported by a grant from the NOAA National Centers for Coastal Ocean Science Centers for Sponsored Coastal Ocean Research. This is the NOAA Monitoring and Event Response to Harmful Algal Blooms (MERHAB) publication #229. We thank Elisa Berdalet for her careful reviews of earlier versions, and Andrea Rivera (MINSAL) and Cristian Segura (INTEMIT) for technical discussions.

References

Adams, C.M. and Larkin, S.L. 2013. Economics of harmful algal blooms: Literature review. Final Report for Gulf of Mexico Alliance Project #00100304. Food and Resource Economics Department, University of Florida, Gainesville, 32 pp.

Adams, C.M., Larkin, S.L., Hoagland, P. and Sancewich, B. 2018. Assessing the economic consequences of harmful algal blooms: a summary of existing literature, research methods, data, and information gaps, pp. 337–354 *in:* Harmful Algal Blooms: A Compendium Desk Reference *edited by* S.E. Shumway, J.A.M. Burkholder and S.L. Morton, John Wiley, New York.

Anderson, D.M and Rensel, J. 2016. Harmful Algal Blooms. Assessing Chile's historic HAB events of 2016. A report prepared for the Global Aquaculture Alliance, 14 pp.

Anderson, D.M., Kaoru, Y. and White, A.W. 2000. Economic impacts from Harmful Algal Blooms (HABs) in the United States. Technical Report WHOI-2000-11. Woods Hole Oceanographic Institution, Woods Hole, MA.

Anderson, D.M., Andersen, P., Bricelj, V.M., Cullen, J.J. and Rensel, J.E. 2001. Monitoring and management strategies for harmful algal blooms in coastal waters, APEC#201-MR-01.1, Asia Pacific Economic Program, Singapore, and International Oceanographic Commission Technical Series No. 59, Paris.

Anderson, L.E. and Plummer, M.L. 2017. Recreational demand for shellfish harvesting under environmental closures. *Marine Resource Economics* **32** : 43–57, https://doi.org/10.1086/688975.

Anonymous 2019. Revista Aqua. N° 222 Marzo 2019, p. 46.

Azanza, R.V. 1999. Seafood poisoning from harmful algal blooms in coastal areas (abstract only). IOC-SOA International Workshop on Coastal Megacities: Challenges of Growing Urbanisation of the World's Coastal Areas Intergovernmental Oceanographic Commission Workshop, Hangzhou, People's Republic of China, 27–30 September 1999. UNESCO Report, 166.

Azanza, R.V. and Taylor, F.J.R. 2001. Are *Pyrodinium* blooms in the Southeast Asian region recurring and spreading? A view at the end of the millennium. *Ambio* **30**: 356–364.

Baron, S., Benrekassa, J., Calavas, D., De Valk, H., Delorme, C., Goué-Benadiba, L., Henry, V., Marcé, C., Santolini, J. and Vaillant, V. 2012. Risques microbiologiques alimentaires dans les produits d'origine animale: surveillance et évaluation. Bulletin épidémiologique hebdomadaire, Hors-Série.

Berdalet, E., Fleming, L.E., Gowen, R., Davidson, K., Hess, P., Backer, L.C., Moore, S.K., Hoagland, P. and Enevoldsen, H. 2016. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the United Kingdom* **96**: 61–91.

Bowland, B.J. and Beghin, J.C. 2001. Robust estimates of value of a statistical life for developing economies. *Journal of Policy Modeling* **23**: 385–396.

Campbell, D.A., Kelly, M.S., Busmann, M., Bolch, C.J., Wiggins, E., Moeller, P.D.R., Morton, S.L., Hess, P. and Shumway, S.E. 2001. Amnesic shellfish poisoning in the king scallop, *Pecten maximus*, from the West Coast of Scotland. *Journal of Shellfish Research* **20**: 75–84.

Chopin, T., Cooper, J.A., Reid, G., Cross, S. and Moore, C. 2012. Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. *Reviews in Aquaculture* **4**: 209–220.

Davidson, K., Gowen, R.J., Harrison, P.J., Fleming, L.E., Hoagland, P. and Moschonas, G. 2014. Anthropogenic nutrients and harmful algae in coastal waters. *Journal of Environmental Management* **146**: 206–216.

Díaz, P., Álvarez, G., Varela, D., Pérez-Santos, I., Díaz, M., Molinet, C., Seguel, M., Aguilera-Belmonte, A., Guzmán, L., Uribe, E., Rengel, J., Hernández, C., Segura, C. and Figueroa, R. 2019. Impacts of harmful algal blooms on the aquaculture industry: Chile as a case study. *Perspectives in Phycology* **6**: 39–50.

Dickie, M. 2003. Defensive behavior and damage cost methods, pp. 395–444 *in:* A Primer on Nonmarket Valuation *edited by* P.A. Champ, K.J. Boyle and T.C. Brown, Dordrecht, Springer Netherlands, https://doi.org/10.1007/978-94-007-0826-6_11.

Dyson, K. and Huppert, D.D. 2010. Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae* **9**: 264–271, https://doi.org/10.1016/j.hal.2009.11.003.

European Union. 2004. Regulation (EC) No 853/2004 of the European Parliament and of the council. *Official Journal of the European Union* 30.04.2004: L139/55.

European Union. 2019. The EU fish market. Publications Office of the European Union, Luxembourg, 102 pp., doi:10.2771/168390.

FAO (Food and Agriculture Organization). 2017. GLOBEFISH – Information and Analysis on World Fish Trade. Production for bivalves lower in 2016. http://www.fao.org/in-action/globefish/market-reports/resource-detail/en/c/887775/ (accessed 11 February 2020).

FAO. 2018. The State of World Fisheries and Aquaculture 2018. Meeting the sustainable development goals. Rome. http://www.fao.org/3/i9540en/i9540en.pdf.

FAO and WHO. 2018. Technical guidance for the development of the growing area aspects of bivalve mollusk sanitation programmes. Food Safety and Quality Series No.5. Rome, 292 pp.

Fehling, J., Green, D.H., Davidson, K., Bolch, C.J. and Bates S.S. 2004. Domoic acid production by *Pseudo-nitzschia seriata* (bacillariophyceae) in Scottish waters. *Journal of Phycology* **40**: 622–630.

Freeman, A.M. III. 2014. The Measurement of Environmental and Resource Values: Theory and Methods. 3rd edition, Routledge, https://doi.org/10.4324/9781315780917.

Garza-Gil, M.D., Vázquez-Rodríguez, M.X. and Varela-Lafuente, M.M. 2016. Marine aquaculture and environment quality as perceived by Spanish consumers. The case of shellfish demand. *Marine Policy* **74**: 1–5.

Highlands and Islands Enterprise, Marine Scotland. 2017. The Value of Aquaculture to Scotland. 130 pp.

Hinder, S.L., Hays, G.C., Brooks, C.J., Davies, A.P., Edwards, M., Walne, A.W. and Gravenor, M.B. 2011. Toxic marine microalgae and shellfish poisoning in the British isles: history, review of epidemiology, and future implications. *Environmental Health: A Global.Access Science Source* **10**: 54, https://doi.org/10.1186/1476-069X-10-54.

Hoagland, P., Anderson, D.M., Kaoru, Y. and White, W. 2002. The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs. *Estuaries* **25**: 819–837.

Hodgson, T.A. and Meiners, M.R. 1982. Cost-of-Illness methodology: A guide to current practices and procedures. The Milbank Memorial Fund Quarterly. *Health and Society* **60**: 429, https://doi.org/10.2307/3349801.

Holdt, S.L. and Edwards, M.D. 2014. Cost-effective IMTA: a comparison of the production efficiencies of mussels and seaweed. *Journal of Applied Phycology* **26**: 933–945.

Holland, D.S., Sanchirico, J., Johnston, R.J. and Joglekar, D. 2009. Economic Analysis for Ecosystem Based Management: Applications to Marine and Coastal Environments. RFF Press, Washington, DC.

Huppert, D.D. and Trainer, V.L. 2014. Economics of razor clam fishery closures due to harmful algal blooms in Washington State, pp. 59–71 *in:* Proceedings of the Workshop on Economic Impacts of Harmful Algal blooms on Fisheries and Aquaculture *edited by* V.L Trainer and T. Yoshida. PICES Scientific Report No. 47, 85 pp.

Jin, D. and Hoagland, P. 2008. The value of HAB predictions to the commercial shellfish fishery in the Gulf of Maine. *Harmful Algae* **7**: 772–781.

Jin, D., Thunberg, E. and Hoagland, P. 2008. Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean and Coastal Management* **51**: 420–429.

Kniesner, T.J., Viscusi, W.K., Woock, C. and Ziliak, J.P. 2012. The value of a statistical life: Evidence from panel data. *The Review of Economics and Statistics* **94**: 74–87.

Le Bihan, V. 2015a. Analyse économique du risque en conchyliculture. PhD thesis, University of Nantes, France.

Le Bihan, V. 2015b. Risks and risk management for shellfish farmers: a few thoughts. International Symposium on Research Outcomes of the Maritime and Inland Waterways Observatory of Cambodia (MIWO). National University of Management, Phnom Penh, Cambodia.

Le Bihan, V., Guillotreau, B., Morineau, B. and Pardo, S. 2019. The impact of shellfish trade bans caused by harmful algal blooms (HABs) on a French regional economy: an Input-Output approach. Oceanext, Interdisciplinary Conference, 3–5 July 2019, Nantes, France.

Marette, S., Roosen, J. and Blanchemanche, S. 2008. Health information and substitution between fish: Lessons from laboratory and field experiments. *Food Policy* **33**: 197–208.

Martino, S., Gianella, F. and Davidson, K. 2020. An approach for evaluating the economic impacts of harmful algal blooms: The effects of blooms of toxic *Dinophysis* spp. on the productivity of Scottish shellfish farms. *Harmful Algae* **99**: 101912, DOI: 10.1016/j.hal.2020.101912.

Matsuyama, Y. and Oda, T. 2020. Toxic effects of harmful algal blooms on finfish and shellfish. Chapter 34, pp. 543–560 *in:* Handbook of Algal Science, Technology and Medicine *edited by* O. Konur, Elsevier, https://doi.org/10.1016/B978-0-12-818305-2.00034-6.

Pérez Agúndez, J.A., Raux, P., Girard, S. and Mongruel, R. 2013. Technological adaptation to harmful algal blooms: Socioeconomics consequences for the shellfish farming sector in Bourgneuf Bay (France). *Aquaculture Economics and Management* **17**: 341–359.

Rice, D.P. 1967. Estimating the cost of illness. *American Journal of Public Health* **57**: 424–440, https://doi.org/10.2105/AJPH.57.3.424.

Rodríguez, G.R., Villasante, S. and García-Negro, M.C. 2011. Are red tides affecting economically the commercialization of the Galician (NW Spain) mussel farming? *Marine Policy* **35**: 252–257.

Sakamoto, S., Lim, W.A., Lu, D., Dai, X., Orlova, T. and Iwataki, M. 2020. Harmful algal blooms and associated fisheries damage in East Asia: Current status and trends in China, Japan, Korea and Russia. *Harmful Algae*, https://doi.org/10.1016/j.hal.2020.101787.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic, S. and Lettieri, T. 2016. Algal bloom and its economic impact. JRC Technical Report. EUR 27905 EN. doi:10.2788/660478.

Satake, M., Ofuji, K., James, K., Fury, A. and Yasumoto, T. 1998. New toxic event caused by Irish mussels, pp. 468–469 *in:* Harmful Algae *edited by* B. Reguera, J. Blanco, M.L. Fernandez and T. Wyatt, Xunta de Galicia and International Oceanographic Commission of UNESCO, Santiago de Compostela.

Seafish, 2016. https://www.seafish.org/media/1643138/final_seafishguidetoaquaculture_final.pdf.

Skjoldal, H.R. and Dundas, I. (Eds.) 1991. The *Chrysochromulina polylepis* bloom in the Skagerrak and the Kattegat in May-June 1988: Environmental conditions, possible causes, and effects. Report of the ICES Workshop on the *Chrysochromulina polylepis* bloom in the in the Skagerrak and the Kattegat in May-June 1988. 28 February–2 March 1989, Bergen.

Smaal, A.C., Ferreira, J.G., Grant, J., Petersen, J.K. and Strand, Ø. (Eds.) 2018. Goods and Services of Marine Bivalves. Springer, doi: 10.1007/978-3-319-96776-9.

STECF (Scientific, Technical and Economic Committee for Fisheries). 2018. Economic Report 963 of the EU Aquaculture sector (STECF-18-19). Publications Office of the European Union, 964 Luxembourg. ISBN 978-92-79-79402-5. https://doi:10.2760/45076, JRC114801.

Stolte, W., Scatasta, S., Graneli, E., Weikard, H.P. and Van Ierland, E. 2001. ECOHARM: The socio-economic impact of harmful algal blooms in european marine waters. Vol. EVK3-CT-20, p. 100. Department of Biology and Environmental Science, Kalmar University, Sweden and Environmental Economics and Natural Resources Group, Wageningen University, The Netherlands.

Tillmann, U. 2018. Harmful algae species fact sheet: Amphidomataceae, pp. 575–582 *in:* Harmful Algal Blooms: A Compendium Desk Reference *edited by* S.E. Shumway, J.A.M. Burkholder and S.L. Morton, John Wiley and Sons, Hoboken.

Todd, E.C.D. 1995. Estimated costs of paralytic shellfish, diarrhetic shellfish and ciguatera poisoning in Canada, pp. 831–834 *in:* Harmful Marine Algae Blooms *edited by* P. Lassus, G. Arzul, E. Erard, P. Gentien and C. Marcaillou (Eds.), Intercept Ltd., Paris, France.

Trainer, V.L., Moore, S.K., Hallegraeff, G., Kudela, R.M., Clément, A., Mardones, J.I., and Cochlan, W.P. 2019. Pelagic harmful algal blooms and climate change: Lessons from nature’s experiments with extremes. *Harmful Algae* **91**: 101591, doi.org/10.1016/j.hal.2019.03.009.

Wartenberg, R., Feng, L., Jun Wu, J., Mak, Y.L., Chan, Telfer, T.C. and Lam, P.K.S. 2017. The impacts of suspended mariculture on coastal zones in China and the scope for Integrated Multi-trophic Aquaculture. *Ecosystem Health and Sustainability* **3**: 1340268.

Watson, P., Wilson, J., Thilmany, D. and Winter, S. 2007. Determining economic contributions and impacts: What is the difference and why do we care? *Journal of Regional Analysis and Policy* **37**: 140–146.

Wessells, C.R., Miller, C.J. and Brooks, P.M. 1995. Toxic algae contamination and demand for shellfish: case study of demand for mussels in Montreal. *Marine Resource Economics* **10**: 143–159.

West, J.J., Travers, M., Le Bihan, V., Appéré, G., Guillotreau, P., Thomas, T., Morineau, M., Pardo, S., Vulturius, G., Cusack, C. and Berdalet E. 2019. CoCliME: Investigating the socio-economic impacts of HABs through co-development with stakeholders in European marine coastal areas. Poster presentation at Workshop on “GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, October 17–19, 2019, PICES-2019, Victoria, B.C. Canada.

Whitehead, J.C., Haaband, T.C. and Parsons, G.R., 2003. Economic effects of *Pfiesteria*. *Ocean and Coastal Management* **46**: 845–858.

Whyte, C., Swan, S. and Davidson, K. 2014. Changing wind patterns linked to unusually high *Dinophysis* blooms around the coast of the Shetland Islands, Scotland. *Harmful Algae* **39**: 365–373.

Yang, Y., Chai, Z., Wang, Q., Chen, W., He, Z. and Jiang, S., 2015. Cultivation of seaweed *Gracilaria* in Chinese coastal waters and its contribution to environmental improvements. *Algal Research* **9**: 236–244.

Yin, K., Harrison, P.J., Chen, J., Huang, W. and Qian, P-Y. 1999. Red tides during spring 1998 in Hong Kong: is El Niño responsible? *Marine Ecology Progress Series* **187**: 289–294, doi: 10.3354/meps187289.

Zerrifi, S.E.A., El Khalloufi, F., Oudra, B. and Vasconcelos, V. 2018. Seaweed bioactive compounds against pathogens and microalgae: potential uses on pharmacology and harmful Algae Bloom control. *Marine Drugs* **16**: E55.

6 The Economic Impacts of Harmful Algal Blooms on Salmon Cage Aquaculture

Keith Davidson[1], Sunny L. Jardine[2], Simone Martino[3], Geir B. Myre[4], Liam E. Peck[5], Rebecca N. Raymond[5] and Jennifer Joy West[6]

[1] Scottish Association for Marine Science, Scottish Marine Institute, Oban, PA37 1QA, Scotland, UK
[2] School of Marine and Environmental Affairs, University of Washington, Seattle, 3707 Brooklyn Ave. NE, WA 98105, USA
[3] Department of Environment & Geography, University of York, Wentworth Way, York, YO10 5NG, England, UK
[4] Aquaculture Department, XL Catlin Norway, part of AXA XL, a division of AXA, C. Sundsgate 37, 5004 Bergen, Norway
[5] Grieg Seafood BC Ltd, #106 – 1180 Ironwood St., Campbell River, V9W 5P7, Canada
[6] CICERO Center for International Climate Research/Senter for Klimaforskning, P.O. Box 1129, 0318 Blindern, Oslo, Norway

Introduction

Salmon aquaculture is typically undertaken in temperate fjordic regions. The largest global producer is Norway, followed by Chile, Scotland and Canada. These countries generate over 90% of global production of farmed Atlantic salmon exceeding 2.6 million tonnes. Export price for Norwegian salmon is between US$7–9 per kg (FAO, 2019).

Harmful Algal Blooms (HABs) are capable of negatively impacting salmon farming. A high profile example is the massive fish kill in Chile in 2016 following a bloom of the raphidophyte *Pseudochattonella.* This resulted in the mortality of 39 million salmon and US$800 million of economic impact (Anderson and Rensel, 2016). In 2019, a bloom of *Chrysochromulina leadbeateri* in northern Norway was estimated to have killed 8 million salmon, total tonnage 14,000, with a direct value of over 850 million NOK (1 NOK = 0.11 USD). This was compounded by a future sales loss of approximately the same amount, as the fish were not fully grown out for sale. On top of this, clean-up cost and extra mitigation cost added up to a further 300 million NOK, with additional loss of tax income and requirements to fund unemployment/social benefits. The direct and indirect gross effects of the bloom have therefore been estimated to be between 2.3 and 2.8 billion NOK (Kontali, 2020). In the same period, algal blooms were observed on the west coast of Scotland to cause the loss of thousands of fish in Loch Fyne (Cockburn, 2019), and in June of 2018, more than 200,000 salmon were killed by *Heterosigma akashiwo* in British Columbia (Robinson, 2018). These mortalities likely had significant impacts on production and on the final prices paid by consumers.

Due to the serious risk to human health from shellfish-accumulated biotoxins, many countries operate rigorous regulatory monitoring of the causative HABs species. These programmes are typically government funded and publish their data routinely and rapidly on the web, potentially allowing a detailed temporal and spatial analyses of biotoxic HAB risk to be developed. While there is some limited overlap, the species of phytoplankton that result in mortalities of aquacultured salmon are mostly different from those that generate shellfish biotoxins and are hence not recorded or reported by regulatory monitoring. Ichthyotioxic HAB monitoring, if it occurs, is usually undertaken by individual aquaculture businesses. Hence, while there are a number of examples of HAB-mediated fish mortalities in the scientific literature, these reports likely relate to the most extreme events (Jin *et al*., 2008; Park *et al*., 2013). Sub-lethal HAB effects are likely to include decreased growth rates, with increased susceptibility to disease and parasites also likely to be important. However, information on modest fish kills, sub-lethal effects, and the HAB species and concentrations that are responsible for them are not routinely available. Hence, these impacts are difficult to quantify but may have large impacts. For example, even if sub-lethal effects lead to small impacts on gill health, aggregating these small impacts over large quantities of production has the potential to significantly affect the global market supply.

Thus, little is known about the multifaceted impacts of HABs on salmon aquaculture. However, the combined losses related to direct farmed fish mortalities and reduced fish welfare and health are likely to lead to lower production levels and increased costs for producers, while also having wider societal consequences linked to potential impacts on jobs and incomes in land-based processing and related service industries. For example, large fish kills may introduce volatility in supply (Rodríguez *et al*., 2011) and producers may suffer the potential loss of market if supply contracts cannot be met or be otherwise penalized in a seafood market that rewards stability in supply.

In this paper, which is a result of discussions undertaken during the GlobalHAB HAB/economics workshop at the 2019 PICES Annual Meeting in Victoria, Canada, we explore the current state of knowledge about the economic impact of HABs on salmon aquaculture, outline economic valuation methods for quantifying potential impacts, and discuss strategies to mitigate negative economic impacts.

HAB impacts, economic costs and mitigating strategies

In considering the total economic impacts of HABs on salmon aquaculture producers and society at large, it is important to include both the direct economic losses from mortalities and sub-lethal effects, as well as indirect economic impacts of mass mortalities of farmed fish for society. The cost of HABs includes, but is not limited to, the costs of any mitigation measures taken by producers such as aeration, oxygenation, increased monitoring of HABs, interruptions to necessary treatments (*i.e*., sea lice removal) and/or in some cases where regulations allow, moving fish to waters with reduced HAB concentrations. Other costs include those associated with the removal and disposal of dead fish, or the costs associated with operating at sub-optimal but HAB-free sites (*e.g*., remote sites with higher transportation costs). Other costs include preventative measures, and the research and development necessary to underpin these (Chávez *et al*., 2019). In the event that HABs lead to large changes in salmon aquaculture production, it is also important to consider whether the consumer price, and thus consumer welfare, is affected (Adams *et al*., 2018).

Policy makers may be also interested in regional economic impacts (direct and indirect effects) on turnover. These include the potential impacts on employment in land-based processing (Agúndez *et al*., 2013) and service industries following mass fish mortalities, as well as the costs of mitigation measures, communication and monitoring during HAB events (Anderson *et al*., 2000; Ralston *et al*., 2011; Adams *et al*., 2013). Moreover, policy makers may be in a position to introduce "compensatory" measures that reduce the total economic impacts of a bloom event.

Consumers of salmon may experience short-term price increases if HABs reduce the supply of farmed fish sufficiently to impact its market value, as happened in 2019 during the *C. leadbeateri* mediated Norwegian fish kill (Klesty, 2019). In extreme cases HABs may also lead (at least temporarily) to job losses or temporary closures on the land-based side of the aquaculture sector, which can then impact sales and jobs in related industries (Perez, 2016).

To better understand the economic impacts of HABs on salmon aquaculture, there are a number of data gaps/needs relating to both ecological and socio-economic information. Coordinated monitoring and data sharing efforts are likely to be key to conducting better economic studies of HAB impacts on salmon aquaculture. Temporal information on the linkages between HAB species presence, densities and toxicity, and fish mortalities or sub-lethal effects are required. The interpretation of these data requires further information on fish health, for example, the quality of smolts, parasite densities and treatments, other diseases that are present, and days of non-feeding due to the presence of the HAB that will influence the health and productivity of the farmed fish, along with an understanding of the environment at a site. Data on public and private compensation measures, including "risk transfer" mechanisms such as insurance held by individual producers, and changes to regulatory practices allowing for an increase in fish production over time are also needed in order to understand the true net "costs" or impacts of a HAB event. These data are potentially commercially sensitive, and industry and researchers need to build trust to allow their sharing. If HAB events are infrequent, there can be a loss of knowledge and capacities to both identify and deal with the consequences of HABs, and hence better systems for sustained collection, recording and sharing of knowledge, expertise and data are required.

Assuming the above information is available, an evaluation of the economic impacts of HABs can be achieved through the quantification of: 1) Inputs to production and input costs (this would be used to estimate the supply curve and producer surplus changes) and 2) Mitigation measures taken, and the costs of these. Because labour is an input to production, the economic impacts (jobs) can be estimated with data from (1). Subsequent economic analysis can then be carried out at several scales considering impacts for the 1) company, 2) community and region and 3) national sector/sub-sector.

Anthropogenic drivers and responses

Anthropogenic impacts on water quality are an important concern for the salmon industry and may have an influence on HABs (Gilbert *et al*., 2005; Davidson *et al*., 2014). The Chilean industry is debating the potential role of coastal eutrophication in HAB dynamics, as nutrients may have had a role in the major 2016 fish kill in that country (Anderson and Rensel, 2016). However, available information does not allow establishing or rejecting a cause–effect relationship (Quiñones *et al*., 2019). Climate change can be relevant too, with an increase in sea surface temperatures potentially promoting changes in the biogeography of HAB species (Berdalet *et al*., 2016; Wells *et al*., 2019). However, there remain significant knowledge gaps about the relative importance of, and precise linkages between physical, ecological and anthropogenic factors affecting HABs, as well as large uncertainties when it comes to modelling these dynamics into the future (Davidson *et al*., 2016).

While an anthropogenic link to HABs has been established in some locations (Davidson *et al*., 2012), many HAB events are thought to occur due to a combination of different biotic and abiotic conditions that vary at different temporal and spatial scales (Anderson *et al*., 2002). In Scotland, for example, many HAB events develop offshore and are advected to the coast by oceanographic processes (Smayda, 2006; Whyte *et al*., 2014). Their mitigation is therefore likely to be best achieved through a combination of preparedness/early warning, effective communication and coordination between institutional and operational actors during a bloom event, and the ability and capacity to take action (Maguire *et al*., 2016).

At present, there is a poor understating of the density or concentration at which particular ichthyotoxic HAB species become toxic or otherwise problematic, and hence when action should be taken. In some cases harmful bloom conditions may arise rapidly, limiting the ability for fish farmers to take preventative or mitigative action unless early warning through regular sampling, monitoring, or *in-situ* modelling and other approaches can be employed (Aleynik *et al*., 2016). If mitigating action is employed, it might include reducing or stopping feeding, undertaking precautionary/early slaughtering, deploying protective tarpaulins or screens, sinking nets, employing bubble walls or the upwelling of deep (algae free) water, delaying planned introduction of smolt, or moving fish to locations that are unaffected by the bloom (Anderson, 2004, 2009). On the processing side, companies may be able to deal with temporary supply problems by sourcing fish from other locations or producers or reducing factory "down time" by shifting maintenance activities to periods with reduced supply of fish (West, unpublished data).

At present, there is poor understanding of the cost-benefits of different practices in different regions and it must be recognised that one approach may not be successful or cost-effective in all locations and for all harmful species (Wells *et al*., 2019). There may be considerable financial, regulatory and other barriers associated with employing mitigations strategies such as relocating fish that lead to differential vulnerability to HAB events among fish farmers (West, unpublished interview data). Baseline data are missing or at least difficult to access, and control experiments are difficult to undertake. The return on investment of these different approaches is also difficult to assess and requires more detailed cost-benefit analysis. Having access to sufficient quality data is a precondition for being able to undertake risk assessments that are relevant for both short-term mitigation and longer term strategic investment decisions, for example, decisions about whether fish farms should be relocated to waters that are less prone to ichthyotoxic HABs.

Examples of valuation approaches used by economists

Reduction in supply and increase in business costs cause impacts and costs for society. Measuring these losses is not easy, but different approaches can be used. One of the first attempts to quantify HAB impacts at a national scale was made by Hoagland *et al*. (2002) who compiled economic estimates of the effects of HABs to commercial fisheries in the U.S., amongst other sectors, for the period 1987–1992. There is now quite a large body of literature on the valuation of HAB impacts in sectors like commercial fisheries and aquaculture with recent reviews, although mainly on research from the USA, having been produced by Sanseverino *et al*. (2016) and Groeneveld *et al*. (2018). Much of this literature is limited by the lack of available data. Hence results are often difficult to compare (Davidson *et al*., 2014) and not always relevant to cost-benefit analysis (Hoagland *et al*., 2002; Hoagland and Scatasta, 2006). For instance, the analysis carried out by Hoagland *et al*. (2002) provides figures of lost sales (or gross revenues rather than producer surplus). Ideally, an estimate of the cost of HABs to society would measure the impacts of HABs on both producer and consumer surplus. The approach would not only incorporate information about increased costs to producers, but also explore the potential impacts on consumers.

Figure 6.1 illustrates how a HAB event can induce consumer and producer economic changes *via* a shift in the supply of the industry (reduction in production) and a change in price (increase) even if consumer demand is not affected by the HAB. It shows how direct impacts (measured as lost revenue) are different from measures of consumer and producer surplus. Benefits for consumers are measured under the demand and above the market price, while measures of surplus for the producers are the area above the supply and below the market price. For the initial market equilibrium P0Q0, areas A+B+C+D represent the benefit for the consumers, while E+F+G is the benefit for the producers.

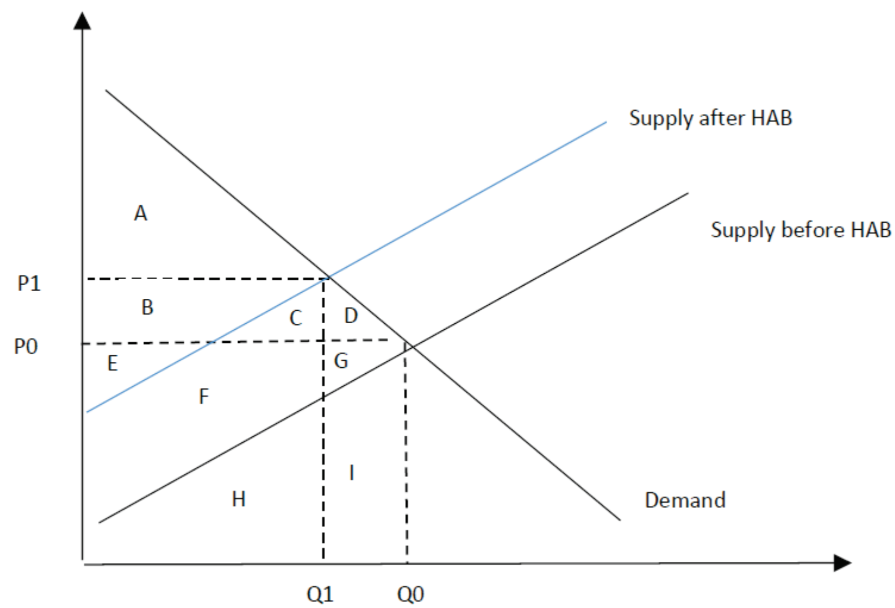

Fig. 6.1 Consumer and producer surplus in industry. From Adams *et al*. (2018).

The total surplus for society is the sum of all these areas. After the HAB event, supply shifts upwards and a new equilibrium is established (P1Q1). The new consumer surplus shrinks to the area A, while the new producer surplus is represented by the areas B+E. The variation in total surplus is the benefit for society measured after the HAB event. This is equivalent to (A+B+E) – (A+B+C+D+E+F+G) = –(C+D+F+G). The areas C+D+F+G measure the loss in welfare after the bloom, assuming the reduction in supply, and this measure is different from the loss of revenue (impact) captured by the areas I and G. Therefore, the direct impact only partially reflects a measure of welfare (equivalent to the area G), while the remaining area I, representing the cost of harvesting, is a resource that can be productively invested or utilized elsewhere in the economy (Anderson *et al*., 2000). The cost (I) must be added to the total welfare lost by the HAB event (C+D+F+G) in the event that the commercial fish have been harvested and the product subsequently prevented from reaching the market because toxicity exceeds safe levels. For price to be affected, the impact of a HAB event needs to be large, *i.e*., even if the total production of a single firm were decimated (unless the majority of production is coming from a single firm), the consumer price would not be affected.

A mathematical approach to analyse changes in producer surplus in a HAB event is provided by Lorentzen and Petterson (2005). These authors formally show how, for a price-taker industry (industry producing at a price generated in competitive markets), a significant HAB event will reduce the producer surplus by inducing a shift (reduction) in supply. However, if the aggregated industry can affect the market price (raising the revenue), the net effect on producer surplus is ambiguous. We can expect an increase in the revenue caused by an increase in price, but this should be too small to compensate for the increase in cost of production.

Much of the literature does not attempt to understand the welfare impacts of HABs to society required by cost-benefit analysis for policy scenario valuations, but instead focuses on impacts to revenues or jobs associated with HABs (Adams *et al*., 2018; Groeneveld *et al*., 2018). A description of the local and regional markets for specific HAB events, capturing the "multiplier" effects or the full ramifications of economic impacts along the supply chain is conducted through input-output or general equilibrium models. An example of a study of HAB impacts in which multipliers have been estimated relates to the U.S. state of Maine's shellfishing closure of September 1980 (Anderson *et al*., 2000). Similarly, Dyson and Hupper (2010) estimate the regional economic impacts of razor clam beach closures due to HABs on the Pacific coast of Washington state. Examples of this approach are few for the European aquaculture industry. Exceptions are Agúndez *et al*. (2013) who estimated direct output impact (lost gross revenue) and economic performance of new technology for the shellfish farming sector in Bourgneuf Bay, France, and Kontali (2020) which quantifies the different aspects of the gross economic impacts of the 2019 *Chrysochromulina* bloom in Norway.

The value of monitoring information in HAB prediction

As noted above, the monitoring of HABs can provide important information to the salmon aquaculture industry, reducing uncertainties in production and enabling the adoption of the best strategies available to mitigate the cost of HABs. The value that information from monitoring provides to the industry can be quantified. While ignoring or underinvesting in monitoring might expose the industry to high risks that a harmful event may dramatically affect the production, monitoring is costly and is not necessarily justified by the incremental benefits expected by the implementation of a mitigating strategy. Therefore, quantifying the expected net benefits that monitoring generates is an essential task. Figure 6.2 explains the flow of actions that a monitoring system entails, where net benefits calculated as the difference between revenues and costs under each mitigating scenario are weighted by the probability of the HAB event to provide an expected (average) value of these benefits.

Monitoring systems can provide improved information on the probability of HABs at any given point in time. An increase in monitoring efforts would increase the expected resolution and reliability of the system to forecast HAB events and concentration of algae above a harmful threshold, and has the potential to predict a change in the potential outcome (expected net benefits). According to the information that the monitoring system provides, to reduce the impact of a HAB, producers may decide to initiate one or more mitigating actions, or to do nothing. The decisions will be made according to which option will generate the highest net benefits (expected increase in net revenue from the mitigating action minus the cost of the mitigation action). To infer net benefits, it is essential to forecast the level of production loss under different mitigating strategies (*e.g*., aeration, tarpaulins, or early slaughter) where different levels of production are expected. Uncertainties in the level of production and revenues under each mitigating strategy can be dealt with sensitivity analysis (Monte Carlo analysis) or through a scenario analysis.

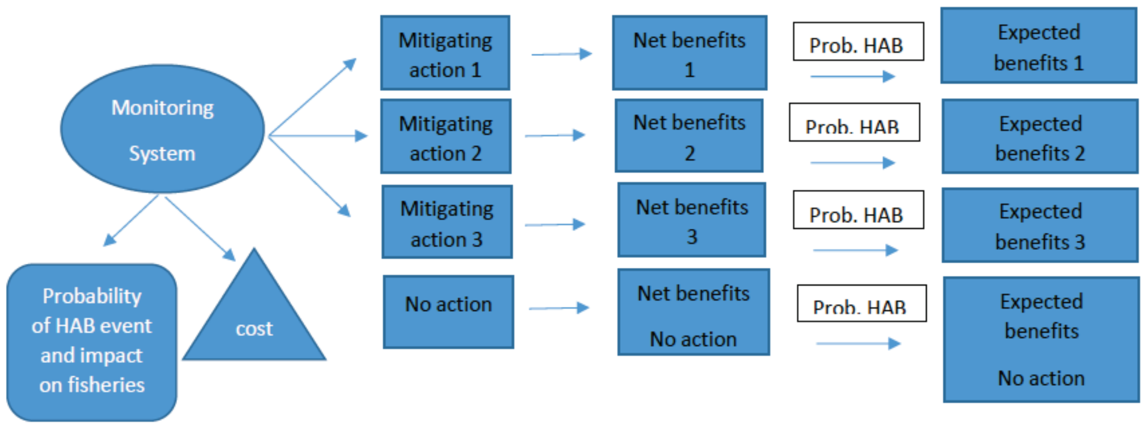

Fig. 6.2 Steps to calculate benefits under uncertainties and different mitigating scenarios.

In case of no information on the level of production that each mitigating action can determine, we could assume that each mitigating strategy is able to reach the highest level of production possible, as if the farm worked at the optimal level of production without a HAB. In this case, the choice of adopting a specific mitigating strategy, given the level of information provided by the monitoring system, is made mainly on the additional cost of production occurring under each mitigating strategy.

In order to quantify the value of monitoring, we first need to calculate the highest net expected benefits for the level of knowledge provided by the monitoring system. This is achieved by multiplying the probability that the fisheries will be in a good status (a good status is expected if the HAB event has a lower probability to occur) by the highest net benefit provided by management options. Summing up these expected benefits from all the states of the fisheries provides the highest possible expected gross value of the monitoring system. Finally, we need to compare this value with the highest expected benefits (amongst all the mitigating strategies) under uncertainties (*e.g.*, when no information is available). The difference between the two benefits is a measure of the net value of monitoring. The decision to invest in monitoring then depends on the cost of monitoring. As long as monitoring costs are less than the value of monitoring, it would be efficient to develop and improve a monitoring system (Nygård *et al.*, 2016).

Table 6.1 illustrates the above discussion with an example. HAB monitoring gives information on the probability that the fisheries will be at a certain status. If we assume that the fisheries will have 90% probability of being in good condition and only 10% to be in poor status (in this example the monitoring system is forecasting a HAB event that is not catastrophic), we can also assume that without the monitoring system, no mitigating actions are taken regardless of the status of the fishery. Different mitigating strategies can then be employed and compared, according to the net benefits that each mitigation action entails.

Table 6.1 Example of calculation of the value of monitoring.

Action or management option	**Cost of management**	**Net benefits given the status of the fisheries**		**Expected net benefit of the mitigating option given uncertainties about the state of the fisheries**
		Good status of the fisheries (low impact from HAB)	**Bad status of the fisheries (high impact from HAB)**	
		Probability to be in good status 0.90	Probability to be in good status 0.10	
Mitigation strategy 1	100	800	500	770
Mitigation strategy 2	500	500	300	480
Do nothing	0	900	100	**820**
Max benefit in each state		900	500	
Max benefit in each state x probability of each status		810	50	**860**
Value of information		**860 – 820 = 40**		

In this example, given the uncertainty about the environmental state, the optimal decision is to employ the "do nothing" scenario as this provides the highest net expected benefit (820). However, the best management action differs between the two environmental states. This means that the producer might make different decisions if the true state of the environment was known. For example, with perfect knowledge that the status will be good with probability 90%, the "do nothing" scenario would be preferred, while under the probability 10% mitigating strategy 1 would be chosen. The expected benefits arising from the information is 860 (the sum of the maximum expected benefit from each status of the fisheries). Therefore, the difference (40) between the expected benefits under information and the expected benefits under uncertainty is a measure of the benefit of monitoring.

Conclusions

HABs have had a demonstrable serious economic impact on salmon aquaculture. However, losses are typically only quantified for high profile extreme events. Economic techniques exist to better evaluate the impact of HABs for more minor fish kills and sub-lethal events. Application of these would allow better business planning, but requires better monitoring and/or sharing of monitoring and potentially sensitive commercial information between industry and scientists and hence, in turn, requires a joint trust building exercise.

Acknowledgments

We thank the SCOR and IOC UNESCO GlobalHAB program and PICES for financial support. KD was funded by the UK RCUK projects OFF-Aqua, CAMPUS and Malaysian HABreports and the EU Atlantic Area Interreg project PRIMROSE. JW was supported by the CoCliME project. CoCliME is part of ERA4CS, an ERA-NET initiated by JPI Climate, and funded by EPA (IE), ANR (FR), BMBF (DE), UEFISCDI (RO), RCN (NO) and FORMAS (SE), with co-funding by the European Union (Grant 690462). We thank Elisa Berdalet and Bengt Karlson for their careful reviews of earlier versions, and Dean Trethewey for his contributions and thoughtful insight during the early stages of this project.

References

Adams, C.M. and Larkin, S.L. 2013. Economics of Harmful Algal Blooms: Literature review. Final report for Gulf of Mexico Alliance Project #00100304, Tallahassee, FL.

Adams, C.M., Larkin, S.L., Hoagland, P. and Sancewich, B. 2018. Assessing the economic consequences of harmful algal blooms: a summary of existing literature, research methods, data and information gaps, pp. 337–354 *in:* Harmful Algal Blooms: A Compendium Desk Reference *edited by* S.E. Shumway, J.A.M. Burkholder and S.L. Morton, John Wiley and Sons Ltd.

Agúndez, J.P., Raux, P., Girard, S. and Mongruel, R. 2013. Technological adaption to harmful algal blooms: socioeconomic consequences for the shellfish farming sectors in Bourgneuf Bay (France). *Aquaculture Economics and Management* **17**: 341–359.

Aleynik, D., Dale, A.C., Porter, M. and Davidson, K., 2016. A high resolution hydrodynamic model system suitable for novel harmful algal bloom modelling in areas of complex coastline and topography. *Harmful Algae* **53**: 102–117.

Anderson, D.M. 2004. Prevention, control and mitigation of harmful algal blooms: multiple approaches to HAB management, pp. 123–130 *in:* Harmful Algae Management and Mitigation Asia-Pacific Economic Cooperation (Singapore): APEC Publication #204-MR-04.2.

Anderson, D.M., 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean and Coastal Management* **52**: 342, doi:10.1016/j.ocecoaman.2009.04.006.

Anderson, D.M. and Rensel, J. 2016. Harmful Algal Blooms. Assessing Chile's historic HAB events of 2016. A report prepared for the Global Aquaculture Alliance, 14 pp.

Anderson, D.M., Hoagland, P., Kaoru Y. and White, A.W. 2000. Estimated annual economic impacts from harmful algal blooms (HABs) in the United States. WHOI-2000-11 Technical Report. 96 pp.

Anderson, D.M., Gilbert, P.M. and Burkholder, J.M. 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries* **25**: 704–726.

Berdalet, E., Fleming, L.E., Gowen, R., Davidson, K., Hess, P., Backer, L.C., Moore, S.K., Hoagland, P. and Enevoldsen, H. 2016. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the United Kingdom* **96**: 61–91.

Chávez, C., Dresdner, J., Figueroa, Y. and Quiroga, M. 2019. Main issue and challenges for sustainable development of salmon farming in Chile: a socioeconomic perspective. *Review in Aquaculture* **11**: 403–421.

Cockburn, H. 2019. Eight million salmon killed in a week by sudden surge of algae in Norway. https://www.independent.co.uk/environment/salmon-farming-norway-algae-killed-fishing-seafood-council-a8925581.html.

Davidson, K., Gowen, R.J., Tett, P., Bresnan, E., Harrison, P.J., McKinney, A., Milligan, S., Mills, D.K., Silke, J. and Crooks, A. 2012. Harmful algal blooms : How strong is the evidence that nutrient ratios and forms influence their occurrence? *Estuarine, Coastal and Shelf Science* **115**: 399–413.

Davidson, K., Gowen, R.J., Harrison, P.J., Fleming, L.E., Hoagland, P. and Moschonas, G. 2014. Anthropogenic nutrients and harmful algae in coastal waters. *Journal of Environmental Management* **146**: 206–216.

Davidson, K., Anderson, D.M., Mateus, M., Reguera, B., Silke, J., Sourisseau, M. and Maguire, J. 2016. Forecasting the risk of harmful algal blooms: preface to the Asimuth special issue. *Harmful Algae* **53**: 1–7.

Dyson, K. and Huppert, D.D. 2010. Regional economic impacts of razor clam beach closure due to harmful algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae* **9**: 264–271.

FAO (Food and Agriculture Organization). 2019. GLOBEFISH – Information and Analysis on World Fish Trade. http://www.fao.org/in-action/globefish/market-reports/resource-detail/en/c/1253536/ (accessed 2 December 2019).

Gilbert, P.M., Seitzinger, S.P., Heil, C.A., Burkholder, J.M., Parrow, M.W., Codispoti, L.A. and Kelly, V. 2005. The role of eutrophication in the global proliferation of harmful algal blooms. *Oceanography* **18**: 198–209.

Groeneveld, R.A., Bartelings, H., Borger, T., Bosello, F., Buisman, E., Delpiazzo, E., Eboli, F., Fernandes, J.A., Hamon, K.G., Hattam, C., Loureiro, M., Nunes, P.A.L.D., Piwowarczy, J., Schasfoort, F.E., Simons, S.L. and Walker., A.N. 2018. Economic impacts of marine ecological change: Review and recent contributions of the VECTORS project on European marine waters. *Estuarine, Coastal and Shelf Science* **201**: 152–163.

Hoagland, P. and Scatasta, S. 2006. The economic effects of harmful algal blooms, pp. 391–402 *in:* Ecology of Harmful Algae Ecological Studies (Analysis and Synthesis), vol. 189, *edited by* E. Granéli and J.T. Turner, Springer, Berlin.

Hoagland, P., Anderson, D.M., Kaoru, Y. and White, A. 2002. The economic effects of harmful algal blooms in the United States: estimates, assessment issues, and information needs. *Estuaries* **25**: 677–695.

Jin, D., Thunberg, E. and Hoagland, P. 2008. Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean and Coastal Management* **51**: 420–429.

Klesty, V. 2019. World Economic Forum. https://www.weforum.org/agenda/2019/05/surge-of-algae-kills-millions-of-salmon-in-norway).

Kontali, 2020. Økonomiske og samfunnsmessige konsekvenser av algeoppblomstringen i Nord-Norge. https://www.kontali.no/references/fhf_901574.

Lorentzen, T. and Petterson L.H. 2005. How to estimate costs from harmful algal blooms. Economic impacts on wild fisheries, aquaculture and commercial tourism. Deliverable D10 under WP10. Contract Number: EVK3-CT2001-00063. Harmful Algal Bloom Initiation and Prediction in Large European Marine Ecosystems.

Maguire, J., Cusack, C., Ruiz-Villarreal, M., Silke, J., McElligott, D. and Davidson, K. 2016. Applied simulations and integrated modelling for the understanding of toxic and harmful algal blooms (ASIMUTH): Integrated HAB forecast systems for Europe's Atlantic Arc. *Harmful Algae* **53**: 160–166.

Nygård, H., Oinonen, S., Hällfors, H.A., Lehtiniemi, M., Rantajärvi, E. and Uusitalo, L. 2016. Price vs value of marine monitoring. *Frontiers in Marine Science* **3**: 205, doi: 10.3389/fmars.2016.00205.

Park, T.G., Lim, W.A., Park, Y.T., Lee, C.K. and Jeong, H.J. 2013. Economic impact, management and mitigation of red tides in Korea. *Harmful Algae* **30**(Suppl. 1): S131–S143.

Perez, C. 2016. Drastic job cuts in Chile. https://www.fishfarmingexpert.com/article/drastic-job-cuts-in-chile/.

Quiñones, R.A., Fuentes, M., Montes, R.M., Soto, D. and León-Muñoz, J. 2019. Environmental issues in Chilean salmon farming: a review. *Review in Aquaculture* **11**: 375–402.

Ralston, E.P., Kite-Powell, H. and Beet, A. 2011. An estimate of the cost of acute health effects from food- and water-borne marine pathogens and toxins in the USA. *Journal of Water and Health* **9**: 680–694.

Robinson, M. 2018. Algae bloom decimates two B.C. fish farms. https://vancouversun.com/news/local-news/algae-bloom-decimates-two-b-c-fish-farms.

Rodríguez, G.R., Villasante, S., García-Negro, M.C., 2011. Are red tides affecting economically the commercialization of the Galician (NW Spain) mussel farming? *Marine Policy* **35**: 52–257.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic S. and Lettieri, T. 2016. Algal bloom and its economic impact. JRC Technical Report. EUR 27905 EN, doi:10.2788/660478.

Smayda, T.J. 2006. Scottish Executive Environment Group Harmful Algal Bloom Communities in Scottish Coastal Waters: Relationship to Fish Farming and Regional Comparisons – A Review, February 2006.

Wells, M.L., Karlson, B., Wul, A., Kudela, R., Trick, C., Asnaghi, V., Berdalet, E., Cochlan, W., Davidson, K., De Rijcke, M., Dutkiewicz, S., Hallegrae, G., Flynn, K.J., Legrand, C., Paerl, H., Silke, J., Suikkanen, S., Thompson, P. and Trainer, V.L. 2019. Future HAB science: Directions and challenges in a changing climate. *Harmful Algae* **91**: doi:10.1016/j.hal.2019.101632.

West, J. (unpublished). Findings from CoCliME stakeholder interviews dealing with the 2019 *Chrysochromulina leadbeateri* algae bloom.

Whyte, C., Swan, S. and Davidson, K. 2014. Changing wind patterns linked to unusually high *Dinophysis* blooms around the Shetland Islands, Scotland. *Harmful Algae* **39**: 365–373.

7 Commonalities and Considerations for the Future

Mark L. Wells[1,2], Raphael Kudela[3], William P. Cochlan[4], Elisa Berdalet[5], Vera L. Trainer[6], Kazumi Wakita[7] and Takafumi Yoshida[8]

[1] School of Marine Sciences, University of Maine, Orono, ME 04469, USA
[2] State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, 36 Baochubei Rd., Hangzhou, Zhejiang, 310012, People's Republic of China
[3] Ocean Sciences Department, University of California, Santa Cruz, 1156 High St.,Santa Cruz, CA, 95064, USA
[4] Estuary and Ocean Science Center, San Francisco State University, 3150 Paradise Dr., Tiburon, CA 94920-1205, USA
[5] Institute of Marine Sciences (ICM-CSIC), Pg. Marítim de la Barceloneta, 37-49 Barcelona, 08003, Catalonia, Spain
[6] Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E, Seattle, WA, 98112, USA
[7] School of Marine Science and Technology, Tokai University, 3-20-1 Orido, Shimizu-ku, Shizuoka, 424-8610, Japan
[8] Special Monitoring and Coastal Environmental Assessment Regional Activity Centre, Northwest Pacific Action Plan (NOWPAP), 5-5 Ushijima Shin-machi, Toyama, 930-0856, Japan

The consequences of Harmful Algal Blooms (HABs) fall into two primary groups: categorical effects on human and ecosystem health, and the varied socio-economic consequences stemming from their occurrence. The effects on human health tend to be limited in much of the developed world due to extensive and costly monitoring practices linked to the implementation of governmental regulations that minimize, and ideally prevent, the transfer of toxic seafood to consumers. Socio-economic impacts, on the other hand, transpire with every HAB event, differ in their character and magnitude, and to date have been poorly quantified, particularly for indirect impacts.

While substantial and ongoing research is directed towards understanding, quantifying, and forecasting HAB occurrences, less attention has been given to understanding, quantifying, and preparing for the socio-economic assaults that these events generate each year. In our view, this shortcoming arises in part from our present inability to forecast either the timing or magnitude of these events, and because HAB scientists are not economists or sociologists. However, as with all natural systems and processes, early knowledge of the timing and locations of HAB events would enable the activation of mitigation steps to minimize economic losses and foster the design of adaptation strategies. But herein is the conundrum: gaining sufficient understanding to enable effective forecasting requires expensive monitoring, observations, and multidisciplinary research. Beyond the intrinsic value generated from better understanding of these critical systems, how do these expenses balance against the socio-economic costs from inadequate preparation for mitigation and adaptation?

In most cases, studies quantifying HAB economic impacts focus on losses from non-marketed product or the direct loss of income from illness (the Cost of Illness model). This limited approach does not account for the broader economic and social repercussions that spread through society. This report is intended to provide insights to more sophisticated assessments that allow a more comprehensive measure of HAB economic impacts – impacts that are far greater than the straightforward costs attributable to lost market products or direct impacts to society. The primary recognition here is that there are no examples of fully comprehensive assessments of the economic losses due to HABs, but there are proven pathways for how to implement these more sophisticated assessments.

While straightforward monitoring practices can minimize human health risks by measuring toxic cells in coastal oceans or toxins in seafood products, minimizing the socio-economic impacts of HABs is far more complex. These events are not just a seafood industry-related problem. HABs are highly integrated, multidisciplinary features of marine and societal systems that encompass environmental, social, economic, and epidemiological factors. Minimizing HAB socio-economic impacts will require more intensive and uninterrupted observations, during both non-HAB and HAB periods, combined with advances in scientific understanding that enable long-range forecasting of impending events. That knowledge, merged with a better grasp of how HAB impacts permeate into socio-economic systems, will accelerate the design of mitigation strategies for appropriate and rapid responses.

It is unlikely that any one mitigation strategy will work across all HAB types or events, and it is expected that more than one strategy will be needed in each case. Moreover, it is almost certain that as the nature of HABs change, so also will the modeling approaches needed to quantify the economic impacts. In some cases, we lack the tools to address these economic and social ramifications; how does one quantify the impact from forced cultural changes (loss of traditional heritages and altered community way of life)? Making things more difficult, the indirect and induced impacts associated with HAB events are influenced by human behavioral choices, often strongly influenced by media coverage, and so go well beyond simple scientific assessment. HAB science is poorly equipped to deal with these complexities. New research strategies will be essential if we are to gain an appreciation of the full economic costs stemming from HAB events.

The workshop that led to this report was unique in that it represented a dialog and partnership between economists, sociologists, reinsurance agents, aquaculturists, and HAB researchers, all seeking to move the field towards more comprehensive assessment strategies. The contributions in this report provide examples describing global economic approaches used to estimate the costs of HABs and their mitigation, focusing on establishing connections between HAB scientists and social and economic specialists. A key take-home point is that there are well defined economic models that can address direct and indirect economic impacts as well as the value of mitigation, once appropriate data are collected and openly available.

A number of problematic issues were raised during the workshop discussions, some stemming from the melding of very different fields of scientific research (environmental and socio-economic), and some surrounding the current lack of data and observations needed to support the development of economic models. These issues fall into three broad categories: what represents a baseline (*i.e.*, outcomes realized without a HAB, known in economic terms as the counterfactual), what are the factors affecting economic impacts, and which data are needed for comprehensive studies of HAB impacts?

One of the fundamental issues is the need to estimate economic impacts by comparing the counterfactual outcomes – periods when HABs are absent – to those when HABs are present. However, HABs are not binary events. They vary geographically, temporally and in magnitude, including spatial extent, duration and intensity, and economic outcomes can shift even when toxin concentrations don't exceed current health limits for harvesting seafood. Superimposed on these factors are natural shifts in coastal conditions that occur on interannual and decadal time scales that are driven by changes in regional atmospheric patterns (*e.g*., Pacific Decadal Oscillation, North Atlantic Oscillation, El Niño), all of which likely exert significant control over HAB occurrences. As with any trend analysis (or in this case, the stability of the counterfactual), characterization improves with increasing years of data, but measurable changes in coastal water conditions associated with climate drivers are occurring on sub-decadal time scales. It is recommended then that more attention be directed toward investigating counterfactuals to ensure their appropriateness as a function of HAB types, regions, and time. It also will be essential to standardize methods for estimating the variability in these counterfactuals so that economic impacts can be compared regionally and globally. Given the non-binary nature of HAB events, it also will be important that economic assessments of HAB impacts not focus only on the "extreme" events or aggregate multi-year averages, since both can provide a misleading view of local or regional economic impacts associated with HAB events.

The nuances associated with indirect and induced effects on economic outputs are many and difficult to assess. While reasonable estimates often are possible for harvest and wage losses associated with decreased yields of seafood products (direct losses), as are the medical costs associated with acute poisonings (induced losses), other, often much larger costs are more difficult to assess. These include impacts on associated industries, which may turn to alternate sources or activities to partially compensate for HAB-related losses in revenue, changes in seafood availability including losses of subsistence harvest potential, losses in recreational and tourism revenues, and losses of consumer confidence in the safety or quality of the product that undercuts demand and thus the price. Although the papers here present case studies illustrating different approaches to incorporate these and other considerations, more focus is needed to acquire the baseline datasets for these economic assessments.

More complex to incorporate are the subtle effects HABs may have on societal systems and human behaviors. For example, losses stemming from HAB-caused delays (or accelerations) in harvest often change the perceived quality or desirability of the product which may affect price (*e.g*., size of the oysters or fish, color of the macroalgae). There also is the potential that groupings of HAB events will generate non-linear economic changes, whereby even small but repetitive events magnify long-term changes in consumer and tourism habits, generating vastly larger socio-economic impacts than similar scale, but less frequent HAB events. Even more difficult to quantify are the effects on long-standing fishing communities and the cultural practices of Indigenous communities, where diets and traditional ways of life are altered due to HABs. It will be essential that our partnerships are expanded to include sociological research on these understudied aspects of HABs on society.

The other major limitation to improving assessments of the economic costs associated with HABs are the datasets needed for effective economic models. These include estimates of monitoring costs, which in some cases are up to two decades old, and perhaps most problematic, financial data from growers. Both large multi-national companies and small local and family enterprises generally have been reluctant to release these valuable data for competitive reasons. In some cases, farmers are cooperating to provide data, as was demonstrated by the eagerness of some to collaboratively participate in this workshop. While this interest is highly encouraging, broader increases in access to industry data will be a key to success in the immediate future. One potential idea to facilitate data sharing is for aquaculture and insurance companies to release historic data (*e.g*., 2+ years old) which will not jeopardize current operations, but still builds the necessary database for modeling purposes. Additionally, it could help generate a professional atmosphere of transparency in an industry often hampered by bad publicity and public distrust.

Our current understanding of the complex issues surrounding development, initiation and “triggers” of HABs is still unclear. HAB researchers have yet to determine how HAB species differ from benign bloom-forming species, and whether the environmental factors thought to enhance phytoplankton growth differ from those responsible for enhanced toxin production. Environmental and ecological data surrounding the pre-development and initiation of HABs are mostly absent, with HAB environmental data records mainly comprising only periods of toxic HAB conditions. Investment in broader observational systems of planktonic and benthic communities and low-level toxin presence will be needed to develop the early warning capabilities called for in this report. This limitation is particularly problematic for Ciguatera Fish Poisoning (CFP), where the temporal and spatial distribution of the causative organisms (benthic dinoflagellates) are poorly defined at best, and there are no practical analytical methods for rigorous toxin analysis in the vast majority of regions where it occurs. Moreover, there is good evidence that even limited but repeated exposure to CFP leads to chronic human health conditions that are difficult to diagnose, making it even more difficult to link socio-economic impacts to specific environmental and toxin data.

The issue of HAB mitigation is two-pronged: minimizing HAB impacts on fisheries products, and minimizing the resultant economic consequences to society. Commercial aquaculturists in many countries have been left largely to their own devices to investigate and experiment with different mitigation strategies for minimizing losses, and while some have failed, there also have been successes. This experience is a significant resource that should be coupled with renewed efforts by scientific investigators and government agencies to accelerate advances in reducing these HAB impacts. As was apparent by the active participation of fish farmers in the workshop, it also would be beneficial for aquaculturists to take a more involved role in investigating HABs near their operations. Such collaboration between HAB researchers and aquaculturists would provide important HAB observational nodes and demonstrate their shared commitment to the preservation of coastal ecosystems. Developing efficient socio-economic mitigation strategies, on the other hand, relies first on a comprehensive understanding of how HAB-related economic stresses cascade through society – a goal which this workshop helped to foster.

One of the major outcomes of the workshop was the demonstrated value of HAB case studies, framed in terms of planning the steps and data needs that would strengthen economic assessments. In particular, HAB scientists and economists should emphasize developing rapid response plans for “extreme events”, thereby enabling a comprehensive assessment of “worst case” type scenarios that clearly inform on the economic consequences. Researchers also should resist pressure to produce average economic costs for HAB events, or efforts to scale impacts by HAB size or duration. HABs are unique events that generate non-linear ecological and economic effects. Instead, efforts should be directed towards developing a library of scenarios, analyzed through case studies, that can serve as a resource for economic assessments and impacts. Justifiable extrapolations, where appropriate, then could be made to estimate general economic impacts in other regions or times. This understanding then can progress towards establishing matrices of optimal, event-scale responses.

We have an opportunity to tackle the globally relevant HAB problem by collaborating across transdisciplinary and transnational boundaries to establish a unified framework describing those data needs. The United Nations (UN) 2030 Agenda for Sustainable Development comprises 17 Sustainable Development Goals (SDGs) that encompass economic, social, and environmental issues, all three dimensions being influenced by HAB impacts on fishing and recreational industries, marine organisms, ecological structures, and human health. Examples are SDG 3 (good health and well-being), SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production) and SDG 14 (life below water). The UN Decade of Ocean Science (2021–2030) promotes steps towards "A healthy and resilient ocean" and "A sustainably harvested and productive ocean", both of which describe our objectives to better quantify, forecast, and mitigate the impacts of HABs worldwide. This program establishes a framework that can be used for knowledge sharing among countries that have made progress in performing detailed economic analyses of HABs with those that have yet to do so. Similarly, the North Pacific Marine Science Organization (PICES), which hosted our workshop, will join the UN Decade of Ocean Science through their integrated Social-Ecological-Environmental System (SEES) approach. The study of HABs provides a unique opportunity for integrated, collaborative science.

By better understanding HABs and in assessing their impacts, there are valuable opportunities to work across national boundaries, to assist under-represented nations, to collaborate with early career ocean professionals, and to better inform policymakers and the public. What better way to measure the relevance of our science than by quantifying the cost of HAB monitoring and management relative to their full economic and cultural harm to society? Through these efforts, together we will attract new resources, new collaborators and new solutions to the field, guided by merging our ever-increasing scientific knowledge with more advanced economic assessments. This workshop and the above sections are a small first step towards achieving this goal. They offer a path towards more sophisticated modeling approaches that provide much more than an "average" cost for HAB events, identify key missing data, and demonstrate through case studies the need for better coordination among social scientists, economists, HAB researchers, industry partners, policy makers, the management community, and end users.

Appendix 1

MEQ Workshop (W18) on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies, at PICES-2019

Co-sponsors: *SCOR, ISSHA, NOWPAP, Greig Seafood Ltd., IOC UNESCO, GlobalHAB, AXA XL Reinsurance*

Convenors: *Vera L. Trainer (USA), Keith Davidson (ICES, WGHABD), Kazumi Wakita (Japan)*

Invited Speakers:
Leif Anderson (NOAA, USA)
Alejandro Clément (Chile)
Keith Davidson (SAMS, Scotland)
Dan Holland (NOAA, USA)
Sunny Jardine (UW, USA)
Di Jin (WHOI, USA)
Jorge Mardones (Chile)
Charles Trick (Canada)

Background

Over the last 2 decades, several reports have compiled what is known about the economic effects of harmful algal blooms. However, both the type and amount of available data are limited, and these reports largely have been compiled by marine scientists rather than economic experts. Most coastal states have neither conducted economic analyses of HABs nor collected data that can be used to generate reliable quantitative estimates of net economic losses and economic impacts. Proposals submitted to NOAA for economic impact studies demonstrate this lack of coordination; they are strong either in the HAB science or economic assessments, but not both.

Summary of presentations

To strategize how specific economic studies can be used to assess the economic impacts of HAB and mitigate their risks, a workshop (W18) was held on October 17–19 at PICES-2019. During this workshop, over 48 international experts on economics and the science of HABs from Australia, Canada, Chile, China, France, Japan, Korea, Norway, the United Arab Emirates, Scotland, Spain, UK and USA discussed a compendium of case studies that highlight the economic impacts of HABs on farmed salmon and shellfish and on wild-caught, reef-based fisheries.

Workshop discussion topics included the net impacts of HABs, their costs, and coastal resilience to HABs worldwide. Plenary lectures included worldwide examples of wild fisheries, recreational fisheries and aquaculture losses. Five case studies included: 1. US west coast *Pseudo-nitzschia* and impacts on shellfish and marine mammals; 2. Korea *Cochlodinium polykridoides* including impacts on wild and aquacultured fish kills; 3. Ciguatera fish poisoning; 4. Fish aquaculture including examples from the European Union, Canada and Chile; and 5. Shellfish aquaculture losses.

Day 1 (½-day) was devoted to looking at the net impacts and cost analysis of U.S. west coast HABs, focusing on the example from a massive 2015 *Pseudo-nitzschia* bloom. Day 2 (full day) was devoted to presentations addressing the net impacts, costs, coastal resilience to HABs worldwide using examples of wild fisheries, recreational fisheries and aquaculture losses, and human wellbeing. On Day 3 (full day), breakout groups were formed to discuss the value of information from better or more refined forecasts and best practices for economic assessment, including economic costs and net economic losses. Questions addressed included: Can contingency planning reduce loss? How do we open areas more quickly? How do we make closures shorter? What is the value of information from better forecasts? What is the cost benefit analysis of monitoring programs? How much should be spent on monitoring? For insurance purposes, how do we reduce the cost of HABs?

The huge HAB-related losses to industry, consumers and governments illustrate the need for insurers, aquaculturists, public health professionals, economists, and HAB scientists to work together to estimate the cost of HAB events relative to the costs of mitigation and management. Studies of economic and social losses and their impacts need to be planned and teams need to be formed prior to HAB events to ensure that they are comprehensively studied. Toward this goal, the workshop further helped to establish greater connections between economists, industry scientists, and HAB researchers. Participants plan to refine and publish case studies to help guide future research and management priorities. A series of white papers are being prepared to document the workshop goals, the five case study examples, and summary recommendations for the future. These white papers will be published on the GlobalHAB and PICES websites. A summary of this work will be published in a peer-reviewed paper, providing several examples that can be used to steer future studies on the economic impact of HABs.

List of papers

Oral presentation

Case study 1: U.S. West Coast *Pseudo-nitzschia* - market analysis and responses
Sunny Jardin and Stephanny Moore

Case study 2: Evaluating the cost of harmful algal blooms in coastal waters of British Columbia, Canada
Svetlana Esenkulova, Isobel Pearsall and Chris Pearce

Case study 3: *Cochlodinium polykridoides* effects on wild and aquacultured fish in Asia
Weol Ae Lim

Case study 4: Chile *Pseudochattonella* impacts on aquacultured fish and Alexandrium impacts on shellfish
Alejandro Clément and Jorge Mardonez

Case study 5: Ciguatoxin impacts on wild fisheries
Charles Trick

Poster presentations

Dynamics of Amoebophrya parasites during recurrent blooms of the ichthyotoxic dinoflagellate *Cochlodinium polykrikoides* in Korean coastal waters
Bum Soo Park, Sunju Kim, Joo-Hwan Kim, Jin Ho Kim and Myung-Soo Han

CoCliME: Investigating the socio-economic impacts of HABs through co-development with stakeholders in European marine coastal areas
Jennifer Joy West, Muriel Travers, Véronique Le Bihan, Gildas Appéré, Patrice Guillotreau, Jérémy Thomas, Baptiste Morineau, Sophie Pardo, Gregor Vulturius, Caroline Cusack and Elisa Berdalet

List of Participants

Name	Affiliation	Country	E-mail
James McLaughlin	Commonwealth Scientific and Industrial Research Org. (CSIRO)	Australia	james.mclaughlin@csiro.au
Joanna Strzelecki	CSIRO	Australia	Joanna.Strzelecki@csiro.au
Ovi Haque	Cermaq Canada	Canada	ovi.haque@cermaq.com
Nicky Haigh	Microthalassia Consultants Inc.	Canada	nixy@telus.net
Liam Peck	Grieg Seafood BC	Canada	Liam.Peck@griegseafood.com
Andrew Ross	Fisheries and Oceans Canada, Institute of Ocean Sciences	Canada	Andrew.Ross@dfo-mpo.gc.ca
Dean Tretheway	Grieg Seafood BC	Canada	Dean.Trethewey@griegseafood.com
Charles Trick	Western University	Canada	trick@uwo.ca
Alejandro Clement	Plancton Andino SpA	Chile	alexcle@plancton.cl
Jorge Mardones	Instituto de Fomento Pesquero	Chile	jorge.mardones@ifop.cl
Chunjiang Guan	National Marine Environmental Monitoring Center	China	cjguan@nmemc.org.cn
Hao Guo	National Marine Environmental Monitoring Center	China	hguo@nmemc.org.cn
Pengbin Wang	Second Institute of Oceanography, MNR	China	algae@sio.org.cn
Veronque Le Bihan	University of Nantes	France	veronique.lebihan@univ-nantes.fr
Yuri Fukai	Hokkaido University	Japan	y.fukai@fish.hokudai.ac.jp
Mitsunori Iwataki	The University of Tokyo	Japan	iwataki@anesc.u-tokyo.ac.jp
Natusuko Nakayama	National Research Institute of Fisheries and Environment of Inland Sea, FRA	Japan	nnakayama@affrc.go.jp
Setuko Sakamoto	National Research Institute of Fisheries and Environment, FRA	Japan	sssaka@affrc.go.jp
Kazumi Wakita	Tokai University	Japan	kazumiw@tokai-u.jp
Takafumi Yoshida	NOWPAP CEARAC	Japan	yoshida@npec.or.jp
Tatsuya Yurimoto	Seikai National Fisheries Research Institute, FRA	Japan	yurimoto@affrc.go.jp
Geir Myre	AXA XL Reinsurance	Norway	geir.myre@axaxl.com
Jennifer West	Center for International Climate Research	Norway	j.j.west@cicero.oslo.no
Seung Ho Baek	Korea Institute of Ocean Science and Technology (KIOST)	Korea	baeksh@kiost.ac.kr
Weol-Ae Lim	National Institute of Fisheries Science (NIFS)	Korea	limwa@korea.kr
Young Kyun Lim	Korea Institute of Ocean Science and Technology (KIOST)	Korea	limyk0913@kiost.ac.kr
Bum Soo Park	Korea Institute of Ocean Science and Technology (KIOST)	Korea	parkbs@kiost.ac.kr
Keith Davidson	Scottish Association for Marine Science	Scotland/UK	kda@sams.ac.uk
Fatima Gianella	Scottish Association for Marine Science	Scotland/UK	fatima_gianella@hotmail.com
Simone Martino	University of York	England/UK	simone.martino@york.ac.uk

Elisa Berdalet	GlobalHAB/Institute of Marine Sciences (ICM-CSIC)	Spain	berdalet@icm.csic.es
Anbiah Rajan	Environment Agency-Abu Dhabi	UAE	anbiahrajan9@hotmail.com
Leif Anderson	NOAA Fisheries	USA	leif.anderson@noaa.gov
Brian Bill	NOAA Fisheries	USA	brian.d.bill@noaa.gov
William Cochlan	San Francisco State University	USA	cochlan@sfsu.edu
Dan Holland	NOAA Fisheries	USA	dan.holland@noaa.gov
Sunny Jardine	University of Washington	USA	jardine@uw.edu
Di Jin	Woods Hole Oceanographic Inst.	USA	djin@whoi.edu
Raphael Kudela	University of California Santa Cruz	USA	kudela@ucsc.edu
Shelbi Madera	Northwest Indian College	USA	smadera@students.nwic.edu
Stephanie Moore	University of Washington	USA	mooresk@u.washington.edu
Misty Peacock	Northwest Indian College	USA	mpeacock@nwic.edu
Vera Trainer	NOAA Fisheries	USA	Vera.L.Trainer@noaa.gov
Marc Suddleson	National Centers for Coastal Ocean Science, NOAA	USA	marc.suddleson@noaa.gov
Mark Wells	University of Maine	USA	mlwells@maine.edu
Layla Wilbur-Westendorf	American Indian Science and Engineering Society	USA	layla13.lw@gmail.com

Appendix 2

PICES Press Article

GlobalHAB: Evaluating, reducing and mitigating the cost of Harmful Algal Blooms: A Compendium of case studies

by Vera L. Trainer, Keith Davidson, Kazumi Wakita, Elisa Berdalet, Marc Suddleson, Geir Myre and Dean Trethewey

Over the last two decades, several reports have been compiled on what is known about the economic impacts of harmful algal blooms (HABs; *e.g*., Anderson *et al*., 2000; Hoagland and Scatasta, 2006; Trainer and Yoshida, 2014, and Sanseverino *et al*., 2016). Although these reports attempted to gather comprehensive economic impact data, both the type and amount of data available were limited. One past study estimated the cost of HABs in the European Union at $800 million USD per year (Hoagland and Scatasta, 2006) but most of that cost was extrapolated for very few HAB organisms. Furthermore, most countries have neither conducted economic analyses of HABs nor collected data that can be used to generate reliable quantitative estimates of net economic losses and economic impacts. The lack of data, appropriate and standardized protocols, and the dearth of peer-reviewed studies hampers efforts to quantify the societal costs of increasingly frequent, intense and long-lasting HAB events and to help evaluate the cost of various strategies being developed for HAB prevention, control, and mitigation.

To strategize how specific economic studies can be used to assess the economic impacts of HAB and mitigate their risks, a workshop (W18) was held on October 17–19 at PICES-2019. During this 2½-day workshop, over 48 international experts on economics and the science of HABs from Australia, Canada, Chile, China, France, Japan, Korea, Norway, the United Arab Emirates, Scotland, Spain, UK and USA, discussed a compendium of case studies that highlight the economic impacts of HABs on farmed salmon and shellfish and on wild-caught, reef-based fisheries.

Workshop discussion topics included the net impacts of HABs, their costs, and coastal resilience to HABs worldwide. Plenary lectures included worldwide examples of wild fisheries, recreational fisheries and aquaculture losses. Five case studies included: 1. US west coast *Pseudo-nitzschia* and impacts on shellfish and marine mammals; 2. Korea *Cochlodinium polykridoides* including impacts on wild and aquacultured fish kills; 3. Ciguatera fish poisoning; 4. Fish aquaculture including examples from the European Union, Canada and Chile; and 5. Shellfish aquaculture losses.

The economic impact of HABs is recognized to be large, although currently poorly quantified in many of the world's coastal areas. The losses faced by insurers are huge. At the workshop, a representative from a reinsurance company specified that 45% of insurance claims are now from HABs. In fact, it was stated that the loss due to HABs is larger than any storm that insurers have ever faced. In Korea, one insurer has already collapsed due to the frequent and enormous losses of aquacultured fish due to HABs.

Participants from the GlobalHAB Workshop (W18): Evaluating, reducing and mitigating the cost of Harmful Algal Blooms, at PICES-2019, Victoria, British Columbia, Canada.

Co-Convenor, Dr. Vera Trainer, speaking to workshop participants.

Several examples of HAB-related losses and loss mitigation were discussed in detail at the workshop. A HAB incident in northern Norway alone resulted in the loss of 14 thousand tons of Atlantic salmon in May 2019, resulting in a total loss of at least 330 million USD, including insured losses of $45 million USD, underinsured values and deductibles of $40 million USD, losses of future salmon sales at $160 million USD, cleanup costs at $30–40 million USD, and loss of taxes and unemployment benefits at $50 million USD. In Brittany, France, the Laboratoire d'Economie et de Management de Nantes-Atlantique (LEMNA), University of Nantes, is conducting a detailed estimation of the impacts of shellfish trade bans caused by HABs. Researchers at LEMNA are creating a database documenting these trade bans from 2004 through 2018 at shellfish harvesting areas in four French departments (Finistère, Morbihan, Loire-Atlantique and Vendée). These four areas encompass about 700 shellfish farms representing 37,600 tonnes of products with an estimated value €141 million (>$156 million USD), *i.e.*, 20% of the national shellfish harvest.

Finally, breakout groups discussed strategies for mitigation including the value of information from better or more refined forecasts. Questions addressed included: Can contingency planning reduce loss? How do we open areas more quickly? How do we make closures shorter? What is the value of information from better forecasts? What is the cost benefit analysis of monitoring programs? How much should be spent on monitoring? For insurance purposes, how do we reduce the cost of HABs?

The huge HAB-related losses to industry, consumers and governments illustrate the need for insurers, aquaculturists, public health professionals, economists, and HAB scientists to work together to estimate the cost of HAB events relative to the costs of mitigation and management. Studies of economic and social losses and their impacts need to be planned and teams need to be formed prior to HAB events to ensure that they are comprehensively studied. Toward this goal, the workshop further helped to establish greater connections between economists, industry scientists, and HAB researchers. Participants plan to refine and publish case studies to help guide future research and management priorities. A series of white papers are being prepared to document the workshop goals, the five case study examples, and summary recommendations for the future. These white papers will be published on the GlobalHAB and PICES websites. A summary of this work will be published in a peer-reviewed paper, providing several examples that can be used to steer future studies on the economic impact of HABs.

Discussing mitigation strategies in one of the breakout groups.

The workshop was sponsored by GlobalHAB, PICES, the Scientific Committee on Ocean Research (SCOR), the International Society for the Study of Harmful Algae (ISSHA), Northwest Pacific Action Plan Coastal Environmental Assessment Regional Activity Centre (NOWPAP CEARAC), Greig Seafood Ltd., the Intergovernmental Oceanographic Commission of UNESCO, GlobalHAB, and AXA XL Reinsurance.

References

Anderson, D.M., Hoagland, P., Kaoru, Y., White, A.W. 2000. Estimated economic impacts from harmful algal blooms (HABs) in the United States. WHOI-2000-11 Technical Report. 96 pp.

Hoagland P., Scatasta S. 2006. The economic effects of Harmful Algal Blooms. *In* Granéli E., Turner J.T. (eds.) Ecology of Harmful Algae. Ecological Studies (Analysis and Synthesis), vol. 189. Springer, Berlin.

Huppert, D.D., Trainer, V.L. 2014. Economics of razor clam fishery closures due to harmful algal blooms in Washington State. pp. 59–71 *In* Trainer, V.L., Yoshida, T. Proceedings of the workshop on economic impacts of harmful algal blooms on fisheries and aquaculture. PICES Sci. Report No. 47, PICES, Sidney, B.C. Canada.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic, S., Lettieri, T. 2016. Algal bloom and its economic impact. JRC Technical Report. EUR 27905 EN.

Dr. Vera Trainer (vera.l.trainer@noaa.gov) is a Supervisory Oceanographer at the Northwest Fisheries Science Center, Seattle, USA. Her current research activities include the study of extreme harmful algal bloom events worldwide and climate impacts on ocean ecosystem health, including phytoplankton diversity. She is the President of the International Society for the Study of Harmful Algae (ISSHA), and is a member, representing PICES, of the GlobalHAB Steering Committee. Vera was Co-Chair of the Section on Ecology of Harmful Algal Blooms in the North Pacific from 2003 to 2017 and is now the Science Board Chair of PICES.

Dr. Keith Davidson (Keith.Davidson@sams.ac.uk) is a full Professor and Associate Director at the Scottish Association for Marine Science (SAMS). His background is in physics but he has become increasingly interested in phytoplankton since he first started to attempt to model their growth as an undergraduate. Much of the focus of his research has been related to harmful algal blooms (HABs) and how the physical/chemical/biological environment of marine waters governs these events. He is a member of the GlobalHAB Steering Committee and the council of the International Society for the Study of Harmful Algae.

Dr. Kazumi Wakita (kazumiw@tokai-u.jp) is a Professor of ocean policy and coastal management in the School of Marine Science and Technology, Tokai University, Japan. Her research interests encompass the socio-psychological aspect and policy framework in managing the marine and coastal environment. She currently works on analyzing historical changes of harmful algal bloom issues in newspaper articles. She is a member of the Task Team on Harmful Algae and Fish Kill of International Program on Harmful Algal Blooms (IPHAB) of IOC/UNESCO, a member of the Steering Group of Harmful Algal Blooms Projects of IOC/WESTPAC, and a member in PICES of Working Group on Common Ecosystem Reference Points across PICES Member Countries (WG 36).

Dr. Elisa Berdalet (berdalet@icm.csic.es) is Research Scientist at the Institute of Marine Sciences (ICM-CSIC), in Barcelona, Spain. Her studies have focused on plankton ecology, in particular on physical–biological interactions and on harmful algal blooms (HABs). Her current research is centered on the benthic dinoflagellate Ostreopsis blooms. Since 2008, she has been involved in the IOC/UNESCO and SCOR programs GEOHAB and GlobalHAB, aimed at the coordination of the international research on HABs. At present she is Chair of the GlobalHAB SSC.

Mr. Marc Suddleson (marc.suddleson@noaa.gov) is a program manager with the National Centers for Coastal Ocean Science, NOAA in Silver Spring Maryland, USA. Marc has overseen the creation and management of national competitive research programs for over 20 years building effective partnerships between federal labs, universities, state and tribal agencies and industry to develop and implement harmful algae monitoring, alert, prediction and response systems. Marc is a member of the U.S. National HAB Committee and a member of International Society for the Study of Harmful Algae.

Mr. Geir Myre (Geir.Myre@axaxl.com) is Global Manager for Aquaculture Insurance with AXA XL Aquaculture Department, based in Bergen Norway. He is educated as Marine Engineer and Production Engineer. Geir has been working with underwriting insurance for the Aquaculture Industry for the last 32 years. His insurance experience includes most of the major HAB insured losses for the last two decades.

Dean Trethewey (Dean.Trethewey@griegseafood.com) is the Director of Saltwater Production and the Director of Regulatory and Certifications for Grieg Seafood BC. Dean has worked in the Aquaculture sector for 25 years with background in Professional Project management. He has led several initiatives towards changing practices and designing equipment for the Salmon Farming industry including ongoing plankton mitigation equipment, ocean data monitoring and machine learning applications. His current work is engaging with all stakeholders involved with ocean science and improving collaborative methods on sharing data to gain a better understanding of climate change and the effects on fin fish species.