Global Aquaculture Alliance™

Harmful Algal Blooms

Assessing Chile's Historic HAB Events of 2016

A Report Prepared for the Global Aquaculture Alliance

Prepared by Dr. Donald M. Anderson and Dr. Jack Rensel in cooperation with GAA
Editing and management assistance provided by Dr. John Forster and Dr. Steve Hart

Executive Summary

The coastal waters of Southern Chile, including the northern region of the Chilean Inland Sea, both coasts of Chiloe Island and environs, were subjected to a series of massive harmful algal blooms (HABs) in early 2016. The blooms resulted in extreme losses of wild and cultured fish, as well as widespread Paralytic Shellfish Poisoning (PSP) toxin contamination. Fish and shellfish farmers, artisanal fishers and other members of the public in these areas suffered serious financial damage. The social upheaval that resulted was pronounced, particularly on Chiloe Island.

The algal blooms coincided with and were enhanced by a strong El Niño event that included higher than normal water temperatures, reduced rainfall and calm wind conditions during the Austral fall season – all conditions that favor HAB development.

With assistance from the Global Aquaculture Alliance, several international HAB and aquaculture experts met with Chilean agencies, researchers, salmon and shellfish aquaculture leaders, and artisanal fishers in August 2016 to gain better understanding of the HAB situation. GAA, an international NGO dedicated to responsible aquaculture and the leading standards-setting organization for farmed seafood, previously worked with government and industry in southern Chile to address the ISA fish virus outbreak that started in 2007.

This report summarizes what is known about the 2016 HAB events and identifies steps that can help enhance prevention, management and mitigation of HABs in Chile in the future. It also explores why HAB mitigation at Chilean farms may not have been as effective as it has been in other regions of the world. A comprehensive set of recommendations is provided, as well.

The 2016 meetings reaffirmed that Chile has many talented aquaculture and fisheries scientists and managers who are performing accurate and efficient services to protect public health. They also highlighted improvements that could be made in services, efficiency, data sharing and collaboration.

For example, different organizations perform independent HAB monitoring by traditional microscope methods, which can result in duplication of effort and reporting delays. Data sharing among the agencies and entities doing the monitoring is limited.

The timeliness of HAB detection, bloom tracking and forecasting can be enhanced through the use of several new technologies. Strategically placed buoys can operate autonomously for months without maintenance, identifying and counting algal cells and transmitting results via the Internet for near real-time use. Satellite-based remote-sensing systems for HAB detection, coupled with physical-biological numerical models, can identify blooms, and their bloom transport and landfall.

Some types of monitoring data are currently very adequately represented, but the algal nutrient measurements needed to understand the concentrations, sources and fates of the natural and human-sourced nitrogen, phosphorus and silica found near aquaculture facilities in the Chilean Inland Sea are limited.

This nutrient data can identify areas that are better at nutrient dispersion and food web assimilation than others. The information would also form a scientific base for an aquaculture zoning program that protects the environment, yet allows appropriate levels of shellfish and fish production.

Coupling of circulation models to available biological models of aquaculture effects has not been implemented in Chile, but would greatly advance understanding of the biological effects of the existing industry. These methods allow classification of the nutrient status of inland sea subareas that can direct limits on production that avoid eutrophication.

Such measures would aid in understanding and improving biosecurity and fish health among existing aquaculture facilities, as the existing zones were drawn primarily on the basis of geographic factors, not hydrographic zonal conditions. Quantitative analysis of production areas’ carrying capacities is needed to inform discussions and lead to eventual agreements among industry, government and the public, while optimizing production efficiency.

The improvement of aquaculture operations in Region X and further development of Chile's southern coastal waters offer huge commercial and social potential. To support it, there is clearly much capacity and experience among those engaged in studying and monitoring HABs in Chile, but the fragmentation of the monitoring and outreach is evident.

The Minister should therefore consider establishing a committee of scientists and regulators, including outside experts, to review current programs and recommend how they might be better coordinated, managed and led. Should external support be sought, this endeavor would strongly support the formulation of requests for funding assistance from international organizations to form an HAB management model that could also be applied in other regions.

About the Authors

This report was prepared by Drs. Don Anderson and Jack Rensel in cooperation with the Global Aquaculture Alliance, an organization committed to responsible aquaculture production through improving production practices focused on environmental conditions, animal welfare, food safety and worker well-being.

Dr. Anderson of Woods Hole Oceanography Institution is a world leader in the HAB research field with extensive experience in the dynamics of blooms as well as in the design of national monitoring and management programs.

Dr. Rensel, an aquaculture consultant and fish farm effects scientist, has extensive experience with fish aquaculture siting and operation, the effects of HABs on fish and computer simulation of benthic and water column effects of aquaculture facilities in many countries.

Dr. John Forster, a highly-experienced aquaculture consultant and former researcher and industry executive, contributed significantly to writing and editing this document.

Dr. Steve Hart, vice president of education and outreach for the Global Aquaculture Alliance, managed the production of this report and contributed writing and editing assistance.

The authors acknowledge the extensive contribution of Dr. Adolfo Alvial of CORFO and Mr. Alejandro Clement of Plancton Andino in providing extensive background information on all aspects of this report and participating in many of the meetings that were conducted in Chile.

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1 Introduction

The coastal and inland marine waters of Southern Chile are a unique Southern Hemisphere ecosystem and resource. They support a variety of business activities, especially fishing and aquaculture, and provide employment for thousands of people. To date, most of the fishing and aquaculture activity is in Region X along the west and east coasts of Chiloe Island and in the fjords to the east along the continental coast. There is also aquaculture development further south. Future expansion there would create thousands of additional jobs and provide Chile with a substantial increase in export earnings.

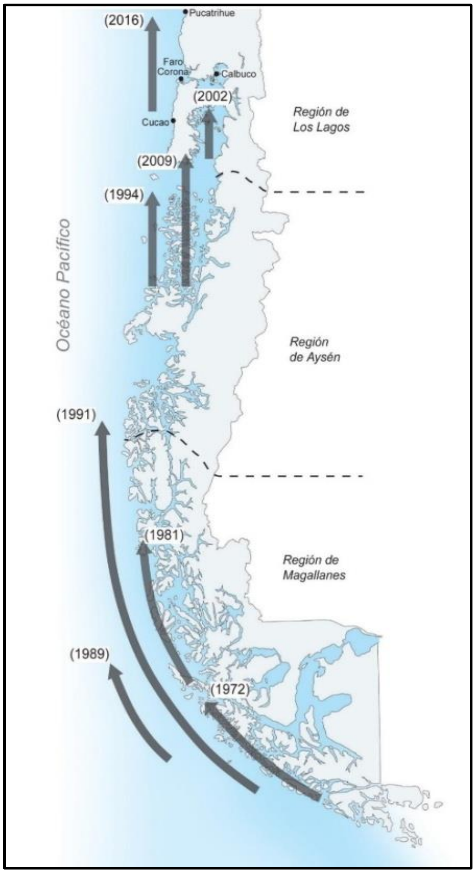

Figure 1. Geographic distribution and northern expansion of *A. catanella* cells in southern Chile. Source: Clément and Alvial (2016).

A growing threat faces this expansion in the form of harmful algal blooms (HABs), which have increased in frequency and severity in Chile and elsewhere in recent years. These blooms, also termed “red tides,” are caused by tiny, mobile single-cell plankton.

Although single-cell algae or phytoplankton form the base of the marine food chain, some species are toxic. When such organisms form large concentrations or blooms, they can cause shellfish toxicity and fish, seabird or marine mammal kills.

Marine HABs in Chile’s southern waters have been documented since 1972, but in the summer of 2016, two major HAB events occurred in close succession, causing severe economic and social disruption in Region X. Artisanal fishermen, as well as mussel and salmon farmers, suffered the worst damage from HABs in Chile’s history.

First, in February and March, a bloom of a *Pseudochattonella* sp. killed 39 million salmon, mostly in Reloncavi Sound and Fjord, with lesser mortality in the adjacent Gulf of Ancud. Reflecting a harvest weight of 100,000 metric tons, the salmon were worth US $800 million.

Subsequently, a prolonged bloom of *Alexandrium catanella,* a plankton species that causes paralytic shellfish poisoning (PSP) in humans, spread up the coast from the south. The bloom affected the Island of Chiloé and coastal facilities in the first bloom of this magnitude that far north (Figure 1). Contamination of wild-caught shellfish, crustaceans, and farmed mussels with *A. catanella* toxins led to harvesting closures of multiple fisheries resources in the affected areas.

The impacts of loss of income on families and communities sparked massively disruptive social protests that lasted three weeks. These protests were also motivated by the belief that the *A. catanella* bloom was exacerbated by the offshore dumping of farmed salmon that died in the previous *Pseudochattonella* bloom. In the same period, a large kill of wild fish, squid and shellfish, caused further anger amongst fishermen, who mistakenly attributed the incident to the *A. catanella* bloom.

Later reports from government and university scientists stated that the *A. catanella* event was caused by the exceptional El Niño oceanic conditions of early 2016. Remote-sensing images and other evidence showed that upwelling of low-oxygen waters killed the other animals.

These incidents and the public turmoil that accompanied them served to heighten awareness among regional government officials of the vulnerability of their coastal communities to HABs and the need for better understanding and management. They also raised questions about the nature and quality of available data that might allow them to better coordinate and manage fisheries resources during future HAB events.

2 Case Study and Model

In May 2016, the Global Aquaculture Alliance (GAA) recognized that the HAB problems and potential solutions in Chile represented a model that might be applicable to assisting developing aquaculture industries in other parts of the world. GAA is an international non-governmental organization dedicated to advancing responsible aquaculture and the leading standards-setting organization for the industry.

With the expert advice of Drs. Don Anderson and Jack Rensel, GAA also recognized the opportunity for Chile to draw on experience from other parts of the world where fisheries and aquaculture activities are also vulnerable to HABs.

The GAA worked with Dr. Adolfo Alvial of CORFO, the Chilean Economic Development Agency, to develop an overview of the history of HABs in Southern Chile. Written by Alvial and Alejandro Clément and others (2012), the study provided a timeline and oceanographic explanation for the 2016 blooms and their impacts. GAA had worked in a similar way in Chile in 2011, when, together with the World Bank, it sponsored a study of the Infectious Salmon Anemia (ISA) crisis in the Chilean salmon-farming industry.

Beyond the 2016 study of algae blooms, a GAA project team met with government leaders and officials responsible coastal management in S. Chile, the Chilean salmon farmers' association and university scientists to discuss the 2016 events and what could be done better to predict and manage subsequent HAB events. The team was impressed by the depth of knowledge and effort being applied to address the HAB problem. These discussions led to recommendations for greater coordination of the various groups' efforts under a strategic plan.

3 Findings and Recommendations

3.1 Background

The contents of this report present perspectives on what occurred in the fish-killing blooms in the marine waters of Chile's Region X in early 2016. The report also summarizes factors involved in the subsequent toxin-producing blooms of *A. catenella* that occurred along the open coast and in some areas of the inland sea. Recommendations to optimize responses to the issues are also included.

By applying established principles of phytoplankton ecology and observations of the characteristics of the affected areas, several factors have been identified that caused the adverse effects on commercial fish and shellfish aquaculture, artisanal fisheries and the marine food web overall. Defining these factors better should help in the identification of solutions.

The physical and biological aspects and HAB behavior of the affected areas were compared to the characteristics of unaffected areas in Region X. Using published literature and technical reports, as well as experience gained elsewhere, perspectives were gained on why certain geographic areas were more adversely affected.

An intended outcome is greater understanding of the causes of fish killing-blooms that can aid in focusing future monitoring and lead to better bloom detection and characterization, and more effective mitigation than occurred in 2016.

3.1.1 Forcing Factors of Fish-Killing Algal Blooms

3.1.1.1 Water temperature effects

All evidence points to exceptional ocean and inshore water conditions in late 2015 and early 2016 as being the main trigger or "forcing factor" for the major HAB events in Region X. More stable and much warmer than normal water masses caused by sustained calm, sunny weather were almost certainly linked to an ongoing super-scale El Niño (Clément et al. 2016, Clément and Alvial 2016, Comisión Mare a Roja 2016).

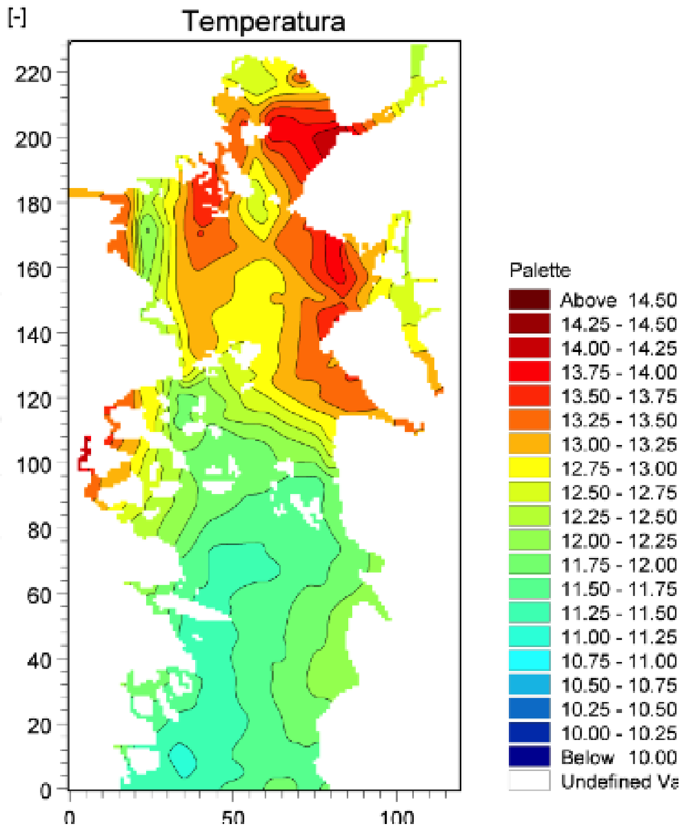

Figure 2. Near-surface average summer water temperature (°C) for Region X, Chile. CIMAR data prepared by Elias Pinilla, IFOP physical oceanographer.

Near-surface water temperatures are typically highest in the northern end of Region X, as shown in Figure 2. Two of the three areas shown in red, Reloncavi Sound and the northeast Gulf of Ancud, experienced the largest aquaculture fish kills in 2016. Lower water temperatures in the south are likely due to factors such as more open water circulation with the Pacific Ocean and deeper mixed layer depth than found in the fjords and estuaries to the north.

Higher water temperatures alone are insufficient to create HAB events, but they often occur with other bloom-enhancing factors. These include reduced mixing and stronger stratification that allow HAB species to thrive while beneficial microalgae sink out of surface waters. Also, greater water transparency allows sunlight to penetrate deeper and support the growth of HAB cells that migrate to obtain nutrients at depth.

3.1.1.2 Circulation patterns, flushing rates

In other regions of the world, slow circulation of inshore waters has been associated with HAB events and eutrophication (e.g., Anderson et al., 2002). Analyses of tidal flushing of water bodies have shown that, given the same tidal force, large basins have lower flushing rates than small basins.

Although few estimates of flushing rates in Region X are available, estimates from existing models of marine circulation serve as useful tools to understand and manage HABs and marine resources. Figure 3 provides estimates of the "net transport" or cumulative movement of surface water based on the Chilean Institute of Fisheries Promotion (IFOP) DELFT3D Region X circulation model. The model has a high degree of accuracy for the Chilean Inland Sea but IFOP scientists have reiterated the need for accurate river flow discharge measurements as a high priority to empower its use for fjords.

Data from this model has been used in Chile with a biogeochemical 3-D model designed to evaluate the benthic and water column effects of fish farming (i.e., AquaModel, Cifuentes et al., 2015), but has not yet been widely applied in Chile.

As some of the first salmon-farming areas developed in southern Chile, Reloncavi Sound and Reloncavi Fjord are highly populated with salmon and mussel farms. Reloncavi Sound displays a near-circular water flow pattern at slow to moderate net transport rates, as shown in Figure 3. Although not quantified, the greater depth, volume and isolated nature of Reloncavi Sound may lead to a relatively lower flushing rate than that of more southerly basins (Figure 4). Prevailing southerly summer winds may further reduce surface water exchange (Saavedra et al., 2010).

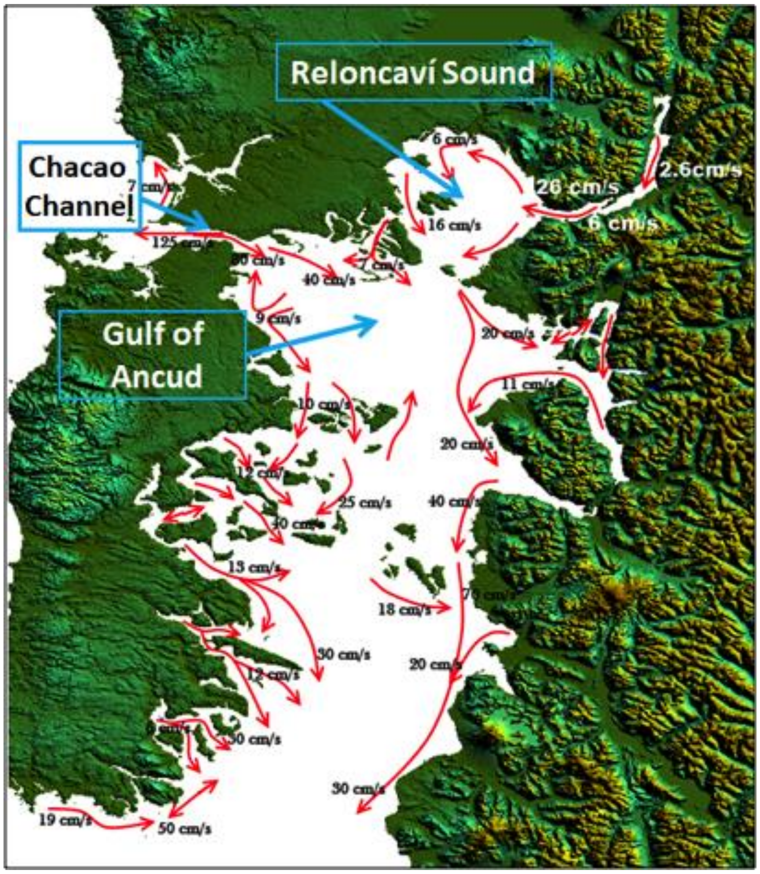

Figure 3. Circulation model net surface water transport vectors (units of cm per second) from a three-month period of a model simulation by Elias Pinilla and colleagues of IFOP. Note the circular flow pattern in Reloncavi Sound.

The relatively narrow main channel and small, shallow side channels that serve Reloncavi Sound may make it naturally more susceptible to phytoplankton blooms than other Region X areas. Most HABs require still water to outcompete more beneficial plankton. The locally dense human population and moderately large river inputs also contribute excess nutrients to support algal bloom development.

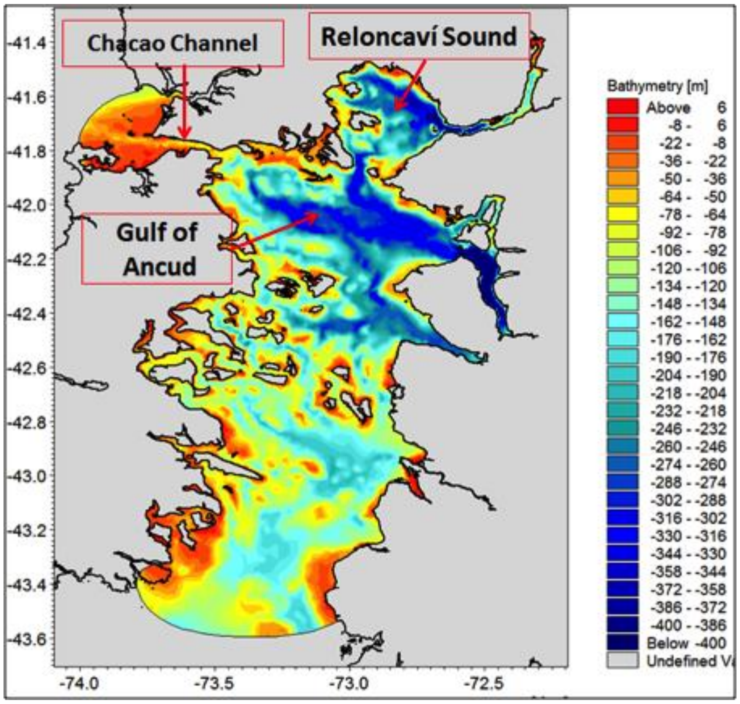

Figure 4. Bathymetry of Chile's northern Region X Inland Sea illustrating relatively great depth of Reloncavi Sound and Gulf of Ancud compared to other subareas and shallowness of the ocean water exchange through Chacao Channel. Drawing prepared by Elias Pinilla and colleagues.

3.1.1.3 Algal growth, nutrient sources and carrying capacity

Well-flushed coastal channels and sounds are typically subject to wind and tidal action that enhance vertical mixing of nutrients such as nitrogen and phosphorus (and silicate for diatoms). Quieter, more isolated backwaters and bays often have minimal levels of dissolved nutrients in surface waters during the summer because the available macronutrients are rapidly used by phytoplankton and other algae. When human sources of nutrients are added, an overabundance of phytoplankton, subsurface oxygen depletion and eventual eutrophication can occur.

In contrast, strong vertical water column mixing can prevent blooms, as the algal cells are moved to depths where sunlight is insufficient for growth. Calm areas with little mixing are thus more prone to HAB events and are considered "nutrient sensitive" in that the introduction of nutrients from human activity may initiate or maintain new algal blooms.

In some countries, siting of floating fish farms in well-mixed areas is a regulatory requirement. In Chile, there is little information on marine water nutrient sensitivity because sampling of nutrient concentrations is infrequent. Several short-term studies of nutrients and algae in the region point to some general conclusions, but are not definitive relative to the 2016 HAB events. There is a need for much more detailed study.

In Reloncavi Sound, the possible sources of nutrients and their probable effects included the following:

Nutrient Source	Probability of Algal Effects	Reason
Runoff from farms, developments, streets and other non-point sources	Low to very low	Extremely dry summer preceding the early 2016 HAB events
Municipal treatment plant discharge and combined sewer (rainfall) overflow	Unknown but calculable, although localized	With population of ~220,000 people in Puerto Montt, new treatment plant in 2008, but tertiary treatment (nitrogen removal) not practiced
Seafood processing plant discharge	Unknown but calculable, although localized	Waste discharges are treated: primary treatment removes most phosphorus and some, but not all, nitrogen – including most of the soluble fractions
Riverine Inflow via Reloncavi Fjord or smaller rivers into Reloncavi Sound	Low to very low	Extremely dry summer preceding the early 2016 HAB events
Dinoflagellates' use of naturally occurring (oceanic) subsurface layer nitrogen from ocean and other sources	Unknown, discernible with sampling and nutrient-tracing methods	The pycnocline (layer of enriched nitrogen) is relatively shallow in Chilean fjords and semi-enclosed basins
Floating ammonia excretions of cultured salmon and mussels	Unknown but widespread and discernible with nutrient-tracing methods	Large number of farms, most relatively large, operation all year, ammonia discharge directly into surface waters

The source or sources of nutrients for the 2016 fish-killing bloom in Reloncavi Sound and Fjord could have been natural or from human activity, or both. The bloom may have been due to naturally occurring conditions, given the distribution of the algal cells and their ability to migrate vertically.

This could imply there were no exceptional nutrient dynamics involved in the 2016 blooms, but that weather conditions, stability of the upper water column and the shallower mixed (surface) layer were important factors. But this cannot be confirmed or rejected, as water column nutrient data during the bloom were very limited or non-existent. The establishment of routine nutrient monitoring and an adaptive sampling plan could provide useful information in the future.

Nutrients from aquaculture and human-related discharges may have been contributing factors for the 2016 Chilean HABs. Scientific consensus worldwide is changing to acknowledge that aquaculture can be a contributing source to HABs in certain locations under some conditions (e.g., Bouwman et al. 2011). Although unproven, a likely source was excreted ammonia from fish and shellfish grown in the region. Ammonia discharges from farms are likely large and widely distributed in Reloncavi Sound and Fjord, but accurate measurements are not available. Other possible human sources of nutrients may have been from multiple origins.

The degree to which slow transport and limited dilution of nutrients from farms may have initiated or intensified the HABs is a key question that has important implications for industry managers. Some believe the present salmon and mussel farming industries in Chile may have been over-developed and exceeded the carrying capacities of some of the areas they occupy.

This position requires further evaluation, but if it is confirmed, the property rights that apply to existing permitted farms would be very difficult to restructure. Self-regulation by the industry through area or zone management agreements may be more effective and implemented more quickly. However, this could be misdirected without better scientific understanding of the connections between aquaculture wastes and HABs or other types of phytoplankton blooms.

3.1.1.4 Recommendations

The relative importance of human versus natural sources of nutrients on the fish-killing blooms cannot be accurately determined for the 2016 fish kill events due to the lack of routinely collected dissolved nitrogen and other data from southern Chilean waters. The initiation of a program to address nutrient monitoring and management would help in the prevention and management of eutrophication and guide future aquaculture management.

Nutrient issues can be assessed using several approaches. A standard practice is to apply basic limnological and oceanographic methods to create a nutrient “budget” for the study area. Nutrient data can be superimposed over a water circulation budget taken from an existing three-dimensional hydrodynamic model to create estimates of the flux and fate of the nutrients within different zones.

A more focused approach would be the application of a fish farm effects model that includes a nutrient-phytoplankton-zooplankton submodel. This could estimate the production of nutrients and their transport and uptake by phytoplankton. Such information could help identify optimum locations for new farms based on environmental protection and fish farm operations. In areas that are already developed, it can create the opportunity for industry members to work together to institute area or zone management agreements to reduce the likelihood of HAB impacts, especially in nutrient-sensitive areas. Tracer methods are available to identify the sources of nutrients in blooms in order to estimate origins and validate models.

The dense, fish-killing *Pseudochattonella* bloom was visible from airplanes and likely from satellites, as well. Although Chile has excellent capabilities for utilizing satellite data, scientists have no experience applying them to HAB identification and tracking. Training initiated with CIREN (Natural Resources Information Center) and other Chilean remote-sensing centers could use outside experts to teach the newest approaches in HAB monitoring using this powerful tool. This training should be followed up with collaborative efforts between the external and local experts to use remote sensing for real-time training during future HAB events.

Currently, fish farms participate in an extensive phytoplankton-monitoring program in which samples are collected and sent to private laboratories for identification and enumeration of potentially dangerous species. This system provides a reasonable degree of protection, but is often too slow to effectively guide the rapid decisions that are necessary during a HAB crisis.

In addition to tracking blooms with remote sensing, other new technologies can provide valuable, species-specific information on a real-time basis to fish farmers and managers in the region. New biosensors could be deployed in key locations near farm sites or in remote areas known for bloom initiation to robotically identify and count phytoplankton species and relay that information to shore via the Internet. Regional testing of this “early-warning” instrumentation could lead to deployment on a larger scale as a management tool for all dependent industries.

Chileans are well aware of the climate changes that have affected their country on many fronts. Ongoing work to monitor and project future climate conditions can assist in the design of workable solutions that prevent or mitigate the sorts of HAB problems that occurred in early 2016.

3.2 Forcing Factors of Algal Blooms Causing Paralytic Shellfish Poisoning

3.2.1 Background

In Chile, Paralytic Shellfish Poisoning (PSP) is associated with the algal species *A. catenella*, which occurs throughout many cold water regions of the world. This organism is responsible for PSP contamination of shellfish in Chile, but has been linked to mortality in wild and farmed fish as well. The effects on fish from this species are relatively rare elsewhere in the world, including all of the other major salmon-growing countries.

In southern Chile, *A. catenella* was first documented in the Magallanes Region in 1972. Since then, the frequency, duration and intensity of PSP events have expanded northward through most of Regions XI and XII. In 2009, the toxic alga moved to most of the Inland Sea on the east coast of Chiloe Island in Region X and the Aysén ocean coast.

A. catenella and related PSP-causing species have also spread in other regions of the world with valuable wild or cultured fish and shellfish resources. While blooms of these species create problems for fisheries (especially for shellfish) and aquaculture interests, monitoring and management systems have adapted and are mostly successful. Chile also has an excellent PSP-monitoring system. Expansion and streamlining of the system can minimize closures and help prepare for the possibility of further geographic expansion and intensity of toxic algal blooms.

3.2.2 2016 bloom events

In late March and most of April 2016, a major PSP event pushed further northward than ever before on Chile's Pacific Ocean seacoast, reaching dangerous cell concentrations through northern Region X (see Figure 5) and lower concentrations in the Los Rios (Region XIV). This occurred a few weeks after the *Pseudochattonella* bloom centered in Reloncavi Sound and Fjord and the adjacent Gulf of Ancud that caused mass mortalities of farmed salmon. The occurrences of PSP on the ocean coast of Chiloe Island and northern Region X were unprecedented.

The offshore disposal of farmed salmon that died over a week-long period was thought by community members in Chiloe and elsewhere to have caused the nearshore PSP blooms. But in examining the distance the fish were dumped from shore, the water depth and the prevailing currents, independent university experts concluded the dead salmon did not cause the PSP blooms (Comisión Mare a Roja 2016).

It remains unclear whether PSP events in Southern Chile will continue to expand northward and intensify. *A. catenella* has a dormant cyst stage that remains in sediment during much of the year before germinating to produce the inoculum cells that initiate blooms. This means the areas where cysts are deposited at the end of blooms can serve as initiation sites for future outbreaks.

As the species expanded to the north in Chile, it undoubtedly established cyst accumulation zones as it colonized new areas. If those regions have favorable conditions to retain those cysts in accumulation zones, and also have favorable growth conditions, the species will continue to bloom in the future and possibly continue its northward expansion.

Experience from hydrographically similar regions of the world indicates a variety of possible outcomes. Puget Sound in the northwestern United States has conditions very similar to those in Chile. There, *A. catenella* blooms periodically occurred for over 200 years on the open coast before spreading into the main basins of that inland sea. After the algae established a foothold, an unusually large river discharge from snowmelt then provided a mechanism for spreading the *A. catenella* cells. To this day, PSP remains a recurrent feature within Puget Sound, but timing of blooms has shifted to earlier in the year. The area remains one of the most important shellfish and fish growing areas in the U.S.

In the Gulf of Maine on the eastern coast of the United States, the PSP problem caused by *Alexandrium sp* was long confined to the far eastern regions of the Gulf in eastern Maine and Canada. In 1972, however, a major storm helped move the population to the west, causing a major red tide and colonization of the gulf's western and southern waters. That geographic expansion remains to this day, but further range expansion is constrained by regional hydrography and environmental conditions. The same may well happen in Chile going forward.

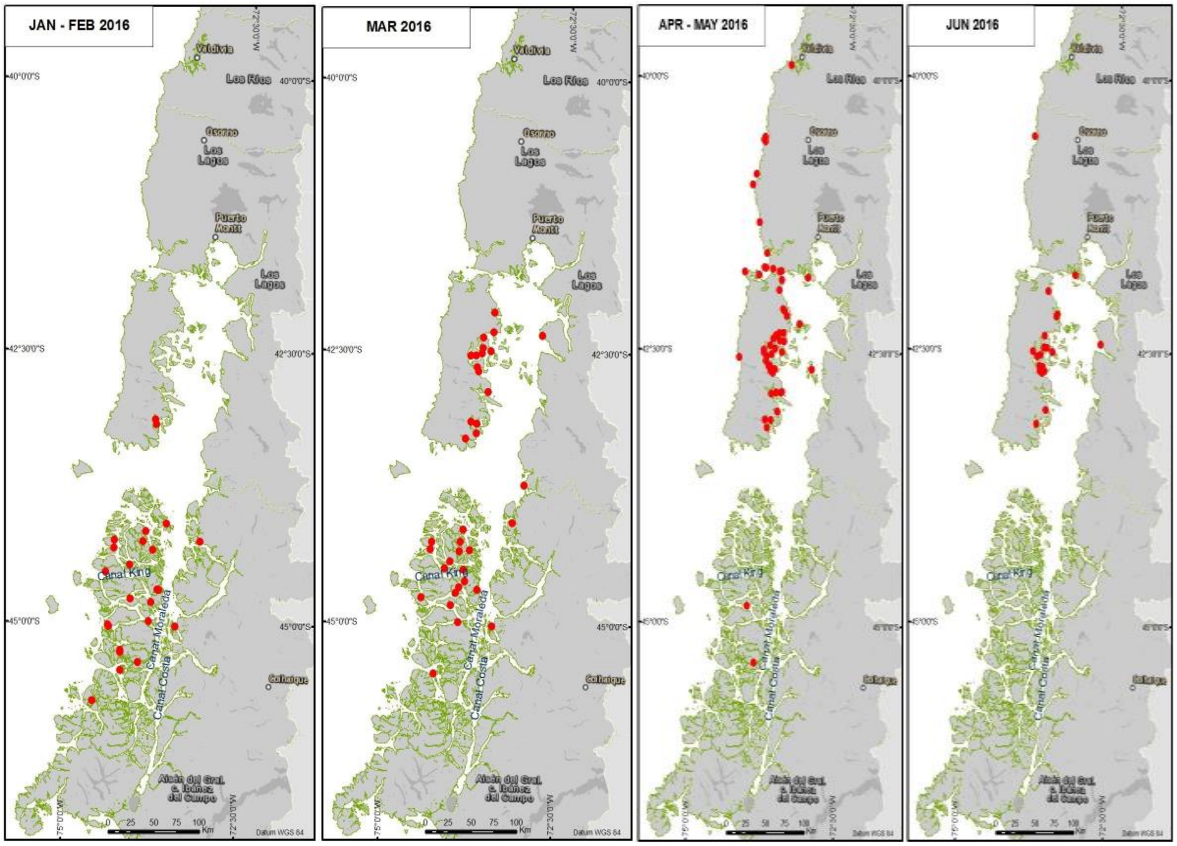

Figure 5. Time series of the spatial distribution of *A. catenella* cells and PSP measurements (red dots) along the coast from Aysen to Los Ríos region. (Source: Clément and Alvial, 2016).

3.2.2.1 Recommendations

In terms of shellfish monitoring, the PSP problem in Chile is managed well. Despite a large and extensive bloom in 2016, no humans were poisoned, which of course is the objective of shellfish biotoxin-monitoring programs. Some changes in procedures and methods, however, could likely improve the overall management of PSP.

For example, during and after the 2016 PSP situation, toxin test data were not always openly shared or available, as some of it was obtained by government agencies, and some came from laboratories contracted by local companies, which considered the results proprietary. It would be helpful to set up a coordinated shellfish toxicity sampling system that allows effective sharing of results between the industry and government agencies so full data is available, should a large-scale crisis situation develop.

Given the legitimate concern that PSP may continue to spread in Chile, it is important to establish the baseline distribution of *A. catenella* in the region. This would best be done through a survey that maps the distribution and abundance of *A. catenella* cysts in Regions X and XI, as well as further north, where PSP has not yet been observed. Although this is a major undertaking, a comprehensive survey would make it possible to definitively determine how the species has moved or expanded by comparing the baseline results with future surveys.

As was the case with the *Pseudochattonella* bloom that killed so many fish, data on ambient nutrient concentrations would have been useful in evaluating the distribution of *A. catenella*. This is another situation where baseline and routine environmental monitoring data would be highly informative.

Although it does not always happen, the 2016 *A. catenella* bloom was visible as discolored water. This means that airplane overflights and satellite imagery could have been useful in tracking the development and progression of the bloom. Here again, an expanded remote-sensing program for HABs in Chile is recommended.

4 HAB Mitigation at Salmon Farms

In other parts of the world where HABs are a recurring threat to aquaculture – including British Columbia, Canada; Singapore; New Zealand; Australia; China and South Korea – several methods of mitigation for HABs have proven successful. One widely used technique involves upwelling of deep water, which is typically free of HAB cells, into fish cages using airlift-upwelling systems (Rensel and Whyte 2003, Selner and Rensel in press).

This was tried by several Chilean salmon farmers during the 2016 *Pseudochattonella* bloom, but apparently was not successful. The efficacy may have been limited because the depth distribution of the harmful algae was not closely tracked to adjust the intake depth of pumping. The cells may have been deeper in the water column than expected, and thus might have been unintentionally pumped into the cages. Variable intake depth and more pumping power would likely have been more effective (Clément and Alvial, 2016).

Other countries, particularly Korea and China, currently use clay dispersal and flocculation as a method to control HABs near fish farms. Extensive studies have demonstrated that the costs and environmental impacts of this method are low, and the benefits are substantial. For example, a chemically modified clay with very high cell-removal capability is now used in China at approximately 5 tons per square kilometer at a materials cost of approximately US $1,000.

4.1 Recommendations

Further examination of upwelling mitigation and other mitigation strategies would be useful. Improved training for monitoring of the vertical location of HABs will likely improve outcomes, as well as simple modifications of equipment to quickly adjust water source depth.

Evaluations of other mitigation methods, such as removal of blooms through clay dispersal and flocculation, should be thoroughly explored. If found to be effective, they should be tested more widely in pilot-scale studies. These types of activities may engender opposition by environmental groups, so careful work is needed to demonstrate that they can be used with acceptable impacts.

5 Well Boats and Biosecurity

Concerns were expressed by mussel farmers and artisanal fishermen that the movement and discharge of seawater from the “well boats” used by salmon farmers to transport live fish to processing plants may have helped spread the *A. catenella* bloom. The purpose of well boat use is to prevent bleeding of the harvested fish into farm waters and to maintain fish quality by moving the fish alive but unfed from remote locations to processing plants. There is no direct evidence that the boats caused or intensified the *A. catenella bloom*, but this was not and has not have been analytically assessed.

5.1 Recommendations

As the full extent of the potential problem is not known there is a need to study this question further. The small size and rigid walls of the cells or cysts of HAB species such as *A. catenella* may make adequate treatment of discharge water during transit a challenge. Therefore, filtering of the intake water to the well boats may be more practical as a means of preventing HAB cell uptake and later discharge in a different area. The risks of this occurring are limited by the fact that the flushing rates of the fish holding tanks are fast. HAB cells pumped in will not remain for long in the tanks and many, including *Pseudochattonella sp.*, would be ruptured due to the turbulence of aeration, constant pumping and live fish swimming. For biosecurity purposes, though, filtered intake water would likely not be sufficient. The final discharge would have to be controlled through other means as infected fish can continually shed pathogens during the entire transport period. The best approach would be to conduct a full evaluation of technologies being developed by the ballast water treatment industry and determine the applicability for salmon live well boats, most probably for fish pathogen biosecurity treatment of discharge flows and not for HABs.

6 Offshore Disposal of Salmon Mortalities

There is no hydrodynamically justifiable link between the disposal of tons of dead salmon 120 kilometers from shore and the subsequent *A. catenella* bloom in the Chiloe Inland Sea and coastal waters. This association was examined in detail by the Chilean scientific group Comisión Mare a Roja and is also discussed by Clément and Alvial (2016). All parties considered the salmon disposal a very unlikely causative factor.

6.1 Recommendations

Offshore disposal of dead salmon is a socially charged practice that should not be done in the future, or done in a manner that even the most critical stakeholders are satisfied can have no adverse effect. If the receiving water masses are far enough offshore and move consistently away from or parallel to the coast, there is no possibility of stimulating a bloom nearshore or inshore. Much of the material will sink to the deep sea, which is already nutrient-rich.

The issue involves the capability of the industry to transport and process salmon mortalities in a timely manner. This is most likely due to limited numbers of capable vessels and crews and should be studied to seek solutions. If future offshore disposal continues to be needed, protocols for proper disposal should be developed.

7 HAB Monitoring, Modeling and Forecasting

Multiple agencies and industries in Chile currently monitor for HAB cells, toxins and general water quality. Some of the information is commercial, and thus proprietary, while other data is available but not easily shared. Nevertheless, Comisión Marea Roja 2016 noted the following regarding the PSP risk from the *A. catanella* bloom: "The capability to prevent effects on the life of the people from the monitoring of abundance of microalgae and concentrations of toxins was verified as a strength at the country level."

This observation reflects well on the quality of HAB toxin monitoring in Chile. However, improvements can likely be made at several levels. For example, there is a good deal of overlap in sampling among agencies and industry, although not all entities examine the same parameters. There also seems to be a general lack of coordination and sharing of information. The community of scientists and managers engaged in studying and monitoring HABs in Chile clearly reflects much capacity and experience, but the fragmentation of the monitoring and outreach is evident.

7.1 Recommendations

The complexity of HAB issues, combined with the likelihood of the HAB situation becoming worse as climate change and coastal development intensify, points to the need for an improved monitoring program with better coordination, modern instrumentation and expanded capabilities, including bloom forecasting and mitigation**.** Outside experts with experience in these areas and technologies can be of great value as Chile takes on this challenge.

8 Coordination and Optimization of HAB Initiatives

Suggestions for greater coordination and direction of HAB work in Chile were mentioned by several representatives of the industry and governmental bodies who met with GAA experts. The Comisión Mare a Roja's 2016 report said: "In order to take advantage of the existing expertise in the country, it is necessary to design a funding body for scientific collaboration that will allow the mobility of the specialists under the common ceiling of the HAB integrated study."

Researchers Clément and Alvial (2016) made a similar statement in their report on HABs in Chile. They said a public-private organization, not bureaucratic, should be developed to coordinate monitoring and management efforts, and provide reliable, timely information to authorities and other stakeholders. This could be facilitated though interactions with appropriate foreign experts and institutions.

There is considerable potential for aquaculture expansion in southern Chile, but such development needs to be planned very carefully. A coordinated approach will be essential in preparing for future HAB issues in Region X and beyond. The concept of a physical center or management structure for coordinating aquaculture monitoring and research has been proposed to oversee responsible expansion.

8.1 Recommendations

Several international assistance organizations are supportive of aquaculture and fisheries development, especially well-managed models that integrate uses of marine waters and can serve as examples in other parts of the world. The improvement of aquaculture operations and interactions in Region X and the further development of Chile's southern coastal waters offer not only huge potential but also the opportunity to develop and implement such a model with significant external funding support.

The establishment of a committee of scientists, including outside experts and regulators, to review current programs and recommend improvements in management and leadership is recommended. Chile can then request support from one or more of the international organizations that specialize in fisheries and aquaculture assistance, if it is thought that such funding would be helpful.

While it is essential that Chile must control this process; the issues are not unique to the country. Experiences elsewhere can assist in resolving difficult problems that may presently seem challenging.

9 Strategic HAB Planning

The Ministry of Economy, Development and Tourism and other cooperating government agencies have recently prepared a broad strategic plan that includes HAB monitoring and other initiatives, including fisheries diversification in Region X (Los Lagos). The monitoring is targeted toward human health protection, as well as shellfish resources.

Sernapesca, Chile’s National Fisheries and Aquaculture Service, recently issued several new directives on aquaculture that include a moratorium on further development in southern Chile. These measures should prove helpful, but seem to have been issued in the absence of an overarching strategic vision for further development of fisheries and aquaculture in Regions XI and XII.

9.1 Recommendations

Coordinated HAB monitoring, mitigation, modeling, forecasting technologies and communications can benefit from economies of scale in providing data and guidance to meet the needs of all stakeholders in S. Chile. Development of a vision and a coordinated implementation plan for national HAB monitoring and management is required to answer these needs.

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