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# Harmful Algal Events in Canadian Marine Ecosystems: Current Status, Impacts, Consequences, and Knowledge Gaps

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**Foreword**

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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## ABSTRACT

Harmful algae (HA) are phytoplankton species with the potential to cause harm to organisms, food webs, ecosystems, and human health. Harmful algal events (HAEs), often called "red tides", may occur when HA reach high abundances in blooms, although many species can also cause harm at relatively low numbers. Mechanisms of harm include production of phycotoxins, mechanical action, or hypoxia. HAEs have emerged as important stressors of marine fisheries and ecosystems and are listed as a priority ecosystem stressor (i.e., one requiring further study) by Fisheries and Oceans Canada (DFO) Ecosystem Stressors Program. Globally, impacts caused by HAEs have been reported on an unprecedented scale in the last decade. Coastal marine activities have also increased, including commercial and recreational vessel traffic and coastal development related to aquaculture, oil and gas, tourism, and other industries. Increasing vessel traffic and climate change are of particular concern for the Arctic marine ecosystem, where they could affect the prevalence of HA and the likelihood of HAEs. A review of HA, HAEs and their impacts in Canada's Atlantic, Pacific and Arctic marine waters over 30 years (1987 to 2017) was conducted to determine areas or issues of particular or emerging concern. A conceptual bow tie model was developed as a framework to link causes to outcomes of HAEs. It incorporates three natural drivers and five emerging anthropogenic pressures that influence the occurrence of HAEs in Canadian marine waters and was applied to identify national and regional key knowledge gaps that might limit Fisheries and Oceans Canada's (DFO) ability to manage consequences of HA, especially those linked to DFO's mandate. National knowledge gaps include limited detection and monitoring of HA and phycotoxins and limited understanding of the effects of specific emerging anthropogenic pressures (EAPs) (climate change, nutrient enrichment, coastal development, and vectors of introduced HA) on oceanographic, atmospheric and biological conditions that drive changes in HA species, phycotoxins, and bloom development and toxicity. These knowledge gaps prevent the development of effective predictive HAE models, which hinders our forecasting/hindcasting capability and hampers development of mitigation and prevention strategies. There is limited understanding of the effects of HA and phycotoxins on most marine organisms (including sublethal/cumulative effects on growth, physiology, reproduction, and behaviour), and on food web and ecosystem function, particularly in Canadian sub-Arctic and Arctic waters. Understanding the effects of HA and phycotoxins is needed to evaluate their impact on species at risk, marine mammals, aquaculture, fishery and fish population health, ecosystem health, and food safety and security. These knowledge gaps must be filled in order to inform management decisions. Monitoring of phytoplankton and phycotoxins, where it currently exists, should be continued and expanded, using new and existing capacity and partnerships. This is particularly important for areas where information is lacking, including the Arctic. Along with traditional methods to identify HA and phycotoxins, novel methods to detect and observe/monitor HA in Canadian marine waters should be implemented. Detection and monitoring programs using existing methodologies can assist the ground-truthing of new technologies and will contribute to international HAE observations and studies for global early warning systems. Implementing these recommendations will benefit DFO by increasing our HA research capability. One advantage would be an early warning system that would increase predictive capacity for these ecosystem stressors, enabling mitigative or preventive actions to ensure healthy and productive marine ecosystems.

# 1. INTRODUCTION

One of the core responsibilities of Fisheries and Oceans Canada (DFO) is to ensure healthy and productive marine ecosystems by protecting ecosystems from the negative impacts of humans, invasive species, and other stressors. Harmful algae (HA) are phytoplankton (pelagic and sympagic, i.e., ice-associated) species with the potential to cause harm to organisms, food webs, ecosystems, and human health. Harmful algal events (HAEs), often called "red tides", may occur when HA reach high abundances in blooms, although many species can also cause harm at relatively low numbers (Martin et al. 2014b). Mechanisms of harm include production of phycotoxins, mechanical action, or hypoxia. HAEs have emerged as important stressors of marine fisheries, and ecosystems, and are listed as a priority for further study under the DFO Ecosystem Stressors Program (DFO National Environmental Working Group, Nov. 2017, Dartmouth, Nova Scotia [NS]). Globally, impacts caused by HAEs have been reported on an unprecedented scale in the last decade (Berdalet et al. 2017; Glibert et al. 2018a; Shumway et al. 2018). A global harmful algal bloom (HAB) status report further determined that "adverse effects on human health are kept under control through increased monitoring activities, but impacts on human activities such as aquaculture, fishery, use of natural marine resources and tourism keep on posing economic activities at risk in many regions" (Hallegraeff et al. 2021b). The resources that are required to investigate the ecological and biological impacts of HAEs in Canada have been limited in recent years. Thus, most reports at the ecosystem level have been incidental to other studies, resulting in incomplete data and limited understanding of causes, impacts and consequences. At the same time, coastal marine activities have increased, including commercial and recreational vessel traffic and coastal development related to aquaculture, oil and gas, tourism and other industries. Increasing vessel traffic (Dawson et al. 2018) and climate change are of particular concern for the Arctic marine ecosystem, where they could affect the prevalence of HA and the likelihood of HAEs (e.g., Joli et al. 2018). The Ecosystem Stressors Program under DFO's Ecosystems and Oceans Science Sector has requested science advice on the national scope of HA incidences and impacts in Canadian marine waters, including the identification of knowledge gaps and areas or issues of particular concern to Canadian marine ecosystems. The objectives of this document are to:

1. review HA, HAEs and their impacts in Canada's Atlantic, Pacific and Arctic marine waters over a 30-year period from 1987 to 2017;
2. determine areas or issues of particular or emerging concern with respect to impacts and consequences to Canadian marine ecosystems and how they may impact core DFO responsibilities;
3. identify key knowledge gaps that limit DFO's ability to evaluate or inform management decisions regarding the impacts and consequences of these HAEs; and
4. recommend actions to address these knowledge gaps.

Globally, HA include at least 90 phytoplankton species, or 2% of the total global biodiversity of marine phytoplankton (Landsberg 2002). Other studies reported 174 (Lassus et al. 2016) and at least 200 species (Allen 2018; Hallegraeff et al. 2021a). Phytoplankton are at the base of marine food webs and produce about half of the world's breathable oxygen (Field et al. 1998; Petsch 2003). While HA provide the same services, some also produce a variety of potent toxic compounds, phycotoxins, that cause harm to fish, seabirds and marine mammals. Other HA cause mechanical and physical damage to gills, or consume high levels of oxygen when large blooms die and sink below the upper water layer (Landsberg 2002). Alternatively, they can also cause problems through excess oxygen production. Because of their great ecological significance as threats to ecosystem structure and function, HA in Canadian waters have been identified as Ecologically and Biologically Significant Species (Scarratt et al. 2006).

Popularly, HA occurrences are sometimes called “red tides” or HABs. However, because HA occurrences are not tides, may display colours other than red or are often visually undetectable, and some species are harmful even in the absence of a bloom or high biomass, this research document will use the term harmful algal event (HAE), unless specifically referring to a bloom situation.

Reports of impacts due to HAEs are increasing worldwide (Anderson 1989; Hallegraeff 1993; Anderson et al. 2008, 2012; Lassus et al. 2016; Hallegraeff et al. 2021a). This is likely explained by a combination of factors, including improved awareness, expanded monitoring efforts, climate change, increased volumes of ship ballast water and novel shipping routes, and anthropogenic eutrophication (Smayda 2007; Anderson et al. 2012; Lassus et al. 2016; Glibert and Burkholder 2018). An Intergovernmental Oceanographic Commission/International Council for Exploration of the Seas (IOC/ICES) Global HAB Status Report has been compiled to provide a worldwide overview of HAB events and the occurrence of phycotoxin-producing microalgae (Hallegraeff et al. 2021c). Elements of the present document were used to fulfill Canada’s contribution to this Global HAB Status Report through DFO’s participation in IOC Intergovernmental Panel on Harmful Algal Blooms (IPHAB) and the IOC/ICES Working Group on Harmful Algal Bloom Dynamics (WGHABD) (McKenzie et al. 2021).

Although Canada has a long history of HAEs and their impacts (reviewed in Bates et al. 2020), this document also utilizes records from the Harmful Algal Event Database (HAEDAT) to analyze the spatial and temporal scale of HAEs in Canada. HAEDAT contains HAE records from ICES and North Pacific Marine Science Organization (PICES) member countries – those bordering the North Atlantic and North Pacific Oceans. This is the most comprehensive database of recent (1987 to present) HAEs for Atlantic and Pacific Canada; it does not contain data from the Canadian Arctic. The IOC/ICES/PICES HAEDAT entries include HAEs that result in management actions such as closures of shellfish harvesting areas, human illness, or negative environmental impacts such as fish kills and mortalities of marine mammals. In HAEDAT, HAEs are defined as: a phycotoxin accumulation in seafood exceeding the regulatory level that is considered safe for human consumption; a water discoloration, scum or foam causing a socio-economic impact due to the presence of toxin-producing HA; or any event where humans, animals or any other organisms are negatively affected by algae (Bresnan et al. 2021). The Canadian information stored in HAEDAT is a 30-year record of the temporal and spatial distribution of HAEs, including data provided by DFO phytoplankton monitoring and research programs, the Canadian Food Inspection Agency (CFIA) biotoxin (= phycotoxin) analyses, and the Harmful Algae Monitoring Program (HAMP; initiated by DFO and the British Columbia [BC]) salmon aquaculture industry, and managed by Microthalassia Consultants Inc.). Although DFO does not currently have a national HA research or monitoring program, it continues to provide representation and HAEDAT records for Canada at the annual IOC/ICES WGHABD and the bi-annual IOC IPHAB meetings.

Based on the number of HAEDAT entries by countries that include temperate, boreal, sub-Arctic and Arctic regions, Canada has the third highest reported number of HAE entries (593) over the last 30 years. Although this may be attributed to the long Canadian coastline and differences in the way each country reports its data, this is a high number of incidents, especially given that monitoring is limited and that HAEDAT contains no reports from the Canadian Arctic.

## 1.1. DFO HARMFUL ALGAE RESEARCH

Although there were some early independent studies, it was in the late 1940s that DFO's focus on HA research and monitoring increased on both the Atlantic and Pacific coasts (Medcof et al. 1947; Quayle and Bernard 1966). However, it was not until the late 1980s that a coordinated national program was established. In 1988, a Phycotoxins Working Group (PWG; 1988–2007) was established by DFO (Whyte 1997), after a novel toxin (domoic acid) caused human deaths from consuming contaminated shellfish in late 1987, in eastern Prince Edward Island (PE). In response to this event, the Treasury Board of Canada substantially increased funding for HAB-related research and monitoring. The PWG provided advice on the coordination, planning and prioritizing of DFO research on HA and their phycotoxins (including environmental factors, bloom forecasting/hindcasting, biological pathways of the toxins, their ultimate fate, and effects on the food web). The working group served as a focal point for communication and collaboration among DFO regions and with other Canadian and international organizations. Ten national workshops were organized between 1989 and 2007, to promote the exchange of new scientific information on HA, phycotoxins, and their effects (see Bates et al. 2020).

The role of DFO Science in researching HA and their early detection, decreased in 1997 after the responsibility for phycotoxin monitoring in shellfish tissue to protect human health was transferred from the DFO Inspection Branch to the CFIA. Some phytoplankton monitoring continued as part of other programs or projects not targeted at HA. DFO retained a role as joint administrator of the Canadian Shellfish Sanitation Program (CSSP), with the CFIA and Environment and Climate Change Canada (ECCC; sanitary monitoring). DFO is responsible for enacting closure and opening of shellfish harvesting areas, and for the enforcement of closure regulations, as recommended by the CFIA based on its biotoxin monitoring data. To date, the CFIA phycotoxin shellfish monitoring program is conducted on the Atlantic and Pacific coasts.

In the last decade, HAEs on both the Atlantic and Pacific coasts have prompted a re-evaluation of the importance of HA to ecosystem health and the propagation of effects to higher trophic levels. Some long-term data sets exist to address these questions about the role of HA in marine systems. To some extent, the CFIA phycotoxin monitoring information can also be used as a proxy of temporal and spatial occurrence of HAEs. One should, however, be aware of the limitations of this dataset (Hamer et al. 2012). The CFIA dataset was not collected for research purposes, but to protect the health of shellfish consumers.

One example where the CFIA phycotoxin dataset did provide valuable support to a study of an ecological impact of HA was the discovery of paralytic shellfish toxins (PSTs) (Toyofuku 2006) in North Atlantic Right Whales (*Eubalaena glacialis*) and their zooplankton prey (dominated by the copepod *Calanus finmarchicus*) in the Bay of Fundy. During this event, the CFIA detected the same toxins in shellfish, at levels over the human health regulatory limit, lending further credence to the occurrence of impacts and consequences of PSTs at an ecosystem scale (Doucette et al. 2006).

In recent years, researchers in Canadian waters, including the Arctic, have detected HA species and toxins that are new to Canada (Poulin et al. 2011; Dhifallah 2019; Bates et al. 2020; McKenzie et al. 2021). Ballast water transport, particularly in unregulated domestic shipping, has been implicated in the appearance of novel species and toxins in Canadian waters, with particular concern for the Arctic (Wells et al. 2015; Laget 2017; Chan et al. 2019). HA species have been detected in Greenland and in the Russian and Canadian Arctic (Okolodkov 1998, 2005; Hansen et al. 2011; Poulin et al. 2011; Dhifallah 2019; Pućko et al. 2019).

Resources to study HAEs in Canada have been limited in recent years. Thus, most reports at the ecosystem level have been incidental to other studies, which results in incomplete data as to causes, impacts and consequences. In the Arctic, where no phycotoxin data are collected, the information is particularly limited to the presence of HA species based on detection from other Arctic studies.

DFO scientists were asked to evaluate the potential involvement of toxic phytoplankton, such as Atlantic Herring (*Clupea harengus harengus*) mortalities along the west coast of NS (December 2016) and an unusual shellfish harvesting closure of parts of the Bay of Fundy (autumn 2017). In some circumstances, investigations revealed that HA were not involved, for example in the 2017 North Atlantic Right Whale mortality event in the Gulf of St. Lawrence (Daoust et al. 2018). These evaluations were conducted with limited available resources and information, including scientific expertise and ability to collect water samples. DFO experts were able to confirm the lack of PST in the zooplankton in this case. However, having better spatial and temporal resolution in the future would facilitate the ability to directly address such questions.

A DFO science workshop was held in July 2017, at the Institute of Ocean Sciences (Sidney, BC), in response to growing concerns regarding HA and their role as ecosystem stressors. The workshop explored how DFO could address research and management issues related to HA, as well as their impacts and consequences. The 16 participants included DFO scientists and emeritus researchers (some of whom were former members of the PWG), and additional HA experts external to DFO, including international researchers. During the 2017 workshop, a national Canadian Harmful Algae Working Group (CAN HAB) was established with participants that have a broad range of expertise, including taxonomy, genomics, HAE population dynamics, modelling, remote sensing, and physiology of phycotoxin production by HA.

One recommendation from this workshop was to produce a formal Canadian Science Advisory Secretariate (CSAS) research document that would review and assess the status of marine HA in Canada, identify knowledge gaps, and highlight areas of particular concern for current and future impacts of HA on ecosystems and resources (McKenzie and Martin 2018).

HA species, phycotoxins, and HAEs in Canada's three oceans were reviewed based on Canadian published and unpublished reports and data. A 30-year time series of records (1987–2017) from HAEDAT, which includes HA data, management actions (shellfish closures), fish kills and extreme events, was analyzed for the Atlantic and Pacific coasts. No HAEDAT records exist for the Arctic, as there is no phycotoxin or HA monitoring program in that region.

## 1.2. THE BOW TIE: A CONCEPTUAL MODEL OF HARMFUL ALGAL EVENTS

Discussions at the 2017 HAB workshop focused on the complex causes and effects of HAEs in Canadian marine ecosystems. It became clear that a single-issue public health view (Figure 1) should be replaced by a multifaceted model that better reflected DFO's ecosystem-level approach (DFO 2007) and the suite of management concerns potentially related to HA.


*Figure 1. Linear view focused on the protection of human health but does not consider the magnitude and extent of ecosystem stress that results from HAEs. The involvement of DFO and the CFIA is also shown.*

Consequently, a conceptual bow tie model was developed (Figure 2) as a framework to link causes to outcomes of HAEs. The model was applied by the participants during the CSAS workshop to identify national and regional key knowledge gaps that might limit DFO's ability to manage consequences of HA, specifically linked to DFO's mandate. Recommendations were developed for actions and research to address these knowledge gaps.

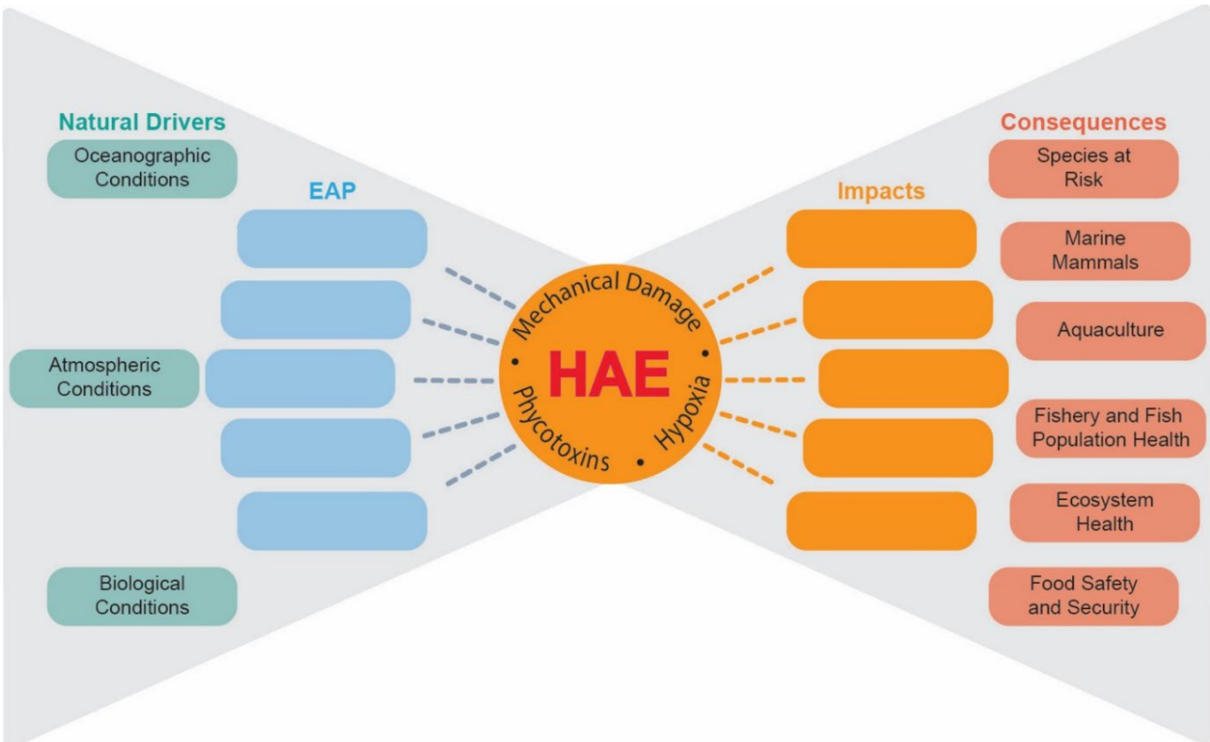


*Figure 2. Conceptual bow tie model showing natural drivers and emerging anthropogenic pressures (EAPs, to be determined for Canadian marine ecosystems and presented in Section 3.1), on the left, which may lead to a HAE. The resulting impacts (to be determined for Canadian marine ecosystems and presented in Section 3.2) and consequences of a HAE on the ecosystem are shown at the right. Consequences are directly related to the core responsibilities and mandates of DFO.*

Bow tie analysis is a risk assessment and risk management method listed under the International Electrotechnical Commission/International Organization for Standardization IEC/ISO 31010:2009 standard and can be used in an ecosystem management context (IEC/ISO 2009; Cormier et al. 2013). It is a structured approach that organizes information from a variety of sources to determine knowledge or management gaps and to prioritize risk management actions (ICES 2014). The full analysis includes risk identification (ecosystem vulnerabilities in relation to the pressures of drivers), risk analysis (likelihood and magnitude of impacts), and risk evaluation (with regard to the need for management). In its simplest form, as used in the present document, a bow tie model is "*a simple diagrammatic way of describing and analysing the pathways of a risk from hazards to outcomes and reviewing controls*" (IEC/ISO 2009).

The "knot" of the bow tie, at the centre of this model, is an undesired event, which in this case is the HAE (Figure 2). Surrounding the HAE are its potential "mechanisms of effect" (phycotoxins, mechanical damage, and hypoxia) that may lead to the event. The natural drivers and emerging anthropogenic pressures (EAPs, which were determined at the CSAS meeting and will be presented in Section 3.1) that contribute to the establishment, proliferation and maintenance of blooms or increases leading to HAEs are shown at the left of the diagram. Natural drivers were defined as environmental variables that may control the initiation and growth of HA species, including those that may promote the reanimation of dormant dinoflagellate cysts. Natural drivers incorporate spatial/temporal variability and dynamics.

Three categories of natural drivers were defined, but further consideration of the role of natural drivers was outside the scope of this review:

- ***Oceanographic conditions*****:** Physical and chemical ocean conditions, including (but not limited to) temperature, salinity, pH, oxygen saturation, stratification, transparency (photosynthetically active radiation), oceanographic currents, nutrient availability, and sea ice;
- ***Atmospheric conditions*****:** Climate and weather conditions that affect local oceanographic conditions and short-term weather events are extremely important in HAE development, duration and dispersal; and
- ***Biological conditions*****:** Composition and abundance of HA species (all life stages) that could potentially initiate a HAE, as well as competitors and/or predators that could control the abundance of the HA. This includes changes in the composition/abundance/mechanism of harm, as well as the northward expansion of species distribution.

Natural drivers that contribute to the relative importance of each EAP and in turn affect the occurrence and/or intensity of HAEs for marine Canadian environments were determined at the CSAS meeting and are presented in Section 3.1.

The right side of the bow tie model presents the impacts and consequences of HAEs. The impacts were determined at the CSAS meeting and are presented in Section 3.2. They include the direct effects of HAEs resulting in consequences. For the purpose of this review, consequences are the expression of impacts to environmental services and ecosystem health in relation to the DFO mandate.

Six consequences were defined and considered:

- ***Species at risk*****:** Impacts to marine species listed under the Species at Risk Act and other species and stocks (or populations) of conservation concern;
- ***Marine mammals*****:** Impacts to marine mammals, including those listed as Species at Risk;
- ***Aquaculture*****:** Impacts to productivity and management of aquaculture and includes both finfish and shellfish;
- ***Fishery and fish population health*****:** Impacts to productivity and management of wild fisheries and to wild population health;
- ***Ecosystem health***: Impacts to health of the oceans, and to management mandated under the Oceans Act (e.g., Integrated Ocean Management, conservation objectives of Marine Protected Areas); and
- ***Food safety and security*****:** Impacts to commercial, recreational and Indigenous fisheries.

The consequences are the expression of impacts at the level of environmental services and ecosystem health and resources. In contrast to the paradigm expressed in Figure 1, it is clear in the bow tie model that the consequences of HAEs extend far beyond public health to include a broad range of ecosystem stressors that are relevant to DFO core responsibilities (Figure 2).

## 1.3. SOURCES OF INFORMATION

An extensive review of marine HABs and phycotoxins of concern to Canada was being finalized during the development of this research document and was a primary source for information on HABs, phycotoxins, monitoring and research in Canada. It was completed in 2020 and co-authored by HAB scientists from DFO, CFIA, National Research Council Canada (NRC), Canadian Museum of Nature, and the private sector (Microthalassia Consultants Inc., Nanaimo, BC), including several emeritus researchers (Bates et al. 2020). Many of the authors were members of the DFO PWG, who participated in the research, investigation of many of the events, and HA workshops documented in the review. The goal of Bates et al. (2020) was to review Canadian marine HAEs and phycotoxins up to late 2018 (including relevant literature from Canada and internationally) and to provide a foundation for future research in this area.

In addition to the information and references from Bates et al. (2020), event information from HAEDAT is reviewed in the present document to evaluate the last three decades of HAEs. All Canadian event data (593 records) were extracted from HAEDAT and summarized to examine spatial and temporal distributions of HAEs. As HAEDAT records are based primarily on harvesting closures caused by phycotoxin levels exceeding regulated standards in shellfish, and reported fish kills attributed to HA, they do not necessarily represent all HAEs.

A Canadian HA workshop was held at the Bedford Institute of Oceanography (Dartmouth, NS) in September 2018, to review and validate records in HAEDAT and to compile HAE information for each coastal DFO region. The workshop brought together scientists from DFO, CFIA, NRC, Microthalassia Consulting Inc. (Harmful Algal Monitoring Program), the aquaculture industry and academia, including several DFO emeritus researchers. This provided a unique opportunity for a comprehensive report of three decades of HAEs in Canada. This Canadian HAEDAT review was published (McKenzie et al. 2021) in a special issue of Harmful Algae, which focused on the Global Status of HABs and the use of HAEDAT to evaluate that status. Information from that publication is summarized in this document. For more detail, particularly decadal event information, see McKenzie et al. (2021).

No HAEDAT records exist for the Canadian Arctic, and there is currently no systematic phycotoxin monitoring program in that region. The Arctic map summary included here is therefore based on available literature and recent studies with records of harmful, and potentially harmful, phytoplankton species and phycotoxins detected in marine mammals, shellfish and other invertebrates in the region.

# 2. HARMFUL ALGAL SPECIES AND EVENTS IN CANADA

The focus of the conceptual bow tie model (Figure 2) is the HAE. The environmental variables and anthropogenic drivers leading to a HAE, and the impacts and consequences that result from a HAE, all relate to the phytoplankton and the events they cause.

The mechanisms by which phytoplankton cause harm to marine ecosystems (i.e., the mechanisms of effect) form the centre of the bow tie model, in this case, the “event”. These mechanisms include:

1. phycotoxin production and its accumulation across multiple trophic levels of food webs, which affect the health and survival of higher trophic levels;
2. oxygen depletion, resulting from high oxygen consumption during algal biomass decay, creating hypoxic or anoxic conditions dangerous to aquatic biota; and
3. mechanical damage to marine organisms (e.g., to fish gills).

Although foam and discoloration of the water can be considered harmful, it will not be included in this document.

## 2.1. HARMFUL ALGAL SPECIES AND POTENTIAL MECHANISMS OF EFFECT

To date, 70 harmful pelagic and sympagic (sea-ice associated) algal species have been reported in Canadian waters. Of those, 27 HA are known to have caused, or to be associated with, HA events on Canadian Atlantic and Pacific coasts. Nine of these species produce phycotoxins (Table 1) and 18 cause mechanical damage or hypoxia (Table 2 bold). Of the other

43 species, 15 produce phycotoxins (Table 1) and 28 cause mechanical damage or hypoxia (Tables 2, 3); some of these are known to have caused, or to be associated with, HA events outside Canada or in the laboratory. Forty-five of the 70 harmful pelagic and sympagic algal species are reported in the Canadian Arctic; details of these are found in Section 2.2.3.

### 2.1.1. Phycotoxins

Phycotoxin production by a given phytoplankton species depends on a number of factors, including its cell abundance, stage in the life cycle of the bloom, environmental conditions, and seasonality (e.g., Guallar et al. 2017). For example, some dinoflagellate species have asexual and sexual stages, or cycle between an active vegetative state and a dormant cyst life stage until environmental variables return to favourable conditions for growth (Azanza et al. 2018). Some of these cysts contain phycotoxins (Persson et al. 2006) and consequently can extend the negative impacts of a HAE (Schwinghamer et al. 1994; Persson et al. 2006).

Phycotoxin-producing phytoplankton species are present on the Atlantic, Pacific, and Arctic coasts of Canada (Table 1). Phycotoxins have been traditionally classified based on the human syndromes or symptoms they generate, as we show here, although it should be noted that they are now categorized into distinct groups based on chemical structure (Toyofuku 2006). Three groups of phycotoxins have been of particular concern in Canada and are regulated under the CSSP. All of these have been detected on both the Atlantic and Pacific coasts.

- **Paralytic Shellfish Toxin** (PST). Saxitoxin (STX) group toxins, which include numerous derivatives, are the phycotoxins responsible for Paralytic Shellfish Poisoning (PSP) and are produced by some dinoflagellates of the genus *Alexandrium* in marine waters. Symptoms of PSP include tingling and numbness, muscular weakness which leads to respiratory paralysis, and death in the most severe cases (Bates et al. 2020).
- **Amnesic Shellfish Toxin** (AST). Domoic acid (DA) is the phycotoxin responsible for Amnesic Shellfish Poisoning (ASP) and is produced by 28 of the 58 diatom species of the genus *Pseudo-nitzschia* (Bates et al. 2018). Symptoms of ASP include disorientation, partial or permanent short-term memory loss, and death in some extreme cases (Trainer et al. 2008).
- **Diarrhetic Shellfish Toxin** (DST). Okadaic acid (OA) group toxins (OA and dinophysistoxin analogues DTX1, DTX2) and pectenotoxins (PTX; a separate group of phycotoxins that are grouped with the DSTs are responsible for Diarrhetic Shellfish Poisoning (DSP) and are produced by some dinoflagellates of the genera *Dinophysis* and *Prorocentrum*. Symptoms of DSP include diarrhea, nausea, and vomiting (Yasumoto et al. 1985). Unlike ASP and PSP, DSP does not appear to cause death after consumption.

At least three other phycotoxin groups (yessotoxins, azaspiracids, cyclic imines [spirolides, pinnatoxins, gymnodimines]) are also present in Canadian waters, but are not yet associated with a syndrome, and Canada has not established regulatory limits for them (Bates et al. 2020).

*Table 1. List of phytoplankton and sympagic (sea ice-associated) algal species recorded in Canadian waters that are known to produce phycotoxins that lead to the morbidity or mortality of marine species and/or humans. Species in* ***bold*** *are reported to produce phycotoxins that caused, or have been associated with, events in Canadian waters. Phycotoxin production has otherwise been demonstrated in waters outside of Canada in similar temperate, boreal, sub-Arctic, and Arctic regions, or in the laboratory. NL = Newfoundland and Labrador; QC = Quebec; NS = Nova Scotia; PE = Prince Edward Island; NB = New Brunswick; BC = British Columbia. AST = Amnesic Shellfish Toxin; AZA = Azaspiracid; GYM = Gymnodimine; PnTX = Pinnatoxin; PST = Paralytic Shellfish Toxin; PTX = Pectenotoxin; SPX = Spirolide; YTX = Yessotoxin.*

| Species [Phycotoxin produced] | Canadian Province/Region | | | | | | | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | NL | QC | NS | PE | NB | BC | Arctic | |
| **PENNATE DIATOMS** | | | | | | | | |
| ***Pseudo-nitzschia australis*** Frenguelli **[AST]** | - | - | ●[1,t] | | ●[t,e] | ●[e] | - | Trainer et al. 2012; Bates et al. 2020; McKenzie et al. 2021 |
| *P. calliantha* Lundholm, Moestrup & Hasle [AST] [2,3] | - | ● | ● | ● | ● | - | ● | Lundholm et al. 2003; Bates and Strain 2006; Lassus et al. 2016 |
| *P. delicatissima* (Cleve) Heiden [AST] | ● | ● | ● | ●[tc] | ● | ● | ●[s] | Smith et al. 1990 [tc]; Taylor and Haigh 1996; Bérard-Therriault et al. 1999; Kaczmarska et al. 2008; Poulin et al. 2011; Trainer et al. 2012; Martin and LeGresley 2014; Bates et al. 2020; McKenzie et al. 2021 |
| *P. fraudulenta* (Cleve) Hasle [AST] [3] | - | - | ● | ● | ● | ● | - | Mather et al. 2010; Martin and LeGresley 2014; Bates et al. 2020 |
| *P. granii* (Hasle) [tc] Hasle [AST] | - | - | - | - | - | - | ● | Lovejoy et al. 2002 |
| ***P. multiseries*** (Hasle) Hasle **[AST]** | ●[1] | - | ● | ●[e] | ● | ● | - | Subba Rao et al. 1988; Bates et al. 1989, 2020; Taylor and Haigh 1996; Kaczmarska et al. 2005; |
| *P. obtusa* (Hasle) Hasle & Lundholm [AST] [4] | - | ● | ●[5] | - | ●[5] | - | ● | Bates et al. 2018, 2020; McKenzie et al. 2021 |
| ***P. pseudodelicatissima*** (Hasle) Hasle **[AST]** | ● | ● | ● | ● | ●[e] | ● | ●[s] | Martin et al. 1990; Bérard-Therriault et al. 1999; Bates et al. 2020; McKenzie et al. 2021 |

| Species [Phycotoxin produced] | Canadian Province/Region | | | | | | | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | NL | QC | NS | PE | NB | BC | Arctic | |
| *P. pungens* (Grunow ex Cleve) Hasle [AST] [3] | ● | ● | ● | ● | ● | ● | ●[s] | Bérard-Therriault et al. 1999; Kaczmarska et al. 2005; Poulin et al. 2011; Martin and LeGresley 2014; Lassus et al. 2016; Bates et al. 2020; McKenzie et al. 2021 |
| ***P. seriata*** (Cleve) H. Peragallo **[AST]** | ● | ●[e] | ●[e] | ●[e] | ●[e] | ● | ●[s] | Bérard-Therriault et al. 1999; Couture et al. 2001; Penney et al. 2001; Kaczmarska et al. 2007; Poulin et al. 2011; Bates et al. 2020; McKenzie et al. 2021 |
| *P. subpacifica* (Hasle) Hasle [AST] | - | - | ●[5] | ● | ● | - | - | Bates and Strain 2006; Martin and LeGresley 2014 |
| *P. turgidula* (Hustedt) Hasle [AST] | - | - | ●[5] | - | ●[5] | - | ●[s] | McLaughlin et al. 2009; Różańska et al. 2009; Poulin et al. 2011; Martin and LeGresley 2014; Fernandes et al. 2014; McKenzie et al. 2021 |
| **DINOFLAGELLATES** | | | | | | | | |
| ***Alexandrium acatenella*** (Whedon & Kofoid) Balech **[PST]** | - | - | - | - | - | ●[e] | - | Taylor and Haigh 1996; Lassus et al. 2016 |
| ***A. catenella*** (Whedon & Kofoid) Balech **[PST]** | ●[e,c] | ●[e] | ●[e] | ● | ●[e,c] | ●[e] | ●[s,1] | White 1977, 1980; McKenzie and Schwinghamer 1994; Taylor and Haigh 1996; McKenzie et al. 1998; Bérard-Therriault et al. 1999; Cembella et al. 2002; Martin et al. 2008, 2014a, b; Bates et al. 2020 |
| ***A. ostenfeldii*** (Paulsen) Balech & Tangen **[PST, SPX**, GYM**]** | - | ● | ● | - | ● | ● | ● | Taylor and Haigh 1996; Harvey et al. 1997; Bérard-Therriault et al. 1999; Poulin et al. 2011; Martin and LeGresley 2014; Bates et al. 2020; McKenzie et al. 2021 |
| ***Dinophysis acuminata*** Claparède & Lachmann **[DST, PTX]** | ● | ●[e] | ● | ● | ● | ●[e] | ●[s] | Taylor and Haigh 1996; Bérard-Therriault et al. 1999; Poulin et al. 2011; Martin and LeGresley 2014; Lassus et al. |

| Species [Phycotoxin produced] | NL | QC | NS | PE | NB | BC | Arctic | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2016; Bates et al. 2020; McKenzie et al. 2021 |
| *D. acuta* Ehrenberg [DST] | ● | ● | ● | ● | ● | ● | ● | Sita Devi and Lakshminarayana 1989; Taylor and Haigh 1996; Bérard-Therriault et al. 1999; Poulin et al. 2011; Martin and LeGresley 2014; McKenzie et al. 2021 |
| *D. fortii* Pavillard [DST] | - | - | ● | - | ● | ● | - | Taylor and Haigh 1996; Martin and LeGresley 2014; |
| ***D. norvegica*** Claparède & Lachmann **[DST]** | ●[e] | ●[e] | ●[e] | ● | ● | ● | ● | McKenzie et al. 1994; Taylor et al. 1994; Taylor and Haigh 1996; Bérard-Therriault et al. 1999; Bates and Strain 2006; Poulin et al. 2011; Martin and LeGresley 2014; Lassus et al. 2016; Bates et al. 2020; McKenzie et al. 2021 |
| *Phalacroma rotundatum* (Claparède & Lachmann) Kofoid & Michener [DST, PTX] | ● | ● | ● | ● | ● | ● | ● | Bérard-Therriault et al. 1999; Poulin et al. 2011; Martin and LeGresley 2014; Lassus et al. 2016; Bates et al. 2020; McKenzie et al. 2021 |
| ***Prorocentrum lima*** (Ehrenberg) Stein **[DST]** | ●[e] | ● | ●[e] | - | - | - | ●[s] | Bérard-Therriault et al. 1999; McKenzie 2006; Poulin et al. 2011; Bates et al. 2020; McKenzie et al. 2021 |
| ***Gonyaulax spinifera*** (Claparède & Lachmann) Diesing [YTX] | ● | ● | ● | ● | ● | ●[e,h] | ● | Bérard-Therriault et al. 1999; Taylor and Harrison 2002; Bates and Strain 2006; Martin and LeGresley 2014; Dhifallah 2019; Bates et al. 2020; McKenzie et al. 2021 |
| *Lingulodinium polyedra* (Stein) Dodge [YTX] | - | - | ● | - | - | ●[c] | ● | Mudie et al. 2002; Bates et al. 2020 |

| Species [Phycotoxin produced] | Canadian Province/Region NL | QC | NS | PE | NB | BC | Arctic | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| *Protoceratium reticulatum* (Claparède & Lachmann) Bütschli [YTX] | ● | ● | ● | - | - | ● | ● | Bérard-Therriault et al. 1999; Stobo et al. 2003; Haigh 2017; Bates et al. 2020; C. McKenzie, unpublished data |
| Unidentified species [6] [PnTX] | ●[t] | ●[t] | ●[t] | ●[t] | ●[t] | ●[t] | - | Bates et al. 2020 |
| Unidentified species [7] [AZA] | ●[t] | ●[t] | ●[t] | - | - | - | - | Bates et al. 2020 |

● *Species presence reported.*
[e] *Region where a species was associated with a documented harmful algal event.*
[h] *Event was hypoxia, not phycotoxin production.*
[t] *Phycotoxin detected.*
[tc] *Toxic in culture.*
[c] *Cysts identified.*
[s] *Species identified in both phytoplankton and sea-ice samples.*
[1] *Species not confirmed.*
[2] *Considered non-toxic in Canada but some species in this complex are AST producers (Bates et al. 2018).*
[3] *No record of toxicity in cold temperate locations.*
[4] *Toxic in culture from cold temperate locations (Disco Bay, Greenland; Harðardóttir et al. 2015).*
[5] *Reference lists its presence in the Bay of Fundy.*
[6] Vulcanodinium rugosum *Nézan & Chomérat has been associated with PnTX production in France, Mexico, Japan, New Zealand and Australia (Lassus et al. 2016). It has not yet been identified in Canadian waters.*
[7] *Cultures of* Azadinium poporum *Tillmann & Elbrächter from Korea and the North Sea, and* A. spinosum *Elbrächter & Tillmann cultures from the North Sea were found to produce AZA. Identification of these species is difficult due to their small size (Lassus et al. 2016). These species have not been identified in Canadian waters.*

### 2.1.2. Hypoxia and Mechanical Damage

Hypoxic conditions are created by HAEs when large phytoplankton (either harmful or not) blooms die and algal cells sink and undergo bacterial degradation, consuming large amounts of subsurface oxygen in the process. Stratification of the water column can exacerbate the effects of hypoxia on aquatic biota by preventing mixing of oxygenated surface waters with hypoxic deep water. Hypoxia may result in the death of affected biota, but has also been found to influence food web interactions by modifying predator-prey dynamics, or by favouring low-oxygen tolerant species (references in Kemp et al. 2009).

Mechanical damage to fish gills caused by HA has been suggested to lead to microbial infections or hemorrhaging of gill tissues, or asphyxiation due to overproduction of mucus on the gill (Bell 1961). For example, the diatom species *Chaetoceros concavicornis* and *C. convolutus* have been found to cause physical damage to gills of Rainbow Trout (*Oncorhynchus mykiss*), resulting in excessive mucus production and subsequent suffocation (Yang and Albright 1992). The same *Chaetoceros* species have led to mortalities of penned Chinook and Coho Salmon (*Oncorhynchus tshawytscha* and *O. kisutch*) due to mucus-induced suffocation, while sub-lethal concentrations of these HA also caused increased mortality due to bacterial or viral infections (Albright et al. 1993). More recently, a new mechanism of fish gill damage by *Alexandrium catenella* was explored by Mardones et al. (2015), who suggested that the synergistic behaviour of non-toxic products of HA could lead to gill damage through cell lysis. Table 2 lists phytoplankton species identified in Canada and known to have caused, or been associated with, HAEs related to hypoxia, oxygen depletion, and mechanical damage. Table 3 lists phytoplankton species reported in Canada and associated with HAEs in waters outside of Canada in dissimilar climate regions.

*Table 2. List of phytoplankton and sympagic algal species, recorded in Canadian waters and known to have caused the morbidity or mortality of marine species through mechanisms other than production of phycotoxins listed in Table 1. Species in **bold** have caused HAEs in Canadian waters; otherwise, the remaining listed species have caused HAEs only in regions outside of Canada in similar temperate, boreal, sub-Arctic, and Arctic regions. NL = Newfoundland and Labrador; QC = Quebec; NS = Nova Scotia; PE = Prince Edward Island; NB = New Brunswick; BC = British Columbia.*

| Species | Canadian Province/Region | | | | | | | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | NL | QC | NS | PE | NB | BC | Arctic | |
| **CENTRIC DIATOMS** | | | | | | | | |
| ***Chaetoceros concavicornis*** [1] Mangin | ● | ● | ● | - | ● | ●[e] | ●[s] | Haigh and Taylor 1990; Bérard-Therriault et al.1999; Bates and Strain 2006; Martin and LeGresley 2014; Lassus et al. 2016; Bates et al. 2020; McKenzie et al. 2021 |
| ***C. convolutus*** [1] Castracane | ● | ● | ● | - | ● | ●[e] | ●[s] | Haigh and Taylor 1990; Bérard-Therriault et al. 1999; Bates and Strain, 2006; Martin and LeGresley 2014; Lassus et al. 2016; Bates et al. 2020; McKenzie et al. 2021 |
| *C. debilis* [1] Cleve | ● | ● | ● | ● | ● | ● | ● | Bérard-Therriault et al. 1999; Penney et al. 2001; Bates and Strain 2006; Martin and LeGresley 2014; Lassus et al. 2016; Bates et al. 2020 |
| *Corethron hystrix* [1] Hensen | ● | ● | ● | ● | ● | ● | ● | Grøntved and Seidenfaden 1938; Bates and Strain 2006; Martin and LeGresley 2014 |
| ***Eucampia zodiacus*** Ehrenberg | ● | - | ● | - | ●[e] | ● | - | Martin et al. 2007b; C. McKenzie, unpublished data |
| ***Skeletonema costatum*** (Greville) Cleve | ● | ● | ● | ● | ● | ●[e] | ● | Landsberg 2002; Penney et al. 2001; Bates and Strain 2006; Martin and LeGresley 2014; Bates et al. 2020 |

| Species | Canadian Province/Region | | | | | | | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | NL | QC | NS | PE | NB | BC | Arctic | |
| ***Thalassiosira gravida*** Cleve | ● | ● | ● | ● | ● | ●[e] | - | Bérard-Therriault et al. 1999; Thompson et al. 2008; Martin and LeGresley 2014; C. McKenzie, unpublished data |
| **DINOFLAGELLATES** | | | | | | | | |
| ***Akashiwo sanguinea***[2] (Hirasaka) Hansen & Moestrup | - | - | - | ● | - | ●[e] | - | Forbes and Waters 1993; Lassus et al. 2016 |
| *Coolia monotis* [3] Meunier | - | ● | ● | - | - | - | ●[s] | Hsiao et al. 1984; Poulin et al. 2011; Lewis et al. 2018 |
| ***Gonyaulax spinifera*** (Claparède & Lachmann) Diesing | ● | ● | ● | ● | ● | ●[e] | ● | Heath and Lindsay 1993; Bérard-Therriault et al. 1999; Bates and Strain 2006; Poulin et al. 2011; Martin and LeGresley 2014; McKenzie et al. 2021 |
| *Karenia mikimotoi* [4] (Miyake & Kominami ex Oda) Hansen & Moestrup | - | ● | | ● | | ● | ● | Bérard-Therriault et al. 1999; Bates and Strain 2006; McLaughlin et al. 2009; Haigh 2017; McKenzie et al. 2021 |
| *Karlodinium veneficum*[5] (Ballantine) Larsen | - | ● | ● | - | - | ● | - | Bérard-Therriault et al.1999; Haigh 2017 |
| ***Margalefidinium fulvescens*** [6] (Iwataki, Kawami & Matsuoka) Gómez, Richlen & Anderson | - | - | - | - | - | ● | - | Bates et al. 2020 |
| ***M. polykrikoides*** [6] (Margalef) Gómez, Richlen & Anderson | - | - | - | - | - | ● | - | Bates et al. 2020 |
| ***Noctiluca scintillans*** (Macartney) Kofoid & Swezy | - | - | - | - | - | ●[e] | - | Haigh 2017; Chittenden et al. 2018 |
| *Prorocentrum minimum*[7] (Pavillard) Schiller | ● | ● | ● | ● | ● | - | ● | Martin and LeGresley 2014; Bates et al. 2020; C. McKenzie, unpublished data |
| **DICTYOCHOPHYTES** | | | | | | | | |

| Species | Canadian Province/Region | | | | | | | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | NL | QC | NS | PE | NB | BC | Arctic | |
| ***Dictyocha fibula*** [1] Ehrenberg | ● | ● | ● | ● | ● | ●[e] | - | Bérard-Therriault et al. 1999; Bates and Strain 2006; Martin and LeGresley 2014; Bates et al. 2020; McKenzie et al. 2021 |
| ***Octactis speculum*** [1,8] (Ehrenberg) Chang, Grieve & Sutherland | ● | ● | ● | ● | ● | ●[e] | ●[s] | Bates and Strain 2006; Różańska et al. 2008; Haigh 2017; Bates et al. 2020; McKenzie et al. 2021 |
| ***Pseudochattonella verruculosa*** [9] (Hara & Chihara) Tanabe-Hosoi, Honda, Fukaya, Inagaki & Sako | - | - | - | - | - | ●[e,tc] | - | Martin and LeGresley 2014; Lassus et al. 2016; Haigh 2017 |
| ***Pseudopedinella pyriformis*** [10] N. Carter | - | ● | - | - | - | ●[e] | - | Haigh 2017 |
| **PRYMNESIOPHYTES** | | | | | | | | |
| ***Chrysochromulina birgeri*** Hällfors & Niemi | ● | - | ●[e] | - | - | - | ● | Daugbjerg and Vørs 1994; Bérard-Therriault et al. 1999; M. Poulin, unpublished data |
| ***Haptolina ericina*** [11] (Parke & Manton) Edvardsen & Eikrem | - | ● | - | - | - | ●[e] | ● | Bérard-Therriault et al. 1999; Haigh 2017; M. Poulin, unpublished data |
| ***H. hirta*** [11] (Manton) Edvardsen & Eikrem | - | - | - | - | - | ●[e] | - | Haigh 2017 |
| *Phaeocystis pouchetii*[12] (Hariot) Lagerheim | ● | ● | ● | - | ● | ● | ●[s] | Bérard-Therriault et al. 1999; Penney et al. 2001; Niemi et al. 2011a; Poulin et al. 2011; Martin and LeGresley 2014; Simo-Matchim et al. 2017 (Suppl. material Table S1); McKenzie et al. 2021 |
| *Prymnesium polylepis*[13] (Manton & Parke) Edvardsen, Eikrem & Probert | - | ● | - | - | - | ● | - | Taylor and Haigh 1996; Bérard-Therriault et al. 1999; Bates et al. 2020 |
| **RAPHIDOPHYTES** | | | | | | | | |
| *Chattonella* cf. *marina*[14] (Subrahmanyan) Hara & Chihara | - | - | - | - | - | ● | - | Haigh 2017 |

| Species | NL | QC | NS | PE | NB | BC | Arctic | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | Canadian Province/Region | | | | | | | |
| ***Heterosigma akashiwo*** [15] (Hada) Hada ex Hara & Chihara | - | ● | - | - | - | ●[e] | ● | Haigh and Taylor 1990; Bérard-Therriault et al. 1999; Poulin et al. 2011; Bates et al. 2020; McKenzie et al. 2021 |
| **CILIATES** | | | | | | | | |
| ***Mesodinium rubrum*** Lohmann | ● | ● | ● | ● | ●[e] | ● | ● | Parrish et al. 1995; Bérard-Therriault et al. 1999; Lovejoy et al. 2002; Bates and Strain 2006; Martin et al. 2007a; Haigh 2017; Dhifallah 2019 |

● *Species presence reported.*
[e] *Region where a species was associated with a documented harmful algal event.*
[tc] *Toxic in culture.*
[s] *Species identified in both phytoplankton and sea-ice samples.*
[1] *Possess barbs or spines that are physically harmful to fish and/or shellfish.*
[2] *Produces surfactants harmful to seabirds and molluscs; responsible for oyster mortalities in BC.*
[3] *May produce haemolytic substances and a potential yessotoxin derivative.*
[4] *Ichthyotoxic, haemolytic and cytotoxic.*
[5] *Produces karlotoxins; ichthyotoxic; neurotoxic, haemolytic.*
[6] *Associated with fish kills; may be ichthyotoxic, producer of reactive oxygen species (ROS) or extracellular mucoid polysaccharide substances.*
[7] *Hepatoxicity in mice; toxicity or adverse effects on molluscs and* Artemia *nauplii; possible link to tetrodotoxin.*
[8] *May produce phycotoxins.*
[9] *Ichthyotoxic.*
[10] *Shown to affect cell metabolism in fish and can cause damage to gills.*
[11] *More than one species of the genus* Haptolina *Edvardsen & Eikrem may have been responsible for farmed salmon mortalities in BC.*
[12] *Toxic to cod larvae in Norway.*
[13] *Produces haemolytic compounds and ichthyotoxic exotoxins.*
[14] *Icthyotoxic, reactive oxygen species, produces haemolytic and neurotoxic substances.*
[15] *Ichthyotoxic species; mechanism of action still unknown; may produce ROS or haemolytic substances.*

*Table 3. List of phytoplankton and sympagic algal species recorded in Canadian waters that have caused harmful algal events in waters outside of Canada in dissimilar climate regions. Only selected references are cited across the regions. NL = Newfoundland and Labrador; QC = Quebec; NS = Nova Scotia; PE = Prince Edward Island; NB = New Brunswick; BC = British Columbia.*

| Species | NL | QC | NS | PE | NB | BC | Arctic | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | Canadian Province/Region | | | | | | | |
| **CENTRIC DIATOMS** | | | | | | | | |
| *Chaetoceros wighamii* [1] Brightwell | - | ● | - | - | - | - | ●[s] | Cross 1982; Hsiao et al. 1984; Percy et al. 1992; Bérard-Therriault et al. 1999; Lovejoy et al. 2002; Różańska et al. 2008 |

| Species | NL | QC | NS | PE | NB | BC | Arctic | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | Canadian Province/Region | | | | | | | |
| *Coscinodiscus wailesii*[1] Gran & Angst | - | - | - | - | ● | - | ● | Bursa 1971; Martin and LeGresley 2014 |
| *Leptocylindrus minimus*[2] Gran | ● | ● | ● | ● | ● | ● | ● | Simard et al. 1996; Penney et al. 2001; Bates and Strain 2006; Taylor and Haigh 1996; Martin and LeGresley 2014; Bates et al. 2020 |
| *Rhizosolenia chunii* [1,3] Karsten | - | - | - | - | - | ● | - | McIntyre et al. 2013 |
| *R. setigera* [4] Brightwell | ● | ● | ● | ● | ● | ● | ● | Poulin et al. 1983; Bates and Strain 2006; Martin and LeGresley 2014; Haigh 2017; C. McKenzie, unpublished data |
| **PENNATE DIATOMS** | | | | | | | | |
| *Cylindrotheca closterium* [5] (Ehrenberg) Reimann & Lewin | ● | ● | ● | ● | ● | ● | ● | Penney et al. 2001; Lovejoy et al. 2002; Bates and Strain 2006; Poulin et al. 2011; Martin and LeGresley 2014; Lassus et al. 2016 |
| **DINOFLAGELLATES** | | | | | | | | |
| *A. monilatum* [7] (Howell) Balech | - | - | - | - | - | - | ●[s] | Poulin et al. 2011; Bates et al. 2020 |
| *A. pseudogonyaulax* [8] (Biecheler) Horiguchi ex Yuki & Fukuyo | - | ● | - | ● | ● | ● | - | Bates and Strain 2006; Martin and LeGresley 2014; Bates et al. 2020 |
| *Amphidinium carterae* [9] Hulburt | - | ● | - | ● | - | - | ● | Bérard-Therriault et al. 1999; Lovejoy et al. 2002; Bates and Strain 2006 |
| *Dinophysis caudata* [10] Kent | - | - | ● | - | - | - | ●[s] | Daugbjerg and Vørs 1994; Poulin et al. 2011; Bates et al. 2020 |
| *Gymnodinium aureolum* [11] (Hulburt) Hansen | - | ● | ● | - | ● | ● | ● | Blasco et al. 1994; Lovejoy et al. 2002; Martin and LeGresley 2014; Haigh 2017 |
| *G. flavum* [12] Kofoid & Swezy | - | - | - | - | - | ● | - | Forbes and Waters 1993 |
| *Karenia brevis* [13] (Davis) Hansen & Moestrup | - | - | - | - | - | - | ● | Roff and Legendre 1986; Poulin et al. 2011 |

| Species | Canadian Province/Region | | | | | | | References for Distribution |
|---|---|---|---|---|---|---|---|---|
| | NL | QC | NS | PE | NB | BC | Arctic | |
| *Kryptoperidinium triquetrum* [14] (Ehrenberg) Tillmann, Gottschling, Elbrächter, Kusber & Hoppenrath | - | ● | ● | ● | ● | ● | ●[s] | Bérard-Therriault et al. 1999; Lovejoy et al. 2002; Bates and Strain 2006; Martin and LeGresley 2014; Haigh 2017 |
| *Prorocentrum mexicanum* [15] Osorio-Tafall | - | ● | - | - | - | - | - | Bérard-Therriault et al. 1999; M. Starr, unpublished data |
| *Tripos fusus* [16] (Ehrenberg) Gómez | ● | ● | ● | ● | ● | ● | ● | Lovejoy et al. 2002; Bates and Strain 2006; McLaughlin et al. 2009; Martin and LeGresley 2014; Dhifallah 2019; C. McKenzie, unpublished data |
| **PRYMNESIOPHYTES** | | | | | | | | |
| *Phaeocystis globosa* [17] Scherffel | - | - | - | - | - | - | ● | Hsiao and Pinkewycz 1985a |

*● Species presence reported.*
*[s] Species present in both phytoplankton and sea-ice samples.*
*[1] Possess barbs or spines that are physically harmful to fish and/or shellfish.*
*[2] Harmful algae of concern to Norwegian fish and shellfish industries (Andersen et al. 2001).*
*[3] The first diatom species to be associated with shellfish mortality in southeastern Australia (Parry et al. 1989).*
*[4] Known to produce monocyclic alkenes, this species has been occasionally reported to cause marine mortalities; most likely due to oxygen depletion upon bloom decay (EOL 2020).*
*[5] May produce mucilage and produces allelopathic chemicals that suppress growth of other species (EOAS 2020).*
*[6] A producer of paralytic shellfish toxins in Europe, Australia, New Zealand, Asia and African regions (Lewis et al. 2018).*
*[7] Responsible for fish mortalities and found to produce hemolytic compounds (Moestrup et al. 2009).*
*[8] Toxic species that produces goniodomin A (Murakami et al. 1988).*
*[9] Produces luteophanol A-like compounds and causes low dissolved oxygen levels during blooms. Associated with fish mortality in Australia (Murray et al. 2015).*
*[10] A producer of diarrhetic shellfish toxins and associated (along with other DST producers) in DSP outbreaks in Europe, America, Asia, and Australia (Moestrup et al. 2009).*
*[11] Cytotoxins and haemolytic toxins documented in the species from Norway, Scotland, and Ireland (Dahl and Tangen 1993).*
*[12] Reported to cause yellow tides in California (Wilton and Barham 1968), and has also been implicated as a possible cause of fish mortality (Lackey and Clendenning 1963).*
*[13] A producer of brevetoxin, a potent neurotoxin and haemotoxin. Associated with red tides, mass mortalities of fish and marine mammals, neurotoxic shellfish poisoning, and respiratory symptoms in humans. Events reported in the southeastern USA and Gulf of Mexico.*
*[14] Produces β-N-methylamino-L-alanine (BMAA) linked to the neurodisease Amyotrophic Lateral Sclerosis (ALS) (Lassus et al. 2016).*
*[15] Potential producers of haemolytic toxins and/or fast-acting toxin (FAT). Harmful potential requires further study (Tindall et al. 1984).*

*[16] Negative effects observed in bloom conditions (i.e., invertebrate larvae mortality, depletion of water quality leading to fish deaths). Responsible for red tide conditions in Eastern Asia (Baek et al. 2007).*
*[17] Reported to form toxins in China (Qi et al. 2002).*

## 2.2. MARINE HARMFUL ALGAL EVENTS IN CANADIAN WATERS

A review of 593 Canadian HAEDAT records from 1987 to 2017, together with other Canadian data and publications, showed that recurring HAEs have been widespread throughout both the Canadian Atlantic and Pacific coastal regions. PST events occurred frequently and annually on both the Atlantic and Pacific coasts, including multi-year PST events in the Bay of Fundy, the Estuary and Gulf of St. Lawrence, and the Strait of Georgia. HAEs caused by AST and DST were commonly reported on both coasts (Bates et al. 2020; McKenzie et al. 2021). Additional emerging phycotoxins include pectenotoxins, yessotoxins, azaspiracids, spirolides, pinnatoxins, and gymnodimines. Of these, only pectenotoxins have a regulatory limit in Canada, and all but azaspiracids are found on both coasts (Bates et al. 2020). Marine species mortalities caused by HA were an annual occurrence in the Pacific coast but have been reported much less frequently in the Atlantic region (McKenzie et al. 2021).

A summary of the results of the review for HAEs is organized by region (Atlantic, Pacific), as well as the occurrence of HA in the Canadian Arctic. This provides the background for discussions on the specific drivers, impacts and consequences that are relevant for each region.

Each regional summary contains a map showing the overall distribution of phycotoxins and their reoccurrence, based on 30 years of HAEDAT reporting. In HAEDAT, the coastline is divided into a regional grid system, and each event is assigned to the appropriate coastal grid area, but the symbol does not reflect the exact location of the event. Maps created using HAEDAT show a summary of all events that occurred within the grid. For Canada, HAEDAT contains reports of shellfish closures due to PST, AST, DST, and “other”, which includes mass mortalities of fish and marine mammals. A 30-year decadal review of Canadian HAEs based on HAEDAT reports provides detailed information and maps (McKenzie et al. 2021). No HAEDAT information exists for the Arctic, so that summary is based on the literature and recent studies.

In addition to the HAEDAT summary for the Atlantic and Pacific, and the HA summary for the Canadian Arctic, regional maps shown below provide a more complete picture of the widespread implications for HAEs, as they include cumulative detections of regulated and unregulated phycotoxins. A more detailed review of Canadian HABs and phycotoxins has been published (Bates et al. 2020).

### 2.2.1. Canadian Atlantic Coast

As shown in Figure 3, recurring HAEs have been widespread throughout the Canadian Atlantic coastal regions. PST events were reported at all Atlantic provinces over the review period, including annual PST events in the Bay of Fundy and the Estuary and Gulf of St. Lawrence (Figure 3A). HAEs caused by AST and DST were reported in all Atlantic provinces (Figure 3B, C). Several mortalities of marine species, caused by HA, were reported in the Atlantic region (Figure 3D; McKenzie et al. 2021), including fish, mammals and birds in the Estuary and Gulf of St. Lawrence (2008) and farmed salmon in NS (2000) and New Brunswick (NB 2003, 2004).

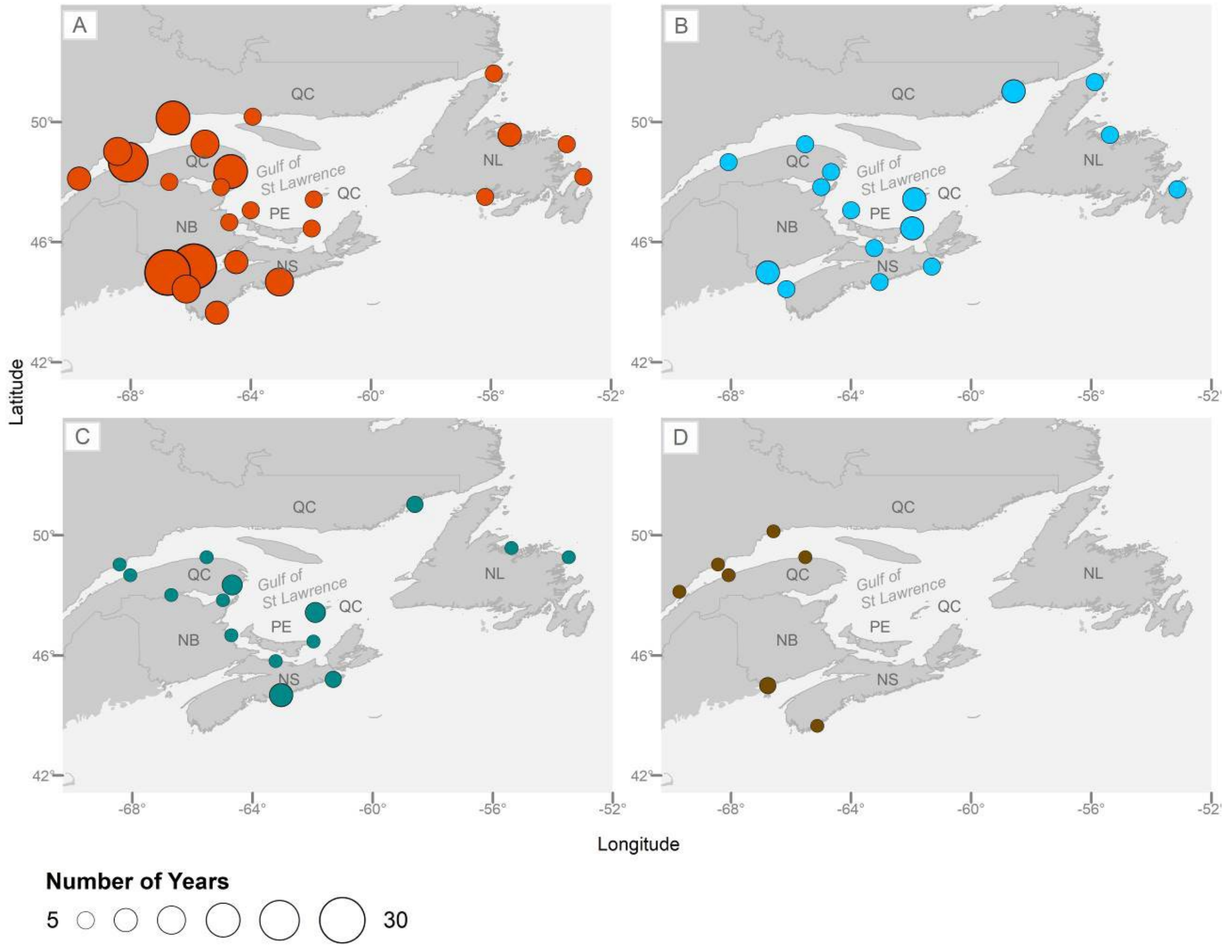


*Figure 3. Canadian Atlantic coast. HAEDAT reports showing the distribution of HAEs: (A) PST (red), (B) AST (blue), (C) DST (green), and (D) marine species mass mortalities (brown), and extent of reoccurrence (size of circle), for 30 years of data reporting (1987–2017). Circles are centered in each HAEDAT grid code area and are not the exact location of the events.*

At least 55 species of HA have been detected on the Atlantic coast, with 11 having caused, or having been associated with, HAEs in Canada (Tables 1, 2). Combining all HAE and phycotoxin detection information for the Atlantic coast into a single map (Figure 4) illustrates the scope of the issue. The varied and recurring events throughout the region highlight the extent to which future events could occur.

Restrictions on shellfish harvesting due to PST have been imposed in Atlantic Canada since 1943, but Indigenous peoples in the Bay of Fundy and the Gulf of St. Lawrence regions were aware of the hazards of shellfish consumption much earlier; it was reported in the 1600s that they would not eat mussels even if they were starving (Tennant et al. 1955; Prakash et al. 1971; McKenzie et al. 2021). In the Bay of Fundy, the annual recurrence of PSTs has led to the establishment, in 1943, of the longest continuous shellfish toxin monitoring dataset in the world and the permanent closure of wild Blue Mussel (*Mytilus edulis*) harvesting in the entire Bay of Fundy since 1944 (Prakash et al. 1971). Currently, some Blue Mussel aquaculture sites are allowed to harvest their product if they test below the regulatory limit. PSTs are not confined to molluscan shellfish but are also detected at low levels in the hepatopancreas (tomalley, eaten as a delicacy) of American Lobster (*Homarus americanus*) from the Bay of Fundy (Watson-Wright et al. 1991). The Bay of Fundy and the Estuary and Gulf of St. Lawrence are both particularly important locations for multi-year events, as indicated by the size of the circles in Figure 3A. The impact of these reoccurring blooms is demonstrated by the large *Alexandrium catenella* bloom in 2008, in the Estuary and Gulf of St. Lawrence, Quebec (QC), which resulted in mass mortalities of fish, seabirds and marine mammals, including species designated at risk (Figure 3D; Starr et al. 2017). Massive blooms of *A. catenella* and related PSTs have also been linked to herring mortalities, in the Bay of Fundy in 1976 and 1979 (White 1977, 1980) and cultured Atlantic Salmon (*Salmo salar*) on the southwestern shore of NS in 2000 (Cembella et al. 2002), and the southwest NB portion of the Bay of Fundy during 2003 and 2004 (Martin et al. 2008). One of the main reasons toxic *Alexandrium* blooms and events recur year after year is the production, by these dinoflagellates, and retention of resting cysts that overwinter in sediments; in following seasons, some cysts can become re-suspended and seed (initiate) blooms. For example, the Bay of Fundy has one of the richest, stable cyst deposits of *A. catenella* in the world.

*Alexandrium catenella* was determined to be the primary species that produces PSTs in the Bay of Fundy (Needler 1949). Over the years a number of investigators have examined the PSTs shellfish toxicity dataset from the Bay of Fundy. For example, White (1987) examined the data over a 40-year period (1944–83) in relation to environmental data. Martin and Richard (1996) evaluated data from a 51-year period (1943–94) in relation to cycles and trends. Hamer et al. (2012) looked for spatial and temporal trends in PSTs in Soft-shell Clams (*Mya arenaria*) (1943–2010). Martin et al. (2014a) examined datasets of shellfish toxicity, toxic *A. catenella* bloom dynamics and cyst distributions since 1980, to look for patterns and trends. Broad surveys were conducted for *A. catenella* distribution and abundance in the Bay of Fundy during 1980 to 1984 (Martin and White 1988), complemented by sediment surveys for resting cysts (White and Lewis 1982; Martin and Wildish 1994; Martin et al. 2014a). Since *A. catenella* is often a minor component of the total phytoplankton community, the Bay of Fundy phytoplankton monitoring program included identification and enumeration of the total phytoplankton community (Martin et al. 2014b). Page et al. (2004) examined the spatial and temporal variation in abundance of *A. catenella* in relation to the total phytoplankton community structure. Although the concentrations of cysts in sediments are important to initiating blooms (as they provide the seed), they do not play a role in predicting bloom intensity from year to year in the Bay of Fundy or the St. Lawrence Estuary (Gracia et al. 2013; Martin et al. 2014b).

In Newfoundland and Labrador (NL), the first reported PSP event occurred in 1982 (White and White 1985), which prompted a monitoring program for phycotoxins in the province (Hockin et al. 1983; Schwinghamer et al. 1994). In December 1991, PSP toxicity was detected in Blue Mussels in Notre Dame Bay. The timing was unusual for vegetative cells of *A. catenella*. Further investigation revealed that resuspended *A. catenella* cysts were responsible for the event; the presence of only four cysts in the Blue Mussel digestive system produced sufficient toxins to result in closure levels (Schwinghamer et al. 1994). Concern about resuspension of toxic cysts led to the permanent closure of several sites to shellfish aquaculture. Closure of one of these aquaculture sites in Pelley's Tickle resulted in the loss of 9.1 tonnes (t) of Blue Mussels, as they were always above the regulatory toxin limit (McKenzie 1996). Several locations in NL, NB and QC have been permanently closed for aquaculture and wild harvest of mussels due to the presence of these cysts or the continued presence of PSTs above the regulatory level in shellfish tissues (reviewed in Bates et al. 2020).

In December 1987, an outbreak of an unidentified toxin was responsible for over 150 human illnesses and four deaths in Canada, following the consumption of Blue Mussels (Bates et al. 1989). DFO inspectors traced the source of the Blue Mussels to aquaculture sites in Cardigan Bay, eastern PE, and shellfish harvesting was closed in all of Atlantic Canada. Within four days, the NRC discovered, for the first time worldwide, the presence of DA in Blue Mussels, and determined that this toxin was responsible for a new syndrome, ASP. The diatom *Pseudo-nitzschia multiseries*, found in the Blue Mussel digestive system, was confirmed to be the source of the DA (Subba Rao et al. 1988; Bates et al. 1989). This was the first discovery of a toxin-producing diatom species. Shellfish harvest closures related to high levels of DA are common in the Gulf of St. Lawrence in summer (Couture et al. 2001). In December 2001, and again in March 2002, several *Pseudo-nitzschia* species caused the largest DA shellfish area closure on record at the time. The bloom covered the majority of the southern Gulf of St. Lawrence, from the Gaspé Peninsula to the Northumberland Shore, including all shores of PE. Approximately 200 km of shoreline was affected until May 2002. Since that first detection, AST events have recurred in the southwest NB portion of the Bay of Fundy and southwest NS, the southern Gulf of St. Lawrence, including Chaleur Bay, the northern shore of the Estuary and Gulf of St. Lawrence, and the southeastern and northeastern shores of NL (Martin et al. 1990, 1998; McKenzie et al. 2021; Figures 3B, 4). Interestingly, *P. australis*, previously reported from a HA bloom on the Canadian Pacific coast in 2015, was also implicated as the source of DA on the east coast in the Bay of Fundy in 2016 (Bates et al. 2018). This species was not previously observed in that region (Martin and LeGresley 2014; Kaczmarska et al. 2005; J. Ehrman, unpublished data).

DSTs were first detected in North America in 1989 (Cembella 1989), in the lower St. Lawrence Estuary, QC, where it was produced by the dinoflagellates *Dinophysis acuminata* and *D. norvegica.* In the 10 years following its discovery, DST events were reported in every province in Atlantic Canada (Quilliam et al. 1993; McKenzie et al. 1994; Figures 3C, 4). In 1999, a shellfish toxicity event occurred in the Magdalen Islands, caused by the dinoflagellates *Prorocentrum lima* and *P. mexicanum*, which were present in the water column, as epiphytes on Blue Mussel socks, and in the gut contents of Blue Mussels (Levasseur et al. 2003). In 2001, *P. lima* cells in NL were also found growing epiphytically on Blue Mussel lines where DSTs contaimation of the mussels, caused the rejection of the product in the UK (McKenzie 2006). DST events have occurred along the south shore of the St. Lawrence Estuary, extending into the northern part of the southern Gulf of St. Lawrence, the Magdalen Islands, the northern Gulf of St. Lawrence, at one location in eastern PE, several sites near the mouth of the Bay of Fundy, and on the northern, eastern and southeastern coasts of NL (reviewed in Bates et al. 2020).

Spirolide toxins have been reported from the NB and NS coasts of the Bay of Fundy, the Atlantic coast of NS, the southern Gulf of St. Lawrence (including areas of PE and the Magdalen Islands), locations in the St. Lawrence Estuary, and several locations around coastal NL. Pectenotoxins have been reported along the south shore of NS, the southern Gulf of St. Lawrence (including the Magdalen Islands and the Gaspé Peninsula), and southern and northeastern NL. Yessotoxins were found, for the first time in Canada, at eight aquaculture sites in eastern NL in Blue Mussel digestive glands, in 2004, in Notre Dame Bay and Green Bay (Finch et al. 2005). These toxins have subsequently been detected along the Atlantic coast of NS, throughout the southern Gulf of St. Lawrence (including the Magdalen Islands and PE, the northeast shore of QC, and one location inside the St. Lawrence Estuary), and at several coastal locations in NL (Rourke and Haigh 2019; Bates et al. 2020).

Non-ichthyotoxic phytoplankton species were found during fish mortality events on the Atlantic coast. On four occasions, mortality events of farmed fish were reported in Passamaquoddy Bay (Bay of Fundy, southwest NB) during which two different diatom species were suspected to have caused events in 2002 (*Eucampia zodiacus*) and 2004 (*Leptocylindrus minimus*) (Martin et al. 2007b). Water discoloration was reported during both events, along with high phytoplankton concentrations. In 1998 and 2003, mass mortalities of farmed fish were again reported, but these events were linked to blooms of the protozoan ciliate *Mesodinium rubrum*, which caused water discoloration and altered oxygen levels, eventually leading to fish death (Martin et al. 2007*a*; reviewed in Bates et al. 2020).

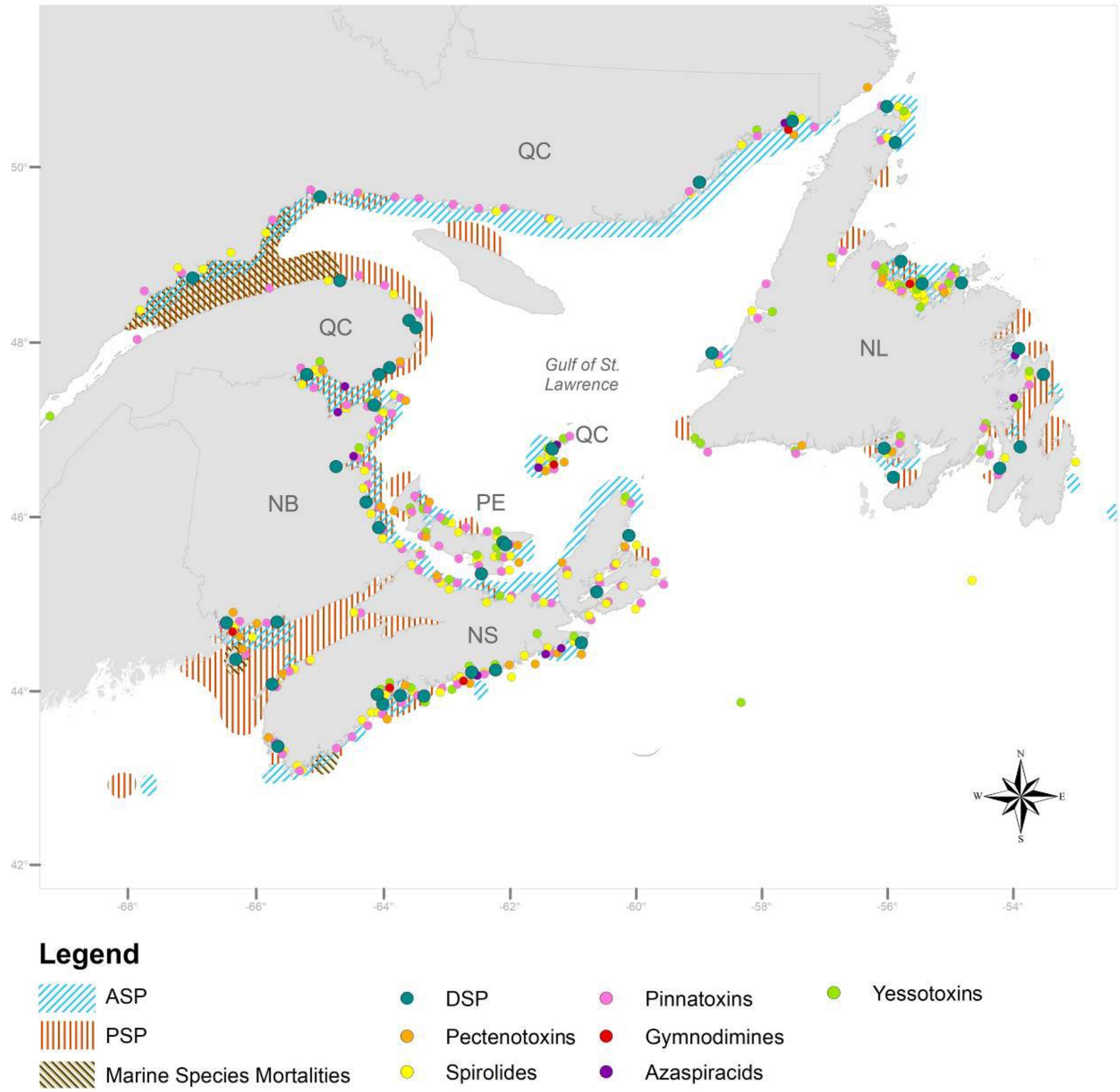


*Figure 4. Atlantic summary of HA toxin detections from 1987 to 2017. This map includes locations of ermerging phycotoxins of global concern: pectenotoxins, spirolides, pinnatoxins, gymnodimines, azspiracids, and yessotoxins. Modified from Bates et al. (2020).*

## 2.2.2. Canadian Pacific Coast

Recurring HAEs have been widespread throughout the Canadian Pacific coastal region (Figure 5). Based on the available observations, PST events are the most common and occur annually in the Pacific region, particularly in the Strait of Georgia (Figure 5A). HAEs caused by AST have occurred since 1992 throughout the Strait of Georgia, the west coast of Vancouver Island, and areas of the northern BC coast. DSTs have been commonly reported in the southern and central portion of the Pacific region since their earliest detection in 2011 (Figure 5B, C). Marine species mortalities caused by several different HA species are an annual occurrence in the Pacific region, particularly affecting farmed Atlantic Salmon on the eastern and western coasts of Vancouver Island (Figure 3D) (McKenzie et al. 2021).

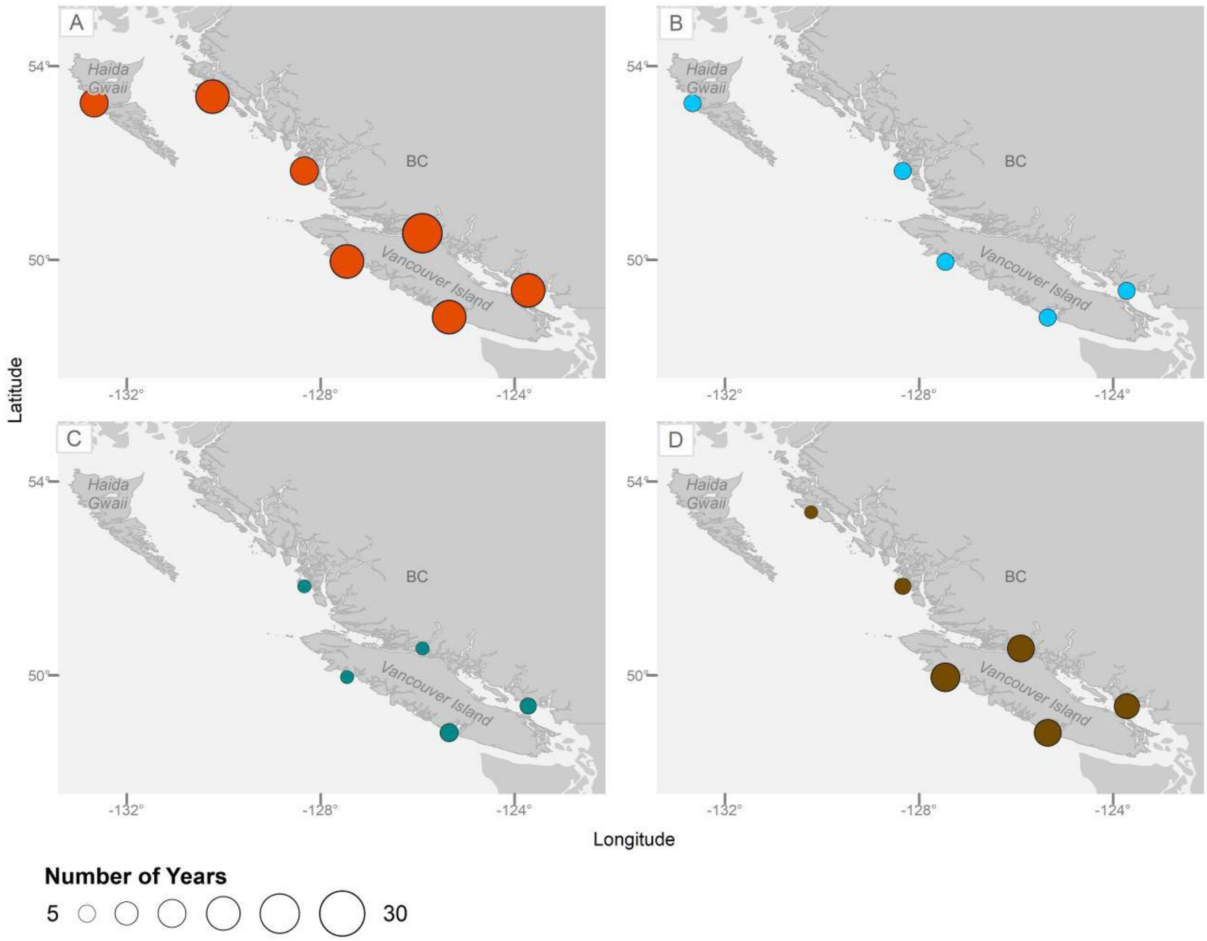


*Figure 5. HAEDAT reports showing the Pacific coast distribution of HAEs: (A) PST (red), (B) AST (blue), (C) DST (green), and (D) marine species mass mortalities (brown), and the extent of reoccurrence (size of circle), for 30 years of data reporting (1987–2017). Circles are centered in each HAEDAT grid code area and are not the exact location of the events.*

At least 53 species of HA have been detected in the Pacific region with 19 causing or associated with HAEs in Canada (Table 1, 2). Combining the HAEDAT records with other HA and phycotoxin reports for the Canadian Pacific coast (Figure 6) illustrates effects of HA that have been observed along virtually the entire coast and in many of its inlets. Future HAEs may be anticipated given their frequent recurrence in the past.

PSTs have a long history on the Pacific coast, although it has not always been fully documented. PSP was known on the BC coast at least by 1793, when a member of Captain George Vancouver's crew died after eating contaminated Blue Mussels and exhibiting symptoms of PSP in an area subsequently named Poison Cove, and was probably well known to the Indigenous peoples (Quayle and Bernard 1966). However, no formal records of PSP in BC exist prior to an outbreak in 1936 (Gibbard et al. 1939; Gibbard and Naubert 1948). According to Taylor and Harrison (2002), "*there has not been a year in which [PSP] toxicity has not occurred and virtually every area on the [BC] coast has been toxic at one time or another. Some areas are toxic every year*." The earliest PSP event recorded in HAEDAT on the Canadian Pacific coast was in 1987, in the upper Strait of Georgia (Figure 5A), and was attributed to *Alexandrium catenella*. Because of the recurrence of high levels of PSTs along the entire BC coast and the slow toxin depuration rate in the Butter Clam (*Saxidomus giganteus*), Taylor and Harrison (2002) stated that harvesting of this species had been permanently prohibited. However, the DFO Intertidal Clams Management Plans for 2000 and subsequent years have allowed fisheries for Butter Clams, where *"openings will be based on the results of biotoxin (PSTs) monitoring*" (DFO 2000). Tissue samples collected from marine mammals found along the BC coast during the large 2015–16 west coast HAE were also found to contain high levels of PSTs (Savage 2017).

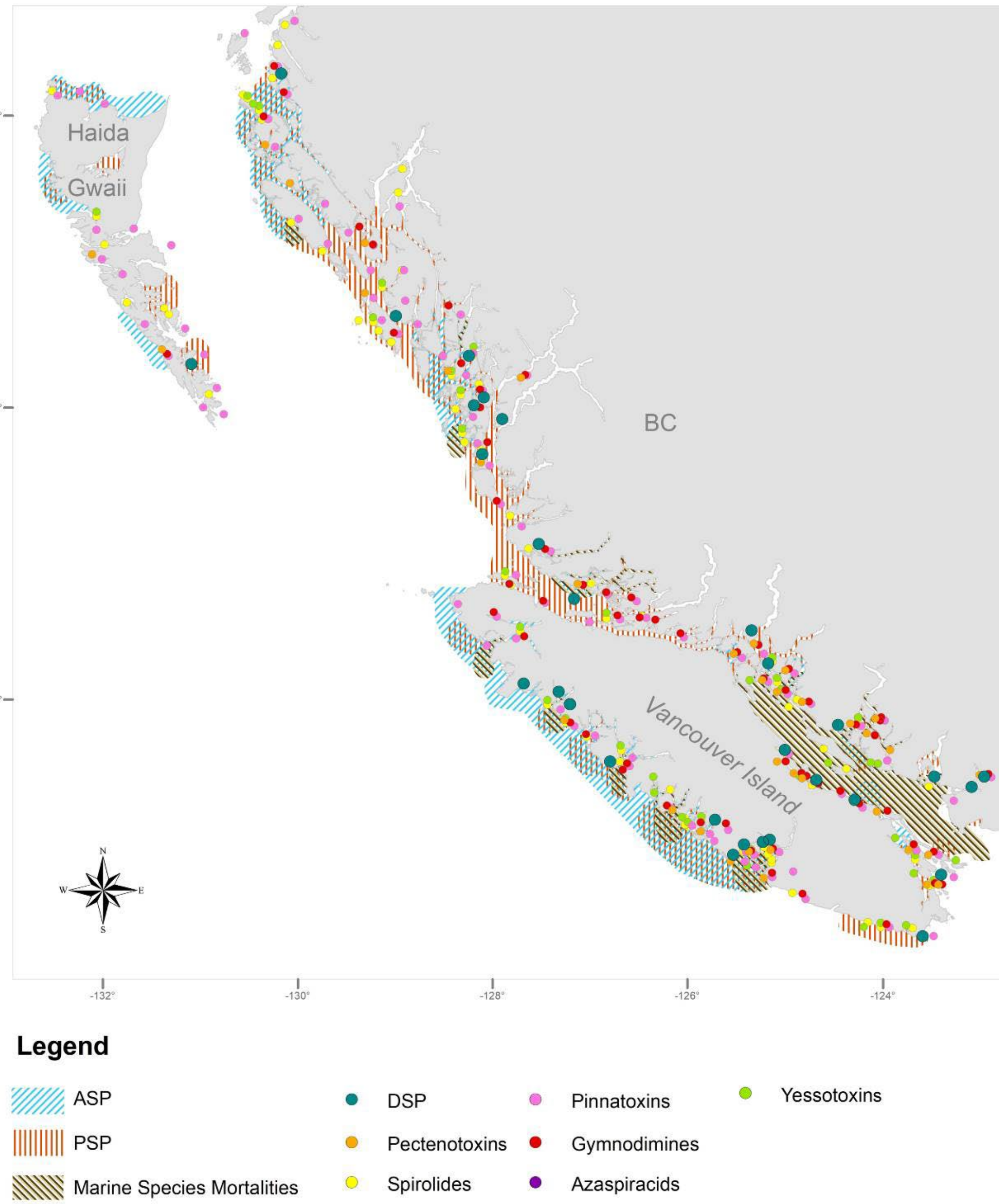


*Figure 6. Pacific summary of HA toxin detections from 1987 to 2017. This map also includes locations of emerging phycotoxins of global concern: pectenotoxins, spirolides, pinnatoxins, gymnodinimes, azaspiracids, and yessotoxins. Modified from Bates et al. (2020)*

AST was detected on the Canadian Pacific coast in 1992, when it was first reported off Vancouver Island (Figures 5B, 6). In following years, AST events have occurred throughout the Strait of Georgia, on the west coast of Vancouver Island, and on the Haida Gwaii archipelago. A widespread phytoplankton bloom that included *Pseudo-nitzschia australis* occurred in 2015, along the entire west coast of North America, including the west coast of Vancouver Island, and coincided with the detection of high levels of AST (Figure 7). Shellfish area closures were issued along the Pacific coast of Canada and the United States. From California to northern Washington, shellfish (Pacific Razor Clam *Siliqua patula* and Dungeness Crab *Cancer magister*) and finfish (Northern Anchovy *Engraulis mordax*) closures were issued. Marine mammals were also found stranded and California Sea Lions (*Zalophus californianus*) were diagnosed with ASP (McCabe et al. 2016). The economic impact of the event forced the State of California to request a federal fishery disaster declaration (McCabe et al. 2016). Marine mammal mortalities were reported in BC waters during this event, including at least 17 large Whales (five Fin *Balaenoptera physalus*, seven Humpback *Megaptera novaeangliae*, three Gray *Eschrichtius robustus*, one Sperm *Physeter macrocephalus*, and one Common Minke *Balaenoptera acutorostrata* Whale) found from the southern tip of Vancouver Island to the northern tip of Haida Gwaii between April 2015 and April 2016 (Savage 2017). A cluster of 12 Fin Whale mortalities in Alaska in the same time period resulted in declaration of a Large Whale Unusual Mortality Event by National Oceanic and Atmospheric Administration (U.S.) (NOAA, Savage 2017). Mass mortalities of seabirds (Piatt et al. 2020; Van Hemert et al. 2020) and Northern Sea Otters *Enhydra lutris kenyoni* were recorded concurrently. Gut content samples collected from seven necropsied Fin and Humpback Whales from the BC coast contained high levels of AST (Savage 2017).

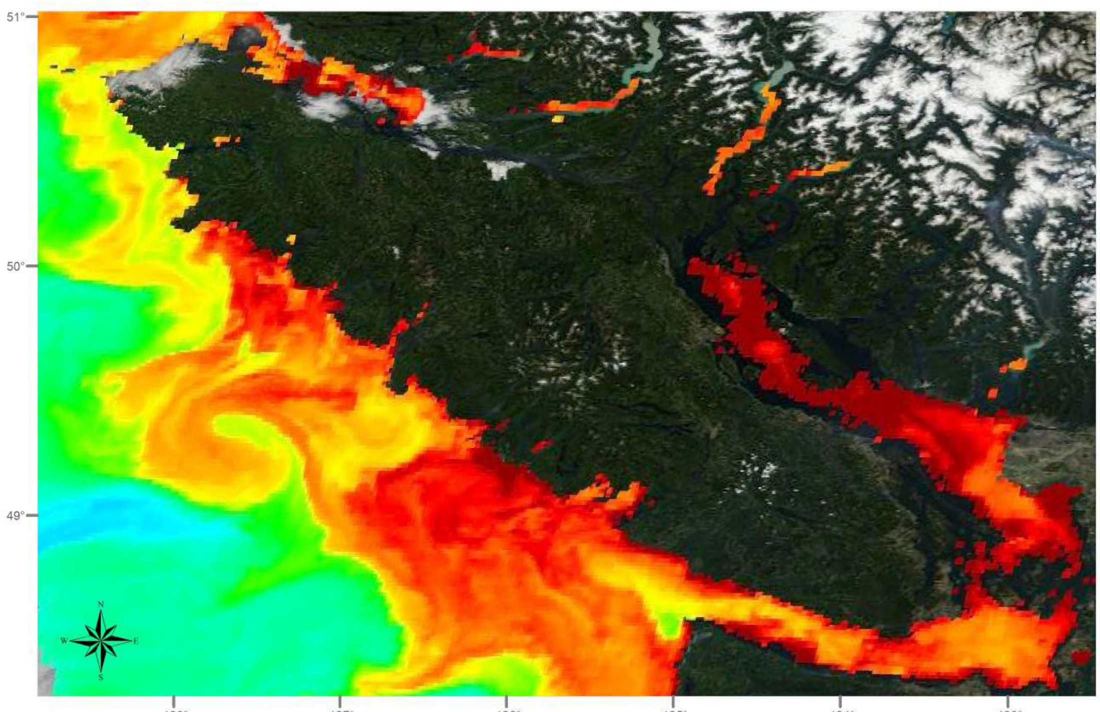


*Figure 7. MODIS satellite imagery taken on July 18, 2015, and enhanced to show a phytoplankton bloom that contained the domoic acid-producing diatom Pseudo-nitzschia australis off the west coast of Vancouver Island. Red indicates the highest concentration of chlorophyll in the algal bloom, and green to blue indicate lower concentrations. Note that while chlorophyll concentrations were high in the Strait of Georgia east of Vancouver Island, no P.* australis *was detected from that region. Image sources: NASA Earth Observations, Fish Info & Services Co. Ltd.*

A study of potentially harmful phytoplankton on the Pacific coast reported the presence of Dinophysis species in 1986 (Haigh and Taylor 1990). It was not until 2011, however, that DSP symptoms in humans were linked to consumption of Blue Mussels from the upper Strait of Georgia (Figure 5C). A phytoplankton monitoring site used by the aquaculture industry, located 25 km away at Conville Bay, identified a mixture of Dinophysis species (*D. acuminata, D. acuta, D. fortii*) and Phalacroma rotundatum. Since then, isolated events have occurred periodically in the Strait of Georgia, the west coast of Vancouver Island, and the central BC coast (Figure 6).

Azaspiracids, gymnodimines, pectinotoxins, pinnatoxins, and spirolides are found throughout the Canadian Pacific coast (Figure 6) (Bates et al. 2020). The CFIA has monitored Canadian shellfish samples for yessotoxins since 2003, in support of export activities and to generate data for a Canadian risk assessment (Rourke and Haigh 2019). To date, YTXs have been found at levels up to 12 µg $g^{-1}$ total YTX at 164 sites in BC (Figure 6; all sites not shown) (Bates et al. 2020).

Mortality of caged finfish is a common occurrence on the Pacific coast, with records dating back to the 1960s (Bell 1961). Atlantic Salmon aquaculture farms established rapidly on the southern BC coast since 1984, and reports of fish mortalities followed soon after (Albright et al. 1992). The first reported event in the upper Strait of Georgia occurred in 1987, when the mortality of farmed fish was observed during a bloom of the diatom Chaetoceros convolutus (Table 2; Figure 5D; Harrison et al. 1993). Following that event, the Pacific coast has experienced the mortality of farmed fish due to blooms of C. concavicornis or C. convolutus frequently, but not annually.

The raphidophyte flagellate *Heterosigma akashiwo* has been responsible for farmed fish kills on the Pacific coast since the 1970s (Haigh and Taylor 1990). The mode of action for fish mortalities by *H. akashiwo* is still not fully understood, but is thought to be due to the production of haemolytic substances (Lassus et al. 2016). The first recorded bloom of *H. akashiwo* on the upper west coast of Vancouver Island was in late August 1992, in Kyuquot Sound and Nootka Sound. The bloom affected several aquaculture operations in the area, resulting in the mortality of ~250,000 kg of Atlantic Salmon. Since then, deaths of farmed fish due to *H. akashiwo* blooms were reported in most years. Between 2009 and 2012, *H. akashiwo* was responsible for 65% of fish-killing HAEs and 90% of high-level (>1,000 fish killed) HAEs at aquaculture sites (Haigh and Esenkulova 2014). Occasional farmed fish mortalities have also been caused by blooms of the ichthyotoxic flagellates *Chattonella* cf. *marina* and *Pseudochattonella verruculosa*. In 2002, the mortality of nearly 1,000 t of aquaculture product due to *C.* cf. *marina* occurred in Esperanza Inlet, on the upper west coast of Vancouver Island. The flagellates *Dictyocha fibula* and *Octactis speculum* are believed to produce a toxin similar to the one produced by *P. verruculosa* (Bates et al. 2020). The HAMP in BC has linked mortalities of farmed salmon to both species.

### 2.2.3. Canadian Arctic Coast

Several potentially harmful phytoplankton and sympagic algal species have been identified throughout Arctic and sub-Arctic regions, including sites within the Hudson Bay Complex (Hudson Bay, Hudson Strait and Foxe Basin), the eastern Arctic (southern Davis Strait to northern Baffin Bay and Nares Strait), the western Arctic (Beaufort Sea), the Canadian Archipelago, including Amundsen Gulf and Franklin Bay, and the Canada Basin (Figure 8). Species distribution information was compiled from the literature and various unpublished datasets to list potentially toxic or harmful phytoplankton species present in the Arctic. Because this is the first compilation of reported HA species in the Canadian Arctic, the citations are extensive to provide detail for future reference.

In the Arctic, 45 potentially harmful pelagic and sympagic algal species have been reported. Of these, 16 have caused, or have been associated with, HAEs on the Atlantic or Pacific coasts of Canada. Eight of these 16 species produce phycotoxins (Table 1) and eight cause mechanical damage or hypoxia (Table 2). Of the other 29 species found in the Arctic, 10 are species which can produce phycotoxins (Table 1) and 19 can cause mechanical damage or hypoxia (Tables 2, 3), and are known to have caused, or to be associated with, HAEs outside Canada or in the laboratory.

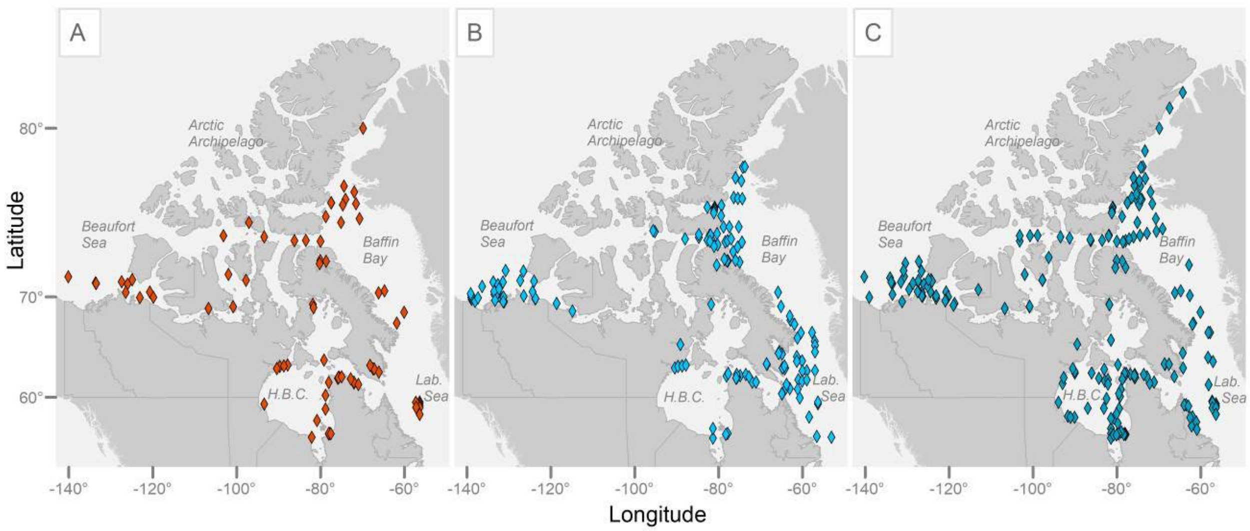


*Figure 8. Distribution of harmful phytoplankton and sympagic (sea ice-associated) algae in the Canadian Arctic. (A) Alexandrium spp. that have the potential to produce PSTs in the Canadian Arctic; (B) Pseudo-nitzschia spp. that have the potential to produce AST in the Canadian Arctic; (C) Dinophysis spp., Phalacroma rotundatum, and Prorocentrum spp. that have the potential to produce DSTs in the Canadian Arctic. H.B.C. = Hudson Bay Complex; Lab. Sea = Labrador Sea.*

Vegetative cells of PSTs producing *Alexandrium* spp. are widely distributed throughout the Canadian Arctic, the Labrador coast, Greenland, Alaska, and Russia. (Bursa 1961a, b; Hsiao 1983; Hsiao and Pinkewycz 1983, 1984, 1985a, b; Hsiao et al. 1984; Pinkewycz et al. 1987; Percy et al. 1992; Simard et al. 1996; Harvey et al. 1997; von Quillfeldt 2000; Lovejoy et al. 2002; Riedel et al. 2003; Niemi et al. 2011a, b; Poulin et al. 2011; Natsuike et al. 2013; Lefebvre et al. 2016; Vandersea et al. 2018; Dhifallah 2019; EMBL 2019; Bates et al. 2020; McKenzie et al. 2021). *Alexandrium ostenfeldii* (Bursa 1961b; Hsiao 1983; Simard et al. 1996; Harvey et al. 1997; Poulin et al. 2011) (Figures 8A, 9) is a species known to have caused, or to be associated, with HAEs on the Atlantic or Pacific coasts of Canada or environments similar to Canada (Table 1). *Alexandrium monilatum* (Hsiao and Pinkewycz 1983, 1984, 1985a, b; Hsiao et al. 1984; Pinkewycz et al. 1987; Poulin et al. 2011) has been reported in the Canadian Arctic and has been found to be toxic in other areas outside Canada or in the laboratory (Table 3). Resting cysts have also been reported in areas of Baffin Bay (Jones Sound; Lovejoy et al. 2002), and the Chukchi Sea off the northwest coast of Alaska (Natsuike et al. 2013), the Labrador Sea, and Davis Strait between Baffin Island and Greenland (Rochon and Mathiessen 1999; Andresen et al. 2010; Zonneveld et al. 2013; Richlen et al. 2016). Moreover, in waters adjacent to the Canadian Arctic, Lefebvre et al. (2016) detected PSTs in marine mammals (Whales, Seals, Sea Lions, Walrus, and Sea Otters) sampled along the coast of Alaska and the eastern tip of Russia.

Two species of *Pseudo-nitzschia* (*P. pseudodelicatissima*, *P. seriata*) known to produce AST in Canadian waters were detected in the Canadian Arctic. Six additional species (*P. calliantha*, *P.*

*delicatissima*, *P. granii*, *P. obtusa*, *P. pungens*, *P. turgidula*) known to produce AST elsewhere, either in the field or laboratory, have been detected in water samples and/or sea ice from various regions of the Canadian Arctic, including the Hudson Bay Complex, Greenland (to 80°N), and on the east coast of Labrador (Table 1; Figures 8B, 9) (Mann 1925; Davidson 1931; Polunin 1934; Grøntved and Seidenfaden 1938; Seidenfaden 1947; Bursa 1961a, b, 1969, 1970, 1971; Adams 1975; Thomson et al. 1975; Foy and Hsiao 1976; Hsiao 1976, 1979a, b, c, 1980, 1983; Sekerak et al. 1976a, b, 1979; Bain et al. 1977; MacLaren Atlantic Limited 1977, 1978; Anderson 1979; MacLaren Marex 1979a, b; Cross 1980, 1982, 1987; Hsiao and Trucco 1980; Anderson et al. 1981; Grainger and Hsiao 1982; Hsiao and Pinkewycz 1983, 1984, 1985a, b, 1987; Pett et al. 1983; Poulin et al. 1983, 2011; Booth 1984; Hsiao et al. 1984; Pinkewycz et al. 1987; Woods and Smiley 1987; Percy et al. 1992; Hopky et al. 1994a, b; Kikuchi-Kawanobe and Kudoh 1995; Simard et al. 1996; Harvey et al. 1997; von Quillfeldt 1997; 2000; Lovejoy et al. 2002; Lundholm et al. 2003; Riedel et al. 2003; Simard 2003; Różańska et al. 2008, 2009; McLaughlin et al. 2009; Mather et al. 2010; Hansen et al. 2011; Mundy et al. 2011; Piontkovski et al. 2011; Brown et al. 2014; Hopcroft 2016; Lefebvre et al. 2016; Simo-Matchim et al. 2017; Crawford et al. 2018; Joli et al. 2018; EMBL 2019; Bates et al. 2020; McKenzie et al. 2021). Although not depicted in the distribution map, *Pseudo-nitzschia* blooms have also been reported from the Far Eastern seas of Russia (Vershinin and Orlova 2008). In waters adjacent to the Canadian Arctic, Lefebvre et al. (2016) detected AST in harvested and stranded marine mammals (Whales, Porpoises, Seals, Sea Lions, Walrus, and Sea Otters) collected along much of the coast of Alaska (including the Alaskan Beaufort Sea) and eastern tip of Russia. In the eastern Davis Strait (Greenland), Miesner et al. (2016) experimentally demonstrated that copepods in the genus *Calanus*, a key prey group of marine fish, birds and mammals in Arctic waters, accumulated AST in their tissues and eggs through consumption of AST-producing *P. seriata*. The presence of low levels of AST (0.3 µg DA $g^{-1}$ tissue) in Scallops (*Similipecten greenlandicus*) was detected during a bloom of *P. seriata* in the Beaufort Sea (W. Rourke, unpublished data).

Five dinoflagellate species known to produce DSTs in Canadian waters (*Dinophysis acuminata*, *D. acuta, D. norvegica, Phalacroma rotundatum*, *Prorocentrum lima*) are widely distributed throughout the Canadian Arctic (northern Baffin Bay to the western portion of the Beaufort Sea), including the Hudson Bay Complex, the east coast of Labrador and the Labrador Sea, and the northwest coast of Greenland (Table 1; Figures 8C, 9) (Grøntved and Seidenfaden 1938; Seidenfaden 1947; Bursa 1961a, 1961b, 1963; Foy and Hsiao 1976; Hsiao 1976, 1983; Hsiao et al. 1977, 1984; Anderson 1979; MacLaren Marex 1979b; Hsiao and Trucco 1980; Anderson et al. 1981; Hsiao and Pinkewycz 1983, 1985a, b, 1987; Roff and Legendre 1986; Woods and Smiley 1987; Percy et al. 1992; Daugbjerg and Vørs 1994; Simard et al. 1996; Harvey et al. 1997; Lovejoy et al. 2002; Lowry and Harbour 2004; Różańska et al. 2008, 2009; McLaughlin et al. 2009; Niemi et al. 2011a, 2011b; Hopcroft 2016; Simo-Matchim et al. 2017; Dhifallah 2019; Bates et al. 2020; McKenzie et al. 2021).

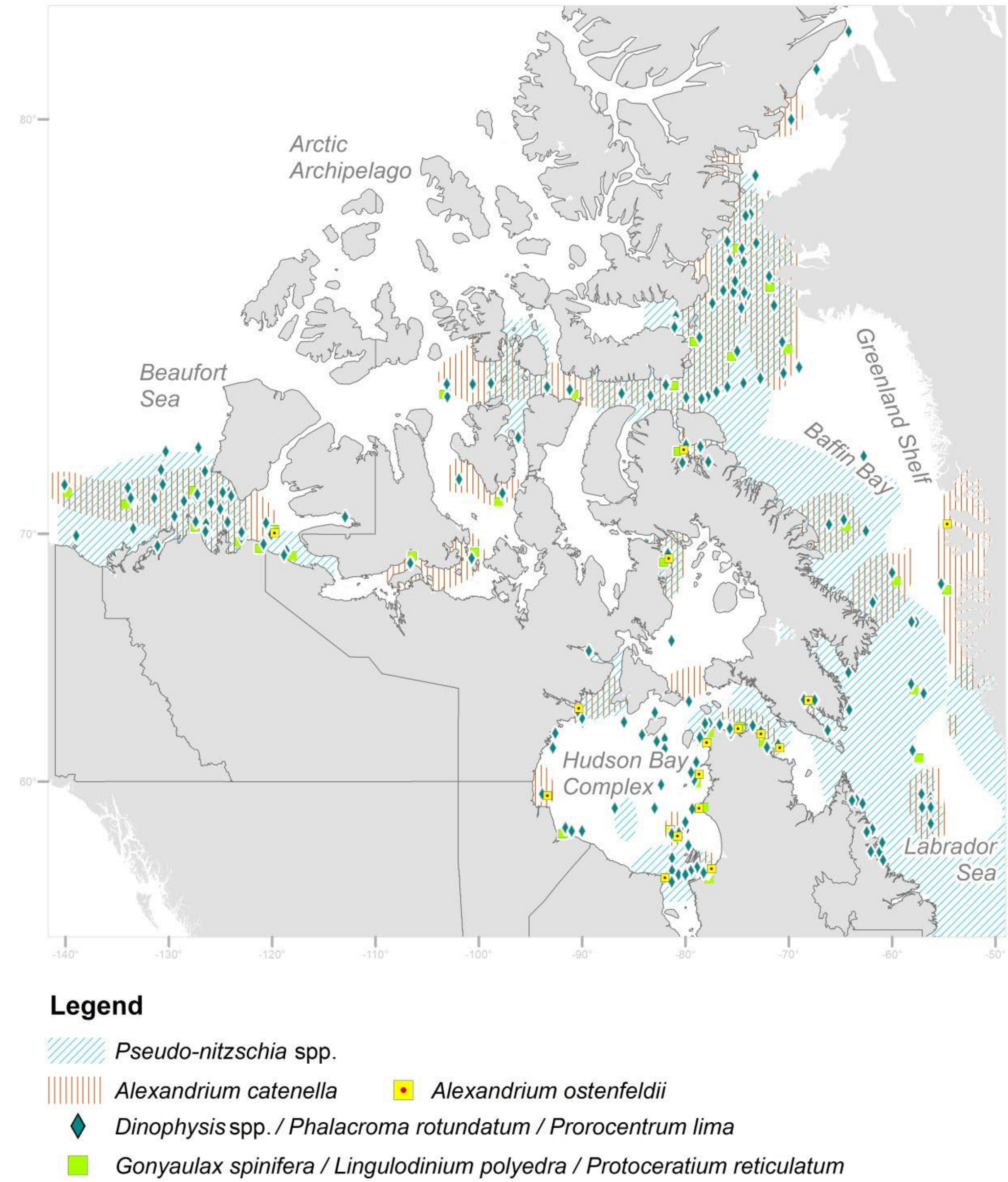


*Figure 9. Arctic region summary of HA species that are capable of producing PSTs, AST, and DSTs. Other phycotoxin producers are also included: Gonyaulax spinifera, Lingulodinium polyedra (for yessotoxins), Alexandrium ostenfeldii (for spirolides). See Bates et al. (2020) for details.*

The yessotoxin-producing species *Gonyaulax spinifera*, *Lingulodinium polyedra*, and *Protoceratium reticulatum* (Table 1; Figure 9) were reported from the Canadian Arctic (Grøntved and Seidenfaden 1938; Seidenfaden 1947; Bursa 1961a, b; Hsiao 1983; Hsiao et al. 1984; Roff and Legendre 1986; Percy et al. 1992; Simard et al. 1996; Harvey et al. 1997; Lovejoy et al. 2002; McLaughlin et al. 2009; Dhifallah 2019).

Other potentially harmful phytoplankton species and sea ice algae have been identified, some of which may produce other toxins, or cause mechanical damage (Table 2). For the Canadian Arctic, they include the centric diatoms *Chaetoceros concavicornis*, *C. convolutus*, *C. debilis*, and *Corethron hystrix* (Davidson 1931; Polunin 1934; Grøntved and Seidenfaden 1938; Seidenfaden 1947; Bursa 1961a, b, 1970, 1971; Thomson et al. 1975; Sekerak et al. 1976a, b, 1979; MacLaren Atlantic Limited 1977, 1978; Anderson 1979; Hsiao and Trucco 1980; Anderson et al. 1981; Hsiao 1983, 1985; Hsiao and Pinkewycz 1984, 1985b; Pinkewycz et al. 1987; Percy et al. 1992; Simard et al. 1996; Harvey et al. 1997; von Quillfeldt 2000; Lovejoy et al. 2002; McLaughlin et al. 2009; Mather et al. 2010; Simo-Matchim et al. 2017; Crawford et al. 2018); the raphidophyte *Heterosigma akashiwo* (Riedel et al. 2003; McLaughlin et al. 2009; Ardyna et al. 2017; Simo-Matchim et al. 2017); the dictyochophyte *Octactis speculum* (Bursa 1961a; Adams 1975; Thomson et al. 1975; Foy and Hsiao 1976; Hsiao 1976, 1977, 1983; Sekerak et al. 1976a, b, 1979; Hsiao et al. 1977, 1984; MacLaren Atlantic Limited 1978; Anderson 1979; MacLaren Marex 1979a, 1979b; Grainger and Hsiao 1982; Booth 1984; Hsiao and Pinkewycz 1985b; Percy et al. 1992; Simard et al. 1996; Harvey et al. 1997; von Quillfeldt 2000; Lovejoy et al. 2002; Riedel et al. 2003; Różańska et al. 2008, 2009; Niemi et al. 2011a; Simo-Matchim et al. 2017; Crawford et al. 2018); the dinoflagellates *Coolia monotis*, *Karenia mikimotoi*, and *Prorocentrum minimum* (formerly known as *P. cordatum*) (Hsiao et al. 1984; Simard et al. 1996; Harvey et al. 1997; Lovejoy et al. 2002; McLaughlin et al. 2009; Poulin et al. 2011; Simo-Matchim et al. 2017; Dhifallah 2019); and the protozoan ciliate *Mesodinium rubrum* (Lovejoy et al. 2002; Dhifallah 2019).

## 3. NATURAL DRIVERS, EMERGING ANTHROPOGENIC PRESSURES, IMPACTS AND CONSEQUENCES OF HARMFUL ALGAL EVENTS

The conceptual bow tie model framework incorporated three natural drivers (oceanographic, atmospheric, and biological conditions) and five EAPs (climate change and extreme events, ocean acidification, nutrient enrichment, coastal development, and vectors of introduction or spread), which influence the occurrence of HAEs in Canadian marine waters. Canadian HAEs have been shown to lead to impacts (environmental modification, food web alterations, sublethal effects, mortality, and cumulative effects) and consequences relevant to DFO responsibilities (Species at Risk, marine mammals, aquaculture, fishery and fish population health, ecosystem health, and food safety and security) (Figure 10).

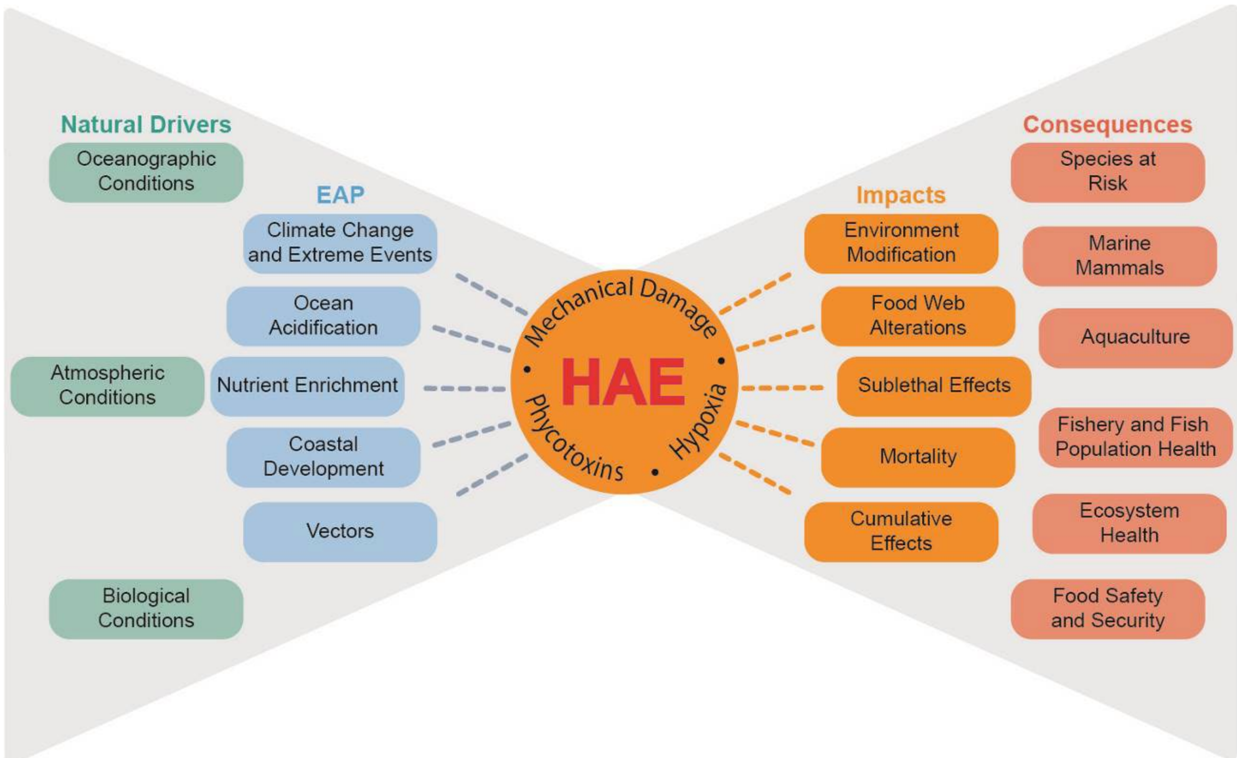


*Figure 10. Conceptual bow tie model showing causes (natural drivers and emerging anthropogenic pressures; EAPs), at left, which may lead to a HAE. The outcomes (impacts and consequences) of a HAE are shown at the right.*

The natural drivers, EAPs, impacts and consequences represented in the model were initially selected by the participants at the organizational workshop in Sidney, BC (July 2017), modified in subsequent workshops in Ottawa, ON (February 2018) and Dartmouth, NS (September 2018), and finalized during the HA CSAS meeting in Victoria, BC (March 2019) as being those of highest importance and relevance to a Canadian HAE model. The EAPs identified by the review process included climate change and extreme events, ocean acidification, nutrient enrichment, coastal development and introduction and spread of HA through vectors. The impacts of HAEs result in ecosystem modification, food web alterations, sublethal effects (impaired physiology and reproduction), mortality, and effects that are cumulative. Gaining a better understanding of the influence of EAPs and natural drivers (on the left side of the bow tie model, Figure 10) that may lead to the development of a HAE, and the impacts and consequences of a HAE (shown on the right side of the bow tie diagram), is a necessary step for predicting, managing, or remediating HAEs. In terms of causes of HAEs, this review focused on EAPs rather than natural drivers, as EAPs are human-controlled and thus more amenable to management.

## 3.1. NATURAL DRIVERS AND EMERGING ANTHROPOGENIC PRESSURES RELATED TO HARMFUL ALGAL EVENTS

The terms “natural drivers” and “emerging anthropogenic pressures” refer to factors that may affect the occurrence and/or intensity of a HAE. We differentiate between natural drivers and EAPs in this review. EAPs (caused or influenced by human activity) are superimposed over the background of natural drivers (environmental factors).

Recognizing the importance of natural drivers, we focus on the role and possible knowledge gaps of EAPs in this review due to their connection to human activities. EAPs are defined as increased pressures resulting from human activities, which may cause a HAE.The causal relationships between EAPs and HAEs are a global concern (IPHAB XIII 2017).

The main EAPs of HAEs, included in the bow tie model, are climate change and extreme events, ocean acidification, nutrient enrichment, coastal development and vectors (of introduction or spread) (Figure 10). We define them as follows, recognizing that each EAP may not be fully independent of other EAPs:

- **Climate Change and Extreme Events:** Climate deviations from long-term average conditions, including extreme events.
- **Ocean Acidification:** The effects of increasing atmospheric $CO_2$ concentrations on ocean chemistry, resulting in changes to the pH of the ocean.
- **Nutrient Enrichment:** Anthropogenic nutrient loading leading to eutrophication, changes in macronutrient ratios (e.g., nitrogen: phosphorus), or micronutrients. Nutrient availability, inputs and ratios may also be altered by climate change.
- **Coastal Development:** Effects on the marine environment of land use and human populations along the coast, such as coastal industries, dredging and disposal at sea, agricultural and municipal river runoff and loading, and other uses of the coastal zone.
- **Vectors of Introduction and Spread:** Anthropogenic agents or mechanisms that may transport HA to a new location (e.g., shipping and boating, ballast transport, hull and anchor fouling, etc.), or introductions and transfers (hitch-hikers).

### 3.1.1. Climate Change and Extreme Events

Climate change impacts marine ecosystems and can potentially affect HAEs through large-scale changes in temperature, salinity, stratification and circulation as well as Arctic sea-ice decline. In addition, extreme climate events, such as heat waves, have increased in recent years causing concern. The effects of climate change are far-reaching and could therefore be expected to contribute to other anthropogenic pressures discussed here.

Temperature increases have been shown to increase rates of growth, nutrient uptake and photosynthesis of some phytoplankton, as well as increasing algal motility. Increasing temperatures also benefit some HA, such as dinoflagellates that are adapted to warmer conditions (Paerl and Huisman 2008; Paerl and Scott 2010). Shifts in temperature towards more favourable conditions could lead to range expansion of HA in Canada, as observed in the North Sea (Townhill et al. 2018). Regional warming events in Kachemak Bay (Gulf of Alaska) were correlated with a greater chance of developing *Alexandrium catenella* blooms and an increased risk of PSTs events (Vandersea et al. 2018). Thus, climatic processes could be a significant driver of HAEs. Indeed, species distribution modelling for a suite of five potential HA species detected in ballast of vessels transiting to the Arctic indicated an overall increase in the extent of suitable habitat in the Arctic under future climate scenarios (2050 and 2100 under RCP4.5 emission scenario; Goldsmit et al. 2020). Major Canadian HAEs have coincided with events related to climate change (Wells et al. 2015), causing considerable concern from the public, industry and DFO clients. A well-documented recent example of an extreme climate event with effects throughout BC waters and much of the northeastern Pacific is the marine heatwave commonly referred to as “the Blob”. This temperature anomaly arrived on the continental shelf of North America by late summer of 2014, and caused significant alterations in coastal marine ecosystems, including an extensive toxic algal bloom that was initiated in spring 2015 and was mainly composed of *Pseudo-nitzschia australis* (McCabe et al. 2016). Mortalities of marine mammals and fish closures (including both shellfish and, in California, Northern Anchovy, *Engraulis mordax*) extended from southern California to Alaska and were of extended duration, in many areas lasting a full year until the spring of 2016 (McCabe et al. 2016; Savage 2017). This was the largest geographic extent of DA detection in marine mammals ever recorded globally (McCabe et al. 2016). Climate change models suggest that extreme temperature events such as this may occur more frequently on the BC coast in the future (Joh and Di Lorenzo 2017). The association between extreme ocean temperature events in BC and initiation of HAEs dates back at least several decades. During record (for the time) high temperatures off the west coast of Vancouver Island in September 1990, a bloom of *Gonyaulax spinifera* caused substantial shellfish mortality and was of great concern to nearby aquaculture operations (Gower and Borstad 1991). The bloom developed as a patch about 100 km across, and at that time was the most intense and extensive HAE ever recorded on the west coast of Canada.

In the northeast Atlantic, an increase in the abundance of diatoms, including toxigenic *Pseudo-nitzschia* species, relative to dinoflagellates has been attributed to warming of surface waters related to climate change (Hinder et al. 2012). However, this diatom increase has not occurred in all parts of the Atlantic, for example it was not observed in the Bay of Fundy. Warming climate has also caused a decline of Arctic sea-ice cover. This increases light penetration and the length of the growing season (Moore et al. 2009). Melting also decreases surface salinities, promoting water column stratification, which is further exacerbated by increases in river discharge, especially where permafrost is also melting (Poulin et al. 2011). Increases in temperature and water column stratification may increase the vulnerability of coastal areas to successful introductions of novel HA (Shumway et al. 2018). For example, *Pseudo-nitzschia* species tended to dominate in waters between Ellesmere Island (Canada) and Greenland because of greater surface freshening and associated high iron concentrations caused by sea-ice melt (Joli et al. 2018); these environmental conditions could promote *Pseudo-nitzschia* species events. Temperature and phycotoxin production have been linked in some species (Wells et al. 2015), and increased phycotoxin production with greater availability of light could be especially important in high-latitude regions if the growing season is extended (Glibert and Burkholder 2018).

### 3.1.2. Ocean Acidification

Ocean acidification, caused by the capacity of the ocean to absorb increased concentration of carbon dioxide in the atmosphere, may create conditions that have the potential to favour HA species over other phytoplankton, to exacerbate the negative effects of certain HA species, and to increase cellular toxicity. Ocean acidification can also affect phytoplankton growth by limiting the availability of important nutrients such as iron, phosphate and ammonium.

Ocean acidification is an important EAP in Canadian waters on the Pacific coast (Haigh et al. 2015), in the Arctic (Azetsu-Scott et al. 2010, 2014), as well as on the Atlantic coast (Azetsu-Scott et al. 2010), and in particular in the St. Lawrence Estuary, which receives high levels of freshwater runoff (Mucci et al. 2018). Declining pH and/or increased aerial extent of acidic waters has been recorded in BC waters of the Strait of Georgia (Marliave et al. 2011; Evans et al. 2019), transboundary Juan de Fuca Strait (Wootton and Pfister 2012) and the shelf waters off BC (Feeley et al. 2008). Based on evidence presented by Kim et al. (2013), Haigh et al. (2015) anticipated that the fish-killing alga *Heterosigma akashiwo* in BC may gain a competitive advantage under conditions of ocean acidification, making blooms more frequent. Glibert and Burkholder (2018) report increases in DA concentrations in *Pseudo-nitzschia* spp. under low pH conditions. Field studies of the toxic *Vicicitus globosus* (formerly *Chattonella globosa*) found that it has a competitive advantage under ocean acidification, which initially increases its dominance in phytoplankton communities and at higher levels promotes formation of blooms (Riebesell et al. 2018).

### 3.1.3. Nutrient Enrichment

Nutrients, such as nitrogen and phosphorus, are required for phytoplankton growth and function, and are available in both inorganic and organic forms in the marine environment.

When anthropogenic nutrient enrichment increases (eutrophication) and light becomes adequate, some phytoplankton, including HA, grow rapidly and form blooms. When nutrients become depleted, the organisms die and sink, stimulating microbial degradation, which consumes oxygen. This may lead to hypoxic or anoxic conditions, resulting in widespread death of fish and benthic fauna. In addition, eutrophication has been shown to contribute to habitat change and to the geographical and temporal expansion of some HA species (Smayda 1990; Anderson et al. 2002; Joli et al. 2018).

Nutrient ratios are also important in determining the relative success of different HA species in phytoplankton assemblages (Glibert et al. 2018b). Hillebrand et al. (2013) suggested that there are optimal nitrogen:phosphorus (N:P) ratios for different types of phytoplankton, such as diatoms (14:9), dinoflagellates (15:1), cyanobacteria (25:8), and chlorophytes (27:0). Therefore, N:P ratios can influence the likelihood of different kinds of HA outbreaks. However, Davidson et al. (2012) noted that this was observed under nutrient-limiting conditions, suggesting that shifts in nutrient ratios may be particularly important for HA in less populated high-latitude and Arctic environments, where anthropogenic nutrient enrichment is less prevalent (Popova et al. 2010). Similar considerations may apply to offshore systems.

### 3.1.4. Coastal Development

Coastal development comprises numerous activities that can affect the marine coastal environment with the potential to drive HAEs, ranging from nearshore dredging and construction (including upstream dams or reservoirs) to resource extraction (logging, mining), fishing, aquaculture, and tourism activities. Dredging and construction can promote mixing of an otherwise stratified water column, resulting in a in a delivery of nutrients to the upper water column. Similarly, these activities can mobilize dormant HA cysts, re-suspending them in the water column and providing a source for new HAEs to occur. Damming and reservoir creation alter upstream hydrology, which can change the rate and timing of freshwater discharge and nutrient enrichment to the marine environment. Resource extraction may also modify upstream hydrology, and/or coastal topography, resulting in increased freshwater runoff, sediment load and nutrient enrichment to the marine environment. Feed and waste from aquaculture activities can also influence nutrient loads. Fishing activities can indirectly stimulate HA growth through trophic cascade effects by relieving grazing pressure on HA species (Lancelot et al. 2002).

### 3.1.5. Anthropogenic Vectors for the Introduction and Spread of Harmful Algae

Vectors that may introduce HA species into new marine habitats include ballast water, ship fouling, and aquaculture activities (Glibert and Burkholder 2018; Murray and Hallegraeff 2018).

Ballast water is a confirmed vector for the transfer of HA, and the ICES/IOC WGHABD conducted a workshop to compile a list of phytoplankton species that had the potential to be introduced via ballast water (ICES 2010). Living vegetative cells of potential HA have been detected in ballast entering ports on the Atlantic and Pacific coasts of Canada (Klein et al. 2010; Roy et al. 2012, 2014; Kaczmarska and Ehrman 2015; Murray and Hallegraeff 2018; Dhifallah 2019). Ballast tanks have also been shown to transport dormant stages (e.g., cysts, resting spores or resting cells) of harmful dinoflagellates and diatoms in sediment (Waters et al. 2001;

Villac and Kaczmarska 2011; Villac et al. 2013). As a result, introductions of cysts and other resting stages may occur in unfavourable receiving environments and remain dormant until a shift in conditions (temperature, salinity) triggers germination and a possible HAE (Azanza et al. 2018). Most attention and regulation of ballast water has focused on international voyages. Unregulated transport of ballast water domestically is also a concern due to the short transit time between many Canadian ports and the similarities of their environmental conditions (Casas-Monroy et al. 2014; DFO 2014; Goldsmit et al. 2019). Indeed, recent studies of risks associated with ballast transport to the Canadian Arctic have found HA species in ballast water of domestic vessels discharging in the ports of this region (Laget 2017; Dhifallah 2019).

The risk of HA introductions depends in part on the conditions of the receiving environment; thus, climate change can compound the effects of ship-based vectors. Global warming is also expected to continue to open up waterways in the Canadian Arctic, resulting in more vessel traffic (Niimi 2007; Chan et al. 2013; DFO 2014; Dawson et al. 2018) and most likely increased opportunities for introduction of HA species. These risks will be exacerbated by altered environmental conditions in the receiving waters (Goldsmit et al. 2018; Joli et al. 2018).

## 3.2. IMPACTS OF HARMFUL ALGAL EVENTS

On the right side of the conceptual bow tie model (Figure 10) are impacts relevant to Canadian marine ecosystems. Impacts are changes to organisms, populations, and/or ecosystems resulting from HAEs. These changes are mediated by one or more of the three HAE mechanisms of effect (phycotoxins, mechanical damage, and/or hypoxia).

Impacts will be discussed below in five categories:

- **Environment modification:** Habitat and physico-chemical modification, e.g., hypoxia or anoxia, shading, nutrient change.
- **Food web alterations:** Changes in biological composition and abundance of HA, their competitors and predators.
- **Sublethal effects:** Impaired physiology, reproduction, behaviour and other sublethal impacts on organisms, e.g., reduced ability to feed, impaired immune system, reduced sperm motility.
- **Mortality:** Acute lethality of HA to organisms caused by exposure to phycotoxin(s), hypoxia or anoxia, or mechanical harm.
- **Cumulative effects:** Combined effects of the above elements on individuals, populations or ecosystem, taking into account the frequency, severity, and spatio-temporal occurrence of HAEs. Cumulative effects may include exposure to multiple phycotoxins (and/or other HAE mechanisms of harm), including repeated or serial exposures, or the effects of toxins (or other HAE mechanisms of harm) combined with other environmental stressors.

### 3.2.1. Environment Modification

HAEs can alter coastal environments, causing modifications that last well beyond the duration of the HAE itself. For example, high nutrient demands of large HAEs may create a nutrient-limiting environment for other phytoplankton or bacterioplankton, altering the level of primary and secondary production supporting the coastal marine food web. Large blooms also have the potential to block light from penetrating to deeper water, significantly diminishing the Photosynthetically Active Radiation (PAR) available to other primary producers and restricting visibility, e.g., for predators that depend on vision.

Hypoxia resulting from HAEs may result in impacts to lower and upper trophic level organisms. Hypoxia or anoxia may be caused by the oxygen-consuming microbial decay of large amounts of sinking algal biomass generated through eutrophication (Wei et al. 2007; Diaz and Rosenberg 2008) or by the reduction in solar radiation under blooms, reducing the depth of available PAR and therefore of primary production, causing a decrease in ambient dissolved oxygen. This ecosystem stress can result in large "dead zones", where mortalities of marine biota result in sparsely populated marine and estuarine environments (Diaz and Rosenberg 2008).

### 3.2.2. Food Web Alterations

Food web alterations include changes in biological composition and abundance of HA, their competitors and predators. PSTs transferred through the food web (via zooplankton, including Pteropods (*Limacina retroversa*) and Cladocerans (*Evadne nordmanni*)) were implicated in the mortality of hundreds of tonnes of Atlantic Herring in the Bay of Fundy during 1976 and 1979 (White 1977, 1980).

A variety of HA may use allelochemicals to obtain a competitive advantage in an area during a bloom (Tillmann et al. 2008). Lytic capacity was widespread in the genus *Alexandrium* and demonstrated direct destructive effects on competing algae and unicellular grazers. The use of these strategies to become the numerically dominant phytoplankton species could alter the structure and possibly the function of lower trophic levels of the food web in an area.

Food webs might also become altered by HA that have direct effects on a wide spectrum of organisms in an environment. Heterosigma akashiwo produces a substance that suppresses phytoplankton competitors, but only at low nutrient concentrations; addition of nutrients shuts down production of the chemical (Black 2000). However, the toxic form of H. akashiwo does affect diverse organisms, including many found in BC waters (Table 4), and therefore could potentially have profound effects on the composition of food webs.

*Table 4 Species affected by* Heterosigma akashiwo *(compiled by E. Black and reported in Scarratt et al. 2006).*

| **Species Affected by *Heterosigma akashiwo*** |
|---|
| Bacteria |
| Undefined sp. |
| Fungi |
| *Aspergillus niger* |
| Bacillariophyta |
| *Skeletonema costatum*, *Chaetoceros* sp., *Thalassiosira* sp. |
| Tintinnida |
| *Tinnopsis tubulosoides*, *Favella* sp. |
| Rotifera |
| *Brachionus plicatilis* |
| Crustacea Copepoda |
| *Pseudodiaptomus marinus*, *Acartia omorii*, *A. hudsonica*, *A. tonsa* |
| Crustacea Anostraca |

| Species Affected by *Heterosigma akashiwo* |
| --- |
| *Artemia salina* |
| Mollusca |
| Blue Mussel *Mytilus edulis*, Pacific Oyster *Crassostrea gigas* |
| Osteichthyes |
| Sockeye Salmon *Oncorhynchus nerka*, Chinook Salmon *O. tshawytscha,* Coho Salmon *O. kisutch*, Rainbow Trout *O. mykiss*, Atlantic Salmon *Salmo salar*, Yellowtail *Seriola quinqueradiata*, Black Seabass *Centropristis striata*, Black Seabream *Spondyliosoma cantharus*, Red Seabream *Pagrus major* |

### 3.2.3. Sublethal Effects

Sublethal effects impair physiology, the immune system and reproduction (e.g., by reducing sperm mobility), and affect behaviour, for example by reducing the ability to feed. Molluscan shellfish may accumulate phycotoxins that cascade through the food web, without being injured or killed by the toxins (Doucette et al. 2006). However, a number of sublethal impacts of HA on molluscs have been described. Exposure of the Pacific Oyster (*Crassostrea gigas*) to toxic *Alexandrium minutum* resulted in multiple impacts associated with feeding and reproduction, including changes in the physiology of the digestive gland, inflammation of soft tissues in several parts of the digestive system (digestive gland, ducts and intestine), reduced motility and adenosine triphosphate (ATP) content in spermatozoa, and changes at the cellular and sub-cellular level in the morphology of spermatozoa (Haberkorn et al. 2010).

As well, the presence of HA may affect feeding of bivalves through behavioural mechanisms. Shell closure and restriction of filtration are behavioural responses by which bivalves can limit exposure of soft tissues to phycotoxins or noxious agents, but paralysis of the adductor muscle of Eastern Oysters (*Crassostrea virginica*) occurred in the presence of *Alexandrium catenella* (Hégaret et al. 2007). The behavioural response of bivalves to HA appears to be species-specific (Hégaret et al. 2007). For example, Eastern Oysters closed valves fully or partially in the presence of *Heterosigma akashiwo* but did not do so with *Alexandrium catenella* (but this may be due to the paralysis noted above) or *Prorocentrum minutum*. Northern Quahog (*Mercenaria mercenaria*) closed valves partially in the presence of *Alexandrium catenella*.

Recent advances in high-frequency valvometry have revealed that the most common response to HA is a series of short and incomplete valve closure reactions, termed microclosures. These brief closures and re-openings of the shell correspond to minor contractions of the adductor muscle, and are linked to an avoidance response, possibly as a result of toxic microalgae cells making contact with external organs (gills, labial palps, mantle) or releasing bioactive extracellular compounds in the surrounding seawater (Borcier et al. 2017). To date, microclosure responses have been reported for the Pacific Oyster (Tran et al. 2010; Haberkorn et al. 2011; Tran et al. 2015; Mat et al. 2016), the Akoya Pearl Oyster (*Pinctada fucata*; Nagai et al. 2006), the Great Scallop (*Pecten maximus*; Coquereau et al. 2016), the Northern Scallop (*Argopecten purpuratus*; Hégaret et al. 2012), the Manila Clam (*Ruditapes philippinarum*; Basti et al. 2009), and the Mediterranean Mussel (*Mytilus galloprovincialis*; Comeau et al. 2019). Soft-shell Clams (*Mya arenaria*) exposed to PSTs were shown to have:

1. withdrawn and contracted siphons that persisted for extended periods following exposure (Shumway et al. 1985);
2. reduced feeding rates (Cucci et al. 1985); and
3. an inability to burrow following exposure to PSTs (Bricelj et al. 1996).

Soft-shell Clams from areas routinely exposed to PSTs were found to accumulate toxins at a greater rate than those from unexposed areas (Bricelj et al. 2005).

Although there appears to be little detectable effect of toxic algal species on survival of the zooplankton species that consume them (Miesner et al. 2016), the presence of toxic algae has been linked to decreases in zooplankton fecundity (Roncalli et al. 2016). Decreased fecundity in turn leads to lower food supply for predators, including fish and larger marine mammals. Toxin accumulation in higher trophic level species that consume zooplankton has also been observed (Doucette et al. 2006; Tammilehto et al. 2012).

Fish are apparently not behaviourally affected by DA during natural bloom events (Lefebvre et al. 2012). However, low-level chronic exposure of Zebrafish (*Danio rerio*) to DA altered gene transcriptomes and reduced mitochondrial function, which could lead to long-term health consequences; chronic exposure increased the sensitivity of fish to subsequent exposures (Hiolski et al. 2014). Larval Zebrafish exposed to PSTs experienced sensorimotor impairments and paralysis, and intermittent chronic exposure significantly reduced growth and survival at 18 and 30 days of age (Lefebvre et al. 2004).

During a toxic *Pseudo-nitzschia* bloom, Northern Fur Seals (*Callorhinus ursinus*) off California exhibited clinical signs of DA toxicosis before death (loss of control of body movements, and seizures) as well as lesions in the central nervous system (Lefebvre 2010). Seizures and coma were observed in animals with as little as 2–3 ng DA $g^{-1}$ in fecal samples. DA toxicosis was described as a recurring problem along the California coast, and was often associated with high levels of California Sea Lion strandings and malnourishment during the 2010 and previous events (Lefebvre et al. 2010). A single acute exposure to DA can cause a persistent toxicity syndrome in marine mammals, characterized by episodic seizures and permanent spatial memory loss; in mice, chronic low-level exposure was found to induce significant spatial learning impairment and hyperactivity, although these could be reversed with cessation of exposure (Lefebvre et al. 2017). Chronic low-level exposure to DA also affects human consumers of marine animals (Grattan et al. 2021; Petroff et al. 2021). Acute exposure causes reproductive failure, acute or sublethal exposure causes a cardiac myopathy in Sea Lions (Ramsdell and Zabka 2008), and recurrent seizures and atypical aggressive behaviours may manifest months after apparent recovery (Tiedeken and Ramsdell 2013). Prenatal exposure to DA may explain novel neurologic seizure presentations and behavioural and cognitive dysfunctions that have appeared in recent years in juvenile and subadult California Sea Lions (Ramsdell and Zabka 2008).

### 3.2.4. Mortality

Mortality is caused by the acute lethality of HA to organisms caused by exposure to phycotoxins, hypoxia or anoxia, or mechanical harm. HAEs have resulted in the accumulation of phycotoxins at multiple trophic levels, causing illness or death in fish, birds and mammals, as well as in the creation of hypoxic conditions leading to mortalities of aquatic biota. The mass mortality event associated with a toxic bloom of Alexandrium catenella in the St. Lawrence Estuary in August 2008, provided strong evidence for trophic transfer of PSTs through the food web (Starr et al. 2017). Unprecedented levels of mortality of marine fish, birds and mammals were recorded during or shortly after the bloom, when carcasses of 10 Beluga Whales (*Delphinapterus leucas*), seven Harbour Porpoises (*Phocoena phocoena*), one juvenile Fin Whale (*Balaenoptara physalus*), and 85 seals (mainly Gray Seals, *Halichoerus grypus*) were found drifting. As well, Starr et al. (2017) reported 76 marine species mortalities involving hundreds of fish- and mollusc-eating birds belonging to 15 different species, plus 591 carcasses of birds were observed during a helicopter survey. Most birds (82%) found dead were larids, especially Black-legged Kittiwake (*Rissa tridactyla*, 59%). Other dead birds included Northern

Gannet (*Morus bassanus*, 7%), Double-crested Cormorant (*Phalacrocorax auritus*, 4%), alcids (Black Guillemot, *Cepphus grille*; Common Murre, *Uria aalge*; and Razorbill, *Alca torda*, all ≤1.4%), loons (Common Loon, *Gavia immer*, and Red-throated Loon, *Gavia stellata*, each <1%), Common Eider (*Somateria mollissima*, <1%), and Northern Fulmar (*Fulmarus glacialis*, <1%). It is likely that mortalities were underestimated.

Pathological analyses on the marine mammals necropsied following the 2008 St. Lawrence Estuary mortality event were unable to identify a cause of death in 85% of cases, but congestion of the lungs and tracheal/oral mucosa consistent with PSTs was observed. Some marine mammals had injuries consistent with motor incoordination caused by PSTs, suggesting that animals paralyzed by PSTs may be more vulnerable to ship collisions (Starr et al. 2017).

Unlike shellfish, finfish affected by HA may die very quickly or be chronically affected, depending on the HA cell concentration, toxin dose, or physiological condition of the fish (Anderson et al. 2001). Cultured finfish are particularly susceptible to HAEs, either through ichthyotoxins, mechanical damage or hypoxia. Recurring events on the Pacific coast, as well as several on the Atlantic coast, have led to salmon aquaculture industries conducting their own HA monitoring programs for early detection and response.

Because wild finfish are typically able to move away from environmental stressors (such as HA blooms), it is usually assumed that this reduces their vulnerability to impacts from HA. Most of what is known about fish mortalities associated with HAEs is from the deaths of farmed fish or wild Atlantic Herring held captive in weirs in the Bay of Fundy. Elsewhere, there are reports of wild fish mortalities related to HA, e.g., the deaths of both wild and cultured fish during a bloom of *Chrysochromulina polylepis* in Norway (Dundas et al. 1989), and mortality of endangered Shortnose Sturgeon (*Acipenser brevirostrum*) associated with extremely high levels of PSTs from an *Alexandrium* sp. bloom along the coast of Maine (Fire et al. 2012).

In Canada, wild fish believed to have been killed by a bloom of Alexandrium catenella in the St. Lawrence Estuary were collected on beaches or were found drifting (Starr et al. 2017). Collected species included Sand Lance (*Ammodytes* sp.), Rainbow Smelt (*Osmerus mordax*), and Atlantic Sturgeon (*Acipenser oxyrynchus*). Phycotoxins have been linked to mass mortalities of wild Atlantic Herring in 1976 and 1979 (White 1984). Subsequent laboratory experiments showed that other wild fish species are also affected. American Pollock (*Pollachius virens*), Winter Flounder (*Pseudopleuronectes americanus*), Atlantic Salmon, and Atlantic Cod (*Gadus morhua*) were all killed by low doses of PSTs injected intraperitoneally (White 1981). Mortality and impairment of larval and juvenile stages of several commercial fish species has also been observed (Gosselin et al. 1989; Robineau et al. 1991a, b). Following Atlantic Salmon mortalities in the Bay of Fundy in 2003 and 2004, threshold limits at which salmon could be affected were determined (Burridge et al. 2010).

Although there are no documented mortalities of species associated with phycotoxins in the Canadian Arctic, an extensive survey of harvested and stranded marine mammals along the Alaskan coast and eastern tip of Russia found both PSTs and AST in all species tested; in some cases, toxin levels were comparable to those found in marine mammals diagnosed as having ASP during *Pseudo-nitzschia* sp. events on the west coast of North America (Lefebvre et al. 2016).

### 3.2.5. Cumulative Effects

Combined effects of the above impacts on individuals, populations or ecosystem, taking into account the frequency, severity and spatio-temporal occurrence of HAEs, are considered cumulative effects. These include exposure to multiple toxins (and/or other HAE mechanisms of harm) or phycotoxins (or other HAE mechanisms of harm), combined with other environmental stressors. Cumulative effects can refer to multiple exposures to a single stressor (such as HA), repeated exposures to the same stressor at different life stages of a species, or the exposure of multiple species in an ecosystem to a stressor, either directly or through a food web pathway. The cumulative effects of HAEs may change local ecosystem health, causing conditions that may stress organisms at any trophic level, as well as physico-chemical changes in the ecosystem (e.g., hypoxia; Anderson et al. 2015). The frequency and severity of events, as well as the spatio-temporal distribution of HAEs, may increase the degree of impact and consequence. Species that have limited mobility, or a small habitat range, may be more susceptible to local cumulative effects if they have chronic exposure to ecosystem stressors over long periods of time. As discussed in the section on food web impacts, phycotoxins can accumulate in animal tissues and are passed up through the food web to large vertebrates (Montie et al. 2012). Some adult fish species, such as Atlantic Mackerel (*Scomber scombrus*), are less sensitive to phycotoxins, and accumulate high sublethal levels of toxins in their livers in areas with chronic HA presence (as in the Bay of Fundy; Haya et al. 1990). Zooplankton can also retain toxins without necessarily experiencing elevated mortality and may be consumed by other species (Tammilehto et al. 2012; Miesner et al. 2016). Predators, including marine mammals, which consume whole mackerel (or other species that accumulate sublethal toxin levels), are most at risk of intoxication. Situations in which a wide range of organisms may be vulnerable to HA are more likely to experience cumulative effects.

Cumulative effects of phycotoxins with other environmental contaminants have been demonstrated, and may be non-additive. Embryonic exposure of Zebrafish to DA increases the severity and threshold of seizures caused by the chemical convulsant pentylenetetrazole (Tiedeken and Ramsdell 2007). Zebrafish exposed to dichlorodiphenyltrichloroethane (DDT) during development and then exposed to DA (a scenario meant to mimic the transfer of maternal organochlorines to fetal Sea Lions, followed by DA exposure) resulted in asymptomatic animals with greater sensitivity to DA-induced seizures (Ramsdell and Zabka 2008).

## 3.3. CONSEQUENCES

For the purpose of this review, consequences are the expression of impacts to environmental services and ecosystem health in relation to the DFO mandate. Six categories of consequences were defined earlier and include species at risk, marine mammals, aquaculture, fishery and fish population health, ecosystem health and food safety and security.

### 3.3.1. Species at Risk

Under the Species at Risk Act (SARA 2002), Canada protects endangered or threatened organisms or their habitats. The Act meets one of Canada's key commitments under the International Convention on Biological Diversity. Several marine or diadromous fishes are listed in the List of wildlife species at risk: schedule 1.

One example of a Schedule 1 species affected by HAEs is the Shortnose Sturgeon, which is listed as a species of special concern in Canada (occurring in the Bay of Fundy) and is also an endangered species in the USA (Fire et al. 2012). Shortnose Sturgeon experienced high mortality in Sagahadoc Bay, Maine, due to trophic transfer of PSTs from ingested clams during a bloom of *Alexandrium catenella* that affected the entire Maine coast (Fire et al. 2012).

The Species at Risk Act also requires the consideration of cumulative effects. Assessments of risk to marine and diadromous species, conducted for the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), often recognize and refer to the potential or existence of cumulative effects, although in most cases the assessments have not attempted to quantify them (e.g., COSEWIC 2015).

At present, the clearest examples of cumulative effects caused by HAEs on Species at Risk in Canadian marine waters involve marine mammal species. High levels of PSTs were found in the feces of endangered North Atlantic Right Whales (*Eubalaena glacialis*) and also in the Calanoid Copepod (*Calanus finmarchicus*), which is the Right Whale's dominant prey in the Bay of Fundy, during a period when PSTs levels in nearby shellfish exceeded the regulatory limit for shellfish fishery closure (Doucette et al. 2006). Doucette et al. (2006) demonstrated trophic transfer of PSTs and suggested this could be a factor contributing to reproductive dysfunction and compromised health of the Right Whale population, which would have been repeatedly exposed to *Alexandrium* blooms in the Bay of Fundy. Marine mammals that are Species at Risk have also experienced acute mortality events associated with HA, such as the Large Whale Unusual Mortality Event that affected the entire BC coast (Savage 2017).

Another example of Species at Risk exposure to a HAE through trophic transfer, as well as direct exposure to phycotoxins, is the 2008 *Alexandrium catenella* bloom in the St. Lawrence Estuary, which resulted in mortalities of invertebrates, fish, birds and marine mammals, including Beluga Whales (St. Lawrence Estuary population), which are listed as endangered, and Fin Whales (Atlantic population), listed as a species of special concern (Starr et al. 2017). In BC, Sockeye Salmon (*Oncorhynchus nerka*) have already been the subject of a major inquiry, which identified HABs as a contributing factor to poor at-sea survival and low returns to spawning grounds (Cohen 2012a, b). If HA are determined to be a factor in the mortality of Sockeye Salmon, it seems reasonable to expect they may also affect survival and condition of other salmon, including Chinook (*Oncorhynchus tshawytsch*) and Chum Salmon (*Oncorhynchus keta*) that are the major prey of Resident Killer Whale (*Orcinus orca*) populations in BC. Species at Risk have experienced acute mortality events in both Canadian Atlantic and Pacific waters. Consequences of HAEs to Species at Risk could occur through direct or indirect effects on either organisms or habitats. Effects on habitats could occur through environment modifications, such as anoxia. Many effects on organisms occur through direct exposure to phycotoxins, food web transfer, or cumulative effects, which may be lethal or sublethal.

### 3.3.2. Marine Mammals

Population health, and consequently management, of other marine mammals that are not listed as Species at Risk may also have the potential to be affected by HAEs. DFO is responsible for enforcing Canada's Marine Mammal Regulations, which control fishing, conservation and protection of marine mammals under the Fisheries Act. Amendments to the Regulations in 2018 included measures to reduce interference and disturbance to marine mammals by vessel presence.

Among the complex of threats experienced by marine mammals, HAEs have the potential to exacerbate the risks, including those associated with vessel presence. The ability of marine mammals to detect and/or avoid oncoming vessels may be impaired by neurological effects of phycotoxin exposure. For example, in 2008, injuries consistent with ship strikes were found on Beluga Whales intoxicated by PSTs in the Gulf of St. Lawrence (Starr et al. 2017). A BC coast-wide large Whale mortality event, that lasted from at least May through November 2015, resulted in the death of at least 16 Whales of five species. PSTs and AST levels were determined for seven Fin and Humpback Whales during necropsy (Savage 2017). Several of the Whales with highest phycotoxin levels in the gut (as high as 613 ng $mL^{-1}$ for DA and 238 ng $mL^{-1}$ for PSTs) had also experienced ship strikes (Savage 2017). From a management point of view, neurological impairment resulting from phycotoxin exposure may affect the efficacy of measures implemented by government and/or industry to protect marine mammals. For example, it is possible that limitations to distance of approach by vessels intended to protect Southern Resident Killer Whales in BC and/or voluntary slowdowns of commercial vessels trialed on the approaches to the Port of Vancouver (Joy et al. 2019) may be less effective in situations where the marine mammals are neurologically impaired by phycotoxins and less able to take an active role in avoiding vessels. These effects are not limited to Whales. In 2009, two Sea Otters (*Enhydra lutris*) with elevated PST levels (45 and >100 ng STX $g^{-1}$ in urine samples) were struck and killed by boats in Kodiak, Alaska (Lefebvre et al. 2016). The Sea Otters had been lethargic and non-responsive at the surface before the vessel strikes. Lethal and sublethal effects of AST on Steller Sea Lions (*Eumetopias jubatus)* are well documented (Scholin et al. 2000; McCabe et al. 2016). These animals may also become a public safety hazard to humans if they become aggressive when neurologically impaired by phycotoxins.

The 2011 version of the recovery strategy for endangered Southern Resident Killer Whales in BC explicitly identified HA as a possible threat, along with the main threats (e.g., food availability, ship collisions, contaminants, noise; DFO 2011). From the impacts already discussed in the present document, it is likely that HA, if present, have the potential to be involved as a factor in some of the major threats to Resident Killer Whales, in particular food availability and ship collisions.

### 3.3.3. Aquaculture

Fisheries, including aquaculture, is a core responsibility of DFO (DFO 2018). Specifically, "*In support of the mandate commitment to use scientific evidence and the precautionary principle, and take into account climate change, when making decisions affecting fish stocks and ecosystem management, the Department's scientists will conduct research and monitoring to produce scientific data, products, services, and peer-reviewed advice that are essential for evidence-based decision making and the development of policy, regulations, and standards*."

Losses of farmed Atlantic Salmon have frequently occurred on both the Atlantic and Pacific coasts (Figures 3D, 5D). HA are the major source of mortality to BC salmon farms. An analysis of fish kills at facilities owned by the four largest aquaculture companies in BC found that 22 fish killing events occurred around Vancouver Island between 2009 and 2012. Direct losses totaled over the four years were estimated as $16,135 million (Haigh and Esenkulova 2014). Indirect losses, such as the costs of mitigation (e.g., barrier curtains, pumping deep water into cages, water oxygenation/aeration) and losses of production due to withholding feed during HAEs and consequent reduced growth of salmon, were $4–8 million annually.

HAEs can reduce shellfish performance (e.g., growth and survival; Talmage and Gobler 2012), but another consequence is suspension of harvests due to high phycotoxin levels. Although harvests resume after depuration and detoxification of shellfish, there may be consequences for business operations at the shellfish facility and marketing of product (Figures 3, 5).

### 3.3.4. Fishery and Fish Population Health

The link between HA and fishery and fish population health is through DFO's responsibilities to protect and promote fisheries in Canada and its overarching goal to maintain a healthy ocean (the mandate letter from the Prime Minister of Canada to the Minister of Fisheries, Oceans and the Coast Guard). Impacts of HAEs on wild fish species are seldom witnessed and are almost certainly underreported (Rensel et al. 2010). Bioassays showed that juvenile Chinook Salmon exposed to *Heterosigma akashiwo* blooms from the Strait of Georgia and west coast of Vancouver Island died after exposures ranging from 30 to 130 min (Whyte 1991). Juvenile Coho Salmon exposed to a *Cochlodinium* sp. bloom from the Strait of Georgia survived only 28 to 212 min in bioassay experiments (Whyte et al. 2001). Average marine survival of Sockeye

Salmon from the Fraser River Chilko stock was reduced to 2.7% in years when the juvenile outmigration period corresponded to major blooms of *Heterosigma akashiwo* in the Strait of Georgia, compared to 10.9% in years of minor or no blooms (Rensel et al. 2010).

When vulnerable species or populations of fish and shellfish experience lethal or sublethal effects of HAEs, it will affect advice being provided on population dynamics and predictions for harvestable biomass. The possible impacts of HAEs on young life stages of wild salmon, and other commercial species (e.g., cod, herring) is an example where knowledge is lacking regarding the location of HAEs, their elevated phycotoxin levels, and the toxicology of any exposure. Geographically, knowledge about HAEs is limited to relatively few areas, primarily the nearshore areas where the CFIA monitors phycotoxins in shellfish. Many fisheries occur in offshore waters where there is no phycotoxin monitoring.

As noted above under the Aquaculture Consequences section, fisheries are a core responsibility of DFO. Specifically, the Departmental Plan states "*Ensuring that Canadian fisheries remain environmentally, economically, and socially sustainable is one of the Department's primary responsibilities*" (DFO 2018).

An additional link between HA and fisheries has been made by the Cohen Commission (Cohen 2012a, b), which is a high priority of DFO according to the Minister's mandate letter and the Departmental Plan (DFO 2018). The Cohen Commission report, along with those of a series of expert advisory panels and working groups convened by DFO and external agencies during 2009 to 2012, identified HA as a plausible threat to the health of Fraser River Sockeye Salmon stocks (Cohen 2012a). Recommendation 65 (Cohen 2012b) states:

"*The Department of Fisheries and Oceans should undertake or commission research, in collaboration with academic researchers and, if possible, the Pacific Salmon Commission or another appropriate organization, into where and when significant mortality occurs in the nearshore marine environment, through studies of the outmigration from the mouth of the Fraser River through to the coastal Gulf of Alaska, including the Strait of Georgia, Juan de Fuca Strait, the west coast of Vancouver Island, Johnstone Strait, Queen Charlotte Sound, and Hecate Strait. Studies should examine:*

- *abundance, health, condition, and rates of mortality of Fraser River sockeye salmon;*
- *biological, chemical, and physical oceanographic variables, including water temperature, the presence or absence of harmful algal blooms, and disease;*
- *predators, pathogens, competition, and interactions with enhanced salmon affecting Fraser River sockeye salmon; and contaminants, especially contaminants of emerging concern, endocrine-disrupting chemicals, and complex mixtures."*

### 3.3.5. Ecosystem Health

The mandate letter further states that the Minister's "*overarching goal will be to protect and promote our three oceans, waterways and fisheries, and ensure that they remain healthy for future generations, while providing important economic opportunities to Canadians and coastal communities*". As such, all Canadian legislation addressing ocean health, such as the Fisheries Act, Oceans Act, Canadian Environmental Assessment Act, is relevant to this mandate.

One of DFO's core responsibilities, identified in the Departmental Plan, is to "*ensure healthy and productive marine ecosystems by protecting them from the negative impacts of humans, invasive species, and other stressors*" (DFO 2018). Harmful algae were identified as a priority stressor under DFO's Ecosystem Stressors Program in 2017.

Ecosystem health includes the consideration of cumulative effects, which is clearly required to support Integrated Oceans Management, as mandated by the Oceans Act. During a review of DFO's Integrated Oceans Management program, most DFO managers, stakeholders, and external experts identified a continued need in Canadian oceans management to understand oceans from an ecosystem perspective, taking into account the cumulative impact of human and environmental interactions (DFO 2012).

### 3.3.6. Food Safety and Security

DFO's role in public health, as it relates to HA, is through its involvement in the CSSP. The CSSP is a federal food safety program that is jointly administered by the CFIA, DFO and ECCC. The goal of the program is to protect Canadians from the health risks of consuming contaminated shellfish (bivalves).

The specific role of DFO is the closure of contaminated shellfish beds to harvesting as indicated by the results of the CFIA's sampling activities. The CFIA maintains a monitoring program for phycotoxins and tests shellfish from selected areas. The safety of traditional foods harvested from marine sources by Indigenous peoples is a concern, particularly in the Arctic, where hunting is an important aspect of Inuit food security (Hoover et al. 2016). Phycotoxin-producing HA have recently been detected in the Canadian Arctic (Bates et al. 2020; McKenzie et al. 2021), but this area is not monitored by the CFIA for phycotoxins. Lower ocean temperatures in the Arctic and sub-Arctic could result in slow phycotoxin depuration rates in bivalves and other species, and this in turn could lead to phycotoxin accumulations.

Recreational fish and shellfish may also represent a threat for those who participate in traditional harvests and consume particular tissues or organs (such as liver) that accumulate high levels of phycotoxins as the fish and shellfish age (Castonguay et al. 1997). The possible bioaccumulation of phycotoxins in fish and shellfish in areas where phycotoxins are not monitored (e.g., remote regions and offshore finfish harvesting areas) is of concern. This may become exacerbated by climate change and vectors, which may introduce novel HA and phycotoxins to Canadian coasts, or expand their distribution. This scenario may become an emerging issue for DFO. According to DFO's Departmental Plan (DFO 2018), "*the Department is also contributing to greater knowledge and understanding of climate change impacts on Arctic marine ecosystems through the Oceans and Climate Change Science Program. Through OPP, work is also advancing with Indigenous and coastal communities to collect baseline information, including in the Arctic*". It should be noted that DFO recently established the Arctic Region.

# 4. KNOWLEDGE GAPS

## 4.1. NATIONAL OR GENERAL KNOWLEDGE GAPS

From the preceding review, it is clear that HA are widespread in Canadian waters, and that HAEs causing disruption to Canadian ecosystems, fisheries and aquaculture are frequent occurrences. DFO has conducted targeted research and monitoring of HA where funding and expertise were available.

Although invaluable to this review and to HAEDAT records, the CFIA dataset was not collected for research purposes, but to protect the health of shellfish consumers under the CSSP. With respect to the full scope of DFO's mandate, i.e., ecological impacts and consequences of HA, the dependence on CFIA phycotoxin monitoring is not suitable to investigate, predict or respond to HAEs. One limitation of the CFIA dataset is the variability in sampling effort in both time and space. Most monitored shellfish were collected from shallow nearshore or intertidal waters, where the majority of recreational and commercial shellfishing activities are concentrated, with detection capability for HAEs outside these areas limited to a relatively few areas and seasons of deeper-water shellfisheries. Many areas are not monitored at all, or only monitored during specific shellfish harvest windows. This results in an inability to detect the onset of phycotoxin events. Additionally, if a sample from a site showed phycotoxin levels exceeding the regulatory threshold, the area was closed to harvesting and sampling was discontinued for three weeks. During the time that an area was closed to harvesting, maximum levels of phycotoxin could not be quantified nor could any subsequent onset of depuration of the phycotoxins by the bivalve species be tracked. Scallops and Blue Mussels are often used as sentinel species for toxin monitoring, but a recent Canadian study found that toxin results significantly differ between bivalve taxa (Rourke et al. 2021). This has implications in areas where multiple shellfish species are harvested. As the CFIA dataset provides information on only the phycotoxins that are regulated under the CSSP, no data are collected for the other phycotoxins present in Canadian waters or for HA with non-toxic mechanisms of harm.

Nationally, there is limited understanding of factors controlling phytoplankton dynamics and HA growth. In particular, there is a lack of sufficient knowledge about what environmental conditions trigger bloom development by HA, (i.e., what controls the magnitude and decline of the bloom, and what conditions favour vegetative growth). Our ability to precisely and rapidly detect HA is limited. Along with traditional methods to identify HA and phycotoxins, novel methods to detect and monitor HA in Canadian marine waters are available. Monitoring programs using existing methodologies can assist the ground-truthing of new technologies. Examples of innovative methods for phytoplankton detection and quantification include molecular (e.g., high-throughput sequencing technologies including microarray, real-time quantitative polymerase chain reaction (PCR) and metagenetic [metabarcoding]) tools for HA monitoring programs (Kudela et al. 2010; Danovaro et al. 2016), satellite-based (Siswanto et al. 2013; Devred et al. 2018), and/or automated *in situ* monitoring techniques (e.g., moored Environmental Sample Processors; Bowers et al. 2016, 2017), the Imaging Flow Cytobot (McClane Research Laboratories, Inc.), portable imaging flow cytometers (Göröcs et al. 2018), or potentially the MolluScan eye for signalling behavioural anomalies in molluscan bivalve sentinels (Andrade et al. 2016).

The mechanisms for dispersing and transporting toxigenic HA requires further investigation, as well as how different life cycle stages behave in the dispersion and retention of motile cells within a particular ecosystem. The importance of climate, oceanographic conditions and other environmental drivers that result in changes in community composition, and why some HABs recur in particular locations and seasons, also require further study, particularly as it affects the prediction of the effect of climate change and ocean acidification on HA. Worldwide, this is an emerging issue, and is particularly relevant in Canadian waters, considering that temperatures (and other environmental conditions) are predicted to increase more rapidly than the global average at higher latitudes.

There is a lack of knowledge with which to build predictive models of HAEs, including growth rates of individual HA species in their natural environments, their response to physical processes, and the link between germination of cysts and blooms. Whether the same factors control development of a HAE of a given species of HA on all coasts is unknown. What is happening in the Arctic sea-ice and in seasonally ice-covered areas elsewhere, such as the Gulf of St. Lawrence, is currently unknown. How does this environment affect the dynamics of HABs?

There is limited knowledge of what environmental conditions trigger production and release of phycotoxins, and how phycotoxins persist and potentially accumulate in sediments. A better understanding of the effect of specific drivers on phycotoxin production is required in order to predict the possible impacts of climate change, improve our forecasting/hindcasting capabilities, and develop mitigation measures and prevention strategies. An understanding of the effects of phycotoxins on most organisms and on the food web is limited, including the effects of chronic exposure to HA and to phycotoxins. Also, the concentration at which toxic phytoplankton become problematic varies between species and locations and is poorly understood (Blasco et al. 2003), as is the knowledge of which species, and what locations, HA result in hypoxic conditions. Some work has been carried out for the Bay of Fundy and may provide a base for additional research (Burridge et al. 2010).

Little is known about the role of phycotoxins in ecosystem function. It has been suggested that phycotoxins might serve as a predator deterrence or to facilitate trace metal uptake, but there is also contrary evidence (Cembella 2003; Legrand et al. 2003; Bates et al. 2018). The effects of HA on the growth, physiology, reproduction and behaviour of marine biota need further study, particularly sublethal and cumulative effects. The extent to which phycotoxins bioaccumulate in food webs also requires further study.

Developing or expanding collaborations with other stakeholders operating HA programs in Canada and worldwide would help to address these knowledge gaps. Specific examples include the aquaculture industries, the CFIA, NRC, universities, as well as international HAB researchers, including continued association with ICES, PICES, and Global Harmful Algal Blooms (GlobalHAB 2021).

In summary, overarching knowledge gaps include limited HA detection and limited understanding of the effect of specific EAPs (climate change, nutrient enrichment, coastal development, and vectors of introduced HA) on oceanographic, atmospheric, and biological conditions that drive changes in HA species, phycotoxins, and bloom development and toxicity. These knowledge gaps prevent the development of effective predictive HAE models, which hinders our forecasting/hindcasting capability and hampers development of mitigation and prevention strategies. There is limited understanding of the effects of HA and phycotoxins on most marine organisms (sublethal/cumulative on the growth, physiology, reproduction, and behaviour), and on food web and ecosystem function, particularly in Canadian sub-Arctic and Arctic waters.

## 4.2. REGIONAL PRIORITIES AND KNOWLEDGE GAPS

In Canada, HA species and impacts vary by region, so knowledge gaps and priorities will vary among regions. The information gained from the review and expert opinion and discussion held at the CSAS meeting provides the basis for the following regional bow tie models and the influence of each EAP and impact specific to the region or coast. The bow tie model identifies the relative strength of known linkages between EAPs and Impacts. Thick lines in the bow tie models indicate that evidence of a strong connection between HAEs and the EAP or impact exists from the region; thin lines mean there is a possible connection based on evidence from outside the region or the literature; and dotted lines mean a lack of information regarding the strength of the link or where little or no relevant information is available, but that a connection is suspected. Breakout sessions during the CSAS meeting allowed regional experts to review these criteria and to develop bow tie models specific to each coast as well as identify specific knowledge gaps and priorities based on the linkages (see the Appendix for a summary of the regional breakout sessions). Future management advice was identified from a discussion of these knowledge gaps and recommendations for targeted research. Following the breakout session, the models were considered by all participants and national knowledge gaps were identified.

### 4.2.1. Canadian Atlantic Coast

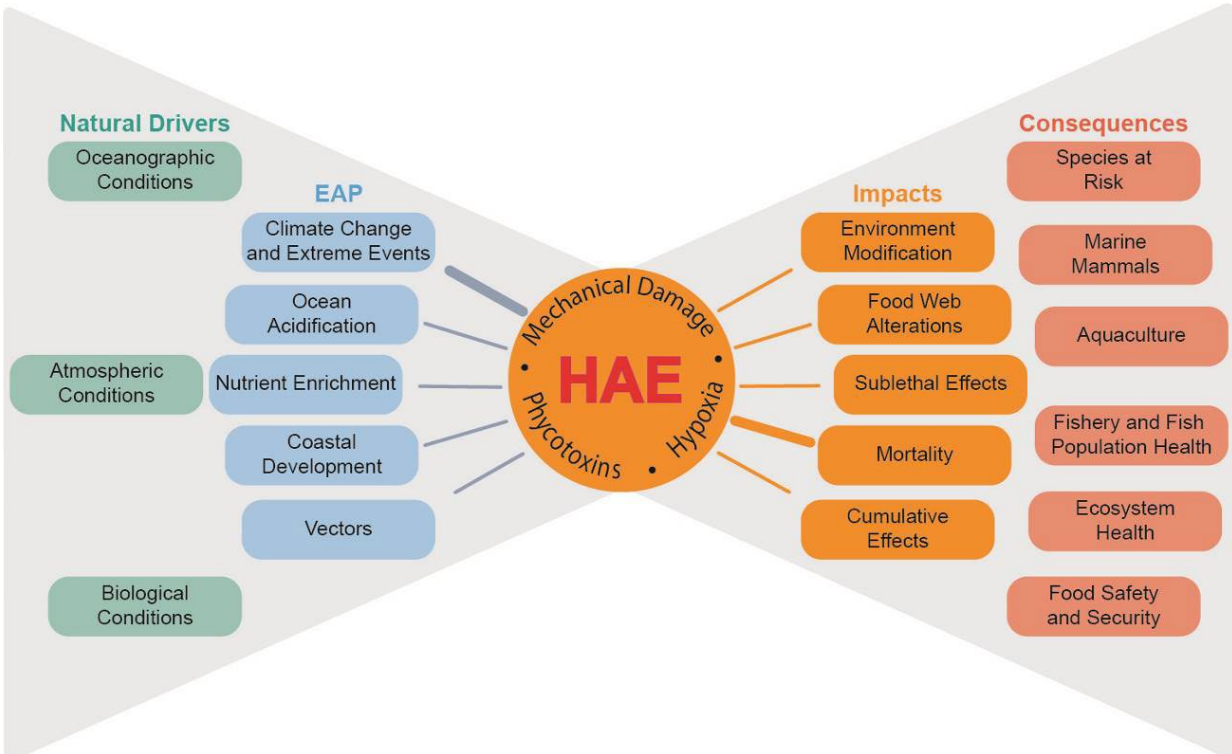


*Figure 11. Atlantic coast bow tie conceptual model.*

**Emerging Anthropogenic Pressures**: Climate change and extreme events are well documented in Atlantic Canada (thick line, Figure 11). Ocean acidification is of increasing concern on the Atlantic coast (Azetsu-Scott et al. 2010) and in particular in the St. Lawrence Estuary (Mucci et al. 2018). Information regarding the impacts of climate change and ocean acidification on reoccurring HAEs was identified as a key knowledge gap on the Atlantic coast. During the CSAS meeting regional experts concluded that modeling and prediction of HAEs were priority gaps to address on the Atlantic coast, along with advancement of observing technologies leading to early warning systems, although observation, monitoring and early warning were also considered National priorities. Nutrient enrichment and coastal development occur on the Atlantic coast but were not identified as the most concerning pressure (thin line, Figure 11). Ship-based vectors may be responsible for the arrival of several potential HA species recently reported for the first time in Atlantic Canada and detected in ballast water arriving in the region (Carver and Mallet 2001, 2002; Roy et al. 2012, 2014). These species (*Pseudo-nitzschia subpacifica* Table 1; *Alexandrium pseudogonyaulax* Table 3) were first recorded in the Bay of Fundy (Martin et al. 2009), and *Alexandrium pseudogonyaulax* was subsequently reported from the St. Lawrence Estuary (Dufour et al. 2010).

**Impacts**: The major mortality (thick line, Figure 11) of fish, marine mammals and birds associated with an *Alexandrium catenella* bloom in the St. Lawrence Estuary following heavy precipitation in 2008 (and which is expected to increase in the future) was one of the strongest demonstrations of ecosystem impacts and cumulative effects in the history of HA in Canada. Other ecosystem impacts and cumulative effects are less understood (thin line, Figure 11). Farmed Atlantic Salmon in NB and NS have been affected by mortality events attributed to known toxin-producing species and other mechanisms. Mitigation actions and early warning approaches were carried out by growers in the Bay of Fundy Atlantic region following advice and training provided through a DFO/industry Aquaculture Collaborative Research and Development Program (ACRDP; Chang et al. 2007). Herring mortalities occurred in the Bay of Fundy due to the toxin-producing *Alexandrium catenella*. Food web alterations and environmental modification are less well understood (thin line, Figure 11) but are not specific to the Atlantic coast and represent National knowledge gaps.

### 4.2.2. Canadian Pacific Coast

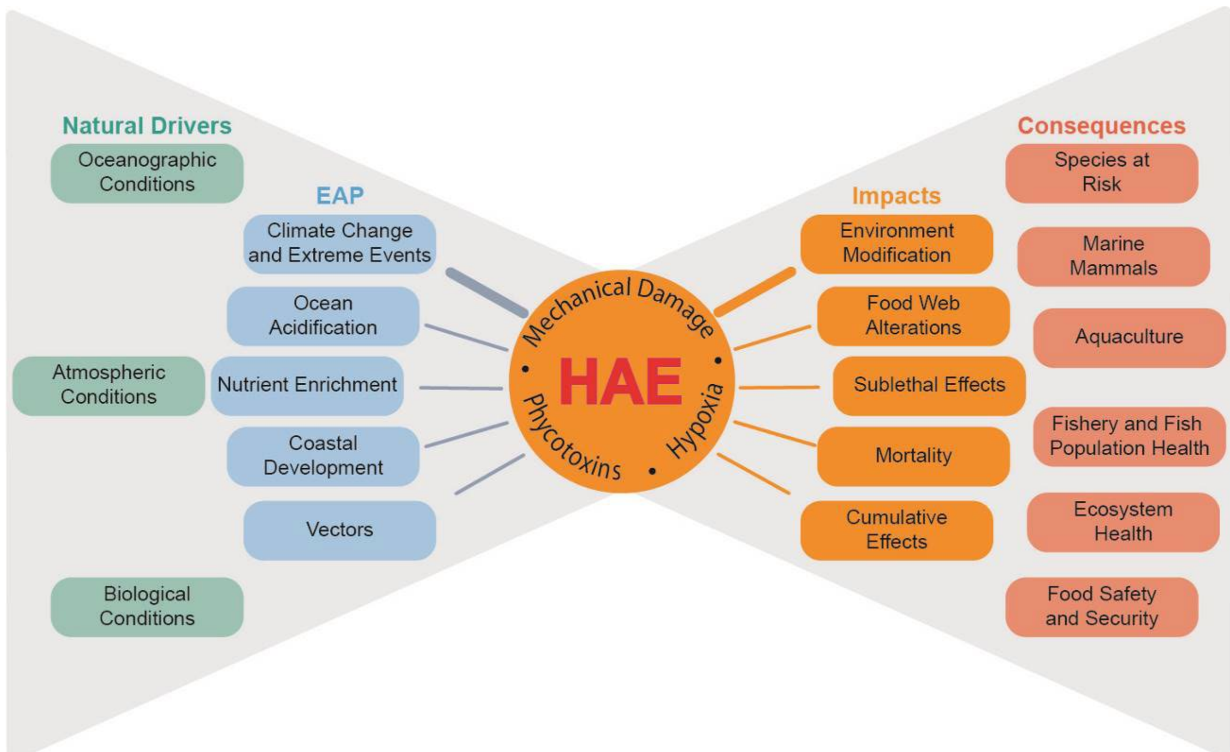


*Figure 12. Pacific coast bow tie conceptual model.*

**Emerging Anthropogenic Pressures**: The thick line connecting climate change and extreme events to HAEs in Figure 12 indicates there is strong evidence that this EAP has caused HAEs in BC. Increases in temperature stimulate phytoplankton growth, resulting in changes in phytoplankton abundance and community composition. Understanding the role of extreme events as a driver of HAEs was considered a knowledge gap and a priority on the Pacific coast. Ocean acidification is connected to HAEs with a thin line in Figure 12, reflecting that ocean acidification is known to be occurring in BC waters but evidence of causation between this and HAEs is currently known from outside the region only.

Availability of nutrients is linked to algal production in BC and elsewhere, but anthropogenic enrichment of nutrients is likely to have a relatively weak affect in BC. The BC coast has naturally high nutrient levels due to summer upwelling, estuarine circulation and tidal mixing (Whitney et al. 2005), so anthropogenic enrichment may be less likely to trigger HAEs than in other coastal regions. Coastal development (thin line, Figure 12) reflects a limited understanding of this EAP in BC coastal regions. Ship-based vectors may be an increasing concern due to increased ship traffic from international ports to BC ports. In northern BC and in the Vancouver area, ship-based vectors are likely to become an increasing concern as a result of the possible development and expansion of oil and gas port infrastructures.

**Impacts**: HAEs have led to environment modification impacts in BC (thick line, Figure 12). Records show that hypoxia resulting from oxygen depletion associated with HAEs is a major cause of fish mortalities in BC, especially at aquaculture farms where the fish cannot move away from the stressor (Rensel and Whyte 2003). HAEs are connected to food web alterations with a thin line in Figure 12, reflecting a relative lack of evidence of this impact in BC waters. McIntyre et al. (2013) suggested that a wide variety of HA found in BC have the potential to cause lethal and sublethal effects (thin lines, Figure 12) on shellfish in the region, based on evidence developed elsewhere. For example, blooms of *Heterosigma akashiwo* in South Carolina have been shown to damage the hepatopancreas of oysters, resulting in long-term physiological effects and compromised oyster health (Keppler et al. 2005). In North Puget Sound, farmed salmon that survived *Heterosigma akashiwo* blooms did not return to normal feeding and growth rates in comparison to cohorts not exposed to a *Heterosigma* bloom, suggesting some sublethal physiological damage (Rensell et al. 2010). The thin line shown connecting HAEs to mortality reflects limited understanding of lethal effects outside of the salmon aquaculture industry. Impacts of HAEs on wild fish species are seldom witnessed and are almost certainly underreported. However, marine survival of Sockeye Salmon (Fraser River Chilko stock) averaged 2.7% in years when the juvenile outmigration period corresponded to major blooms of *Heterosigma akashiwo* in the Strait of Georgia, and 10.9% in years of minor or no blooms (Rensel et al. 2010). Cumulative effects of an HAE could result from repeated or continuous exposure to phycotoxins over a long duration, occurring in many locations, as well as the diversity of taxa exposed (leading, for example to food web impacts that are not independent of cumulative effects). An example is the toxic *Pseudo-nitzschia australis* bloom (spring 2015), which propagated up the food chain to Whales, Dolphins, Porpoises, Seals and Sea lions from southern California to Alaska (McCabe et al. 2016; Savage 2017). This was the largest geographic extent of AST detection in marine mammals ever recorded globally (McCabe et al. 2016). Although strong evidence of cumulative effects was presented through investigations of the event in the Pacific USA and Alaska, there was limited investigation and reporting of the event in the Canadian Pacific. For this reason, the link between HAEs and impact in the bow tie model (Figure 12) was given a thin line.

### 4.2.3. Canadian Arctic Coast

While knowledge gaps exist for all Canadian marine waters, the biggest knowledge gaps are in the Arctic. Due to lack of information, the links between the EAPs and impacts of HAEs is largely unknown and in several cases are represented by a dotted line. This is the region least understood at present, where changes over time are likely to be the greatest. While phycotoxins have been detected in the Arctic, it is not known which HA are currently producing them.

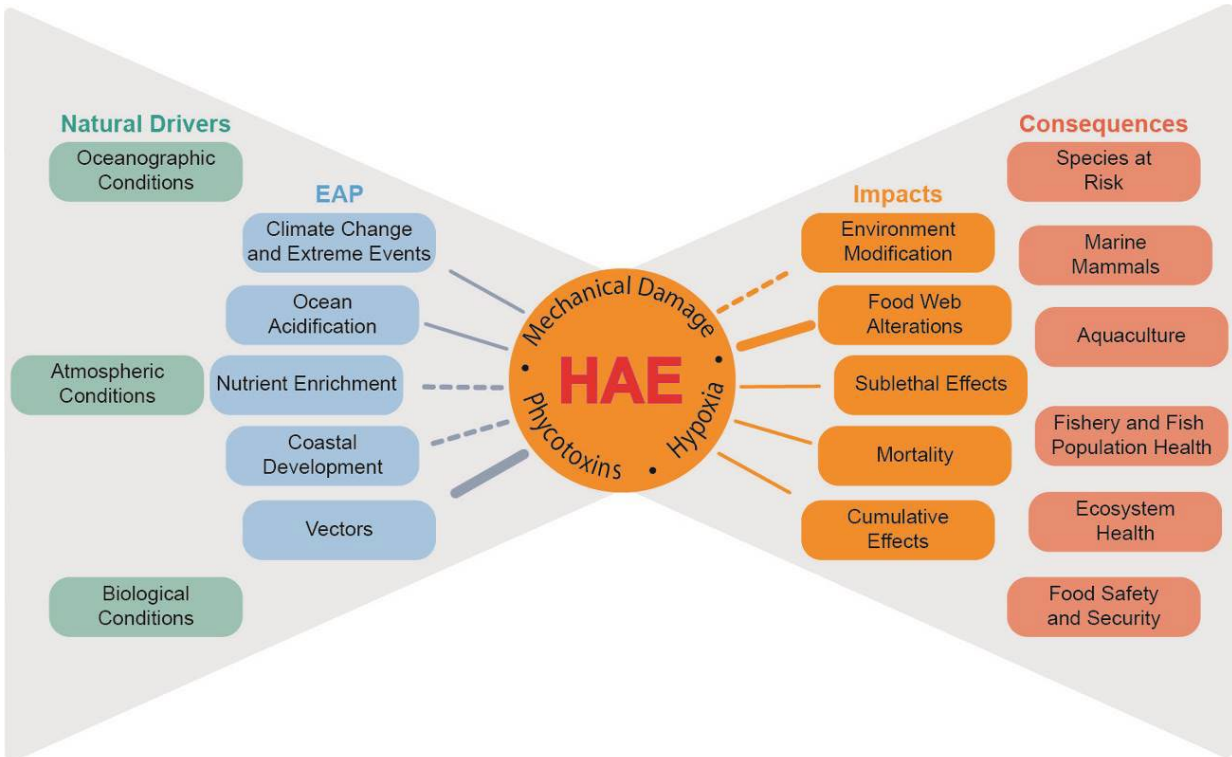


*Figure 13 Arctic coast bow tie conceptual model.*

**Emerging Anthropogenic Pressures**: Warming ocean temperatures and decreased seasonal ice cover will further expand the window of growth for potentially toxic algae in the Arctic, increasing the threat of climate change (thin line, Figure 13) (Anderson et al. 2018; Joli et al. 2018). Ocean acidification is also a concern in the Arctic (thin line, Figure 13) (Azetsu-Scott et al. 2010, 2014). The expert group considered nutrient enrichment and coastal development were likely to be less important in the Arctic than in Atlantic or Pacific Canadian waters although there is a lack of information to assess this issue. Considering currently low levels of development and limited extent of human settlements, any effects are most likely local in extent. The same conditions that expand the growth window for algae will also expand the window for vessel traffic into the Arctic. It is expected that ship-based vectors of potentially HA will increase in the near future, as they already have in recent years (thick line, Figure 13) (Laget 2017; Dawson et al. 2018; Dhifallah 2019).

**Impacts**: Studies in eastern Baffin Bay show that copepod species of the genus *Calanus* feeding on the DA-producing diatom *Pseudo-nitzschia seriata* do not discriminate between toxic and non-toxic cells. They are thus capable of retaining the toxin in their tissues and acting as vectors for transfer through the food web (Tammilehto et al. 2012; Harðardóttir et al. 2015). There was general agreement that there should be a thin line for sublethal and cumulative effects in the Arctic bow tie model, although given the specific physiology of Arctic phytoplankton, it was also argued that any change in one species could alter the food web. Furthermore, published evidence indicates that phycotoxin levels in the Arctic (so far outside of Canadian waters) have the potential to impact marine mammals (Lefebvre et al. 2016). Phycotoxins could also impact commercial and traditional harvesting, but information is currently inadequate to evaluate this aspect. Given that phycotoxins can enter the food chain at different levels, this would support the higher rating of food web alterations in the Arctic bow tie model (thick line, Figure 13). In summary, the greatest knowledge gaps are in the Arctic, which lacks information about the presence of HA and phycotoxins, bloom frequency and dynamics, and about possible cumulative effects of phycotoxins in the food web, including harvested species.

## 5. SOURCES OF UNCERTAINTY/LIMITATIONS

Resources to study HAEs in Canada have been limited in recent years. Thus, most reports at the ecosystem level have been incidental to other studies, which results in incomplete data as to causes and consequences. A key area of uncertainty is the Arctic, where no phycotoxin data are collected and where limited information on the presence of HA species is the only available indicator of risk.

This review of Canadian HAEDAT events, supplemented by temporal and geographic HAE information obtained from monitoring programs and scientific publications, examines temporal and geographic HAE occurrences in Canadian marine waters. However, there are limitations of HAEDAT reporting, including the limited time period available (maximum of 30 years), the lack of consistent reporting, especially in the early part of that time frame, and the limitation of the type of data provided by restricted monitoring programs. HAEDAT primarily tracks HAEs that result in shellfish closures or fish kills. HAEDAT reporting for Canada depends largely on results obtained through CFIA phycotoxin monitoring, which is designed to protect human health and not to investigate, predict or respond to HA blooms. Area closures occur at a particular phycotoxin concentration threshold. Following a shellfish closure, CFIA does not sample the area again for a specific period of time, i.e., three weeks under current protocols. If the phycotoxins measured at that time are below the regulatory threshold, the area is approved for re-opening. This process, while fulfilling the requirement to protect food safety, provides little or no information on the spatial extent and duration of HAEs and their maximum toxin levels. Distribution, magnitude and duration of HAEs are therefore underestimated in this study. However, HAEDAT records provide important information on the occurrences of blooms, phycotoxins and harvesting closures in Canada.

The HAEDAT dataset was initiated in 1987. It is a considerable resource and summarizes a large quantity of data, some of which are no longer accessible elsewhere. It captures some long-term regional and temporal changes in HAE distributions. It is acknowledged that there are gaps in the data and HAEDAT event reports should be treated with caution for the following reasons:

- There were often inconsistencies in sampling protocol. Some of these were for logistical reasons, such as time available to sample, the number of samplers available, the tidal cycle, as well as the ability to process a certain number of samples.
- A number of Canadian records prior to 2000 are missing from the dataset. This is more apparent from the Pacific records.
- In 2003, all countries' coastlines were split into HAEDAT zones that were to be comprised of 200 km stretches. In many cases, this resulted in the need to combine multiple earlier recorded events into one event for a particular zone.

## 6. OTHER CONSIDERATIONS

Canada is part of a global community that seeks to better understand the fundamental causes and effects of HAEs. The present report was developed concurrently with several major international reviews of HA monitoring, research and management, and ongoing collaborative initiatives.

The IOC/ICES Global HAB Status Report was under development at the time of the CSAS meeting and was identified as a key part of the Canadian HAB review. It has since been published and provides a worldwide overview of HAEs and the occurrence of phycotoxin-producing microalgae (Hallegraeff et al. 2021a).

The goal of the report was to assess the status and probability of change in HAE frequencies, intensities, and spatial distribution resulting from environmental changes at the local and global scale. This project was initiated by the IOC IPHAB, in partnership with ICES, PICES and the International Atomic Energy Agency (IAEA). Elements of the present document were used to fulfill Canada's contribution to this Global HAB Status Report, and the special issue of Harmful Algae devoted to a global review of HAEDAT and Ocean Biogeographic Information System (OBIS) by countries to determine their HAE status (McKenzie et al. 2021). In addition to Canada, the global report and special Harmful Algae issue includes studies from the United States (Anderson et al. 2021), France (Belin et al. 2021), the Atlantic margin of Europe (Bresnan et al. 2021), Northern Europe (Karlson et al. 2021), the Mediterranean Sea (Zingone et al. 2021), Latin America and the Caribbean (Sunesen et al. 2021), Australian and New Zealand (Hallegraeff et al. 2021d), East Asia (Sakamoto et al. 2021), and the Philippines and Malaysia (Yñiguez et al. 2021).

In January 2020, the Ocean Frontier Institute (OFI) hosted, with the IOC of the United Nations Educational, Scientific and Cultural Organization (UNESCO), DFO, and others, the North Atlantic Regional Workshop for the United Nations (UN) Decade of Ocean Science for Sustainable Development (2021–2030) in Halifax, NS. The goal of the workshop was to discuss priorities and identify actions for the North Atlantic Ocean that would support achieving the objectives of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030). The impact of HABs on coastal communities (including aquaculture operations) was included in the working group discussions on "*a safe ocean where human communities are protected from ocean hazards*". One recommendation of the workshop was a call for multi-hazard Early Warning Systems (EWS) that incorporates physical, biological and social data, as well as new technologies. The previous year (May 2019), IPHAB adopted the decision to create a Task Team on the early detection, warning and forecasting of HAEs. A technical guidance document is being developed in collaboration with the IOC, Food and Agriculture Organization of the Untied Nations (FAO) and IAEA to address requirements for HAB EWS, including pelagic algae associated with large fish killing events.

The international research network, GlobalHAB (not the same group as the Global HABs Status Report), focuses on HAB research and is sponsored jointly by the Scientific Committee on Oceanic Research (SCOR) and the IOC of UNESCO. GlobalHAB was built on the foundations of the previous international research network, Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB).

The objectives of the IOC SCOR GlobalHAB network are to improve understanding and prediction of HABs, and to manage and mitigate their impacts. Several knowledge gaps and research priorities recommended by the above network are also included in this research document. The connections with the GlobalHAB Status Report and the shared priorities with GlobalHAB can potentially firmly position DFO and Canada at the forefront of global HA collaborative research and HAB impact management.

# 7. RECOMMENDATIONS

- Research is needed to fill the critical knowledge gaps about HA and the EAPs that drive HAEs in Canadian marine waters (the left side of the bow tie model- the drivers of the event). These include the detection and distribution of HA; integration and expansion, where necessary, of phycotoxin monitoring into HAE risk management; investigation into how EAPs alter HAE dynamics (bloom initiation and duration); This information will support the overall goal of more accurate predictive models of HAEs in order to provide an early warning system for management purposes.

- Knowledge about what HA species and phycotoxins are present is essential in order to anticipate what harm might occur, the HAE (the central knot or risk event in the bow tie model). A list of existing relevant long-term data sets should be compiled that could be leveraged for analyses of phytoplankton patterns and trends for HAE. Increased communication with partners and development of standardized operating procedures should facilitate knowledge and technology transfer, particularly linking HA and phycotoxin data.
- Understanding the effects of HA and phycotoxins (including sublethal and cumulative) on the growth, physiology, reproduction and behaviour of marine biota is needed to evaluate their impact on food webs and ecosystems, and their consequences to species at risk, marine mammals, aquaculture, fishery and fish population health, ecosystem health, and food safety and security (the right side of the bow tie model – impacts and consequences of the event).
- Monitoring of phytoplankton and phycotoxins should be continued and expanded where it currently exists, and expanded to other regions of concern, using new and existing capacity and partnerships. This is particularly important for areas where information is lacking, including the Arctic. Along with traditional methods to identify HA and phycotoxins, novel methods to detect and monitor HA in Canadian marine waters should be implemented. Monitoring programs using existing methodologies can assist the ground-truthing of new technologies.

## 8. CONCLUSIONS AND NEXT STEPS

The review of HA, HAEs and their impacts in Canada's Atlantic, Pacific and Arctic marine waters over the 30-year period identified areas and issues of emerging concern with respect to impacts and consequences to Canadian marine ecosystems and how they may impact core DFO responsibilities. National knowledge gaps include limited HA detection and limited understanding of the effect of specific EAPs (climate change, nutrient enrichment, coastal development, and vectors of introduced HA) on oceanographic, atmospheric, and biological conditions that drive changes in HA species, phycotoxins, and bloom development and toxicity. In the Atlantic region, information regarding the impacts of climate change and ocean acidification on reoccurring HAEs was identified as a key knowledge gap. On the Pacific coast, investigating the role of extreme events as a driver of HAEs was a key priority. These knowledge gaps prevent the development of effective predictive HAE models, which hinders forecasting/hindcasting capability and hampers development of mitigation and prevention strategies.

There is limited understanding of the effects of HA and phycotoxins on most marine organisms (sublethal/cumulative effects on the growth, physiology, reproduction, and behaviour), and on food web and ecosystem function, particularly in Canadian sub-Arctic and Arctic waters. The biggest knowledge gaps are in the Arctic, which lacks information about the presence of HA and phycotoxins, frequency and extent of blooms, and possible cumulative effects of phycotoxins in the food web, including harvested species. Understanding the effects of HA and phycotoxins is required to evaluate their impact on species at risk, marine mammals, aquaculture, fishery and fish population health, ecosystem health, and food safety and security. These knowledge gaps must be filled in order to inform management decisions.

Detecting and monitoring phytoplankton and phycotoxins should be continued where it currently exists and be expanded into new areas, using new and existing capacity and partnerships. Along with traditional methods to identify HA and phycotoxins, novel methods to detect and observe/monitor HA in Canadian marine waters should be implemented. Observation and monitoring programs using existing methodologies can assist the ground-truthing of new technologies. One advantage would be an early warning system that would increase predictive capacity for these ecosystem stressors, enabling mitigative or preventive actions to ensure healthy and productive marine ecosystems.

Next Steps:

A list of Canadian experts on HA and phycotoxins should be compiled so as to expedite contact when HAEs are detected and as a resource for national and international reporting purposes. Communication and collaboration on HA should be encouraged and expanded.

A list of existing relevant long-term datasets should be compiled that could be used for analyses of phytoplankton patterns and trends.

Priority research plans:

- Determine the current and potential distribution and composition of HA and phycotoxins in Canadian waters and sea ice, and the environmental correlates triggering HAEs, taking advantage of past research and current and emerging technologies.
- Determine if HA species in the Canadian Arctic are producing phycotoxins, and whether these are found in the food web, including harvested species. Analyze archived tissue samples and new samples in conjunction with harvesters to evaluate phycotoxins in harvested species.
- Investigate the acute, sublethal and cumulative effects of HA on marine systems.
- Develop predictive models of HAEs to inform early warning systems and to mitigate their impacts.
- Include observation and early warning systems for HAEs as Canada’s contribution to the UN Decade.

## 9. LIST OF ABBREVIATIONS

| | |
|---|---|
| ASP | Amnesic Shellfish Poisoning |
| AST | Amnesic Shellfish Toxin |
| AZA | Azaspiracid |
| CAN HAB | Canadian Harmful Algae Working Group |
| CFIA | Canadian Food Inspection Agency |
| COSEWIC | Committee on the Status of Endangered Wildlife in Canada |
| CSSP | Canadian Shellfish Sanitation Program |
| DA | Domoic Acid |
| DSP | Diarrheic Shellfish Poisoning |
| DST | Diarrheic Shellfish Toxin |
| EAP | Emerging Anthropogenic Pressure |

| | |
|---|---|
| ECCC | Environment and Climate Change Canada |
| EWS | Early Warning Systems |
| GEOHAB | Global Ecology and Oceanography of Harmful Algal Blooms |
| GYM | Gymnodimine |
| HA | Harmful Algae |
| HAB | Harmful Algal Bloom |
| HAE | Harmful Algal Event |
| HAEDAT | Harmful Algae Event Database |
| HAMP | Harmful Algae Monitoring Program (BC) |
| ICES | International Council for the Exploration of the Sea |
| IAEA | International Atomic Energy Agency |
| IOC | Intergovernmental Oceanographic Commissions of UNESCO |
| IPHAB | Intergovernmental Panel on Harmful Algal Blooms |
| NOAA | National Oceanic and Atmospheric Administration (U.S.) |
| NRC | National Research Council of Canada |
| OA | Okadaic Acid |
| OBIS | Ocean Biogeographic Information System |
| OFI | Ocean Frontier Institute |
| PAR | Photosynthetically Active Radiation |
| PICES | North Pacific Marine Science Organization |
| PnTX | Pinnatoxin |
| PSP | Paralytic Shellfish Poisoning |
| PST | Paralytic Shellfish Toxin |
| PTX | Pectenotoxin |
| PWG | Phycotoxins Working Group |
| SCOR | Scientific Committee on Oceanic Research |
| SPX | Spirolide toxin |
| STX | Saxitoxin |
| WGHABD | Working Group on Harmful Algal Bloom Dynamics (of ICES and IOC) |
| YTX | Yessotoxin |

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# APPENDIX

Breakout session Knowledge Gaps and Research Priorities

Canadian Atlantic Coast

A breakout group of Atlantic researchers generated the following based on their expert opinion of important knowledge gaps on HA, including emerging issues, on the Atlantic Coast. Such questions have the goal of positioning DFO to design monitoring programs (medium-term objective) and to model HAEs and toxicity (longer-term objective), which would help to predict HAEs and to understand the impact of phycotoxins on marine biota.

1. Can we develop an operational model that predicts the initiation, duration and intensity of *Alexandrium* blooms in Atlantic Canada?
2. What evidence exists to support the impact of sublethal effects and bioaccumulation of toxins on marine species? (Indicators of stress, etc.)
3. What is controlling *Pseudo-nitzschia* blooms and their toxicity on the east coast and how does that compare to the west coast?
4. How will warming and ocean acidification affect the dynamics of HAEs (cumulative effects) and large-scale distribution of HAEs?

- The role of natural drivers and EAPs is unclear
- Lack of predictive capacity
- Lack of full understanding of impacts
- Lack of knowledge on individual species and their interactions with total phytoplankton community
- Existing long-term datasets should be analysed to fill knowledge gaps

Canadian Pacific Coast

A breakout group of Pacific researchers generated the following questions (grouped under themes) based on their expert opinion of important knowledge gaps on HA, including emerging issues, in BC. Such questions have the goal of positioning DFO to design monitoring programs (medium-term objective) and to model HAEs and toxicity (longer-term objective), which would help to predict HAEs and to understand the impact of phycotoxins on marine biota.

1. What is the distribution and composition of HA and phycotoxins in BC, and what are their environmental correlates?
    - Where are the hot spots for HAE initiation?
    - What phycotoxins are in the environment in BC?
    - What phycotoxins are known fish-killing species producing, if any?
    - What is the impact of fish farms (environmental conditions associated with aquaculture) on HA?
    - What is the role of ballast water/sediment as vectors?
2. What determines toxicity?
    - What are the environmental correlates / drivers of phycotoxin production?
    - What are the genetic regulators of phycotoxin production?
    - What is the toxicity of particulate vs. dissolved fractions in the environment? (Retention vs. release)

3. Do HA (through phycotoxin production) affect the fitness of marine biota in BC?
    - What is an ecologically meaningful level of phycotoxins that will cause lethal and sublethal effects?
    - What is the effect of chronic vs. acute exposure to phycotoxins?
    - What is the effect of interactions with other stressors (including multiple phycotoxins)?
    - What is the bioavailability and movement of phycotoxins through the food web?
    - What, if any, physiological mechanisms allow biota to adapt to or tolerate phycotoxins?
    - Are there impacts on wild fish of phycotoxins, including more subtle changes such as delays in migration?
    - What is the role of HA in summer shellfish mortality syndrome?

Recommendations and Knowledge Gaps for the Pacific Region:

This CSAS process has found that HAEs have a negative influence on marine ecosystems in Pacific Canada and need to be considered as a potentially important stressor.

Canadian Arctic Coast

**Priority Questions/Topics**:

1. Are species producing toxins? (In open water)
    - There is only one unpublished study for DA in shellfish in the Beaufort Sea – scallops with very low levels of DA found (C. Michel & W. Rourke, Pers. Comm.). However, there are issues with lag times in these sorts of correlative studies since toxins may remain in benthic species long after a bloom has occurred. It is better to use liquid chromatographic (LC) fluorescence, liquid chromatographic mass spectrometry (LCMS) methods to figure out specific toxins directly in phytoplankton samples – with this method, multiple toxins can be checked at once (up to 12) – on filters or frozen samples.
    - Molecular tools are another option? Existing data (Connie Lovejoy, Pers. Comm. has plankton samples in RNA later; Kim Howland (Pers. Comm.) has eDNA samples in Longmire's buffer. 18S metabarcoding already done on a number of these). Population genetics (origins), gene expression.
2. Have there been changes over time? Are some areas of the Arctic more important than others?
    - Analysis of archived tissue samples (many years of marine mammal and fish available in freezers) and benthic/shellfish collections;
    - Collection of new samples in conjunction with harvesters – immune assays with follow-up testing for toxin types >focus on fatty tissues;
    - Whale feces collected from nets can also provide appropriate samples to identify if there is a problem with phycotoxins in Arctic.
3. What's going on in the sea ice? Are these species producing toxins? How do they interact with open water species?

**Prioritizing locations for work**:

- Identify candidate communities – e.g., where they harvest shellfish; piggyback on existing programs where relationships with local Inuit have been established – Ocean Protection Program (OPP)
- Possibilities: Iqaluit, Belcher Islands, Lancaster Sound (Arctic Bay/Pond, Marine Conservation area)

- Coastal areas are more relevant to local people – also tends to be greater concentrations of toxic dinoflagellates in shallow water, mouths of fjords, shallow basins (Allan Cembella, Pers. Comm.)
- Prioritize areas that may be more affected by climate – Hudson Bay, Labrador coast, other areas (Beaufort?)

**Other points**:

- Themisto kill? Reported off in Paulatuk, Amundsen Gulf
- About 15 potential HA taxa were reported in Northern Labrador fjords in Simo-Matchim et al. (2017). These taxa should be added to the maps
- Michel Poulin (Pers. Comm.) has a list of HA in the water column and sea ice across the Canadian Arctic regions
- Species occurrence and toxin data from mussels, scallops and plankton could also be provided by Allan Cembella (Pers. Comm.) for West Greenland area.

The role of the community of sea ice phytoplankton as a seed population for toxic blooms within the water column, or to what extent phycotoxins are produced within the ice, and whether they are transferred to the benthic or pelagic food webs is still unknown.

The impacts of not having organized monitoring programs, including none for human health (i.e., CSSP), in the Arctic, are unknown.