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1 **Three decades of Canadian marine harmful algal events: Phytoplankton and**
2 **phycotoxins of concern to human and ecosystem health**

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4
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33
34

35 ABSTRACT

36
37 Spatial and temporal trends of marine harmful algal events in Canada over the last three decades
38 (1988 to 2017) are examined using data from the Harmful Algal Event Database (HAEDAT).
39 This database contains the most complete record of the occurrence of algal blooms, phycotoxins
40 and shellfish harvesting area closures in Canada since 1987. Notable Canadian records contained
41 in HAEDAT include the first detection worldwide of amnesic shellfish poisoning (ASP),
42 attributed to the production of domoic acid by a diatom (*Pseudo-nitzschia multiseries*) in Prince
43 Edward Island in 1987. The following year, closures of shellfish harvesting areas were issued
44 due to amnesic shellfish toxin (AST) in the Bay of Fundy (New Brunswick), with *Pseudo-*
45 *nitzschia pseudodelicatissima* as the causative organism. HAEDAT also includes the first proven
46 case of diarrhetic shellfish poisoning (DSP) in Canada and North America in 1990, and the first
47 closures of shellfish harvesting due to diarrhetic shellfish toxins (DSTs) (associated with the
48 presence of *Dinophysis norvegica*) occurring in Nova Scotia in 1992, followed by Newfoundland
49 and Labrador in 1993. Paralytic shellfish toxin (PST) closures associated with *Alexandrium*
50 species have recurred along portions of the Canadian Atlantic (Bay of Fundy, Estuary and Gulf
51 of St. Lawrence) and the Canadian Pacific (British Columbia) coasts since the early 1940s. In
52 2008, mass mortalities of fish, birds and mammals in the St. Lawrence Estuary were caused by
53 *Alexandrium catenella* and high levels of PSTs. Mortalities of both wild and cultured finfish
54 associated with *Alexandrium* species have also been reported on the Atlantic coast. In coastal
55 British Columbia, mortalities of salmon have occurred at aquaculture sites due to the presence of
56 the diatoms *Chaetoceros convolutus* and *C. concavicornis*, the raphidophyte *Heterosigma*
57 *akashiwo*, the dinoflagellates *Cochlodinium fulvescens* and *Alexandrium catenella*, and the
58 dictyochophytes *Dictyocha fibula*, *Octactis speculum*, and *Pseudochattonella verruculosa*.
59 During 2015, the northeast Pacific coast experienced a large algal bloom that extended from
60 California to Alaska. It resulted in the closure of several shellfish harvesting areas in British
61 Columbia due to AST, produced by *Pseudo-nitzschia australis*. The Canadian Arctic coast is not
62 included in the spatial coverage of HAEDAT, and to date there are no harmful algal events
63 recorded in this region. Nevertheless, because of its emerging importance, information on the
64 occurrence of harmful algal species in the Canadian Arctic was also compiled from relevant
65 literature and data. Little is known of the impacts of harmful algal species in this region.
66 Nevertheless, a comprehensive review was conducted of potentially harmful algal species
67 (pelagic and sympagic or sea ice-associated), including their occurrences and evidence for
68 phycotoxin accumulation by organisms in the Canadian Arctic. The results suggest that these
69 taxa may be more widespread than previously thought in that region. Compilation of spatial and
70 temporal information from HAEDAT, and other records, is an important step in evaluating the
71 potential role of harmful algae as a stressor on Canadian marine ecosystems, determining its
72 consequences on human and ecosystem health, and developing a knowledge gap analysis to
73 establish research priorities.

74
75 *Keywords:* Phycotoxin, harmful algal event, saxitoxin, domoic acid, okadaic acid, HAEDAT,
76 *Alexandrium*, *Pseudo-nitzschia*, *Dinophysis*, *Chaetoceros*, *Heterosigma*, Northeast Pacific,
77 Northwest Atlantic, Arctic, Canada

78 1.0. Introduction

79

80 1.1. Background

81

82 Globally, harmful algae (HA) are considered important ecosystem stressors, in particular
83 when they produce phycotoxins or reach high abundances in blooms, although some species are
84 harmful even in the absence of a bloom (Shumway et al., 2018). Incidences of harmful algal
85 events have been increasing worldwide, impacting marine food webs as well as human health
86 (Berdalet et al., 2017; Glibert et al., 2018; Shumway et al., 2018). Our understanding of harmful
87 algal blooms has progressed, thanks to advances in research, monitoring, and management
88 (Anderson et al., 2008, 2012; Glibert and Burkholder, 2018). Because of their ecological
89 significance as threats to ecosystem structure and function, HA in Canadian Atlantic and Pacific
90 waters have been identified as ecologically and biologically significant species (Scarratt et al.,
91 2006).

92

93 The major marine phycotoxins were originally categorized according to the symptoms they
94 generate, i.e. paralytic shellfish poisoning (PSP); amnesic shellfish poisoning (ASP); and
95 diarrhetic shellfish poisoning (DSP). The phycotoxins responsible for these syndromes are
96 currently categorized into distinct groups based on chemical structure, rather than on the
97 symptoms they generate (Toyofuku, 2006). This includes the following groups of toxins:
98 saxitoxin (STX); domoic acid (DA); okadaic acid (OA); and pectenotoxin (PTX), which are all
99 regulated in Canada. As lipophilic PTXs are extracted with OA group toxins from shellfish, they
100 are still grouped together in the Canadian Shellfish Sanitation Program (CSSP) manual. In this
101 paper, Canadian reports are referred to by the syndrome name if the event included human
102 poisonings (i.e. ASP, PSP, DSP). If the event was caused by the detection of a phycotoxin at a
103 concentration over the regulatory limit, the phycotoxin group is referred to in a general form, i.e.
104 amnesic shellfish toxin (AST); paralytic shellfish toxin (PST); and diarrhetic shellfish toxin (DST,
105 which includes OA group toxins and PTXs), as this terminology has been standardized for this
106 HAEDAT special issue.

107

108 Historical records dating back to the early 1600s in the Annapolis Basin, Bay of Fundy,
109 Nova Scotia (NS), and anecdotal reports along the Gaspé Peninsula in Quebec (QC) and the
110 southwest New Brunswick (NB) portion of the Bay of Fundy, suggest a degree of traditional
111 knowledge of shellfish toxicity in Indigenous communities. Reports indicate that Indigenous
112 peoples along the coasts of the Bay of Fundy (NB and NS) and the Gulf of St. Lawrence (QC)
113 were aware of the hazards associated with the consumption of blue mussels (*Mytilus edulis*); they
114 would not eat them during the summer months, even if they were starving (Prakash et al., 1971;
115 Bates et al., 2020). PSP was known on the British Columbia (BC) coast at least by 1793, when a
116 member of Captain George Vancouver's crew died after eating contaminated mussels and
117 exhibiting symptoms of PSP in an area subsequently named Poison Cove (Prakash et al., 1971).
118 However, no formal records exist prior to an outbreak in 1936 (Murphy, 1936; Gibbard et al.,
119 1939; Gibbard and Naubert, 1948). According to Taylor and Harrison (2002), in BC "there has
120 not been a year in which toxicity has not occurred and virtually every area on the coast has been
121 toxic at one time or another. Some areas are toxic every year."

122

123 Restrictions on shellfish harvesting due to PSTs have been imposed in Atlantic Canada since
124 1943 (Tennant et al., 1955). In Newfoundland and Labrador (NL), the first reported PSP event
125 occurred in 1982 (White and White, 1985), which prompted a monitoring program for
126 phycotoxins in the province (Hockin et al., 1983; Schwinghamer et al., 1994). The annual
127 recurrence of PSTs has led to the permanent closure of wild mussel harvesting in the entire Bay
128 of Fundy since 1943 (Medcof et al., 1947; Prakash et al., 1971), and nine areas throughout NL in
129 1982, with other areas added in 1997 (Bates et al., 2020). The 1943 recommendation to close
130 wild mussel harvesting in the Bay of Fundy was recently revised to allow the development of
131 mussel aquaculture sites, but this took years to initiate after the original closures (Rayner, 2013;
132 Martin, 2016). Although the Bay of Fundy continues to have a viable soft-shell clam (*Mya*
133 *arenaria*) industry, harvest area closures are implemented when phycotoxin levels are unsafe.
134 Interestingly, one location (Crow Harbour in southwest NB) has been closed to harvesting of all
135 bivalve species, including the soft-shell clam, since 1980, because of continued unsafe levels of
136 phycotoxins (Martin et al., 1990a; Hamer et al., 2012). Other locations in southwest NB have
137 also experienced periodic extended closures due to the retention of phycotoxins in the shellfish
138 tissues (Hamer et al., 2012).

139
140 Mortality of caged finfish (mainly Atlantic salmon, *Salmo salar*, and Chinook salmon,
141 *Oncorhynchus tshawytscha*) is a common occurrence on the Canadian Pacific coast, with records
142 dating back to the 1960s (Bell, 1961). Finfish aquaculture farms established rapidly on the
143 southern BC coast after 1984, and reports of fish mortalities followed soon after (Albright et al.,
144 1992). The raphidophyte flagellate *Heterosigma akashiwo*, which has been responsible for
145 aquaculture fish kills since the 1970s, is the species that causes most harm to farmed salmon in
146 BC (Haigh and Taylor, 1990; Haigh and Esenkulova, 2014). Finfish aquaculture farms (Atlantic
147 salmon) were established on the Atlantic coast in 1979, but it was not until 1998 that the first
148 mortalities were observed (Martin et al., 2007). Several studies demonstrate the potential risk to
149 fish and fisheries, and overall ecosystem health, due to HA on the Atlantic coast. White (1977,
150 1980) suggested that Atlantic herring (*Clupea harengus harengus*) mortalities that occurred in
151 1976 and 1979 in the Bay of Fundy were a result of accumulation of PSTs through the food
152 chain. White (1981) showed that these toxins injected either orally or intraperitoneally into
153 Atlantic herring, American pollock (*Pollachius virens*), winter flounder (*Pseudopleuronectes*
154 *americanus*), Atlantic salmon, and Atlantic cod (*Gadus morhua*) were all lethal. Affected fish
155 from that study exhibited symptoms similar to those of Atlantic salmon exposed to high
156 concentrations of *A. catenella* cells in the laboratory (Burrige et al., 2010). In 2001, North
157 Atlantic right whales (*Eubalaena glacialis*) and their zooplankton prey (dominated by the
158 copepod *Calanus finmarchicus*) in the Bay of Fundy were found to contain PSTs (Doucette et
159 al., 2006). During the investigation of this event, the Canadian Food Inspection Agency (CFIA)
160 detected the same phycotoxins at levels over the human health regulatory limit in blue mussels.
161 Whales that had died of possible ship collisions in BC have also contained AST and PSTs at
162 levels believed to cause neurological impairment (Savage, 2017).

163
164 The history of HA studies in Canada began with research and monitoring in the early 1940s
165 on both the Atlantic and Pacific coasts, following incidents of PSP (Medcof et al., 1947; Quayle
166 and Bernard, 1966; Prakash et al., 1971). However, it was not until the late 1980s that a
167 coordinated national Canadian HA program was established. The occurrence of a novel
168 phycotoxin (DA) in eastern Prince Edward Island (PE), in December 1987, caused human deaths

169 from the consumption of contaminated shellfish (Bates et al., 1989) and resulted in increased and
170 renewed interest in HA research and monitoring.

171

172 From 1987 to 1997, a combined phytoplankton and phycotoxin monitoring program was
173 managed by the Department of Fisheries and Oceans (DFO). In 1997 phycotoxin monitoring of
174 shellfish tissue (i.e. human food) became the responsibility of the newly created CFIA. DFO
175 retained a role as joint administrator of the CSSP, with the CFIA and Environment and Climate
176 Change Canada (ECCC). DFO's current role in the CSSP is primarily regulatory. The
177 Conservation and Protection Branch of DFO continues to be responsible for enacting closure and
178 opening of shellfish harvesting areas, and for enforcing closure regulations, as recommended by
179 the CFIA based on its phycotoxin monitoring data or by ECCC based on its sanitary (faecal
180 coliforms) monitoring data. There is currently no national phytoplankton monitoring program in
181 Canada. DFO HA researchers worked closely with DFO Inspection until 1997, and subsequently
182 with the CFIA, for many years. However, the duration and extent of this collaboration varied by
183 region, as DFO's national HA program gradually decreased. Some regions (NL, PE, QC, BC)
184 continue with limited project-based coastal monitoring for phytoplankton, including HA.

185

186 Canada has been contributing data for three decades to the Intergovernmental
187 Oceanographic Commission (IOC) of United Nations Educational Scientific Committee and
188 Cultural Organization (UNESCO) Harmful Algal Event Database (HAEDAT; Bresnan et al., this
189 special issue) through the International Council for the Exploration of the Sea (ICES)/IOC
190 Working Group on Harmful Algal Bloom Dynamics (WGHABD). Although this dataset has
191 limitations, it provides an important spatial and temporal record of the occurrence of blooms,
192 phycotoxins and harvesting closures in Canada. HAEDAT reports were provided by regional
193 members of the Canadian Phycotoxins Working Group and/or co-ordinated by the Canadian
194 delegate and attendee to the ICES/IOC WGHABD meeting for a given year, with supplementary
195 material from the CFIA providing phycotoxin values when available. During the early years,
196 there were gaps in event reporting due to several problems such as: difficulties obtaining data
197 (communication; much of the early data remains in paper copies, data are held by different
198 departments, and have never been entered electronically); inconsistencies in sampling protocols,
199 and changes in monitoring effort that sometimes resulted in "no events". In recent years, most
200 reports for AST, PSTs and DSTs have been based on the CFIA shellfish phycotoxin monitoring
201 program, supplemented by phytoplankton identifications, bloom events, aquaculture-related fish
202 kills, and harvesting closures provided by phytoplankton monitoring programs and DFO, when
203 available. The CFIA phycotoxin data were collected to protect the health of shellfish consumers,
204 not for research purposes, and consequently are focussed on areas with active commercial or
205 recreational shellfish harvesting. Harvest areas are closed when results show phycotoxin levels
206 higher than the regulatory threshold, and must remain closed for at least 14 days. At least three
207 acceptable sample results are required before an area is re-opened for harvest. The onset and
208 subsequent depuration of phycotoxins in the bivalve species are monitored via routine sampling,
209 but this sampling frequency is generally not increased to capture information about rapid
210 changes in shellfish phycotoxins in closed harvest areas; the maximum levels of phycotoxins (i.e.
211 the magnitude of the event) may therefore not be quantified during that period. Phycotoxins
212 regulated in Canada or shellfish export markets are routinely reported (e.g. AST, DSTs, PSTs,
213 PTXs). Given these limitations, any detailed analyses regarding spatial and temporal trends must
214 be considered carefully (Hamer et al., 2012). Although HAEDAT includes temperate, boreal,

215 sub-arctic and arctic regions, the Canadian Arctic/sub-Arctic has not been included to date, as
216 there has been no reporting mechanism for this region.

217
218 In recent years, novel HA species and phycotoxins have been detected in Canadian Arctic
219 waters (Poulin et al., 2011; Dhifallah, 2019; Pućko et al., 2019; Bates et al., 2020), suggesting
220 the potential for harmful algal events. Ballast water transport, particularly in unregulated
221 domestic shipping, has been implicated in the appearance of some of these species and
222 phycotoxins in Canadian waters, with particular concern for the Arctic region (Smayda, 2007;
223 Klein et al., 2010; Laget et al., 2017). HA species or the presence of phycotoxins in organisms
224 have also been detected in northern latitudes of other regions, such as Greenland, Alaska and
225 Russia (Okolodkov, 1998, 2005; Hansen et al., 2011; Lefebvre et al., 2016). These findings raise
226 the level of concern for the Canadian Arctic, which may share similar environmental conditions.

227
228 Global warming has resulted in sea ice reductions (Stroeve et al., 2012; Meier et al., 2014)
229 and increased vessel traffic (Dawson et al., 2018) in several areas of the Canadian Arctic. This
230 has led to broader questions about how climate change could affect the prevalence of HA, the
231 likelihood of harmful algal events (Wells et al., 2015; Joli et al., 2018), and their future impact
232 on human and ecosystem health in this region. In the last decades, Canadian harmful algal events
233 on both the Atlantic and Pacific coasts have caused shellfish harvesting closures and mortalities
234 of marine life (fish, mammals, and seabirds), as discussed below. These concerns have prompted
235 a re-evaluation of the importance of HA to ecosystem health and the propagation of effects to
236 higher trophic levels. Harmful algal events have increased awareness and concern from the
237 public, Indigenous groups, and industries (fishery, aquaculture, ecotourism), who regard HA as a
238 stressor leading to pressures on ecosystem services that depend on healthy systems.

239
240 In response to these growing concerns regarding HA and their role as ecosystem stressors,
241 DFO held a science workshop at the Institute of Ocean Sciences (Sidney, BC) in July 2017.
242 Following recommendations from the workshop (McKenzie and Martin, 2018), a comprehensive
243 review of the occurrence and impacts of marine harmful algal events and phycotoxins in
244 Canadian waters over the last three decades was compiled using information from HAEDAT, as
245 well as from the literature and additional sources (e.g. Bates et al., 2020). Information from that
246 review forms the basis of the present paper.

247
248 Beyond the scope of this paper are the consequences of the impacts of harmful algal events
249 on ecosystem health, fisheries, fish populations, aquaculture, marine mammals, as well as food
250 safety and security issues, and the emerging anthropogenic pressures that modify these events
251 and impacts.

252 253 *1.2. Overview of harmful algal species in Canada*

254
255 Phycotoxin-producing pelagic phytoplankton and sympagic algal species that are known to
256 have caused, or to be associated, with HA events on the coasts of Canada are listed in Table 1.
257 Also included in Table 1 are species that are known to produce phycotoxins that lead to the
258 morbidity or mortality of marine species and/or humans in areas outside of Canada. Three groups
259 of phytoplankton are of particular concern on both the Atlantic and Pacific coasts of Canada
260 because they produce phycotoxins that are regulated. The diatom genus *Pseudo-nitzschia*

261 contains 26 species, out of over 50, that produce AST, the phycotoxin that is responsible for ASP
 262 (Bates et al., 2018). Some dinoflagellates of the genus *Alexandrium* produce PSTs (STX group
 263 toxins that include numerous derivatives), which are responsible for PSP. Some dinoflagellates
 264 of the genera *Dinophysis* and *Prorocentrum* produce DSTs, which are responsible for DSP.
 265 Some species of *Dinophysis* also produce PTXs (Bates et al., 2020).

266

267 **Table 1.** List of phytoplankton, including sympagic (sea ice-associated) algal species, recorded
 268 in Canadian waters and known to produce phycotoxins that lead to the morbidity or mortality of
 269 marine species and/or humans. Species in bold have produced phycotoxins that caused, or have
 270 been associated with, events in Canadian waters. Phycotoxin production by the remaining
 271 species has only been demonstrated in waters outside of Canada.

272

Species [Phycotoxin produced]	Canadian province/region							References for distribution
	NL	QC	NS	PE	NB	BC	Arctic	
PENNATE DIATOMS								
<i>Pseudo-nitzschia australis</i> Frenguelli [AST]			• ^{1,t}		• ^{tc}	• ^e		Trainer et al., 2012; Bates et al., 2020; J.L. Martin, unpubl. data
<i>P. calliantha</i> Lundholm, Moestrup & Hasle [AST] ^{2,3}		•	•	•	•			Lundholm et al., 2003; Bates and Strain, 2006; Lassus et al., 2016
<i>P. delicatissima</i> (Cleve) Heiden [AST]	•	•	•	• ^{tc}	•	•	• ^s	Smith et al., 1990 ^{tc} ; Taylor and Haigh, 1996; Bérard-Therriault et al., 1999; Kaczmarek et al., 2008; Róžańska et al., 2009; Poulin et al., 2011; Trainer et al., 2012; Martin and LeGresley, 2014; OBIS, 2019; Bates et al., 2020; K. Howland; M. Poulin; N. Simard, unpubl. data
<i>P. fraudulenta</i> (Cleve) Hasle [AST] ³			•	•	•	•		Mather et al., 2010; Martin and LeGresley, 2014; Bates et al., 2020
<i>P. granii</i> (Hasle) ^{tc} Hasle [AST]							•	Lovejoy et al., 2002
<i>P. multiseriis</i> (Hasle) Hasle [AST]	• ¹		•	• ^e	•	•		Subba Rao et al., 1988; Bates et al., 1989, 2020; Taylor and Haigh, 1996; Kaczmarek et al., 2005; Lassus et al., 2016
<i>P. obtusa</i> (Hasle) Hasle & Lundholm [AST] ⁴		•	• ⁵		• ⁵		•	Bates et al., 2018, 2020; M. Poulin, unpubl. data
<i>P. pseudodelicatissima</i> (Hasle) Hasle [AST]	•	•	•	•	• ^e	•	• ^s	Martin et al., 1990b; Bérard-Therriault et al., 1999; Róžańska et al., 2009; Simo-Matchim et al., 2017 (Suppl. material, Table S1); OBIS, 2019; Bates et al., 2020; K. Howland; C. McKenzie; M. Poulin; N. Simard, unpubl. data
<i>P. pungens</i> (Grunow ex Cleve) Hasle [AST] ³	•	•	•	•	•	•	• ^s	Bérard-Therriault et al., 1999; Kaczmarek et al., 2005; Róžańska et al., 2009; Poulin et al., 2011; Martin and LeGresley, 2014; Lassus et al., 2016; OBIS, 2019; Bates et al., 2020; C. McKenzie; M. Poulin, unpubl. data

Species [Phycotoxin produced]	Canadian province/region							References for distribution
	NL	QC	NS	PE	NB	BC	Arctic	
<i>P. seriata</i> (Cleve) H. Peragallo [AST]	•	• ^e	• ^e	• ^e	• ^e	•	• ^s	Bérard-Therriault et al., 1999; Penney et al., 2001; Kaczmarek et al., 2007; Róžańska et al., 2009; Mather et al., 2010; Poulin et al., 2011; Simo-Matchim et al., 2017 (Suppl. material, Table S1); OBIS, 2019; Bates et al., 2020; K. Howland; C. McKenzie; M. Poulin; N. Simard, unpubl. data
<i>P. subpacifici</i> (Hasle) Hasle [AST]			• ⁵	•	•			Bates and Strain, 2006; Martin and LeGresley, 2014
<i>P. turgidula</i> (Hustedt) Hasle [AST]			• ⁵			• ⁵	• ^s	Róžańska et al., 2009; Poulin et al., 2011; Fernandes et al., 2014; K. Howland; M. Poulin; N. Simard, unpubl. data
DINOFLAGELLATES								
<i>Alexandrium acatenella</i> (Whedon & Kofoid) Balech [PST]							• ^e	Taylor and Haigh, 1996; Lassus et al., 2016
<i>A. catenella</i> (Whedon & Kofoid) Balech [PST]	• ^e	• ^e	• ^e	•	• ^e	• ^e	• ^s	White, 1977, 1980; McKenzie and Schwinghamer, 1994; Taylor and Haigh, 1996; McKenzie et al., 1998; Bérard-Therriault et al., 1999; Cembella, 2002; Martin et al., 2008, 2014a,b; Niemi et al., 2011; Bates et al., 2020
<i>A. ostenfeldii</i> (Paulsen) Balech & Tangen [PST]		•	•		•	•	•	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; K. Howland; M. Poulin; N. Simard, unpubl. data
<i>Dinophysis acuminata</i> Claparède & Lachmann [DST, PTX]	•	•	•	•	•	• ^e	• ^s	Taylor and Haigh, 1996; Bérard-Therriault et al., 1999; Róžańska et al., 2008; Poulin et al., 2011; Martin and LeGresley, 2014; Lassus et al., 2016; Dhifallah, 2019; OBIS, 2019; Bates et al., 2020; K. Howland; C. McKenzie; M. Poulin; A. Rochon; N. Simard, unpubl. data
<i>D. acuta</i> Ehrenberg [DST]	•	•	•	•	•	•	•	Sita Devi and Lakshminarayana, 1989; Taylor and Haigh, 1996; Bérard-Therriault et al., 1999; Poulin et al., 2011; Martin and LeGresley, 2014; Simo-Matchim et al., 2017 (Suppl. material, Table S1); Dhifallah, 2019; OBIS, 2019; C. McKenzie; M. Poulin; A. Rochon, unpubl. data
<i>D. fortii</i> Pavillard [DST]			•		•	•		Taylor and Haigh, 1996; Poulin et al., 2011; Martin and LeGresley, 2014; OBIS, 2019; Bates et al., 2020; C. M. Poulin, unpubl. data
<i>D. norvegica</i> Claparède & Lachmann [DST]	• ^e	• ^e	• ^e	•	•		•	McKenzie 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; Simo-Matchim et al., 2017 (Suppl. material, Table S1); OBIS, 2019; Dhifallah, 2019; Bates et al., 2020; K. Howland; C. McKenzie; M. Poulin; A. Rochon; N. Simard, unpubl. data

Species [Phycotoxin produced]	Canadian province/region							References for distribution
	NL	QC	NS	PE	NB	BC	Arctic	
<i>Phalacroma rotundatum</i> (Claparède & Lachmann) Kofoid & Michener [DST, PTX]	•	•	•	•	•	•	•	Bérard-Therriault et al., 1999; Poulin et al., 2011; Martin and LeGresley, 2014; Lassus et al., 2016; Simo-Matchim et al., 2017 (Suppl. material, Table S1); Dhifalah, 2019; OBIS, 2019; C. McKenzie; M. Poulin; A. Rochon, unpubl. data
<i>Prorocentrum lima</i> (Ehrenberg) Stein [DST]	• ^e	•	• ^e				• ^s	Bérard-Therriault et al., 1999; McKenzie, 2006; Niemi et al., 2011; Poulin et al., 2011; OBIS, 2019; Bates et al., 2020; C. McKenzie; M. Poulin, unpubl. data

- 273
- 274 • Species presence reported.
- 275 ^e Region where a species caused a documented harmful algal event.
- 276 [†] Phycotoxin detected.
- 277 ^{†c} Toxic in culture.
- 278 ^s Species identified in both pelagic and sympagic samples.
- 279 ¹ Species not confirmed.
- 280 ² Considered non-toxic in Canada but some species in this complex are AST producers (Bates et
281 al., 2018).
- 282 ³ No record of toxicity in cold temperate locations.
- 283 ⁴ Toxic in culture from cold temperate locations (Disco Bay, Greenland; Harðardóttir et al.,
284 2015).
- 285 ⁵ Reference lists its presence in the Bay of Fundy.
- 286
- 287

288 Species included in Table 2 are those designated as harmful in Lassus et al. (2016) and/or
289 are listed in the IOC-UNESCO Taxonomic Reference List of Harmful Micro Algae (Moestrup et
290 al., 2009) and that have caused non-phycotoxin related events in Canadian waters, or are present
291 in Canada and have caused events in regions outside of Canada. In addition to these listed
292 species any bloom-forming phytoplankton species, under the right conditions, could create a
293 hypoxic environment and thereby a harmful algal event.

294

295 **Table 2.** List of phytoplankton, including sympagic (sea ice-associated) algal species, found in
296 Canadian waters and known to cause the morbidity or mortality of marine species. Species in
297 bold have caused harmful algal events in Canadian waters. The remaining species have caused
298 events only in regions outside of Canada.

299

Species	Canadian province/region							References for distribution
	NL	QC	NS	PE	NB	BC	Arctic	
CENTRIC DIATOMS								
<i>Chaetoceros concavicornis</i> ¹ Mangin	•	•	•		•	• ^e	• ^s	Haigh and Taylor, 1990; Bérard-Therriault et al., 1999; Lovejoy et al., 2002; Melnikov et al., 2002; Bates and Strain, 2006; Martin and LeGresley, 2014; Lassus et al., 2016; OBIS, 2019; C. McKenzie; M. Poulin,

Species	Canadian province/region							References for distribution
	NL	QC	NS	PE	NB	BC	Arctic	
								unpubl. data
<i>C. convolutus</i> ¹ Castracane	•	•	•		•	• ^e	• ^s	Haigh and Taylor, 1990; Bérard-Therriault et al., 1999; Lovejoy et al., 2002; Melnikov et al., 2002; Bates and Strain, 2006; Martin and LeGresley, 2014; Lassus et al., 2016; OBIS, 2019; Bates et al., 2020; C. McKenzie, unpubl. data
<i>C. debilis</i> ¹ Cleve	•	•	•	•	•	•	•	Bérard-Therriault et al., 1999; Penney et al., 2001; Lovejoy et al., 2002; Bates and Strain, 2006; Martin and LeGresley, 2014; Lassus et al., 2016; OBIS, 2019
<i>Corethron hystrix</i> ¹ Hensen	•	•	•	•	•	•	•	Grøntved and Seidenfaden, 1938; Bates and Strain, 2006; Martin and LeGresley, 2014; OBIS, 2019
DINOFLAGELLATES								
<i>Akashiwo sanguinea</i> ² (Hirasaka) Hansen & Moestrup				•		• ^e		Lassus et al., 2016; OBIS, 2019
<i>Coolia monotis</i> ³ Meunier		•	•				• ^s	Hsiao et al., 1984; Poulin et al., 2011; Lewis et al., 2018; OBIS, 2019
<i>Gonyaulax spinifera</i> (Claparède & Lachmann) Diesing	•	•	•	•	•	• ^e	•	Heath and Lindsay, 1993; Bérard-Therriault et al., 1999; Lovejoy et al., 2002; Bates and Strain, 2006; Poulin et al., 2011; Martin and LeGresley, 2014; Dhifallah, 2019; C. McKenzie; A. Rochon, unpubl. data
<i>Karenia mikimotoi</i> ⁴ (Miyake & Kominami ex Oda) Hansen & Moestrup		•		•		•	•	Bérard-Therriault et al., 1999; Bates and Strain, 2006; Haigh, 2017; OBIS, 2019; M. Poulin, unpubl. data
<i>Karlodinium veneficum</i> ⁵ (Ballantine) Larsen		•	•			•		Bérard-Therriault et al., 1999; Lassus et al., 2016; Haigh, 2017
<i>Margalefidinium fulvescens</i> ⁶ (Iwataki, Kawami & Matsuoka) Gómez, Richlen & Anderson						•		Bates et al., 2020
<i>M. polykrikoides</i> ⁶ (Margalef) Gómez, Richlen & Anderson						•		Bates et al., 2020
<i>Prorocentrum cordatum</i> ⁷ (Ostenfeld) Dodge		•	•	•			•	Lovejoy et al., 2002; OBIS, 2019
DICTYOCOPHYTES								
<i>Dictyocha fibula</i> ¹ Ehrenberg	•	•	•	•	•	• ^e		Bérard-Therriault et al., 1999; Bates and Strain, 2006; Martin and LeGresley, 2014; OBIS, 2019; Bates et al., 2020; C. McKenzie, unpubl. data

Species	Canadian province/region							References for distribution
	NL	QC	NS	PE	NB	BC	Arctic	
<i>Octactis speculum</i> ^{1,8} (Ehrenberg) Chang, Grieve & Sutherland	•	•	•	•	•	• ^e	• ^s	Lovejoy et al., 2002; Bates and Strain, 2006; Róžańska et al., 2008; Haigh, 2017; OBIS, 2019; C. McKenzie; M. Poulin, unpubl. data
<i>Pseudochattonella verruculosa</i> ⁹ (Hara & Chihara) Tanabe-Hosoi, Honda, Fukaya, Inagaki & Sako						• ^{e,tc}		Lassus et al., 2016; Haigh, 2017
PRYMNESIOPHYTES								
<i>Haptolina ericina</i> ¹⁰ (Parke & Manton) Edvardsen & Eikrem		•				• ^e		Bérard-Therriault et al., 1999; Haigh, 2017; OBIS, 2019
<i>H. hirta</i> ¹⁰ (Manton) Edvardsen & Eikrem						• ^e		Haigh, 2017
<i>Phaeocystis pouchetii</i> ¹¹ (Hariot) Lagerheim	•	•	•		•	•	• ^s	Bérard-Therriault et al., 1999; Penney et al., 2001; Niemi et al., 2011; Poulin et al., 2011; Martin and LeGresley, 2014; Simo-Matchim et al., 2017 (Suppl. material, Table S1); OBIS, 2019; C. McKenzie, unpubl. data
<i>Prymnesium polylepis</i> ¹² (Manton & Parke) Edvardsen, Eikrem & Probert		•				•		Taylor and Haigh, 1996; Bérard-Therriault et al., 1999; OBIS, 2019; Bates et al., 2020
RAPHIDOPHYTES								
<i>Heterosigma akashiwo</i> ¹³ (Hada) Hada ex Hara & Chihara		•				• ^e	•	Haigh and Taylor, 1990; Bérard-Therriault et al., 1999; Poulin et al., 2011; Simo-Matchim et al., 2017 (Suppl. material, Table S1); Bates et al., 2020; K. Howland; M. Poulin; N. Simard, unpubl. data
CILIATES								
<i>Mesodinium rubrum</i> Leegaard	•	•	•	•	• ^e	•	•	Parrish et al., 1995; Bérard-Therriault et al., 1999; Lovejoy et al., 2002; Bates and Strain, 2006; Martin et al., 2007; Haigh, 2017; Dhifallah, 2019; OBIS, 2019

300

301 • Species presence reported.

302 ^e Region where a species caused a documented harmful algal event.303 ^{tc} Toxic in culture.304 ^s Species identified in both pelagic and sympagic samples.305 ¹ Possess barbs or spines that are physically harmful to fish and/or shellfish.306 ² Produces surfactants harmful to seabirds and molluscs; responsible for oyster mortalities in BC.307 ³ May produce haemolytic substances and a potential yessotoxin derivative.308 ⁴ Ichthyotoxic, haemolytic and cytotoxic.309 ⁵ Produces karlotoxins; ichthyotoxic; neurotoxic, haemolytic.310 ⁶ Associated with fish kills; may be ichthyotoxic, producer of reactive oxygen species (ROS) or

311 extracellular mucoid polysaccharide substances.

312 ⁷ Hepatotoxicity in mice; toxicity or adverse effects on molluscs and *Artemia* nauplii; possible link
313 to tetrodotoxin.

314 ⁸ May produce phycotoxins.

315 ⁹ Ichthyotoxic.

316 ¹⁰ More than one species of the genus *Haptolina* may have been responsible for farmed salmon
317 mortalities in BC.

318 ¹¹ Toxic to cod larvae in Norway.

319 ¹² Produces haemolytic compounds and ichthyotoxic exotoxins.

320 ¹³ Ichthyotoxic species; mechanism of action still unknown; may produce ROS or haemolytic
321 substances.

322

323 *1.3. Compilation of harmful algal events in Canadian marine waters*

324

325 To evaluate the last three decades of harmful algal events, all Canadian data were extracted
326 from HAEDAT and summarized to examine spatial and temporal distributions of events.

327 Additional information and references from Bates et al. (2020), and other primary publications
328 and government reports, augment the event information from HAEDAT.

329

330 A Canadian harmful algae workshop with scientists from DFO, CFIA, the National
331 Research Council (NRC) and academia, including several retired researchers, was held at the
332 Bedford Institute of Oceanography (Dartmouth, NS) in September 2018. It provided a unique
333 opportunity to examine and validate the HAEDAT data in preparation for a comprehensive
334 report of HA events in Canada. Thirty years of Canadian HAEDAT reports and supplemental
335 information were examined. Information on HA species monitoring and detection was combined
336 with shellfish phycotoxin monitoring and accompanying closure events, when data were
337 available. All HAEDAT reports that met the requirement of an event were included,
338 supplemented by additional information on phytoplankton detections. Due to changes in
339 monitoring programs and data reporting, the most complete and standardized Canadian event
340 information added to HAEDAT is from 2000 to present.

341

342 No HAEDAT information exists for the Canadian Arctic, and there is currently no
343 phycotoxin monitoring program in that region. The Arctic summary included in this paper is
344 therefore based on recent studies and available literature of harmful pelagic phytoplankton and
345 sympagic algal species that have previously been associated with harmful algal events in Canada
346 (e.g. Poulin et al., 2011; Dhifallah, 2019; K. Howland; C. McKenzie; M. Poulin; A. Rochon; N.
347 Simard, unpubl. data).

348

349 **2.0. Harmful algal events in Canadian marine waters recorded in HAEDAT**

350

351 *2.1. Overview of events*

352

353 A summary of HAEDAT events reported in Canada (2000 to 2017) is shown in Fig. 1.
354 Events reported prior to 2000 preclude robust comparison due to limitations (and gaps) in the
355 reporting method. During 2000-2017, phycotoxin events associated with AST, PST and DST
356 were reported, with PST events being the most common and widespread (Fig. 1A). Marine
357 mortalities due to physical effects or unknown causes were reported on both coasts but are more

358 prevalent on the Pacific coast at farmed salmon sites, whereas finfish mortalities due to
359 phycotoxins are more prevalent on the Atlantic coast.

360

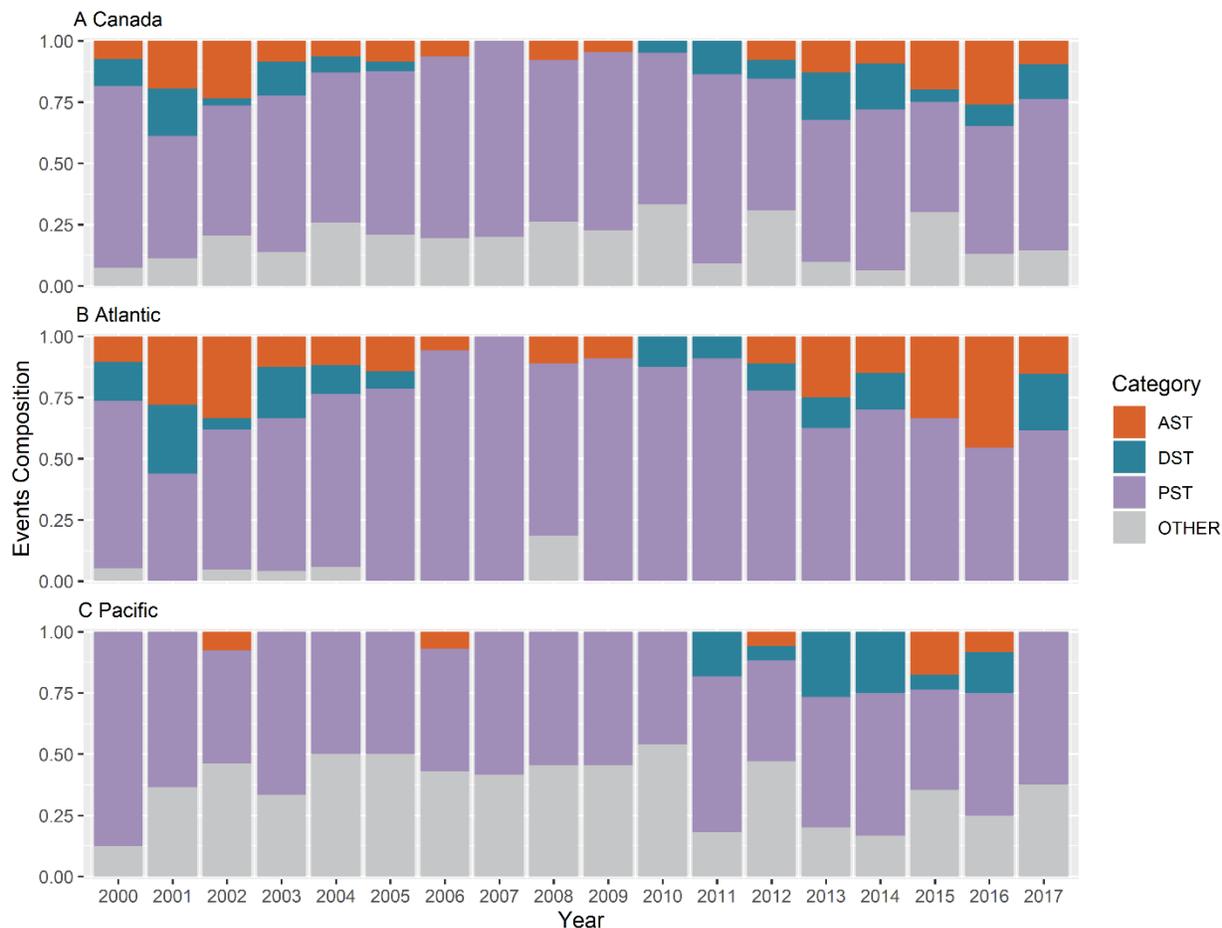
361 On the Atlantic coast, PST events occurred annually and are the most frequently reported
362 HA event (Fig. 1B), constituting the highest proportion of HAEDAT reports since 2000. AST
363 events are reported in all but three years and DST events in all but six years. Marine mortalities
364 due to HA occurred in both farmed and wild fish but did not occur every year.

365

366 PST events are the most widespread category on the BC coast, occurring annually since
367 2000, although not always in the same area (Fig. 1C). From 2000 to 2017, fish mortalities were
368 also observed every year and, following PST events, were the dominant events (Fig. 1C). Fish
369 mortality events were first reported sporadically, but they increased after 2001, in part due to
370 increased monitoring after establishment of the Harmful Algae Monitoring Program (HAMP) by
371 DFO and the BC salmon farming industry in 1999. Multiple species of flagellates have been
372 linked to mass mortalities of farmed Atlantic salmon (*Salmo salar*) on the Pacific coast since
373 2001. These mortality events have occurred in most years, from 2001 to 2017, sometimes
374 involving multiple flagellate species. The earliest HAEDAT report of an AST event on the
375 Pacific coast was in 1992. There were five HAEDAT reports of AST events from 2000 to 2017
376 (Fig. 1C). DST events were first reported in 2011, and were observed in all but one year since
377 then (Fig. 1C).

378

379



380
 381 **Fig. 1.** Proportion of harmful algal events reported in HAEDAT (2000 to 2017) for AST =
 382 amnesic shellfish toxin, DST = diarrhetic shellfish toxin, PST = paralytic shellfish toxin, and
 383 OTHER = marine mortalities for Canada (A), Atlantic Canadian coast (B), and Pacific Canadian
 384 coast (C).

385
 386 To identify recurring events and their spatial spread over the past 30 years, events were mapped
 387 using information from HAEDAT records (Figs 2-5). Events that occurred as a result of
 388 phycotoxins (AST, PST, DST) include those that caused morbidity or mortality of humans, resulted
 389 in shellfish area closures, or were associated with mass die-offs of marine species. The marine
 390 mortalities category includes mass die-offs of marine species due to any phytoplankton-related
 391 event, either through production of phycotoxins (in which case it is also counted as a phycotoxin
 392 event), physical damage (e.g. to fish gills), or hypoxia resulting from dense phytoplankton blooms.
 393 Event occurrences were summarized for three 10-year periods (1988-1997; 1998-2007; 2008-2017),
 394 with a final cumulative map for the 30-year period (1988-2017). These maps illustrate changes in
 395 the spatial distribution of reported events and identify areas of recurrence. However, when
 396 comparing the map data from the Canadian Pacific and Atlantic coasts it should be noted that the
 397 Pacific coast has only seven HAEDAT areas, whereas the Atlantic coast has been divided into more
 398 than 20 areas. This artefact of the ICES / Atlantic origin of HAEDAT means that Pacific data are
 399 pooled into larger areas and therefore give less information on fine-scale geographic distribution of
 400 HA in this area.

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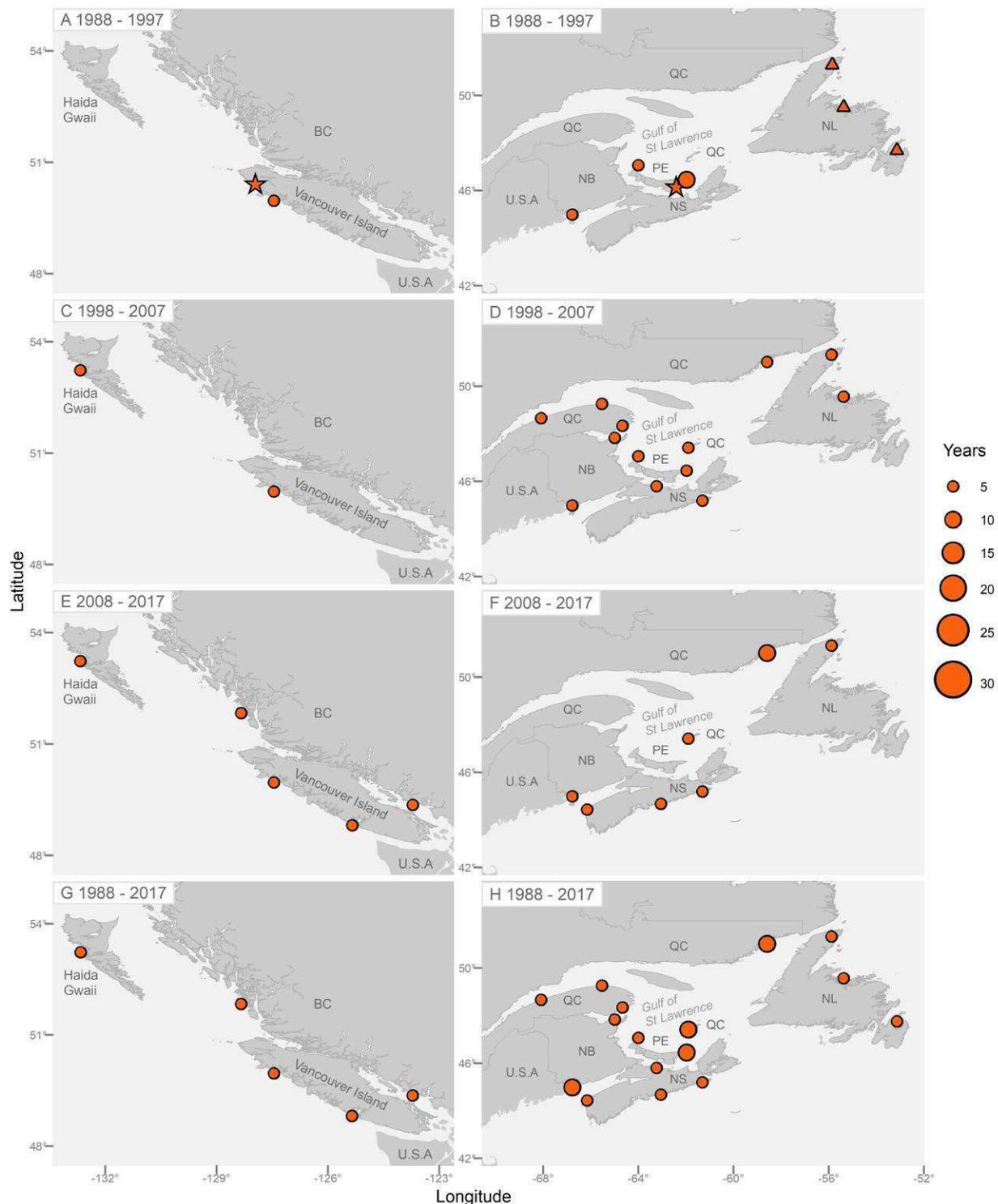
2.2. Decadal overview of AST events for Atlantic and Pacific Canada

In 1987, an outbreak of an unidentified toxin was responsible for over 150 human illnesses and three deaths in Canada, following the consumption of blue mussels (*Mytilus edulis*) (Bates et al., 1989). DFO inspectors traced the source of the mussels to aquaculture sites in Cardigan Bay, PE (Fig. 2B), and shellfish harvesting in all of Atlantic Canada was closed on December 11. Five days later, the NRC detected the presence of the neurotoxin DA in blue mussels, for the first time worldwide (Quilliam and Wright, 1989). The syndrome was termed amnesic shellfish poisoning based on the characteristic symptoms observed. The pennate diatom *Pseudo-nitzschia multiseriis* was found in the mussel digestive tract, and was confirmed to be the source of the AST (Subba Rao et al., 1988; Bates et al., 1989). This was the first discovery of a phycotoxin-producing diatom species. In the years following the discovery of AST, harmful algae events due to high levels of this phycotoxin recurred in PE (1988-1992, 1994, 2000, 2001, 2002; Bates et al., 2020).

In 1988, AST was reported for the first time in southwestern NB (Bay of Fundy) (Fig. 2B), and resulted in a shellfish harvest closure only in Passamaquoddy Bay. Later AST events (1995, 2008, 2016) occurred elsewhere in the Bay of Fundy, including the Annapolis Basin (NS), but did not recur in Passamaquoddy Bay. The NB events in 1988, 1995, and 2008 were linked to high cell concentrations of *P. pseudodelicatissima* (Martin et al., 1990b, 1998; J.L. Martin, unpubl. data), whereas the 2016 event was associated with *P. australis* (J. Ehrman; J.L. Martin, unpubl. data). This species was not previously observed in that region (Kaczmarska et al., 2005; Bates et al., 2018). Low levels of AST were also detected for the first time in NL in 1994 (Fig. 2B); no closures were issued as levels remained below the regulatory limit. Closures continued in the St. Lawrence Estuary in 2000, and the north coast of the Gulf of St. Lawrence (Mecatina Trough, near Tête-à-la-Baleine) in 2001, and St. Lunaire Bay, northern NL, in 2001 (Fig. 3D). In December 2001, and again in March 2002, several *Pseudo-nitzschia* species caused the largest AST 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 (Bates et al., 2020).

Between 1998 and 2007, AST events occurred on the Magdalen Islands (in the Gulf of St. Lawrence, QC) (1998), the Atlantic coast of NS (2001), and much of Atlantic Canada including the Estuary and Gulf of St. Lawrence, the Strait of Belle Isle (between Labrador and the island of Newfoundland), and the Bay of Fundy (2008) (Fig. 2F).

On the Pacific coast, the first AST event was reported on Vancouver Island in 1992 (Fig. 2A). In the following years, AST events occurred throughout the Strait of Georgia, on the west coast of Vancouver Island, and on the Haida Gwaii archipelago (Fig. 2C, E). In 2015, an extensive AST-producing *Pseudo-nitzschia australis* bloom on the North American Pacific coast, including BC, was linked to anomalous warm ocean conditions (McCabe et al., 2016). It caused shellfish harvesting closures and mortalities of marine life (fish, mammals, and seabirds) (McCabe et al., 2016; McKibben et al., 2017).



446
 447 **Fig. 2.** Distribution and recurrence (number of years with events) of AST events reported in
 448 HAEDAT in 10-year periods and 30-year summary: Pacific (A,C,E,G) and Atlantic (B,D,F,H)
 449 coasts of Canada. Stars indicate the first reported ASP event in PE (1987) (B) and AST event in
 450 BC (1992) (A), and triangles the first detections of AST below the regulatory limit in NL (1994)
 451 (B).
 452

453 Trends in the prevalence of AST events are illustrated in maps showing their recurrence
454 over a 30-year period (Fig. 2G, H). On the Pacific coast, AST events have occurred throughout the
455 Strait of Georgia, the west coast of Vancouver Island, in selected areas of the north coast of
456 Vancouver Island, and on the Haida Gwaii archipelago (Fig. 2G). On the Atlantic coast, AST
457 events have occurred on the southwest NB portion of the Bay of Fundy and southwest NS, the
458 southern Gulf of St. Lawrence, including Chaleur Bay (QC), the northern shore of the Estuary
459 and Gulf of St. Lawrence (QC), and the southeastern and northeastern shores of NL (Fig. 2H).

460

461 2.3 Decadal overview of PST events for Atlantic and Pacific Canada

462

463 The earliest HAEDAT record of PSTs on the Pacific coast was in 1987, in the upper Strait
464 of Georgia and was also reported during the review period Fig. 3A). However, it was
465 underreported due to broad closures along the coast. On the Atlantic coast, several areas,
466 including the Bay of Fundy, the Estuary and Gulf of St. Lawrence, and the south and northwest
467 coast of NL, were known to have recurring levels of PSTs from 1987 and 1988 to 1997, as
468 documented in HAEDAT (Fig. 3B). These events recurred and their spatial range spread during
469 the next decade (1998 to 2007) (Fig. 3D). The Bay of Fundy and the Estuary and Gulf of St.
470 Lawrence are both particularly important locations for multi-year events, as indicated by the size
471 of the circles (Fig. 3H).

472

473 One of the main reasons for the yearly events caused by toxic *Alexandrium* blooms is their
474 ability to produce resting cysts that overwinter in sediments; resuspension of cysts can initiate
475 blooms in subsequent seasons. For example, the Bay of Fundy has one of the richest, stable cyst
476 deposits of *A. catenella* in the world. Although cysts in sediments are important for initiating
477 blooms, their concentration does not play a role in predicting bloom intensity from year to year
478 in the St. Lawrence Estuary or the Bay of Fundy (Gracia et al., 2013; Martin et al., 2014a).

479

480 In December 1991, PSTs were detected in mussels in Notre Dame Bay (NL). The timing
481 was unusual for vegetative cells of *A. catenella*. Further investigation revealed that resuspended
482 *A. catenella* cysts were responsible for the event. The presence of *A. catenella* cysts or the
483 continued presence of PSTs above the regulatory level in shellfish tissues led to the permanent
484 closure of several sites to molluscan shellfish aquaculture and wild harvest in NL, the Bay of
485 Fundy (NB) and QC. Closure of one site in Pilley's Tickle (NL) resulted in the loss of 9.1 tonnes
486 of farmed mussels, as they remained above the PST regulatory limit (McKenzie, 1996).

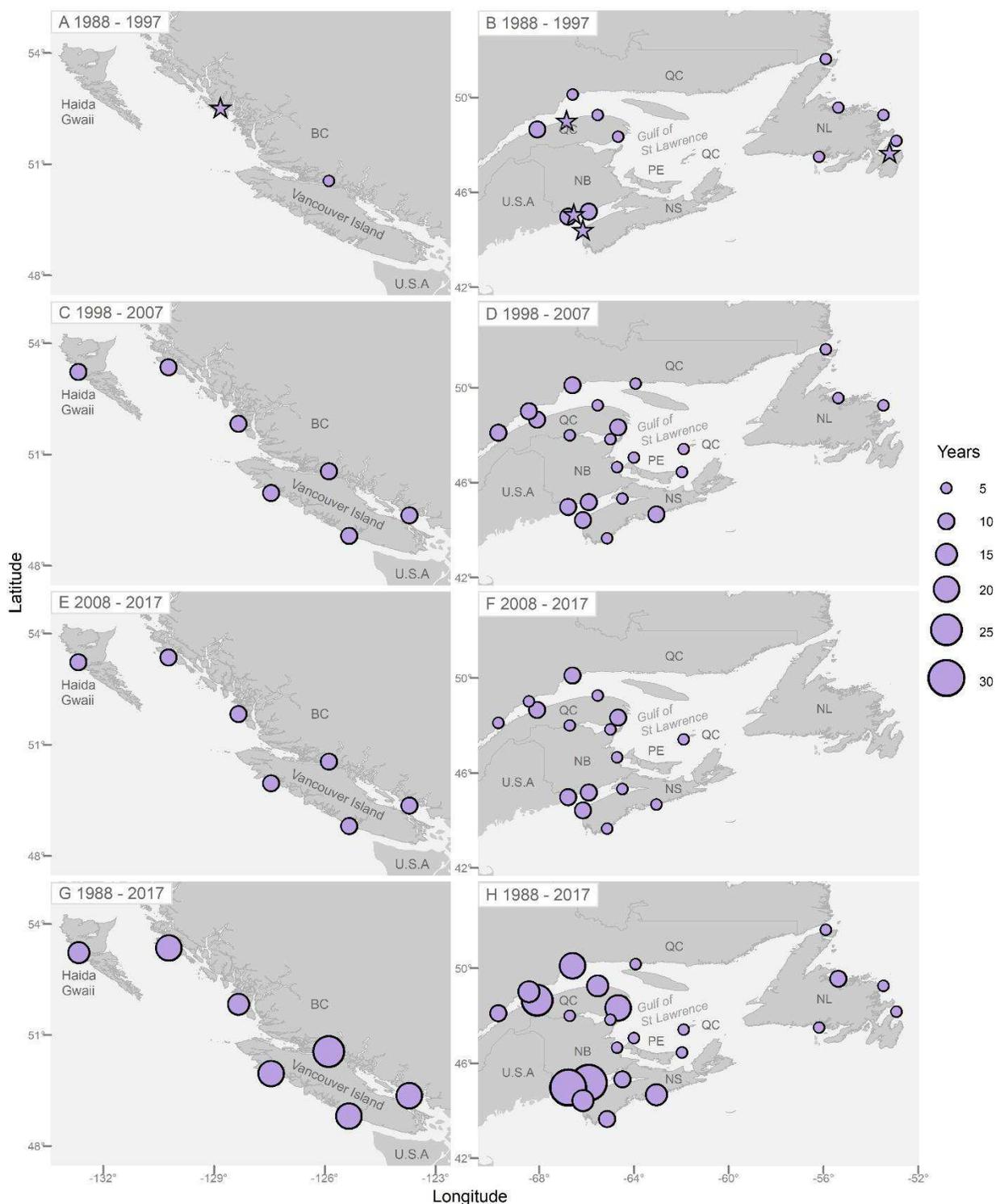
487

488 The lack of reports when shellfish harvesting areas were closed to harvesting for extended
489 periods does not mean that no blooms or events occurred during this closure, as in most cases
490 samples were not taken at these closed sites. An exception is the Bay of Fundy, where samples
491 continued to be collected regularly during closure and results indicated the persistence of PSTs
492 above the regulatory limit since 1980. On the Pacific coast, shellfish monitoring occurs every
493 year (since 1942). However, large areas remain closed because of difficulties sampling the
494 remote and complex shoreline (Taylor, 1993). These closures include areas that are difficult to
495 access, have low habitation, and where there are local Indigenous laws against shellfish
496 consumption (Taylor and Horner, 1994).

497

498

499



500
 501 **Fig. 3.** Distribution and recurrence (number of years with events) of PST events reported in
 502 HAEDAT in 10-year periods and 30-year summary: Pacific (A,C,E,G) and Atlantic (B,D,F,H)
 503 coasts of Canada. Stars in maps A and B indicate the first reported PSP events in BC (1793), NS
 504 (1936), NB (1936), QC (1948), and NL (1982).
 505

506 When the reports of PST events are combined over a 30-year period, there is a clear trend of
507 frequently recurring events throughout both the Pacific (Fig. 3G) and Atlantic (Fig. 3H) regions.
508 PST events have been recorded in HAEDAT annually on Canada's Atlantic and Pacific coasts
509 since the dataset was initiated. These events are prevalent throughout the Bay of Fundy, the St.
510 Lawrence Estuary, and QC/NB shores of the Gulf of St. Lawrence. Their distribution is
511 discontinuous on the Atlantic shores of NS, PE and NL. PST events are widespread on the
512 Canadian Pacific coast, occurring regularly in many coastal areas.

513

514 2.4. Decadal overview of DST events for Atlantic and Pacific Canada

515

516 Cembella (1989) documented the first detection of DSTs (below the regulatory limit) in
517 North America, produced by the dinoflagellates *Dinophysis norvegica* and *D. acuminata*, in the
518 lower St. Lawrence Estuary (Fig. 4B). The first case of DSP was reported in July 1990, in
519 eastern NS. Remnants of *D. norvegica* were found in mussel digestive glands, and several
520 *Dinophysis* species (including *D. norvegica*) were found throughout the water column (Quilliam
521 et al., 1993; Subba Rao et al., 1993). The first official closure of shellfish harvesting due to DSTs
522 in Canada was in August-September 1992, in Mahone Bay, NS (Gilgan et al., 1995). Another
523 DST closure, with three human poisonings reported, occurred in late October 1993, associated
524 with a *D. norvegica* bloom, in Bonavista Bay, NL (McKenzie, 1996). This event continued for
525 many months into the next year, as cold temperatures slowed the mussels' depuration rate.
526 Isolated DST events are common, although not reported annually throughout the 30-year
527 HAEDAT dataset.

528

529 During the first decade (1988 to 1997) and after its initial detection in 1989, DST events
530 were reported in every province in Atlantic Canada (Fig. 4B). On the Magdalen Islands (QC), an
531 area previously considered to be free of phycotoxins, trace levels of DSTs were detected in
532 farmed blue mussels in 1998 (Levasseur et al., 2003) following 26 reported DSP human
533 poisonings in QC. Further investigation in 1999 revealed the presence of dinoflagellates
534 *Prorocentrum lima* and *P. mexicanum* in the water column, as epiphytes on mussel socks, and in
535 the gut contents of mussels (Levasseur et al., 2003). In 2001, following rejection of NL mussel
536 product by the United Kingdom due to DST levels, investigation of the aquaculture mussel lines
537 in Notre Dame Bay (NL) revealed the dinoflagellate *P. lima* growing epiphytically on mussel
538 socks, as well as in the gut contents of mussels (McKenzie, 2006).

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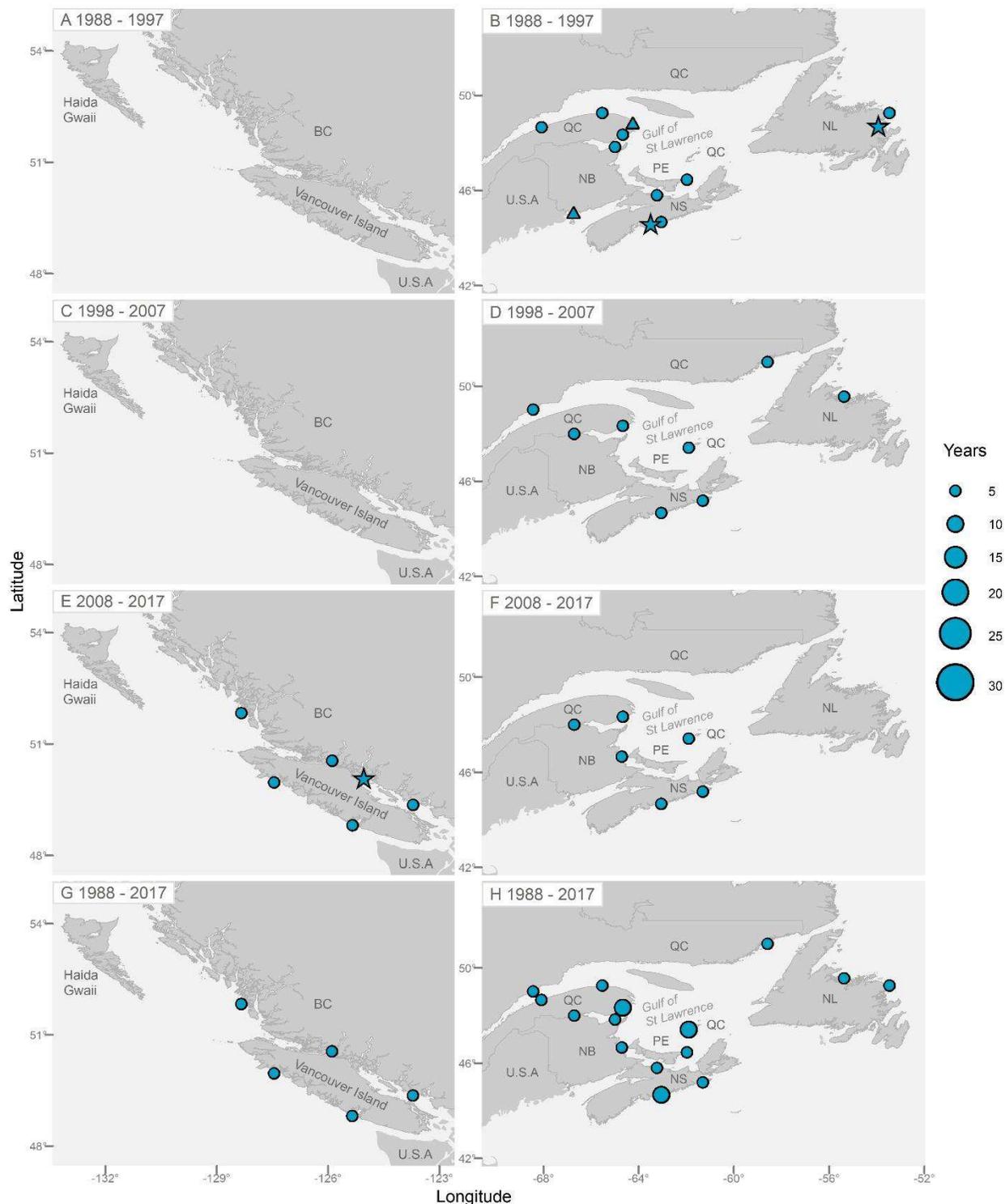
540 A study of potentially harmful phytoplankton in the Pacific region revealed the presence of
541 *Dinophysis* species in 1986 (Haigh and Taylor, 1990). It was not until 2011 that DSP symptoms
542 were linked to the human consumption of mussels from the upper Strait of Georgia (Taylor et al.,
543 2013). A HAMP phytoplankton monitoring site for the salmon aquaculture industry, located 25
544 km away from the mussel culture site, identified a mixture of *Dinophysis* species (*D. acuminata*,
545 *D. fortii*, *D. acuta*) and *Phalacrocoma rotundatum*. Since then, DST events have occurred
546 periodically in the Strait of Georgia, the west coast of Vancouver Island, and the central BC
547 coast.

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551



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 553 **Fig. 4.** Distribution and recurrence (number of years with events) of DST events reported in
 554 HAEDAT in 10-year periods and 30-year summary: Pacific (A,C,E,G) and Atlantic (B,D,F,H)
 555 coasts of Canada. The maps also indicate the first detection of DSTs in QC (1989), NB (1992)
 556 (triangles), and the first DSP events in NS (1990), NL (1993), and BC (2011) (stars).
 557

558 Trends in DST events are illustrated in maps showing their recurrence over a 30-year period
 559 (Fig. 4). On the Atlantic coast, DST events have been reported along the south shore of the St.
 560 Lawrence Estuary, extending into the northern part of the southern Gulf of St. Lawrence, the
 561 northern Gulf of St. Lawrence, at one location in eastern PE, the Magdalen Islands (QC),
 562 Bedford Basin and Mahone Bay (NS), and on the northeast coasts of NL (Fig. 4H). Along the
 563 Pacific coast, DST events have been reported on the south or central coast of the mainland, and
 564 several locations on the west coast of Vancouver Island (Fig. 4G). The limited number of
 565 samples analysed for DSTs before 2011 may explain the absence of events recorded along the
 566 Pacific coast (Fig. 4A, C).

567

568 2.5. Decadal overview of marine species mortality and other events

569

570 On the Pacific coast, although the diatoms *Chaetoceros convolutus* and *C. concavicornis*
 571 have been reported to cause fish kills since 1961 (Bell, 1961), and flagellate-related fish
 572 mortality events have been described since 1976 (Gaines and Taylor, 1986), the first reported
 573 HAEDAT fish kill events were in the upper Strait of Georgia during March to November 1987,
 574 when mortalities of aquaculture salmon were observed during blooms of *C. convolutus* and *C.*
 575 *concavicornis*. Salmon mortalities were again caused by a mixture of these species on the lower
 576 Strait of Georgia in 2001, followed by the upper west coast of Vancouver Island in 2002, and the
 577 lower west coast of Vancouver Island in 2010. Mortality is caused by physical damage to fish
 578 gills, which was suggested to lead to microbial infections or hemorrhaging of gill tissues, or to
 579 asphyxiation due to overproduction of mucus on the gills (Bell, 1961; Yang and Albright,
 580 1992). Sub-lethal concentrations of these HA have also led to mortalities due to bacterial or viral
 581 infections (Albright et al., 1993). The mortality of aquaculture fish due to blooms of these diatom
 582 species has been reported frequently (Fig. 5A), but not annually. There has been increased
 583 monitoring after establishing the HAMP in 1999.

584

585 In 1990, an intense bloom of the dinoflagellate *Gonyaulax spinifera* was accompanied by
 586 mass mortalities of clams, mussels and oysters in Barkley Sound on the west coast of Vancouver
 587 Island (Heath and Lindsay, 1993). The mode of action was suggested to be oxygen depletion
 588 during the bloom decline.

589

590 The raphidophyte *Heterosigma akashiwo* has been responsible for the mortality of
 591 aquaculture fish in the Pacific region since the 1970s (Gaines and Taylor, 1986; Haigh and
 592 Taylor, 1990; Taylor, 1993; Haigh and Esenkulova, 2014). Although the mode of action is still
 593 not fully understood, it is thought to be due to the production of haemolytic substances (Lassus et
 594 al., 2016). The first recorded bloom of *H. akashiwo* in HAEDAT was on the upper west coast of
 595 Vancouver Island, in Kyuquot Sound and Nootka Sound in late August 1992 (Fig. 5A). It
 596 affected several aquaculture operations in the area, resulting in the mortality of ~250,000 kg of
 597 salmon and over \$1.5 million in economic losses. In June 2018, two salmon farms lost ~250,000
 598 fish, nearly half of their product, because of a bloom of *H. akashiwo* (Bates et al., 2020).
 599 Aquaculture fish kills due to *H. akashiwo* blooms have been reported almost every year (Fig.
 600 1C). In 2002, another ichthyotoxic raphidophyte, an unidentified species of the genus
 601 *Chattonella*, was responsible for the mortality of almost one thousand tonnes of farmed Atlantic
 602 salmon (*Salmo salar*) in Esperanza Inlet, on the upper west coast of Vancouver Island (Fig. 5C).

603

604 Multiple flagellate species were linked to mass mortalities of aquaculture fish on the Pacific
605 coast from 2001 to 2017 (Fig. 5C, E). Blooms of prymnesiophytes (*Haptolina ericina* and *H.*
606 *hirta*) have been responsible for farmed salmon mortalities and for negatively affecting their
607 behavior (Haigh, 2017). Ichthyotoxic dictyochophytes (*Octactis speculum*, *Dictyocha fibula*, and
608 *Pseudochattonella verruculosa*) have also been linked to mortalities in BC salmon aquaculture
609 facilities (Haigh et al., 2014; Haigh et al., 2018).

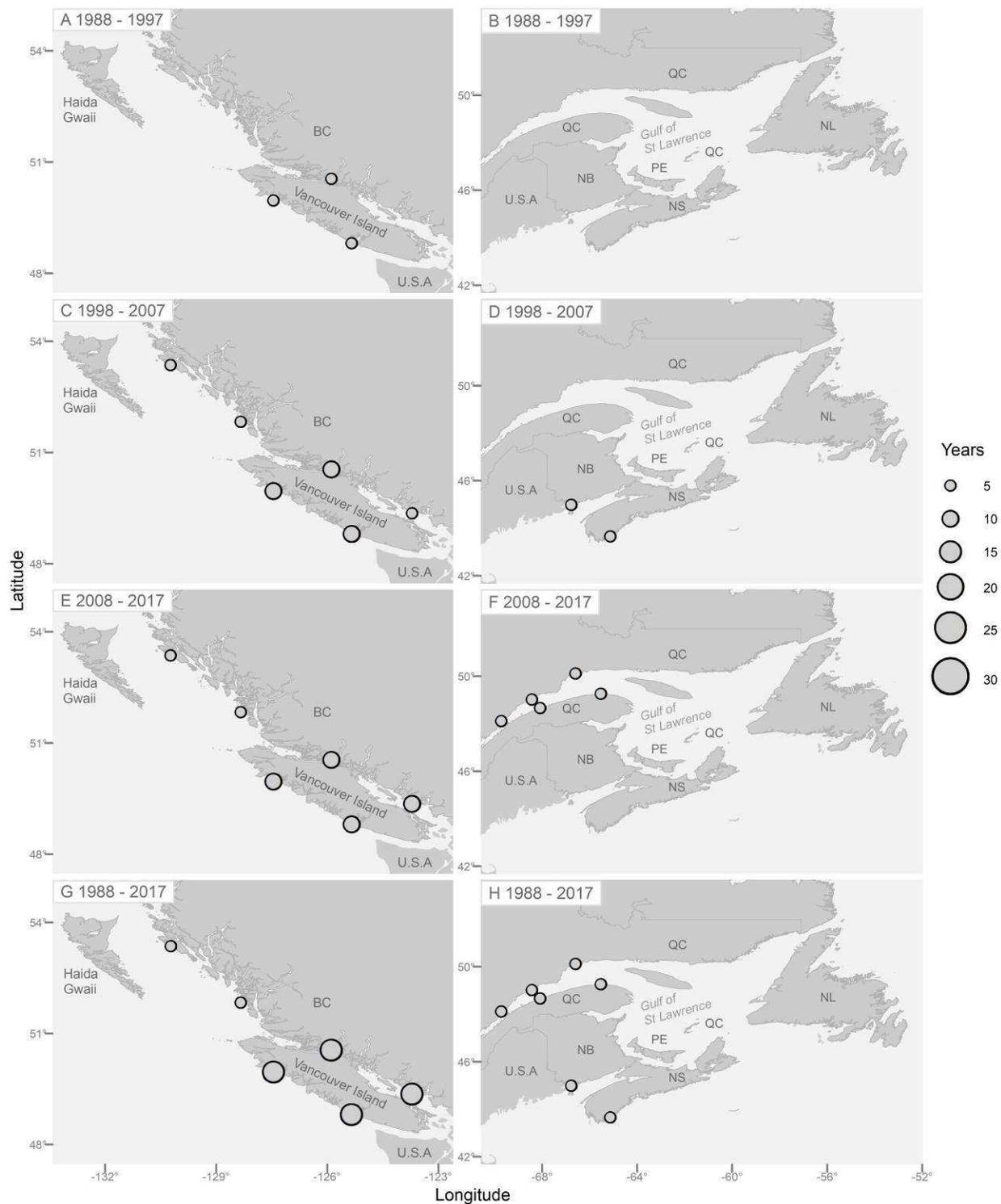
610
611 In 1998, and 2003, mass mortalities of aquaculture fish in Passamaquoddy Bay (NB, Bay of
612 Fundy) (Fig. 5D) were linked to a bloom of the ciliate *Mesodinium rubrum*, which also caused
613 water discoloration, hypoxia and anoxia (Martin et al., 2007; J.L. Martin, unpubl. data). A bloom
614 of *M. rubrum* in Ship Harbour (NS) caused concern within the aquaculture industry in 1991,
615 when cells of this species altered the taste and appearance of commercial mussels that had
616 filtered the cells from the water. Although non-toxic, this ciliate caused a red-brown color in the
617 mussels, a sulfur-like smell, and a peppery taste (Watson-Wright et al., 1993).

618
619 Blooms of *A. catenella* caused mass mortalities of Atlantic salmon (*Salmo salar*) at finfish
620 aquaculture sites in 2000 (NS); and in 2003/2004 (NB, Bay of Fundy) (Fig. 5D). All three cases
621 were linked to PSTs. In 2000, salmon mortalities occurred at an aquaculture site near Shelburne,
622 on the southwest shore of NS, when the cell concentration of *A. catenella* was $>700,000 \text{ cells}\cdot\text{L}^{-1}$
623 (Cembella et al., 2002). That bloom was detected after growers observed fish swimming near the
624 surface, in the opposite direction to the school, and acting lethargically. Dead fish exhibited
625 irritation around the gills and low levels of PSTs were detected in gill tissue. PSTs above the
626 regulatory limit were detected in blue mussels collected at the time of the bloom. In 2003,
627 salmon mortalities occurred near Grand Manan Island (Bay of Fundy), when the *A. catenella*
628 concentration reached $888,000 \text{ cells}\cdot\text{L}^{-1}$. In 2004, salmon mortalities occurred along the
629 southwest coast of NB in the Bay of Fundy as a result of *A. catenella* concentrations as great as 3
630 million $\text{cells}\cdot\text{L}^{-1}$ (Martin et al., 2008). Laboratory experiments conducted on salmon exposed to
631 various concentrations of *A. catenella* cells determined that exposure to $100,000 \text{ cells}\cdot\text{L}^{-1}$ or
632 fewer had no lethal effect on salmon (Burrige et al., 2010).

633
634 The impact of recurring *A. catenella* blooms is demonstrated by the large event in 2008, in
635 the Estuary and Gulf of St. Lawrence (Fig. 5F), which resulted in mass mortalities of fish,
636 seabirds and marine mammals, including species designated at risk (Starr et al., 2017). High
637 levels of PSTs were detected in planktivorous fish, molluscs, and plankton during the bloom.
638 This unusually high mortality was associated with the trajectory of the bloom, which affected all
639 areas of the St. Lawrence Estuary and the northern coast of the Gaspé Peninsula (QC). This was
640 the first well-documented study of the cumulative effects of PSTs throughout the food web in
641 Canada. PST events were an annual occurrence in the St. Lawrence Estuary in the five years
642 leading up to this event (2003-2007).

643

644



645

646 **Fig. 5.** Distribution and recurrence (number of years with events) of marine species mortality
 647 reported to HAEDAT in 10-year periods and 30-year summary: Pacific (A,C,E,G) and Atlantic
 648 (B,D,F,H) coasts of Canada.

649

650 In 30 years of data reported to HAEDAT, it is clear that marine species mortalities caused
651 by HA are a common occurrence in the Pacific region (Fig. 5G). Most of the marine species
652 mortality records in HAEDAT for the Pacific coast are mass mortalities of aquaculture fish,
653 documented and reported through the HAMP, operating in the Pacific region since 1999. Marine
654 species mortality events have been reported much less frequently in the Atlantic region (Fig.
655 5H). A few mass die-offs of aquaculture fish were documented in the Bay of Fundy and
656 southwest NS, and a widespread mass mortality of marine species occurred in the St. Lawrence
657 Estuary in 2008 (Fig. 5H).

658

659 **3.0. Canadian Arctic harmful species known to produce regulated phycotoxins**

660

661 At least 14 phycotoxin-producing phytoplankton species, including eight sympagic algal
662 species that have caused harmful events on other Canadian coasts, have been identified in the
663 Canadian Arctic (Table 1). The distribution of *Pseudo-nitzschia*, *Alexandrium*, and *Dinophysis*
664 species is widespread throughout the Canadian Arctic (Fig. 6). Twelve additional species,
665 including five sympagic species that have caused marine mortalities on the Pacific or Atlantic
666 Canadian coasts, have also been identified in the Canadian Arctic (Table 2).

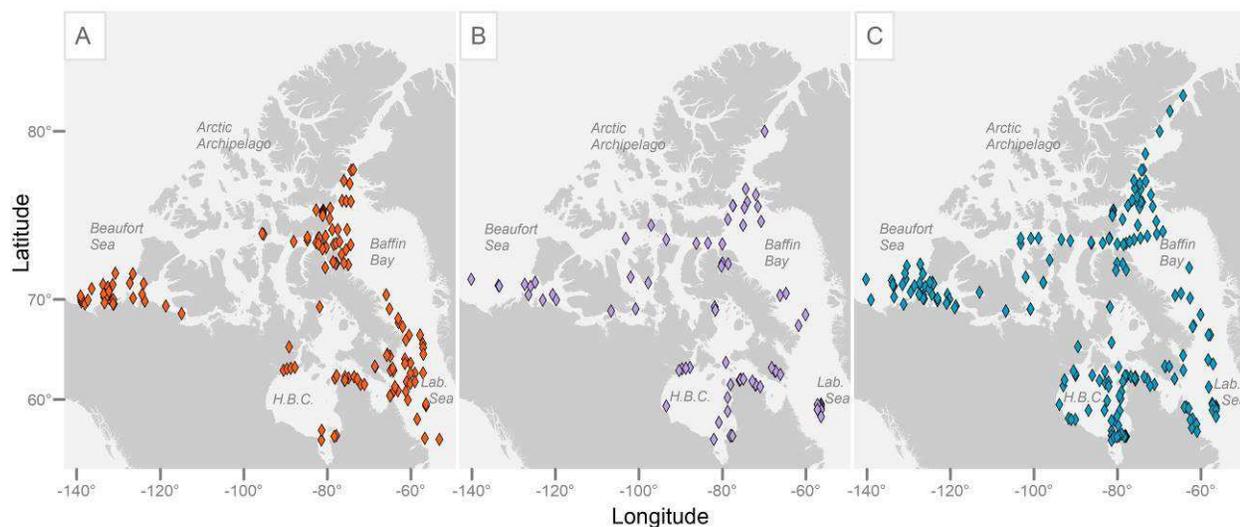
667

668 *3.1. Pseudo-nitzschia spp. in the Canadian Arctic and potential for events*

669

670 Two species of *Pseudo-nitzschia* (*P. pseudodelicatissima*, *P. seriata*), known to produce
671 AST in Canadian waters, and five additional species (*P. delicatissima*, *P. granii*, *P. pungens*, *P.*
672 *obtusata*, *P. turgidula*), documented to have produced AST elsewhere, either in the field or in
673 culture, have been detected in water samples and/or sea ice from the Canadian Arctic (Table 1;
674 Fig. 6A) (Bursa, 1961; von Quillfeldt, 2000; Lovejoy et al., 2002; Róžańska et al., 2008; Mundy,
675 2011; Hopcroft, 2016; Simo-Matchim et al., 2017; Joli et al., 2018; K. Howland; C. McKenzie;
676 M. Poulin; N. Simard; M. Starr, unpubl. data). Although phycotoxins have not been reported for
677 Canadian Arctic waters, they have been detected in nearby Arctic regions. For example,
678 Lefebvre et al. (2016) detected AST in harvested and stranded marine mammals (whales,
679 porpoises, seals, sea lions, walrus, and sea otters) collected along much of the coast of Alaska,
680 including the Beaufort Sea and the eastern tip of Russia. Miesner et al. (2016) also
681 experimentally demonstrated that copepods of the genus *Calanus* (a key prey group for marine
682 fish, birds and mammals in Arctic waters) accumulated AST in their tissues and eggs via
683 consumption of AST-producing *P. seriata* in western Greenland waters.

684



685
686

687 **Fig. 6.** Harmful phytoplankton and sympagic (sea ice-associated) algae in the Canadian Arctic.
688 (A) Distribution of *Pseudo-nitzschia pseudodelicatissima*, *P. seriata*, *P. delicatissima*, *P. granii*,
689 *P. obtusa*, *P. pungens* and *P. turgidula* that have the potential to produce AST in the Canadian
690 Arctic. (B) Distribution of *Alexandrium catenella* and *A. ostenfeldii* that have the potential to
691 produce PSTs in the Canadian Arctic. (C) Distribution of *Dinophysis acuminata*, *D. norvegica*,
692 *D. acuta*, *Phalacroma rotundatum*, and *Prorocentrum lima* that have the potential to produce
693 DSTs in the Canadian Arctic. H.B.C = Hudson Bay Complex; Lab. Sea = Labrador Sea.

694

695 3.2. *Alexandrium* spp. in the Canadian Arctic and potential for events

696

697 Vegetative cells of *Alexandrium* spp. are widely distributed throughout the Canadian Arctic,
698 (Table 1; Fig. 6B) (Bursa, 1961; Harvey et al., 1997; Lovejoy et al., 2002; Dhifallah, 2019; K.
699 Howland; C. McKenzie; M. Poulin; A. Rochon; N. Simard; M. Starr, unpubl. data) and have also
700 been reported in other polar regions, including Alaska and west Greenland (von Quillfeldt, 2000;
701 Vandersea et al., 2018). Baggensen et al. (2012) recorded the first detection of PSTs in *A.*
702 *catenella* cultures from western Greenland waters associated with toxic wild scallops
703 (*Placopecten magellanicus*), indicating the potential for PST production in polar regions.

704

705 Resting *Alexandrium* cysts have been reported in areas of Baffin Bay (Jones Sound; Lovejoy
706 et al., 2002), the Davis Strait, the Labrador Sea between Baffin Island and Greenland, and the
707 Chukchi Sea off the northwest coast of Alaska (Rochon and Matthiessen, 1999; Andresen et al.,
708 2010; Natsuike et al., 2013; Zonneveld et al., 2013). Lefebvre et al. (2016) detected PSTs in
709 marine mammals sampled along the entire coast of Alaska and the eastern tip of Russia.

710

711 3.3. *Dinophysis* spp., *Prorocentrum lima* and *Phalacroma rotundatum* in the Canadian Arctic

712

713 Five species known to produce DSTs in Canadian waters (*Dinophysis norvegica*, *D.*
714 *acuminata*, *D. acuta*, *P. rotundatum*, and *Prorocentrum lima*) are widely distributed throughout
715 northern Baffin Bay from west Greenland to the western portion of the Beaufort Sea, the east
716 coast of Labrador and the Labrador Sea (Table 1; Fig. 6C) (Bursa, 1961; von Quillfeldt, 2000;

717 Lovejoy et al., 2002; Niemi et al., 2011; Hopcroft, 2016; Simo-Matchim et al., 2017; Dhifallah,
718 2019; K. Howland; C. McKenzie; M. Poulin; A. Rochon; N. Simard, unpubl. data).

719
720 *3.4. Other harmful species that could cause morbidity or mortality of marine species in the*
721 *Canadian Arctic*

722
723 In addition to the phycotoxin-producing species reported in the Canadian Arctic, at least 12
724 other phytoplankton species (including five that are also sympagic) with potential to cause the
725 morbidity or mortality of marine organisms, have been found in the region. Species that have
726 been known to cause physical harm to fish and/or shellfish through the possession of sharp barbs
727 or spines (*Chaetoceros concavicornis*, *C. convolutus*, *C. debilis*, and *Corethron hystrix*) are
728 widely distributed in the Canadian Arctic, including in the Beaufort Sea, the Canadian
729 Archipelago, the Davis Strait to Baffin Bay, and within the Hudson Bay complex (M. Poulin; M.
730 Starr, unpubl. data). Other phytoplankton species and sympagic algae that produce ichthyotoxins,
731 or other harmful substances (*Coolia monotis*, *Haptolina hirta*, *Heterosigma akashiwo*, *Karenia*
732 *mikimotoi*, *Octactis speculum*, *Phaeocystis pouchetii*, and *Prorocentrum cordatum*) and the
733 ciliate, *Mesodinium rubrum*, are also widely distributed throughout the Beaufort Sea, the
734 Canadian Archipelago, the Labrador Sea, Davis Strait to Baffin Bay, and in the Hudson Bay
735 complex (Dhifallah, 2019; K. Howland; M. Poulin; N. Simard; M. Starr, unpubl. data).
736 Historically, in other Canadian regions, events (primarily fish mortalities) attributed to the
737 above-mentioned species have almost exclusively been reported for aquaculture fish that are
738 caged or confined, thus preventing them from moving away from the HA. The impact of many of
739 these HA species on wild fish and mammals in the Canadian Arctic is still largely unknown
740 (particularly those phytoplankton species that cause physical damage or produce harmful
741 substances other than phycotoxins). Some evidence, however, suggests that at least some of these
742 HA species have the potential to cause harm in wild Arctic populations. For example, a study in
743 Norway demonstrated the mortality of cod larvae in the presence of high concentrations of *P.*
744 *pouchetii*, a common prey item for larval cod (Aanesen et al., 1998). This negative effect on
745 larval survival in the wild could impact subsequent year classes of cod populations.

746 747 **4.0. Conclusions**

748
749 Human health and food safety have been the primary concerns when considering the
750 impacts of harmful algae that cause high levels of phycotoxins in shellfish and other seafood.
751 Recent harmful algal events on the Canadian Atlantic and Pacific coasts, and increasing concern
752 for the Canadian Arctic, have prompted a re-evaluation of impacts beyond human health, with
753 more focus on ecosystem stress and ocean health. These impacts include ecosystem
754 modification, food web alterations, sublethal effects on species, mortality, and cumulative
755 effects. The examples of harmful algal events given in the previous sections for the Atlantic and
756 Pacific regions ultimately underscore the effects beyond human health, and indicate the very real
757 probability that a broader, more complex, issue exists.

758
759 Although HAEDAT does not include records for the Canadian Arctic, potentially harmful
760 algal species have been recorded in many Canadian Arctic locations. Phycotoxin production and
761 other harmful effects have not yet been documented in this environment, although studies have
762 been initiated. However, phycotoxins have been detected in organisms living in other Arctic

763 waters (western Greenland and Alaska). Climate change, which is occurring at an accelerated
 764 rate in the Arctic, and the accompanying increases in shipping traffic, make that region of
 765 particular concern for future harmful algal events and their impacts.

766
 767 This review of HAEDAT data from 1988 to 2017, together with other Canadian data and
 768 publications, clearly shows that recurring harmful algal events have been widespread throughout
 769 both the Atlantic and Pacific regions of Canada. Given the gaps and other inconsistencies in
 770 HAEDAT, it is not possible to provide quantitative trends in harmful algal events in Canadian
 771 waters. However, several areas where events recur during this period do indicate knowledge gaps
 772 and particular areas of interest for more focussed research. Compilation of spatial and temporal
 773 events from HAEDAT, and other records, is an important step in evaluating the potential role of
 774 harmful algae as a stressor on Canadian marine ecosystems and on the consequent impacts on
 775 human and ecosystem health.

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778
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