BIOLOGICAL SYNOPSIS OF PHYTOPLANKTON NEW TO THE BAY OF FUNDY

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ABSTRACT

Klein, G., Martin, J.L., and Kaczmarska, I. 2010. Biological synopsis of phytoplankton new to the Bay of Fundy. Can. Man. Rep. Fish. Aquat. Sci. 2919: v + 37 p.

A monitoring program was initiated in 1987 to study phytoplankton populations in the Western Isles region of the Bay of Fundy, southwest New Brunswick. Samples are collected weekly from May through October, and monthly during the remaining months for phytoplankton distribution and abundance at Brandy Cove, Lime Kiln Bay, Deadmans Harbour, the Wolves Islands and mid-Passamaquoddy Bay. Since the programme was initiated a number of new species have been observed suggesting the introduction of new species. In order to determine species non-indigenous to the Bay of Fundy waters, we have taken a conservative approach and listed species that have been observed since 1995. Those new species include the following: (dinoflagellates) *Alexandrium pseudogonyaulax*, *Amphidinium carterae*, *Amphidinium sphenoides*, *Ceratium macroceros*, *Polykrikos schwartzi, Preperidinium meunieri*, *Protoperidinium crassipes*, and *Dissodinium pseudolunata* and (diatoms) *Attheya septentrionalis*, *Attheya longicornis*, *Chaetoceros radicans*, *Cylindrotheca gracilis*, *Grammatophora serpentina*, *Lithodesmium undulatum*, *Mediopyxis helysia, Membraneis challengeri, Neodenticula seminae*, *Odontella sinensis*, *Proboscia eumorpha*, *Pseudo-nitzschia subpacifica*, *Pseudo-nitzschia fraudulenta* and *Thalassiosira punctigera*.

Phytoplankton transport and relocation to other regions of the world are a major concern as are the effects of establishment on the new environment. Many of the species recently detected in the Bay of Fundy are being focused on to formulate a biological synopsis to evaluate potential risk for introduction to the major ports in Canada. Available information on these phytoplankton species, including biological characteristics, distributions and harmful/invasive potential are discussed.

RÉSUMÉ

Klein, G., Martin, J.L., and Kaczmarska, I. 2010. Biological synopsis of phytoplankton new to the Bay of Fundy. Can. Man. Rep. Fish. Aquat. Sci. 2919: v + 37 p.

En 1987, un programme de surveillance a été mis en place afin que l'on puisse étudier les populations de phytoplancton de la région de des îles Western dans la baie de Fundy, au sud-ouest du Nouveau-Brunswick. Pour l'analyse de la répartition et de l'abondance du phytoplancton à l'anse Brandy, à la baie Lime Kiln, au port de Deadmans, aux îles Wolves et dans le centre de la baie de Passamaquoddy, on recueille des échantillons sur une base hebdomadaire de mai à octobre et sur une base mensuelle le reste de l'année. On a observé un certain nombre d'espèces nouvelles depuis le début du programme, ce qui nous porte à croire qu'il s'agit d'espèces introduites. Afin d'identifier les espèces non indigènes dans les eaux de la baie de Fundy, nous avons adopté une approche prudente et dressé la liste des espèces observées depuis 1995. Les nouvelles espèces sont les suivantes : (dinoflagellés) *Alexandrium pseudogonyaulax*, *Amphidinium carterae*, *Amphidinium sphenoides*, *Ceratium macroceros*, *Polykrikos schwartzi, Preperidinium meunieri*, *Protoperidinium crassipes*, and *Dissodinium pseudolunata* and (diatomés) *Attheya septentrionalis*, *Attheya longicornis*, *Chaetoceros radicans*, *Cylindrotheca gracilis*, *Grammatophora serpentina*, *Lithodesmium undulatum*, *Mediopyxis helysia, Membraneis challengeri, Neodenticula seminae*, *Odontella sinensis*, *Proboscia eumorpha*, *Pseudo-nitzschia subpacifica*, *Pseudo-nitzschia fraudulenta* et *Thalassiosira punctigera*.

Le transport du phytoplancton vers d'autres régions du monde est un sujet de grande préoccupation, tout comme les effets que cause son implantation dans un nouveau milieu. De nombreuses espèces découvertes récemment dans la baie de Fundy font l'objet d'un synopsis biologique qui servira à évaluer le risque potentiel que pose leur introduction dans les principaux ports du Canada. Les points examinés sont les suivants : l'information disponible concernant ces espèces de phytoplancton, leurs caractéristiques biologiques, leurs aires de répartition et les risques de dommage et d'invasion qu'elles présentent.

1.0 INTRODUCTION

There is increasing concern throughout the world that an increased number of organisms are being introduced to new regions. A number of natural vectors such as climate change, currents, and changes in hydrographical patterns have been identified as transport mechanisms for non-indigenous species in the marine environment. Additionally, humans have been implicated in transfers and introductions through a number of modes such as either intentional or non-intentional releases, shipping (ballast and hull fouling), and transfer of aquaculture stock and attached organisms. Today, ballast water has been identified as one of the main vectors for the introduction of non-indigenous organisms (Hallegraeff and Bolch 1992, Grigorovich et al. 2003). It was documented that in the 1880s, ocean-going cargo-moving vessels began using water for trim and stability (Carlton and Geller 1993, McCarthy and Crowder 2000). A global increase in trade and travel has been documented to have led to an increased number of non-indigenous species being transported into new habitats. Today’s highly efficient shipping includes shorter transfers and transport periods facilitating the potential for survival for organisms in ballast water tanks (Medcof 1975, Dickman and Zhang 1999, Zhang and Dickman 1999, Lavoie et al. 1999). Canada is currently dealing with 1442 non-indigenous species that include terrestrial and aquatic forms (MacIsaac et al. 2002).

Any non-indigenous organism has the potential to become invasive and harmful to a receiving ecosystem including its fauna and flora as well as to the economy and inhabitants (for example, harmful algal blooms and their impact on bivalve and finfish fisheries and health). In many cases, the new arrival may not become a resident and it may not impact the environment negatively. However, high propagule pressure (the number of individuals released at a number of events) can facilitate the probability of a successful invasion, despite a number of factors, such as geographical and ecological barriers, which can play a key role in allowing an organism to permanently establish a new population in the area of dispersal.

Various adverse consequences can be attributed to invasive organisms and many species such as the zebra mussel and Chinese mitten crab (*Eriocheir sinensis*) receive greater public attention due to their high profile as poster-species.

Micro-organisms have been seriously underestimated in their potential as not only invasive but also as harmful organisms as there is little documentation of phytoplankton organisms being recognized as non-indigenous, or even invasive species and their effects on the local ecosystem. Phytoplankton species are often difficult to identify, further complicating the detection of non-indigenous microbiota. Their ecological and bio-geographical information is often lacking due to: 1) non-existing or little monitoring to determine baseline data, 2) lack of expertise in taxonomy, and 3) limited or no historical data. In addition, lag-phases with low cell densities in certain species can make it difficult to recognize invasion progression and status in areas where there is no monitoring. These factors can also impede implementation of eradication measures. Often a target species has to be monitored and studied extensively in order to understand its ecology and status within an existing ecosystem. It is also necessary to determine conditions essential for managing the extent of its invasion. Other factors important to consider are whether the introduced phytoplankton species impacts the receiving environment and whether it might only be present for a short period. For example, *Rhizosolenia robusta* (an Atlantic species) is known as a “temporal immigrant” in the North Sea where it is occasionally observed and transported by currents (Nehring 1998). Similarly, Drebes (1991) suggests that the occurrence of two new diatom species on the German coast of the North Sea in 1990, *Corethron criophilum* and *Stephanopyxis palmeriana* were detected following specific current patterns. Prior to 1990, *C. criophilum* was considered as an oceanic, dominant species in Atlantic waters.

Due to the ability of phytoplankton to live within a wide range of physical environments (such as salinity and temperature), many phytoplankton species can overcome bio-geographical barriers through more rapid transport times. In addition, the ability of many species to form resting stages provides them with a structure to withstand adverse conditions such as lack of light and unfavourable nutrient conditions present in ballast tanks and donor regions. Dormant cysts of dinoflagellates and resting stages of diatoms have been detected in high numbers in sediments at the bottom of ballast water tanks (Hallegraeff 1998, Hamer et al. 2000). Resting spores or cysts can remain viable for extended periods of time. There is documentation of instances greater than six months and up to 10-20 years in the case of some of the toxic dinoflagellates (Hallegraeff and Bolch 1992, McQuoid et al. 2002). Resting cells of some freshwater diatom species have been documented to have even longer survival times (Sicko-Goad et al. 1989).

A number of harmful phytoplankton species belong to the dinoflagellate group, many of which form resting cysts. This results in an additional concern when establishing the invasiveness potential. Harmful species are defined as those that cause illness or mortality as a result of toxins transferred to vertebrate consumers (humans, fish and marine mammals), but also through physical damage to fish such as by gill damage (*Chaetoceros concavicornis* and *C. convolutus* (Horner et al. 1997)) or through oxygen depletion during a single-species bloom die-off (Evelyn 1972, Holmes and Lam 1985). Released products from decaying bloom can also cause problems to fish or shellfish in adjacent aquaculture operations (Manabe and Ishio 1991). Because of their direct threat to human health, toxic flagellates have historically been a major focus for research in many regions of the world (Elbrächter 1999, Gomez 2003). Harmful effects and associated production of a broad spectrum of toxins associated with various shellfish poisonings have brought attention to the dinoflagellates. The dispersal and subsequent invasion of species into new habitats has been documented (Hallegraeff 1998).

In 1987, a toxin was linked for the first time to a diatom when *Pseudo-nitzschia* spp. was linked to the production of domoic acid (DA) in Atlantic Canada, and resulted in fatalities from a syndrome called amnesic shellfish poisoning (ASP) (Bates et al. 1989).

This particular genus includes approximately 30 species, many of which do not produce DA.

A further cause for concern from harmful species is that the production of toxins varies not only among species but also between geographic locations (Hargraves and Maranda 2002, Kaczmarska et al. 2008). Strains of the same species have varying toxin production from different regions of the world. Progress in the field of molecular fingerprinting will support efforts to determine the origin of geographically distinct populations or semi-cryptic species among phytoplankton previously thought to be cosmopolitan.

Thanks to local long-term studies and monitoring processes in various countries, diatoms appear to be a well-recorded group among the phytoplankton organisms. However, publications documenting diatom species specifically as invasive species are rare. One of the oldest and most cited records about the appearance of a non-indigenous species is the publication by Ostenfeld (1908) on the appearance of *Odontella sinensis* (formerly *Biddulphia*) Greville in the North Sea. One of the best recorded intruders is *Coscinodiscus wailesii* Gran and Angst where Edwards et al. (2001) provide a detailed case history of the species and its distribution. In Canada, the diatom *Thalassiosira baltica* was probably introduced into the Great Lakes via ballast water from coastal, brackish waters of western and northern Europe (Edlund et al. 2000). The Great Lakes currently have identified over 180 non-native species which include 17 diatom species (Mills et al. 1993, Ricciardi 2001).

There have been major economic impacts as a result of invasions of species such as the zebra mussels, quagga mussels and sea lampreys in the Great Lakes area (Keller et al. 2009). Unfortunately, there is little documentation as to the extent of phytoplankton species invasions in Canadian bodies of water. One example of a documentation is from the long-term regular monitoring programme in the southwest New Brunswick portion of the Bay of Fundy (Fig. 1) since 1987 where the appearance of eight dinoflagellate and 14 diatom taxa are identified as new arrivals (Martin et al. 2008).

This report presents a biological synopsis of a number of species of diatoms and dinoflagellates based on literature searches and occurrences in other regions of the world in order to use this information to evaluate the potential risk of these species to Canadian waters for introduction and the possibility of becoming a nuisance species in terms of ecosystem biodiversity, and economic and/or human health.

1.1 DIATOMS

1.1.1. *Attheya septentrionalis* (Østrup) Crawford

Basionym: *Chaetoceros septentrionalis* Østrup.
Synonym: *Gonioceros septentrionalis* (Østrup) Round, Crawford and Mann, *C. gracilis* Paulsen (non Schütt), *C. glaciale* Meunier, *C. tortilisetus* Mangin

Cells are solitary or in pairs, 4-8 µm long on the apical axis, with one or two chloroplasts per cell. The horns are three times as long as the apical axis. The species is known to exist epiphytically on *Melosira arctica*. It occurs in plankton in northern cold waters, on sea-ice, and epiphytic on phytoplankton. Hustedt (1962) indicated that spores of *A. septentrionalis* were not observed; Brunel (1962) claimed to have detected spores; and Crawford et al. (1994) suggest that there is some doubt that spores exist within the genus *Attheya*. According to Tomas (1997), it is likely that *A. longicornis* was misidentified as *Chaetoceros septentrionalis* in the past, and cells recorded as *C. septentrionalis* in temperate waters belong to *A. longicornis*. Cleve-Euler (1951) confirmed that there were findings of spores from *C. septentrionalis* in the Skagerrak and Kattegatt regions in April 1914. At the time of their publication in 1999, Bérard-Therriault et al. could not confirm that *A. longicornis* was present in the Gulf of St. Lawrence but they indicated that the species might be present during the spring bloom. Brunel (1962) confirms the species' presence in north-east Canadian waters, and it was often observed between the setae of *C. diadema* or *C. decipiens*. Its first appearance in the Bay of Fundy was in 2001 (Martin and LeGresley 2008).

1.1.2. *Attheya longicornis* Crawford and Gardner

Synonym: *Chaetoceros septentrionalis sensu* Rines and Hargraves 1988; *Ch*. *gracilis* Schütt *sensu* Apstein 1910

Cells are small and rectangular and exist either singly or in pairs. They have an apical axis that is 4-12 µm, and the transapical axis is 2-3 µm. It has one single chloroplast. The horns are longer and less undulated than those of *A. septentrionalis* and are about 8-10 times the length of the apical axis. It occurs in the off-shore plankton in the North Sea and has been found in some regions in association with *Asterionellopsis glacialis, Chaetoceros teres* or *C. diadema* during spring. Rines and Hargraves (1988) observed this species regularly in the northwest Atlantic throughout the year and at temperatures above 20°C, and it appeared among the setae of *Chaetoceros compressus*. It was also reported by Bérard-Therriault et al. (1999) from the Gulf of St. Lawrence as a common species in the plankton from May to December, sometimes abundant and often entangled in chains of *Chaetoceros* (no particular species named). In their description of *C. septentrionalis*, Rines and Hargraves (1988) report on its presence in Narragansett Bay during the winter and spring months and occasionally at other times of the year. They also note that the species is more euryhaline than generally reported. *A. longicornis* was first documented in the Bay of Fundy in 2004 (Martin and LeGresley 2008).

Both *Attheya* species discussed in this manuscript are described as benthic and each has a distinct niche. *A. septentrionalis* is attached to the subsurface of sea-ice and found in the plankton after the ice melt. *A. longicornis* appears to form an association with other planktonic diatoms (Crawford et al. 1994). *A. septentrionalis* has the ability to be transported as a "hitch-hiker" attached to other *Chaetoceros* species or to *A. glacialis*, a species found to arrive with ballast water in Canada (Klein, pers. comm.). *A.*

longicornis could be transported in a similar way as *Neodenticula seminae*, which may have been introduced to the Bay of Fundy through changes in ocean currents or changes in sea surface temperatures in the Arctic regions, respectively. No data was found as to temperature limits.

1.1.3. *Chaetoceros radicans* Schütt

Synonym: *C. scolopendra* Cleve

Chaetoceros radicans is a marine, pelagic species that is cosmopolitan. Cells occur in loose, twisted chains and are often embedded in mucus. Its size ranges from 5.7-25 µm (apical axis), to around 8 µm (pervalvar axis). It forms resting spores. The setae are strongly silicified and possess hair-like siliceous spines. Brunel (1962) observed a salinity and temperature optimum for C. radicans of 26.6 psu and 5.8°C, respectively. Hasle and Syvertsen (1997) note the seasonal variability in its morphology and the resulting similarity to C. cinctus and C. tortissimus. The basal plates of the spores in C. radicans can be found to be lacking spines, thus making them easily confused with C. cinctus spores. Hustedt (1962) noted the species' distribution to be along the Atlantic coast of Europe and in the Mediterranean Sea; also documented the generally sporadic occurrence of the species. Rines and Hargraves (1988) describe C. radicans as occurring in Narragansett Bay in late winter and spring and in lesser numbers in fall. Throndsen et al. (2007) report C. radicans as being abundant in some years in Oslo-Fjord, Norway. Chaetoceros radicans is present in the Gulf of St. Lawrence from May to October but it has also been documented to be a common species in the succession of bloom formers in the summer months from July to September (Bérard-Therriault 1999). The presence of C. radicans in Canadian waters (Atlantic and Pacific) as well as the arrival of the species in ballast water has been confirmed (Carver and Mallet 2002, Hargraves and Maranda 2002, Klein et al. 2009). The species' first appearance in the Bay of Fundy was in 2000 (Martin and LeGresley 2008).

1.1.4. *Cylindrotheca gracilis* (Brébisson ex Kützing) Grunow

Synonyms: Nitzschia taenia W.Smith; Cylindrotheca gerstenbergeri Rabenhorst; Ceratoneis gracilis Brébisson ex Kützing

Cylindrotheca gracilis cells are solitary with their valve morphology fusiform and with numerous chloroplasts. Its size ranges from 98-212 µm in length to 2-8 µm in width. It exists in marine to brackish waters, and is described as a rare species in the Gulf of St. Lawrence with a rather sporadic presence from May to October (Bérard-Therriault 1999). Rawlence (1987) describes C. gracilis in his phytoplankton guide based on a 12-month survey in 1982 in the St. Croix estuary (Bay of Fundy) but does not relay information on seasonality or abundance. The first sighting in the Bay of Fundy through a phytoplankton monitoring programme initiated in 1987 was in 2001 (Martin and LeGresley 2008). Perhaps the sighting in 1982 was a single incident and its regular occurrence in the region since 2001 is an indicator for changed environmental conditions within the Bay of Fundy. This diatom was also found on two mudflats in the Upper Bay of Fundy in 2001, suggesting either spread since 1982 or perhaps it had been overlooked earlier as C. fusiformis (Rawlence 1987).

1.1.5. *Grammatophora serpentina* (Ralfs) Ehrenberg

Grammatophora serpentina cells tend to exist in colonies and can be either planktonic or epiphytic/epilithic. Its distribution is cosmopolitan. In 1877, samples were collected by Rabenhorst (1848-1882) from the Falkland Islands region confirming its presence in the coastal southern Atlantic. It has also been reported from the Northwest Atlantic (http://www.marinespecies.org/). This species has also been observed as part of the periphyton community in the Gomoti River, India, where it exists with a salinity of 0.05-0.09 psu. The species was recorded by Linkletter (1977) as present in the pelagic community in the lower Bay of Fundy but unfortunately there was no associated further information such as time of year or depth in the water column. It seems to have disappeared and was not observed again in the Bay of Fundy until 2001 (Martin and LeGresley 2008). Grammatophora serpentina is euryhaline and eurythermal in addition to being a part of the epiphytic/epilithic communities.

1.1.6. *Lithodesmium undulatum* Ehrenberg

Lithodesmium undulatum cell size is from 35-74 µm (pervalvar axis) by 37-93 µm. The species is neritic, with its distribution spread from warm-water regions to temperate waters. Its presence on the Canadian east and west coasts has been confirmed. Carver and Mallet (2002) reported the species from ballast water samples from ships arriving at Atlantic Canadian ports. Its first appearance in the Bay of Fundy was reported in 1997 (Hargraves and Maranda 2002, Martin and LeGresley 2008). According to Cupp (1943) it is not uncommon off southern California and large concentrations (up to 1.2 x 105 cells•L-1) were observed in August, 1927 off La Jolla. It was also observed to be moderately abundant in the Gulf of California.

1.1.7. *Mediopyxis helysia* gen.nov. and sp.nov. S.Kühn, Hargraves and Halliger

Mediopyxis helysia cells occur as solitary or in short chains of 2-6 cells. Their sizes range from 44-125 µm in length and 22-78 µm in width. It is a planktonic, coastal, marine, and cold to temperate water species that can occur year round. It has been recorded at depths ranging from the surface waters to a depth of 45 m. This species has only recently been described and may have previously been identified as an unknown species or misidentified as Helicotheca tamesis (Shrubsole) Ricard. It has been reported as a new species in the Gulf of Maine, German Bight and Bay of Fundy. The first record of the species was from Helgoland, North Sea, in 2003 (Kuehn et al. 2006). Mediopyxis helysia was also observed in low abundance from northeast Scotland (McCollin 2008). The species is susceptible to infection by the parasitoid dinoflagellate Paulsenella vonstoschii, suggesting potential for the additional introduction of a parasite with its host.

1.1.8. *Membraneis challengeri* (Grun. in Cleve and Grunow) Paddock

Basionym: Navicula challengeri Grunow in Cleve and Grunow
Synonym: Tropidoneis antarctica (Grunow in Cleve and Möller) Cleve

Membraneis challengeri cell size ranges from 58-270 µm (apical axis). Its recent introduction into the North Atlantic could possibly have happened via the Labrador current and the Arctic Sea from its native range in the Bering Sea, North Pacific. It also occurs in the Antarctic Ocean and is part of the late spring/early summer assemblage in the Strait of Georgia, British Columbia, Canada. It has also been documented from the North Sea where it was found in depths between water surface and 7 m (Hoppenrath et al. 2009). The species was reported for the first time in Dutch marine waters in 2001 (ICES 2003). Membraneis challengeri has been documented in phytoplankton surveys in Chesapeake Bay from 1985 to 2007 (Virginia Chesapeake Bay Water Quality Monitoring Program). The species occurs on Canada’s east and west coasts (Hargraves and Maranda 2002) and was observed in ballast water samples in ships arriving at Atlantic ports (Carver and Mallet 2002). It was first observed in the Bay of Fundy in 2001 (Martin and LeGresley 2008).

1.1.9. *Neodenticula seminae* (Simonsen and Kanayo) Akiba and Yanagisawa

Basionym: Denticula seminae Simonsen and Kanayo
Synonyms: Denticula marina Semina; Denticulopsis seminae (Simonsen and Kanaya) Simonsen

This diatom is a planktonic, marine cold water species that forms long, chain-like colonies. Neodendicula seminae is endemic to the eastern part of the north Pacific. Cell sizes range from 8.2-60 µm in length to 4-11.6 µm in width. Sporadic and episodic occurrences have been reported from the subtropical gyres in the Indian Ocean. It is usually limited to the north Pacific and the Bering Sea where it is thought that it reproduces both sexually and asexually (inferred for multi-modal size-class distribution) throughout the year (Kurihara and Takahashi 2002). However, it has also been observed in a large spring bloom in the Estuary and Gulf of St. Lawrence in 2001 (Starr et al. 2002). Its reappearance in the North Atlantic may be due to changes in the ocean circulation and the decline in the Arctic ice from changes in temperature and salinity. Neodendicula seminae was first sighted in the Labrador Sea in 1999. It is assumed that the species was introduced to the North Atlantic through the Labrador currents via the Bering Strait and the Antarctic Sea. To date, no spores or resting stages have been observed. The first record from the Bay of Fundy was in 2005 (Martin and LeGresley 2008). The species is thought to be a key player in bio-geochemical cycles in the subarctic regions where it accounts for 50% or more of the total cell counts in surface waters and bottom sediments (Shimada and Tanimura 2006). It seems to compete for silica with prevalent diatom species.

1.1.10. *Odontella sinensis* (Greville) Grunow

Basionym: Biddulphia sinensis Greville

Odontella sinensis is a marine, planktonic species. The cells are solitary or in pairs and their size ranges from 80-440 µm on the apical axis. Odontella sinensis is the first diatom reported as an invasive species in the North Sea since 1903. Its successful establishment in the North Sea ecosystem showed an effect on the diatom population dynamics by depressing the rise of the indigenous routine succession of local species. It has been suggested that it may have been introduced in ballast water from Hong Kong Harbour and was until that time known to occur in tropical and high-salinity waters such as the Pacific and the Red Sea. Odontella sinensis spread rapidly across European waters within 10 years of first observation. It is distributed along the Atlantic coasts and the Baltic Sea and is considered to be an important constituent of the winter and spring diatom flora around Britain (Boalch 1987). A North Sea spring bloom in April 2001 with 1300 cells per litre would not be considered as very dense (http://www.nloe.de.). Schnepf et al. (2000) observed the parasitic Plasmodiophoromycete Phagomyxa odontellae feeding on Odontella sinensis in the North Sea. Its occurrence in Canadian waters can be confirmed for the east coast (Hargraves and Maranda 2002, Martin and LeGresley 2008). The species has also been reported from ballast water arriving at the Maritimes by Carver and Mallet (2002).

1.1.11. *Proboscia eumorpha* Takahashi, Jordan and Priddle

Synonyms: Rhizosolenia alata var. truncate (Gran); Rhizosolenia obtusa (Hensen sensu Ostenfeld); Rhizosolenia alata f. inermis (Castracane) Hustedt; Rhizosolenia alata Brightwell

Cells of P. eumorpha are solitary or in pairs and sizes range from 5-24 µm in diameter. Typically, it has been found at depths between 0 and 5000 m. It has been described from the subarctic and Pacific waters (Takahashi et al. 1994). There have also been reports of observations from the Gulf of Mexico, North Pacific and North Atlantic (http://data.gbif.org/welcome.htm). Its occurrence in the Bering Sea has been confirmed (Onodera and Takahashi 2009) as well as on the US west coast (Cupp 1943); it was also detected in samples from ballast water from ships arriving at Canadian east coast ports (Carver and Mallet 2002). Proboscia eumorpha was first detected in the Bay of Fundy in 2001 (Martin and LeGresley 2008).

1.1.12. *Pseudo-nitzschia fraudulenta* (Cleve) Hasle

Basionym: Nitzschia fraudulenta Cleve
Synonym: Pseudo-nitzschia seriata var. fraudulenta

Cell size ranges from 64-164 µm in length to 4.5-8 µm in width. The species is thought to be cosmopolitan and known to produce the neurotoxin domoic acid (DA) (Lundholm and Moestrup 2006). It was frequently observed off the Irish coast from spring to autumn with high abundances in October/November (Cusack et al. 2004). The species has been reported from the North Sea, Adriatic Sea, Chile, Japan, common and periodically abundant on the US Pacific coast and also reported from the Atlantic coast (Villac et al. 1993, Hasle et al. 1996, Fryxell et al. 1997). Carver and Mallet (2002) reported the species' arrival in ships' ballast waters on the Canadian east coast. Its first occurrence in the Bay of Fundy was reported in 2000 (Martin and LeGresley 2008).

1.1.13. *Pseudo-nitzschia subpacifica* (Hasle) Hasle

Basionym: *Nitzschia subpacifica* Hasle

Pseudo-nitzschia subpacifica cell size ranges from 33-70 µm in length and 5-7 µm in width. It occurs in warm to temperate waters. According to Hasle et al. (1996), the species is an important component of the plankton in the Atlantic south of 50°N, with a northernmost limit of 51°N (Hasle 1972). However, Cusack et al. (2004) report the appearance of P. subpacifica off the coast of Ireland and suggest that its presence – similar to frequently recorded temperate/subtropical dinoflagellate species – is wholly or in part due to transport from the northward slope current. Martin and LeGresley (2008) report the species' appearance in the Bay of Fundy in 2001. Statistical analysis of P. subpacifica populations from the Bay of Fundy indicate that the species did not correlate with environmental variables such as nutrients, tidal levels and oxygen (Kaczmarska et al. 2008). This suggests that P. subpacifica is flexible with regards to its growth requirements. The species has been observed in samples collected from ships' ballast tanks on the Canadian East coast by Carver and Mallet (2002). It was determined to be new in the Bay of Fundy by Kaczmarska et al. (2005). Pseudo-nitzschia subpacifica is common and periodically abundant on the US west coast (Fryxell et al. 1997, Buck et al. 1992).

1.1.14. *Thalassiosira punctigera* (Castracane) Hasle

Basionym: Ethmodiscus punctiger Castracane
Synonym: Ethmodiscus japonicus Castracane, Thalassiosira japonica Kiselev, Thalassiosira angstii (Gran) Makarova

Thalassiosira punctigera cells are 24-186 µm in diameter. The species has been recorded from warm to temperate water regions (Hasle and Syvertsen 1997). It is frequently observed in the North Pacific and rare in the North Atlantic. Thalassiosira punctigera information has been well documented since its first appearance in the

German Bight in the 1980s. It is present in the North Sea year round. Its first documented appearance in the English Channel was in 1978 and in the Skagerrak region in 1979 (Hasle 2008). The species prefers lower salinities and seems to be able to cover larger ecological ranges compared to other diatom species with regard to physical and chemical parameters. It also has a tolerance for heavy metals (Rick and Dürselen 1995). This species already occurs on both Canada's Pacific and Atlantic coasts (Hargraves and Maranda 2002, Martin and LeGresley 2008). It was also observed in ships' ballast water at ports on the Canadian East coast (Carver and Mallet 2002). It is also common in plankton in the southern Strait of Georgia, British Columbia (Hobson and McQuoid 2001).

1.2. DINOFLAGELLATES

1.2.1. *Dinophysis tripos* Gourret

Dinophysis tripos is an armoured, marine dinoflagellate with cell sizes ranging from 90-125 µm in length and 50-60 µm in dorso-ventral width (Faust and Gulledge 2002). The species is toxic, producing dinophysistoxin-1 (DTX1), and associated with diarerhetic shellfish poisoning (DSP) events. Dinophysis tripos is a photosynthetic, planktonic species commonly found in neritic, estuarine and oceanic waters. It is widely distributed in tropical and temperate waters, but has occasionally been documented in colder regions.

Reports from the Bay of Fundy (Martin et al. 1999, 2001, 2006, Wildish et al. 1988, 1990) indicate that D. tripos has been observed during the months of August and October at densities between 20 and 60 cells/L since 1993. It has been documented as arriving at the Laurentian Great Lakes and the upper St. Lawrence during 1990/91 (Subba Rao et al. 1994). Other regions from which it has been reported include: the Scottish coastal waters (Hart et al. 2007), the Black Sea (Vershinin et al. 2005), and the Baltic Sea, Denmark (Mouritsen and Richardson 2003). This particular species has not been mentioned in phytoplankton records from the St. Lawrence area by Brunel (1962) and Bérard-Therriault et al. (1999). Further records from the Canadian coasts (Atlantic and Pacific) can be found at Global Diversity Information Facility, http://data.gbif.org/countries/CA (Dataset by Agriculture and Bio Agri-Food Canada, Fredericton Collection).

1.2.2. *Alexandrium pseudogonyaulax* (Biecheler) Horiguchi ex Kita et Fukuyo

Basionym: Goniodoma pseudogoniaulax Biecheler
Synonyms: Goniodoma pseudogonyaulax Biecheler; Alexandrium pseudogonyaulax (Biecheler) Horiguchi; Triadinium pseudogonyaulax (Biecheler) Dodge

Alexandrium pseudogoniaulax cells are 30-58 µm long and 58-80 µm wide (Throndsen et al. 2007, Hoppenrath et al. 2009). Its blooms are known to develop in high biomass and when this occurs, they can have harmful effects and cause problems. They produce a toxin, goniodomin A, that can result in harmful effects to vertebrate consumers through a syndrome called paralytic shellfish poisoning (PSP). Alexandrium pseudogonyaulax is an armoured dinoflagellate that is photosynthetic, marine, planktonic and primarily neritic (Faust et al. 2002). It is generally found in coastal regions and brackish environments. It has been recorded from the Mediterranean Sea, German Bight, North Adriatic Sea, Portugal, Norwegian fjords, coastal waters of Japan and Gulf of Georgia (British Columbia). It was also reported as a bloom-forming species in parts of the Norwegian Sea (Throndsen et al. 2007). Alexandrium pseudogonyaulax forms resting cysts. The first record from the Bay of Fundy was in 2001 (Martin et al. 2008).

1.2.3. *Amphidinium carterae* Hulburt

Synonyms: Amphidinium klebsii Carter, Amphidinium microcephalum Norris

Amphidinium carterae cell sizes range is 12-29 µm in length and 7-17 µm in width (Throndsen et al. 2007, Bérard-Therriault et al. 1999). It is a toxin-producing species that also produces resting cysts. It is primarily benthic but occasionally occurs in the water column. The species is known to be ichthyotoxic (Hallegraeff et al. 2001, Hansen et al. 2001). It seems to be cosmopolitan, found in both temperate and tropical waters, in coastal as well as estuarine conditions. There are records of sporadic occurrences in inshore plankton in Norway (Throndsen et al. 2007). In Canada it has been recorded from the Gulf of St. Lawrence (Bérard-Therriault et al. 1999). Its first appearance in the Bay of Fundy was in 2000 (Martin and LeGresley 2008).

1.2.4. *Amphidinium sphenoides* Wulff

Synonyms: Gymnodinium filum Lebour, Spirodinium glaucum Lebour, Katodinium glaucum (Lebour) Loeblich, Massartia glauca Schiller
Hoppenrath et al. (2009) also indicate Gymnodinium filum as a taxonomical synonym for A. sphenoides.

Amphidinium sphenoides is a naked, heterotrophic dinoflagellate. The size ranges from 22-51 µm in length and 7-17 µm in width (Bérard-Therriault et al. 1999, Hoppenrath et al. 2009). Chloroplasts are absent and the species' nutrition is by phagotrophy either through ingestion of particles or by myzocytosis. Drebes (1991) reported possible representatives of the species feeding on Chaetoceros eibenii (Hoppenrath et al. 2009). It has been documented from the Gulf of St. Lawrence (Bérard-Therriault et al. 1999), Barents Sea, North Sea, Woods Hole, Atlantic Ocean, Chesapeake Bay (SERC Phytoplankton Guide). Its first appearance in the Bay of Fundy was observed in 2000 (Martin and LeGresley, 2008). Additional records from the Canadian coasts (Atlantic and Pacific) can be found at: Global Diversity Information Facility, http://data.gbif.org/countries/US.

1.2.5. *Ceratium macroceros* (Ehrenberg) Vanhöffen

Basionym: Peridinium macroceros Ehrenberg.

This is a warm to temperate water species, cosmopolitan, oceanic and coastal, observed worldwide in cold temperate to tropical waters (Steidinger and Tangen 1996). Cells are up to 400 µm long by 45-55 µm wide (Horner 2002). It has been detected in the North Sea (Hoppenrath et al. 2009), the Baltic Sea (Pankow 1976) and its first appearance in the Bay of Fundy was 2001 (Martin and LeGresley 2008).

Data collected by Continous Plankton Recorder Database, SOHFOS, showed appearances between 1961 and 1999 off the south of Nova Scotia (Canada) (see Global Diversity Information Facility, http://data.gbif.org/species/13296487).

1.2.6. *Polykrikos schwartzii* Bütschli

Polykrikos schwartzii is an unarmored dinoflagellate. Chloroplasts are absent; it feeds by active phagocytic nutrition, feeding on other dinoflagellates such as Ceratium, Protoperidinium, Scrippsiella, Gonyaulax, Gymnodinium katenatum colonies and others, as well as on diatoms (Steidinger and Tangen 1996). It migrates vertically in the water column and is a potential cyst former. Cell (chain) length is 100-160 µm and width is 60-100 µm (Throndsen et al. 2007). It has been identified in all oceans, is mostly neritic, temperate, but according to Hoppenrath et al. (2009), the exact distribution is not clear as the species is often confused with P. kofoidii. Typically, it can be found at depths between 0 and 2763 m. When present in high abundance, it might reflect a hypertrophic nutrient situation. According to Throndsen et al. (2007), it is also common in coastal waters. The species has been documented in Japan (Kazumi et. al. 2003, Matsuoka et al. 2003), and New Zealand (MacKenzie 1991). Its first appearance in the Bay of Fundy was in 2001 (Martin and LeGresley 2008). Polykrikos schwartzii has been documented to be present in the Gulf of St. Lawrence (Bérard-Therriault et al. 1999) and Horner (2002) observed it in the northwest US in the Pacific.
Further records from the Canadian coasts report the species south of Newfoundland in 1995 (Global Bio-Diversity Information Facility, http://data.gbif.org/occurrences/searchWithMap.htm?c[0].s=20&c[0].p=0&c[0].o=13299071). Further sources of databases can be found on the following web site: Zipcodezoo.com/Protozoa/P/Polykrikos_schwartzii/.

1.2.7. *Preperidinium meunieri* (Pavillard) Elbrächter

Synonyms: Peridinium paulsenii Mangin, Peridinium meunieri (Pavillard) Elbrächter, Peridinium lenticulatum (Loeblich Jr. & Loeblich III), Diplopeltopsis minor Pavillard, Diplopsalis lenticula f. minor Paulsen, Glenodinium lenticula f. minor Paulsen, Zygabikodinium lenticulatum (Paulsen) Loeblich et Loeblich, Preperidinium paulsenii (Mangin) Mangin.

Preperidinium meunieri cells lack chloroplasts but form cysts. They have a cosmopolitan, coastal and estuarine distribution in temperate to tropical waters (Steidinger and Tangen 1996). Sizes range from 25-60 µm in length to 30-74 µm in diameter/width (Throndsen et al. 2007, Bérard-Therriault et al. 1999).

In the Norwegian Sea, it has been observed as abundant by Throndsen et al. (2007). It has been reported as common in the phytoplankton community in the Gulf of St. Lawrence by Bérard-Therriault et al. (1999). It has also been observed to be abundant in the Baltic Sea (Pankow 1976) and in the North Sea (Hoppenrath et al. 2009). It was first observed in the Bay of Fundy in 2001 (Martin and LeGresley 2008).

1.2.8. *Protoperidinum crassipes* (Kofoid) Balech

Synonym: Peridinium crassipes Kofoid

Protoperidinum crassipes is an armoured dinoflagellate which produces the toxin azaspiracid (AZA). It is also an obligate heterotrophic (phagotrophic). Size ranges from 70-120 µm (Throndsen et al. 2007). It exhibits feeding preferences for red tide dinoflagellates such as Gymnodinium and Gonyaulax (Jeong and Latz 1994). This species is cosmopolitan, prefers temperate to tropical waters, is planktonic, and is observed in coastal, oceanic and brackish waters from the surface to a depth of 1000 m, and forms blooms in warm water estuaries (Steidinger and Tangen 1996). Sexual and asexual reproduction are known to occur within this genus and this species is a major contributor to harmful algae blooms (HABs). Their seasonal occurrence has not been well documented. It has been reported as common in Norwegian waters by Throndsen et al. (2007). Bérard-Therriault et al. (1999) and Brunel (1962) have reported it as occurring in the Gulf of St. Lawrence and the Baie de Chaleurs. Additionally, Gribble et al. (2007) documented it from the Gulf of Maine as well as in polar regions. Gribble states “Phototrophic dinoflagellates are the preferred prey of P. crassipes, so if this low grazing rate were constant in the field, P. crassipes could consume 30% of the standing stock of phototrophic dinoflagellates per day offshore”. James et al. (2003) suggest that P. crassipes does not produce AZA endogenously but might accumulate the toxin from selectively consumed phytoplankton prey. The species was found in ships’ ballast waters arriving at the Canadian East coast by Carver and Mallet (2002). Its first appearance in the Bay of Fundy in 2001 was reported by Martin and LeGresley (2008).

1.2.9. *Dissodinium pseudolunula* Swift ex Elbr. and Dreb

Dissodinium pseudolunula is ectoparasite on copepod eggs in marine plankton. The spherical primary cyst is from 60-130 µm in diameter, its lunate secondary cyst is from 100-140 µm, it forms 5-8 dinospores that are 23-28 µm in length and 18-21 µm in width and are considered to be of Gymnodinium type (Elbrächter and Drebes 1978).

The species has been confused with Pyrocystis lunula which also has lunate shaped cells containing only two dinospores. Its distribution appears to be cosmopolitan and it has been documented in temperate and tropical oceans. Horner (2002) reported it from the northwest coast of the US. Pankow (1976) documented it from the Baltic Sea as Dissodinium lunula. Steidinger et al. 1996 identify D. lunula as a synonym for Pyrocystis noctiluca. Bérard-Therriault et al. (1999) have recorded it from the Gulf of St. Lawrence as Pyrocystis lunula. Throndsen et al. (2007) indicate that it occurs in Norwegian waters and suggest that it may be parasitic on salmon sea lice eggs. The occurrences in the North Sea and eastern North Atlantic were recorded by John and Reid (1983). The widespread distribution and, at times, large numbers of resting cysts of D. pseudolunula in the plankton over a large area of the northeastern Atlantic and North Sea may, in certain years, have important effects on the survival of copepod eggs and the population dynamics of copepods. This species, and other parasites on copepod eggs, may be a contributory factor to the large year-to-year variability in the standing stock of copepods seen in sea areas around Britain (Colebrook 1978). Due to the possible confusion with Pyrocystis lunula it should be mentioned here that the latter has been reported to arrive in ship's ballast water at the Canadian East coast (Carver and Mallet 2002). The first occurrence in the Bay of Fundy was observed in 2002 (Martin and LeGresley 2008).

2.0 DISCUSSION

The spread of non-indigenous species can be irreversible and their effects long term. The role of phytoplankton as invasive species has likely been underestimated and it is (apart from events where human health is considered to be at risk e.g., due to shellfish poisoning) less of a focus for public attention compared to the rather spectacular documentations of invasions such as the invasive zebra mussel. However, the impacts can prove to be serious: harmful algal blooms composed of dinoflagellates as well as diatoms can result in fish kills due to the production of toxins, or anoxia caused by decaying blooms, clogging of fish gills and nets or water inlets. Further impacts, less obvious on first view, are changes in biodiversity, biological homogenisation of habitats and loss of genetic diversity.

Apart from the species, Grammatophora serpentina, none of the species discussed in this synopsis were reported by Linkletter (1977) in her checklist of marine flora and fauna from Passamaquoddy Bay and Grand Manan Island. Periodic appearances of species can be induced by natural cycles and changes in ocean currents or climate variability (e.g. ENSO, NAO, etc.), one of the reasons illustrating the difficulty in establishing the status of invasiveness in a non-local organism.

2.1. GLOBAL CLIMATE CHANGE

In addition to increased international shipping, global climate change might be one of the driving factors for an increase in harmful algal blooms on the Canadian Pacific and

Atlantic coasts. Mudie et al. (2002) could show that Pacific and Atlantic red tide histories show a similar late glacial-early Holocene succession of sustained high production of non-toxic and toxic red tide blooms, with the only obvious common denominator being the warmer (up to 5°C) sea surface temperature in summer. Furthermore, abundances of cysts (e.g. of toxic Alexandrium species) up to one order of magnitude larger correlated with the rise in temperature. This finding suggests the importance of climate change for the increase in frequency of so called red tides and other harmful algal blooms. Of the dinoflagellates listed in this synopsis, Alexandrium, Amphidinium, Polykrikos, and Preperidinium are cyst-forming genera which could suggest the possibility of a disappearance of the cells from the water column and re-appearance after an unknown period, maybe years, under favourable conditions.

2.2. Currents as vectors

Off-site dispersal by currents is a vector that has to be taken into consideration when we are discussing transport mechanisms and their potential to introduce non-indigenous species. Many organisms can travel along the coastline through currents and also can be brought through the same route in the opposing direction via ballast water (Smayda 2007, Lewis et al. 2003). It becomes complex when we look at the report of P. subpacifica by Cusack et al. (2004) where the authors consider the possibility of dispersal due to the transport by the northward slope current off southwestern Ireland. As a consequence, ships exchanging ballast water in such areas can pick up and transport dinoflagellates and diatoms to other regions. This example shows how organisms can be transferred across the Atlantic by currents and ballast water. Regarding transport by currents directly into the Bay of Fundy, inflow from the Gulf of Maine eddy could result in the transport of non-indigenous species into the Bay.

The two diatom species, Neodenticula seminae and Membraneis challengeri, are examples of disposition and introduction of non-indigenous organisms through ocean currents. It is very likely that they arrived from the Pacific to the Atlantic due to the decline in ice in the Arctic Sea and via the Labrador currents. The heavily silicified species N. seminae is a key player in the biogenic silica/carbon cycles in the Pacific and might therefore be a competitive species in the new environment with the potential for changing species composition and/or succession in the water column.

2.3. Ecosystems

The role of non-native species in ecosystem functions (e.g., nutrient cycling) and their ability to displace native species is still poorly understood. There are many cases where new arrivals and local species co-exist (e.g. Byers 2005, Kestrup and Ricciardi 2009). However, changes to biodiversity, or biological homogenisation of coastal marine plankton communities and the loss of genetic diversity, are effects that are not foreseeable. The successful establishment of a species depends on a multitude of factors such as competition, grazing pressure and physiological stress due to salinity/temperature gradients. A problem could occur such as with Protoperidinum crassipes, a bloom forming and potentially toxic species that preys on phototrophic dinoflagellates and was reported to reduce a standing stock of this preferred prey by 30% per day (Gribble et al. 2007). Under suitable conditions on arrival, P. crassipes could alter the trophic conditions and pose a threat or compete with local mesozooplankton communities (Gribble et al. 2007). Overall similarities between the old and the new habitat can facilitate the establishment of organisms (e.g. intra-coastal displacements or across-Atlantic). Some species have traits that enable them to establish successfully (e.g. non-selective diet, fast propagation) even if released as small propagules (low number of release events), others require substantial propagule pressure (inoculum size and number of events), depending on the state of disturbance of the receiving ecosystem (D'Antonio et al. 2001, Reaser et al. 2008). It has been observed that the more disturbed a location (physiological stress or resource flux), the lower the propagule pressure necessary to enable successful establishment of an introduced species (D'Antonio et al. 2001).

2.4 Toxicity

There are a number of diatoms and dinoflagellates that are known to produce toxins that can in turn cause damage to vertebrate consumers, including fisheries. Alexandrium fundyense, the paralytic shellfish poisoning (PSP) producing organism, has been responsible for causing mortalities to Atlantic herring, Clupea harengus harengus, (White 1977, 1980) and Atlantic salmon, Salmo salar, (Martin et al. 2006b) on Canada's Atlantic coast.

In their report on introduction of phyto- and zooplankton via ballast water, Carver and Mallet (2002) mention 17 taxa (6 diatoms and 11 dinoflagellates) classified as toxic/harmful, of which 5 were not reported in Atlantic Canadian waters.

It is critical to identify to species level in phytoplankton as some species among the diatom genus Pseudo-nitzschia are known to produce the potent neurotoxin DA. Serious illness or even death in humans, fish and marine birds can result from toxin uptake (Bates 2000). In Prince Edward Island in 1987, an outbreak of amnesic shellfish poisoning (ASP) accompanied by human fatalities and closure of shellfish harvesting areas was attributed to a toxic bloom of Pseudo-nitzschia multiseries. As a number of Pseudo-nitzschia species have proven to produce toxins, the possible introduction of new and potentially toxic species of this genus, P. fraudulenta and P. subpacifica, should be closely monitored and investigated.

2.5 Secondary introduction

As mentioned before, introduced organisms do not necessarily have to have a detrimental effect on their environment. In most cases, they are not successful in establishing a population in the receiving ecosystem. However, there are many new arrivals that carry hitch-hikers. Chaetoceros species, for example, carry flagellates attached to their setae. Parasites feeding on diatoms and/or other phytoplankton are common in the marine environment and are often host-specific. For example, Mediopyxis helysia is often infected by the parasitoid dinoflagellate Paulsenella vonstoschii, and Odontella sinensis by Phagomyxa odontellae. Both diatoms are listed by Martin and LeGresley (2008) as potential new arrivals to the Canadian East coast. Therefore, they carry the risk of introducing a parasite together with the host.

Bays and estuaries are particularly vulnerable systems. Their community structures are subject to many factors such as freshwater run-offs, nutrient loads introduced into the system and many more. Changes in wind patterns can cause changes in water body residence times and the resulting accumulation of cells in one spot. These changes can create situations favourable for local and also for non-indigenous species to outgrow or out-compete competitors in the water column.

The multitude of vectors for introduction, the scarcity of long-term phytoplankton monitoring datasets and publications, the lack of knowledge of the ecology of the species plus their physiological/ecological needs, makes the evaluation and assessment of new arrivals as potentially invasive species difficult. The basis of this synopsis is an extensive literature search done in order to gather important information on species listed above that were identified as new to the Bay of Fundy, eastern Canada. However, it is surprising how little information is available on some species (e.g. Lithodesmium undulatum) and how often only fragmented and insufficient information are published or available on Internet databases and in the literature. This deficiency clearly shows the need for constant continuous long-term monitoring of coastal and inland waters and, in addition, laboratory experiments using molecular methods. These can be useful tools for keeping track of new arrivals and determining their origin. Training of personnel in taxonomy and accurate identification is essential in order to minimize the error of misidentification (which was likely in the case of Mediopysis helysia being mistaken for Helicotheca tamesis) and hence, increasing the difficulty of analysing datasets that may have unreliable identifications.

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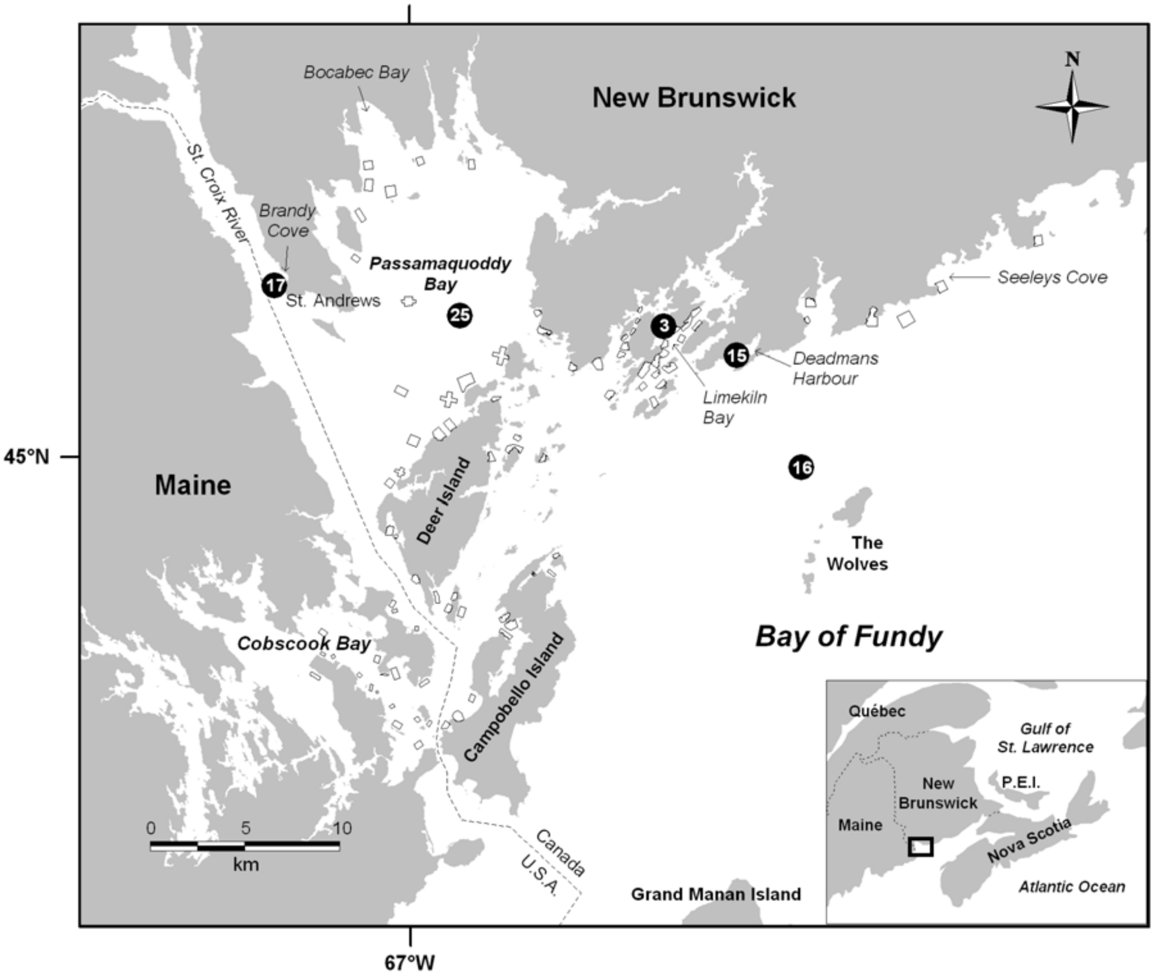

Fig. 1. Map showing sampling stations Brandy Cove (#17), Lime Kiln (#3), Deadmans Harbour (#15), the Wolves Islands (#16) and mid-Passamaquoddy Bay (#25). Salmon farm locations in 2004 are indicated by the outlines.