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Research Article

Northward expansion of the invasive green algae *Codium fragile* spp. *fragile* (Suringar) Hariot, 1889 into coastal waters of Newfoundland, Canada

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Abstract

Invasive green alga *Codium fragile* spp. *fragile* (Suringar) Hariot, 1889 thalli were first detected in Newfoundland (Canada) within Mortier Bay (southwestern Placentia Bay) in August 2012. Subsequent SCUBA surveys in 2013 found *Codium* attached to subtidal substrates in Arnold's Cove (northeastern Placentia Bay) and on the northern coast of central Newfoundland near Pilley's Island (Notre Dame Bay), which is currently the most northern location of *Codium* in Atlantic Canada. Due to large distances between confirmed sightings, further surveys are recommended to determine the distribution range of *Codium* and its possible dispersal vectors in Newfoundland coastal waters. Implications of an invasion by *Codium* on coastal Newfoundland ecosystems are yet to be determined but potential concerns include the replacement of native kelp species, as previously documented elsewhere in Atlantic Canada.

Key words: aquatic invasive species, non-indigenous, *Codium*, oyster thief, alga, survey

Introduction

Non-indigenous species represent an increasing global threat to coastal marine biodiversity and community structure (Ruiz et al. 1997; Cohen and Carlton 1998). The green, branching macroalga, the oyster thief, *Codium fragile* (Suringar) Hariot, 1889 (hereafter called *Codium*) is a notorious, global, invasive seaweed (Trowbridge 1998). In coastal ecosystems, *Codium* can influence biodiversity and community structure by outcompeting native seaweeds and exploiting open space created by local disturbances within native kelp beds (Scheibling and Gagnon 2006). Although *Codium* has mostly been studied in association with rocky shores and attached to hard substrates (including shellfish), recent research has documented *Codium* thriving attached to eelgrass (*Zostera marina* Linneaus, 1753) in sandy habitats (Drouin et al. 2012). In the shellfish aquaculture industry, *Codium* can foul gear and product (e.g. oysters or mussel lines) generating increased labour and impacting the movement of seed stock or product (Bird et al. 1993). Such opportunistic fouling, in addition to various reproductive strategies (e.g. sexual, asexual, and vegetative) (Mathieson et al. 2003), and capacity to disperse long distances (Watanabe et al. 2009) contribute to the invasive success and ecological and economic concerns associated with *Codium*.

Codium is native to the northwest Pacific but invaded coastal European waters by 1900 (Van Goor 1923 cited by Silva 1955) and was first reported near Long Island, New York (United States) in 1957, where it was likely introduced through transfers of shellfish product (Bouck and Morgan 1957; Malinowski and Ramus 1973; Carlton and Scanlon 1985). Cold waters were once thought to limit the spread of *Codium* into Atlantic Canada (Bird et al. 1993). Nevertheless, it has since spread into the Gulf of Maine (Mathieson et al. 2003) and Nova Scotia (Canada) since 1989 (Bird et al. 1993; Scheibling and Gagnon 2006), and along the Gulf of St. Lawrence coast since 1996 (Garbary et al. 1997). In fact, at many sites along the Atlantic coast of Nova Scotia native kelps and other seaweeds have been replaced by *Codium* as the dominant canopy species (Scheibling and Gagnon 2006). Morphological and molecular evidence suggests that two subspecies of *Codium fragile* are present in Atlantic Canada, ssp. *atlanticum* (Cotton) Silva and ssp. *fragile* (formerly referred to as ssp. *tomentosoides* [Van Goor] Silva) (Hubbard and Garbary 2002; Kusakina et al. 2006). The distribution and morphology of *Codium* has been well described in southern Atlantic Canada (e.g. Hubbard and Garbary 2002; Kusakina et al. 2006; Lyons and Scheibling 2009), but this paper describes the first observations of *Codium* in Newfoundland (at its current northern limit in the northwest Atlantic).

Surveys to detect non-indigenous species in coastal Newfoundland waters have been conducted since 2006 by the Department of Fisheries and Oceans (Canada) Aquatic Invasive Species (DFO AIS) Program in collaboration with the Department of Ocean Sciences, Memorial University of Newfoundland (MUN) (Callahan et al. 2010). In total 231 locations, primarily harbours, throughout Newfoundland have been surveyed for non-native, and in particular aquatic invasive species (C. McKenzie, unpublished data). Site selection was based on previous reports of aquatic invasive species, areas expected to be of high risk to introductions (e.g. high boat traffic and low wave energy), and consideration of local ecological knowledge.

Materials and methods

The Newfoundland DFO AIS program conducted surveys comprised of shoreline and underwater surveys (by SCUBA divers from DFO and MUN), including transects conducted perpendicular to shore to assess biological communities, along with visual inspections of wharf structures, boat hulls, other artificial materials, and natural subtidal and intertidal substrates. Following detection of *Codium*, divers conducted further visual surveys (20 min) to assess cover of *Codium* in the area. Analyses of underwater video determined percent cover of *Codium* within 10 m sections along each transect. Temperature data were collected from 2010 to 2013 from Arnold's Cove (Ma 2012), Little Bay, Come by Chance (Smart Bay 2013), and Notre Dame Bay to provide preliminary comparisons of environmental conditions between locations.

To determine the subspecies of *C. fragile* in Newfoundland we considered indicative features such as the size and shape of the utricles and mucron. Divers collected *Codium* specimens from Arnold's Cove and transported them in seawater to the Northwest Atlantic Fisheries Centre (St. John's, Newfoundland). Thalli were maintained at 5°C prior to analyses and 13 morphometric (4 macroscopic and 9 microscopic) traits were measured on ten thalli (based on Hubbard and Garbary 2002). Utricles were sampled approximately 2 cm from the tip of the plant (based on Trowbridge 1998; Hubbard and Garbary 2002) and five utricles were measured from each plant (one tip). Unfortunately, *Codium* specimens collected earlier from other locations were frozen upon collection, which affected cell structure and decreased accuracy of morphological measurements. Features were assessed qualitatively for these collections.

Results

Distribution of Codium *in Newfoundland*

Thalli of *Codium* were detected washed onshore in Mortier Bay, Newfoundland, in Spanish Room (47.195ºN, 55.075ºW) on 22 August 2012, and small fragments (< 10 cm) of *Codium* washed onshore Woody Island (47.784ºN, 54.180ºW) were collected on 27 September 2012 (Figure 1). No *Codium* was detected in underwater transects or during rapid dive surveys at 18 locations surveyed throughout Placentia Bay between August and October 2012. Follow-up targeted surveys discovered thalli attached to the subtidal seabed in Mortier Bay in Marystown (47.166 ºN, 55.148 ºW) on 27 November 2012 and Little Bay (47.164ºN, 55.115ºW) on 6 June 2013 (approximately 5 and 7 km from Spanish Room, respectively) (Figure 1). In Marystown, divers observed scattered plants at < 7 m depths. In 2013, seawater in Little Bay ranged from 1.2 C (March) up to 18.1 C (August), although March was the earliest temperature data recorded in 2013.

In 2013, DFO divers detected sparsely distributed (i.e. no meadow formation evident) *Codium* near the public wharf in Arnold's Cove (47.756ºN, 53.988ºW) on 30 August 2013 (Figure 1). Average (± SE) cover of *Codium* across all transects (8 in total) at two sites in Arnold's Cove conducted on 1 October 2013 was estimated at 1.30 ± 0.24 % and was at most 3.26 ± 0.85 %, which occurred between 60–70 m along the transect for both sites. Most (> 75%) of the *Codium* at Arnold's Cove

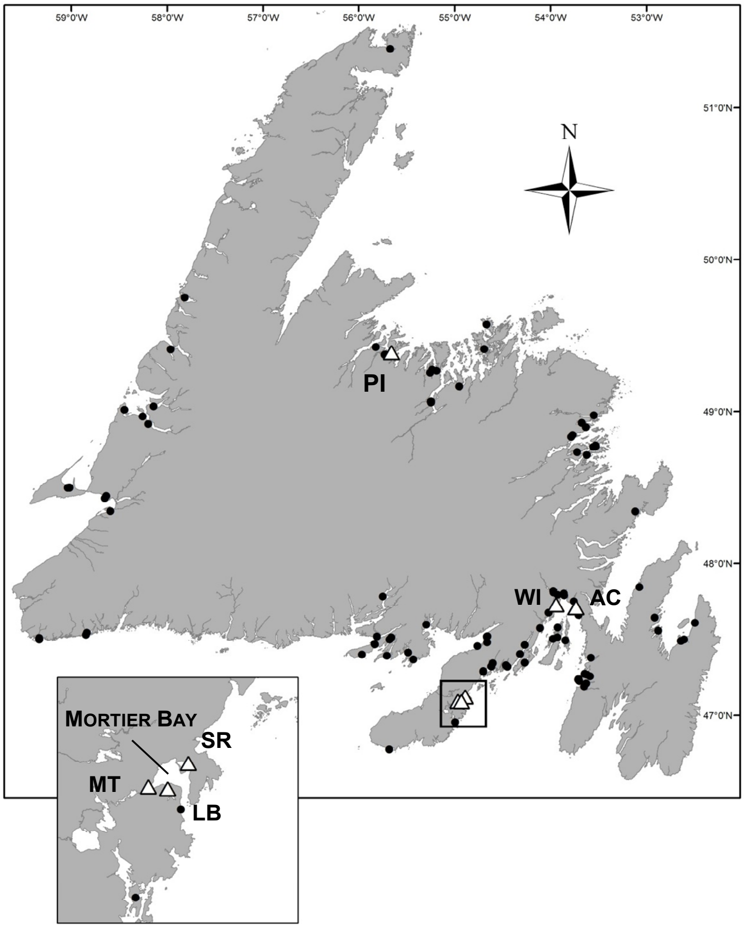

Figure 1. Distribution of aquatic invasive species survey locations in Newfoundland indicating presence (open triangles) and absence (closed circles) of *Codium fragile* ssp. *fragile*. Survey locations with confirmed *Codium* are labelled and abbreviated (PI *Pilley's Island*; WI *Woody Island*; AC *Arnold's Cove*; SR *Spanish Room*; MT *Marystown*; LB *Little Bay*). For details see supplementary material Table S1.

was unattached; however, thalli were observed attached to anthropogenic debris (e.g. bottles), horse mussels (*Modiolus modiolus* Linneaus, 1758), sea scallops (*Placopecten magellanicus* Gmelin, 1791), the shell of a hermit crab (*Pagurus* sp.), other shell remains, the holdfast of a native kelp (*Saccharina longicruris* Kuntz, 1891), and small rocks. When *Codium* was observed attached to horse mussels, it most often attached to the posterior end of the mussel, which protruded from the sediment while it was attached by byssal threads to small rocks below the sediment surface. Seawater temperature was 14.4°C during August surveys, but ranged between 0.8 and 16.7°C (2010 to 2011) in Arnold's Cove (Ma. 2012) and attained temperatures up to 21.3 °C in August 2012 (between 2011 to 2013) in nearby Come by Chance (~ 7 km from Arnold's Cove, 47.789ºN, 54.049ºW) (Smart Bay). Seabed in Arnold's Cove was gently sloping and transects extended to depths up to 7 m. The substrate of one site was primarily mud and gravel with few scattered rocks, while the substrate at the second site was bedrock and boulder nearshore and transitioned to sand and small cobble (< 10 cm diameter) along each transect. Native kelp (*S. longicruris*) was the most common macroalgae, followed by *Codium*. Other benthic vegetation observed included brown algae (*Laminaria digitata* [Hudson] J.V. Lamouroux, 1813, *Desmarestia* sp., *Ascophyllum nodosum* (Linnaeus) Le Jolis, 1863, *Fucus* sp., *Colpomenia peregrina* Sauvageau, 1927), coralline algae, eelgrass (*Z. marina*), and various red and green (e.g. *Ulva* sp.) algae.

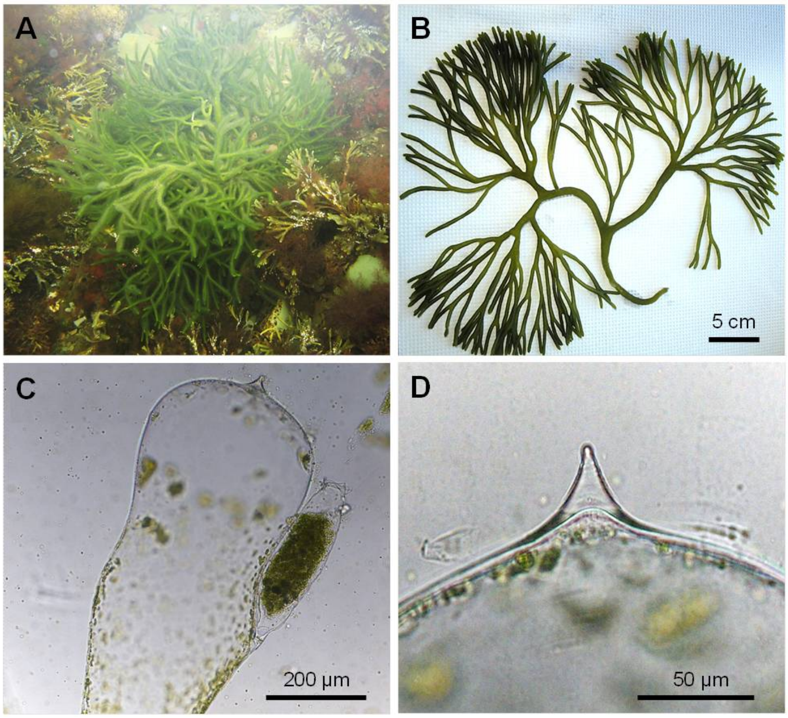

Figure 2. Photographs of *Codium fragile* ssp. *fragile* from Newfoundland showing (A) *Codium* attached to subtidal seabed in Arnold's Cove, (B) an example of dichotomy of drift thalli collected from Spanish Room, (C) utricle of *Codium* showing gametangium and pointed mucron, and (D) a close view of long and pointed mucron on top of utricle. Photographs by P. Sargent (A), T. Wells (B), and K. Matheson (C and D).

Table 1. Macroscopic and microscopic morphometric data of *Codium* (n=10) collected from Arnold's Cove (Newfoundland) with comparison to morphometric data of diagnostic features of *C. fragile* ssp. *fragile* collected from more southern locations in Atlantic Canada (from Hubbard and Garbary 2002).

Character	This study		Nova Scotia/Prince Edward Island	
	Mean	± SE	Mean	± SE
Total length of plant (cm)	44.7	4.7	34.4	1.8
Diameter of widest frond (mm)	11.0	0.6	5.9	0.2
Number of dichotomies on longest axis	7.3	0.5	5.9	0.2
Number of fronds per holdfast	3.6	1.2	4.3	0.9
Maximum utricle diameter (µm)	310.0	8.3	291.0	5.0
Position of maximum utricle diameter (µm)	135.1	3.4	188.0	13.0
Length of utricle (µm)	977.0	28.6	963.0	13.0
Cell wall thickness (µm)	3.5	0.1	3.3	0.1
Mucron length (µm)	27.6	1.3	29.3	1.4
Position of hair (or scar) (µm)	363.0	53.0	192.0	4.0
Position of gametangium (µm)	417.3	13.0	478.0	8.0
Length of gametangium (µm)	318.7	9.8	339.0	10.0
Diameter of gametangium (µm)	105.9	2.7	129.0	14.0

Divers from MUN discovered *Codium* along the northern coast of central Newfoundland near Pilley's Island (Notre Dame Bay; 49.477ºN, 55.725ºW) on 23 September 2013 (Figure 1). Thalli were sparsely distributed and attached to an otherwise barren bedrock platform at depths up to 7 m. Although previously recorded temperature data near this location is limited, in 2004, sea water temperatures reached a high of 19.2°C (August) in Flat Rock Tickle (49.484ºN, 55.735ºW).

Morphology of Codium

Thalli from Arnold's Cove were irregularly dichotomous and grew up to 69 cm high (Figure 2, Table 1). Microscopically, utricles were long with a slight constriction near the centre and mucrons on the top of utricles were long and pointed, characteristic of *Codium fragile* ssp. *fragile* (Figure 2). The microscopic characteristics examined showed similarities to specimens from more southern locations in Atlantic Canada (Hubbard and Garbary 2002) (Table 1). Qualitatively, thalli collected from other locations in Newfoundland also demonstrated long and pointed mucrons on utricles, suggesting that the same subspecies was present throughout the various Newfoundland locations.

Discussion

This is the first record of *Codium* in Newfoundland and, to date, represents the most northern populations of *Codium* in the northwest Atlantic. Plants were large with elongated and pointed mucrons, similar to diagnostic characters of plants identified as *Codium fragile* ssp. *fragile* in Atlantic Canada (Hubbard and Garbary 2002, Kusakina et al. 2006). Mucrons of specimens collected in this study were long and sharp and on average 27.6 µm (and up to 46.5 µm). Our results are similar to the mean length of mucrons of *Codium fragile* ssp. *fragile* collected elsewhere in southern Atlantic Canada in studies by Hubbard and Garbary (2002) (29.3 µm) and Kusakina et al. (2006) (25–44 µm). Morphological data, in particular shape and length of mucrons, are inherited features that have been used effectively to identify *Codium* subspecies (Kusakina et al. 2006). However, Verbruggen et al. (2007) suggests that using morphological characteristics, such as the mucron, may not always be reliable to distinguish *Codium* subspecies. Furthermore, a combination of morphological and molecular evidence established that different subspecies of *Codium* arrived in Atlantic Canada through separate introduction events. Therefore, molecular comparisons between *Codium* populations in Atlantic Canada may be able to identify the source of this introduction to Newfoundland (i.e. from Atlantic Canada or Europe).

So far, *Codium* has not formed dense stands in subtidal regions in Newfoundland comparable to those recorded along the east coast of Nova Scotia (Canada) (Mathieson et al. 2003). However, areas with high numbers of thalli (i.e. Arnold's Cove) suggests close proximity to a point of initial establishment and a source from which new populations may spread within Newfoundland. In Placentia Bay, a counter clockwise gyre can disperse *Codium* in a southwest direction (Ma et al. 2012). Such a current suggests it is not likely that plants found onshore Mortier Bay drifted from nearby islands of St. Pierre and Miquelon (~ 90 km southwest of Mortier Bay), where *Codium* was first detected in 2009 (F. Urtizberea, pers. com.). Instead, if *Codium* in Arnold's Cove is the introduction source within Placentia Bay, a counter clockwise current may have contributed to dispersal of *Codium* to Woody Island (approximately 15 km west of Arnold's Cove) and Mortier Bay (i.e. Little Bay and Marystown, approximately 120 km southwest of Arnold's Cove). Buoyant fragments of *Codium* can be influenced by environmental variables (such as light intensity) and may play an integral role in long-range dispersal of this alga (Gagnon et al. 2011). Although *Codium* can disperse up to 70 km yr^{-1} (Trowbridge 1998), the large distance between Arnold's Cove and Mortier Bay, combined with the high number of drift thalli washed onshore Spanish Room in 2012, suggests that undetected populations may exist nearby. Further surveys are required to determine the precise distribution of *Codium* in Placentia Bay, particularly between Arnold's Cove and Mortier Bay. The proximity of known *Codium* populations to areas of high boat traffic or aquaculture activities suggest that anthropogenic vectors may have contributed to *Codium* transfer within Placentia Bay and from Placentia Bay to the northern coast of central Newfoundland (i.e. Pilley's Island).

The global spread of non-indigenous species has been accelerated by human-mediated pathways including ballast water exchange, vessel hull fouling, recreational boating, aquarium trade, and movement of aquaculture gear and product (Cohen and Carlton 1998; Bax et al. 2003; Blakeslee et al. 2010; Clarke Murray et al. 2012). International translocation and domestic range discontinuities of *Codium* have most likely resulted from transport through fouling of ship hulls or shellfish and use as packaging for transport of product (Carlton and Scanlon 1985; Trowbridge 1998). The presence of *Codium* in locations with relatively high vessel activity (i.e. Arnold's Cove and Mortier Bay) and the large geographic discontinuities between populations in Newfoundland (e.g. Placentia Bay and Pilley's Island) suggest that anthropogenic pathways may have contributed to introductions and subsequent distribution of *Codium* in Newfoundland. In fact, Arnold's Cove is a high risk location for non-indigenous species in Newfoundland exemplified by established populations of golden star tunicate (*Botryllus schlosseri* Pallas, 1766), European green crab (*Carcinus maenas* Linnaeus, 1758), coffin box bryozoan (*Membranipora membranacea* Linneaus, 1767), and sea potato (*Colpomenia peregrina* Sauvageau, 1927). Recent surveys have discovered these species in Mortier Bay (minus sea potato) (C. McKenzie, unpublished data), along with the detection of vase tunicate (*Ciona intestinalis* Linneaus, 1767 Type B) in 2012 (Sargent et al. 2013). Vessels from Mortier Bay often travel to other regions within Newfoundland, other Atlantic Canadian provinces, and to St. Pierre and Miquelon. Therefore, additional surveys are required to document secondary spread of *Codium* to nearby locations.

Codium can tolerate a wide range of environmental conditions including temperatures from -2 to 33°C, salinities from 12 to 40, and relatively short periods (< 6 h) of desiccation and exposure to freshwater (Trowbridge 1998; Kim and Garbary 2007). The establishment of *Codium* in Arnold's Cove and near Pilley's Island suggests that *Codium* on both north and south coasts has survived at least one Newfoundland winter and, in the case of thalli near Pilley's Island, considerable ice cover. However, populations in the southern Gulf of St. Lawrence also survive under extended periods of ice cover every year thus presence of ice, in itself, does not appear to be a limiting factor. Therefore, further establishment of *Codium* in Newfoundland is unlikely to be precluded by seawater temperatures, although growth may be slower at lower water temperatures. Studies in the northwest Atlantic have observed optimal growth at 24°C (Trowbridge 1998), but minimal growth thresholds have been reported between 10 and 13°C (Malinowski and Ramus 1973) and limited growth at 6°C (Hanisak 1979). For example, a field study in Nova Scotia demonstrated that *Codium* growth peaked at 5.6 cm month^{-1} in August-September in water temperatures > 20 °C, but was only 2.6 cm month^{-1} in May-June in water temperatures averaging 11°C (Bégin and Scheibling 2003). Based on temperature data from Placentia Bay, it is likely that *Codium* may grow more slowly in Newfoundland than in some southern Atlantic Canadian locations. Therefore, the largest plants observed in Arnold's Cove (up to 69 cm in height) likely grew over two or three years. Although, fragmentation during colder months (Fralick and Mathieson 1972) may extend the time required for *Codium* buds to become large branched fronds. Seawater temperatures in the most northern regions of Newfoundland only reach 10 to 15°C and occur for short and variable intervals (Caines and Gagnon 2012). Therefore, we suggest such conditions may lead to truncated periods of growth in *Codium*. Similarly, *Codium* reproduction may be limited in cold waters. Observations in the northwest Atlantic indicate gametangia are produced and released at temperatures ≥ 10°C (Trowbridge 1998); however, vegetative propagation may occur through budding and fragmentation, which can further increase the dispersal of *Codium* (Bégin and Scheibling 2003). Additional studies are required to determine if environmental variability limits the formation of dense stands of *Codium* similar to populations elsewhere in Atlantic Canada.

Research in Nova Scotia has demonstrated that *Codium* can opportunistically exploit breaks in kelp canopy and prevent re-establishment of native kelps (Scheibling and Gagnon 2006). *Codium* has also been observed to invade soft-bottom estuaries dominated by eelgrass by attaching to rhizomes (Garbary et al. 2004; Drouin et al. 2012). Such physical changes in subtidal macrophyte canopies can exert significant changes to benthic communities, including limitation of movement and recruitment of fish and invertebrate species inhabiting kelp and eelgrass ecosystems (Levin et al. 2002). However, the invasion of *Codium* may also positively affect biodiversity as research by Drouin et al (2011) demonstrated increases in density and diversity of faunal assemblages within eelgrass beds invaded by *Codium*.

Invasions of *Codium* can impact the shellfish aquaculture industry (Bird et al. 1993). Settlement of *Codium* may reduce filtering in bivalves, affect growth and survival, foul equipment and raise cleaning costs, and introduce risks of further transport and spread of *Codium*, which can lead to novel protocols and permit restrictions (Fralick and Mathieson 1973; Carlton and Scanlon 1985; Bird et al. 1993). Although *Codium* has not been documented on aquaculture sites in Newfoundland, *Codium* detected near Pilley's Island is located adjacent to important mussel aquaculture sites (< 15 km). Overall, the effects of *Codium* in Newfoundland are currently unknown. Further sampling and research on this introduction is required to establish range boundaries and study large-scale and long-term effects of this introduction in the predominantly cold water ecosystems of Newfoundland.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Records of *Codium fragile* spp. *fragile*, in coastal waters of Newfoundland, Canada.

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2014/Supplements/BIR_2014_Matheson_etal_Supplement.xls