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Sonic tracking of wild cod, *Gadus morhua*, in an inshore region of the Bay of Fundy: a contribution to understanding the impact of cod farming for wild cod and endangered salmon populations

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Sea cage trials of Atlantic cod farming have begun in the Bay of Fundy region. We fitted inshore wild cod ($n = 10$) captured in the Quoddy region with sonic tags during the late summer of 2004 to provide data on their temporal and spatial residency and habitat usage, with a view to understanding the potential for impact between escaped farmed cod and wild cod and other fish species, particularly Atlantic salmon. Most of the tagged cod remained within a restricted corridor in the inshore zone, occupied deep water (75–130 m) within several kilometres of the release point, and undertook local movements. Three cod undertook more extensive movements; one fish emigrated offshore immediately, and two fish moved as far as 14 km from the release point before returning, 52–54 h later, to the area in which the other cod were located. The mean residence time in the inshore zone was 55 days. In the late autumn, there was a staggered pattern of departure from the coastal zone, although one fish over-wintered in Passamaquoddy Bay. Three of the nine cod that migrated offshore in autumn 2004 returned within a three-week period in May 2005, after a mean absence of 172 days, and reoccupied the inshore region inhabited the previous year. These cod left the region again after a mean residence of 120 days during the spring and summer. The presence of some of the tagged cod in the principal migration corridor for wild salmon smolts during the period of their migration suggests that escapes from cod farms could result in increased predation on salmon smolts from endangered populations.

Keywords: Atlantic cod, Atlantic salmon predation, migration, sonic telemetry.

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Introduction

In North America, wild cod (*Gadus morhua*) populations are severely depressed (Hunt *et al.*, 1999; Clark *et al.*, 2002; DFO, 2002; COSEWIC, 2003), leading to high prices and an economic incentive to farm them. In Norway, the cod farming industry is growing rapidly, with more than 600 licenses issued up to May 2005 (WWF, 2005), and in the Bay of Fundy, grow-out trials with the species are under way. The cage technology used to farm cod is similar to that for Atlantic salmon (*Salmo salar*) farming.

Atlantic salmon are known to escape from marine cages, and the escapees occur in the same freshwater and marine habitats as wild salmon (Fleming and Petersson, 2001; Hansen and Jacobsen, 2003). In Norway, 75 000 cod were reported to have escaped from farms in 2003 (Holm *et al.*, 2003), raising the possibility of impacts on wild cod populations and other components of the ecosystem. For example, Hvidsten and Møkkelgjerd (1987) found that at least 24.8% of the wild salmon smolts leaving the Surna River in Norway were consumed by cod that had assembled in the estuary at the time of the smolt migration. Therefore, escaped farmed cod could have an impact on the severely depressed local Atlantic salmon populations (e.g. Carr *et al.*, 1997; Amiro, 2003) if they occurred in the migration corridors of smolts at the time of their migration to sea.

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Wild cod in North America are found in discrete populations, some of which are highly migratory (Campana *et al.*, 1999). Others, such as those in New Brunswick's Quoddy region (Figure 1a), may be resident in inshore areas (Graham *et al.*, 2002). However, little is known about the behaviour and local movements of the inshore cod populations. Data are needed on the temporal and spatial residence patterns and habitat preferences of wild cod in this region, before cod farming becomes established. In this study, we tracked ten sonically tagged wild cod, in some cases over a period of about one year, to provide information on the areas they used at different times of the year and, in particular, to determine if the areas they used coincided with the marine migration routes of Atlantic salmon smolts from rivers in the Quoddy region.

Material and methods

Study area

The Quoddy region is an inlet of the Bay of Fundy between Maine, USA, and southwestern New Brunswick, Canada (Figure 1a). Islands delineate the two principal entrances to Passamaquoddy Bay, the Letete Passage and Western

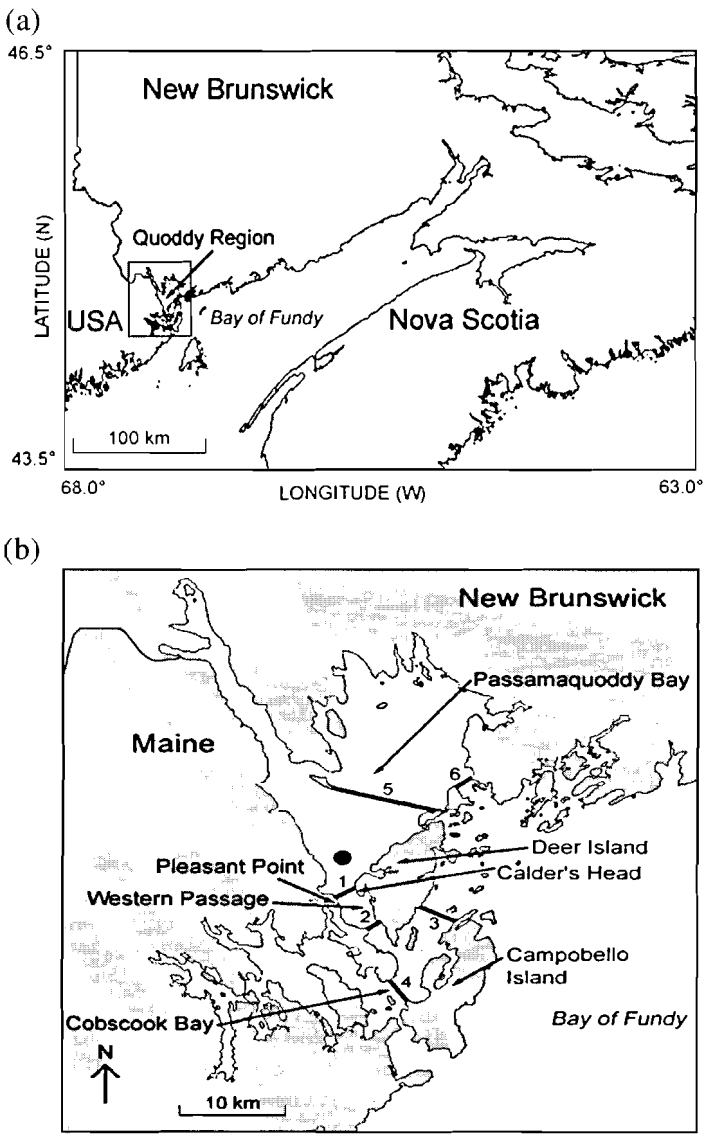

Figure 1. (a) The location of the Quoddy region and (b) the Quoddy region in detail. The release point is indicated by the circle in Passamaquoddy Bay. The hydrophone arrays are shown as dark lines: 1 = Western Passage North, 2 = Western passage South, 3 = Quoddy River/Head Harbor Passage, 4 = Cobscook Bay (CB), 5 = Passamaquoddy Bay, and 6 = Letete Passage.

Passage (Figure 1b). The maximum water depth in this region is approximately 130 m, and the tide is semi-diurnal with a maximum range of 8.3 m, producing extreme tides and currents (Trites and Garrett, 1983).

Cod capture

Cod were captured by an otter trawl deployed from the Huntsman Marine Research Centre's RV "W. B. Scott" on 16–17 September 2004. Eleven tows, each lasting 34 min, were made in Passamaquoddy Bay near the entrance to Western Passage and inside the passage itself, at a mean water depth of 66 m. The trawl was retrieved slowly from the bottom to minimize damage to the experimental fish, which were held in a live well provided with running seawater, before transfer to an onshore holding facility where they were allowed to recover for 16–40 h before tagging.

Tagging

Ten wild cod (mean length 64 cm, range 51–86 cm; mean weight 3.1 kg, range 1.3–7.6 kg) were fitted with 16 × 65 mm (weight in water 10 g) V16 coded acoustic transmitters (Vemco Ltd, Shad Bay, Nova Scotia, Canada). The tags had a battery life of 570 days, minimum and maximum off times of 20 and 69 s, and operated on a frequency of 69 kHz.

Each cod was anaesthetized in an alcohol/clove oil mixture (40 mg clove oil l^{-1}). The anaesthetized cod were placed ventral-side up on a v-shaped trough lined with sponge and the abdomen was disinfected with a solution of Furacin® and distilled water. Surgical implantation of the tag was performed as described by Lacroix *et al.* (2004a). An external T-bar tag (Floy Tag Manufacturing Inc., Seattle, Washington) was attached to each fish at the base of the first dorsal fin to facilitate identification in the event of capture. During surgery, the gills were continuously flushed with seawater, and each fish recovered within a few minutes. The cod were held for 5 h before being released back into Passamaquoddy Bay. They were transported in a 1000-l insulated container aboard a small boat and released close to the point of capture, between 44°58.558′N 67°02.370′W and 44°58.404′N 67°02.404′W on 18 September 2004 at 1600 AST on the ebb tide.

Deployment of hydrophones

Twenty-two hydrophones (VR2, operating on 69 kHz, Vemco Ltd) were deployed between 18 September 2004 and 4 February 2005 in Passamaquoddy Bay and the exit corridors leading to the Bay of Fundy (Figure 1b). The Letete Passage and Cobscook Bay arrays were near cod farms. A redeployment of three hydrophones was made on 27 April 2005 in Western Passage and Letete Passage to detect returning cod. Hydrophone coverage was compromised in the Head Harbour Passage along the Campobello shoreline (Figure 1b) after 23 October 2004 as a result of the entanglement of a single VR2 in a nearby herring weir. Another unit was lost to shipping traffic in Western Passage in the spring of 2005 but was later replaced.

The hydrophones were positioned with an average distance of 380 m between units and are capable of detecting a tagged fish at a distance of >500 m radius (Vemco Ltd specifications and from our own range tests). Most were deployed 15–20 m below the water surface on anchored ropes but, where navigational buoys were available, they were attached to the mooring chains 7 m below the water surface. The hydrophones recorded the individual fish identification code and the time and date of detection and these data were downloaded regularly to a laptop computer.

Weather permitting, active tracking was conducted using a portable receiver (VR60, Vemco Ltd) with an omnidirectional hydrophone in Western Passage and adjacent areas on a biweekly basis during autumn 2004 and early winter 2005, until most of the cod had left the region. Tracking resumed when some of the tagged cod were detected again on 27 April 2005. In total, 19 search transects were made, six of which occurred in autumn 2004. The boat was stopped at 500 m intervals, the portable receiver was deployed for 3–4 min, and the time, date, depth, and location were recorded for each tagged cod that was identified. Positions were recorded with a GPS (Garmin Map 76).

Results

Following release, nine of the ten tagged cod remained predominantly in the deeper areas of Western Passage (70–130 m) and were concentrated in an area between Calder's Head on Deer Island and Pleasant Point, Maine, USA (Figure 1b). They stayed within several kilometres of the release area, ranging short distances within the passage or into neighbouring Passamaquoddy Bay. However, one cod, #1507, left the area immediately and was not detected again (Table 1). Most of the tagged cod ($n = 8$) resided in the Quoddy region for about two months (mean residence time = 55 days) before departing offshore for the winter (Table 1). However, two cod, #1501 and #1505, moved out of Western Passage within a few hours of their release but returned on the same flood tide 52–54 h later. The course tracks of these two fish are shown in Figure 2a and b.

Most of the active tracking detections were also within the range of the hydrophone arrays in Western Passage (Figure 3). No cod were detected on the Passamaquoddy Bay and Letete Passage arrays (Figure 1b). Canadian Hydrographic Service charts indicate that the bottom substrata in the area occupied by the tagged cod included mud, sand, gravel, and rock. The tagged fish exhibited a preference for deep water (70 to 100 m) off Calder's Head, where 98% (range 85–99%) of all hydrophone detections were recorded (Table 2, Figure 2).

Table 1. Timeline of events for the ten tagged wild cod released on 18 September 2004. All tagged cod were first detected on the Western Passage North array.

Cod ID	Length (cm)	Weight (g)	Hours to first detection	Number of days in study area in 2004	Departure date in 2004	Number of days away	Return date in 2005	Number of days in study area 2005	Departure date in 2005
1501	64	2700	<2	60	17 November	182	18 May	90	21 August
1502	58	1500	<4	71	28 November				
1503	86	7600	<6	77	4 December	172	25 May	120	22 September
1504	56	1850	<5	80	7 December				
1505	78	5050	<2	N/A	Resident				Resident
1506	61	2650	<3	23	11 October				
1507	61	2400	<2	<1	18 September				
1508	65	3150	<16	77	4 December				
1509	51	1300	<3	65	22 November	163	4 May	145	29 September
1510	60	2500	<5	35	23 October				

Nine of the tagged cod (including #1507, which left immediately following release) left the Quoddy region during autumn 2004 between 18 September and 4 December (Table 1). All emigrated on the ebb tide and travelled through Head Harbour Passage and the Quoddy River (Figure 2c), which experience strong currents. The cod departed at night or shortly before the onset of darkness. Three of these fish returned in May 2005 to Western Passage (Table 1). They remained within the Quoddy region during the summer, with regular activity recorded near Calder's Head over four months. They emigrated from Western Passage for the second time between 21 August and 29 September 2005, after a mean spring and summer residence of 120 days.

One cod, #1505 (Table 1), over-wintered in the study area and was detected regularly until 7 March 2005. Subsequent visits to Western Passage failed to locate this fish by active tracking. However, it was recorded again on 27 April 2005, after the redeployment of hydrophones. It was similarly detected on the Western Passage North array (Figure 1b) and was followed by active tracking during consecutive months until the last information was downloaded from the hydrophones in early February 2006. This cod remained primarily in the deep section of Western Passage off Calder's Head in the area used by the tagged cod in the summer.

Discussion

Our data indicate that most cod in the Quoddy region migrate seasonally. All except one of the ten tagged cod migrated offshore during autumn and early winter 2004. Their departure from the region was staggered over a period of approximately three months, and they left the area individually, with three cod returning the following spring. Previous studies in this region indicated that adult Atlantic cod are abundant in summer but absent or present in very low abundance in winter (Macdonald *et al.*, 1984). A similar migratory pattern was observed in an acoustic tracking study of an inshore population of Atlantic cod in Cape Breton, Nova Scotia (Comeau *et al.*, 2002). Cod tagged in Passamaquoddy Bay in 1966, and subsequently recaptured in fisheries, moved across the Bay of Fundy to the Scotian Shelf and Georges Bank and also into the Gulf of Maine (Scott and Scott, 1988). In 2001, externally tagged cod released from Deer Island and nearby areas of the Quoddy region were recaptured several hundred kilometres away along the US coast, in higher proportions relative to cod tagged from other areas of the Bay of Fundy (D. S. Clark, pers. comm.). That one of the tagged cod over-wintered in Western Passage and adjacent areas for two consecutive years, however, indicates the possibility of a year-round resident population within the Quoddy region. Historically, a substantial winter-resident inshore cod population may have occurred in this region, including Passamaquoddy Bay (Graham *et al.*, 2002).

The tagged cod displayed a behavioural pattern of site fidelity to Western Passage, especially the deeper waters off Calder's Head (Figure 1b), and their movements in Western Passage and Passamaquoddy Bay, before their migration offshore, appeared to be tidally driven. Only two of the tagged cod were observed to move south into adjacent coastal areas, and this occurred immediately after their release and was followed by a return to Western Passage two days later. Most hydrophone detections were within Western Passage, predominately the northern end, with the cod moving between the two arrays with the tide. Almost without exception, movements were in the direction of the tidal flow.

Small cod, captured from an inshore region in Newfoundland, reared to a larger size in culture (56–77 cm), and released back into the wild, over-wintered in the bay into which they were released and associated with the resident wild cod population (Wroblewski *et al.*, 1996). Similarly, Wroblewski and Hiscock (2002) demonstrated that wild cod held in cages for several growing seasons would reintegrate into wild populations in spawning areas when

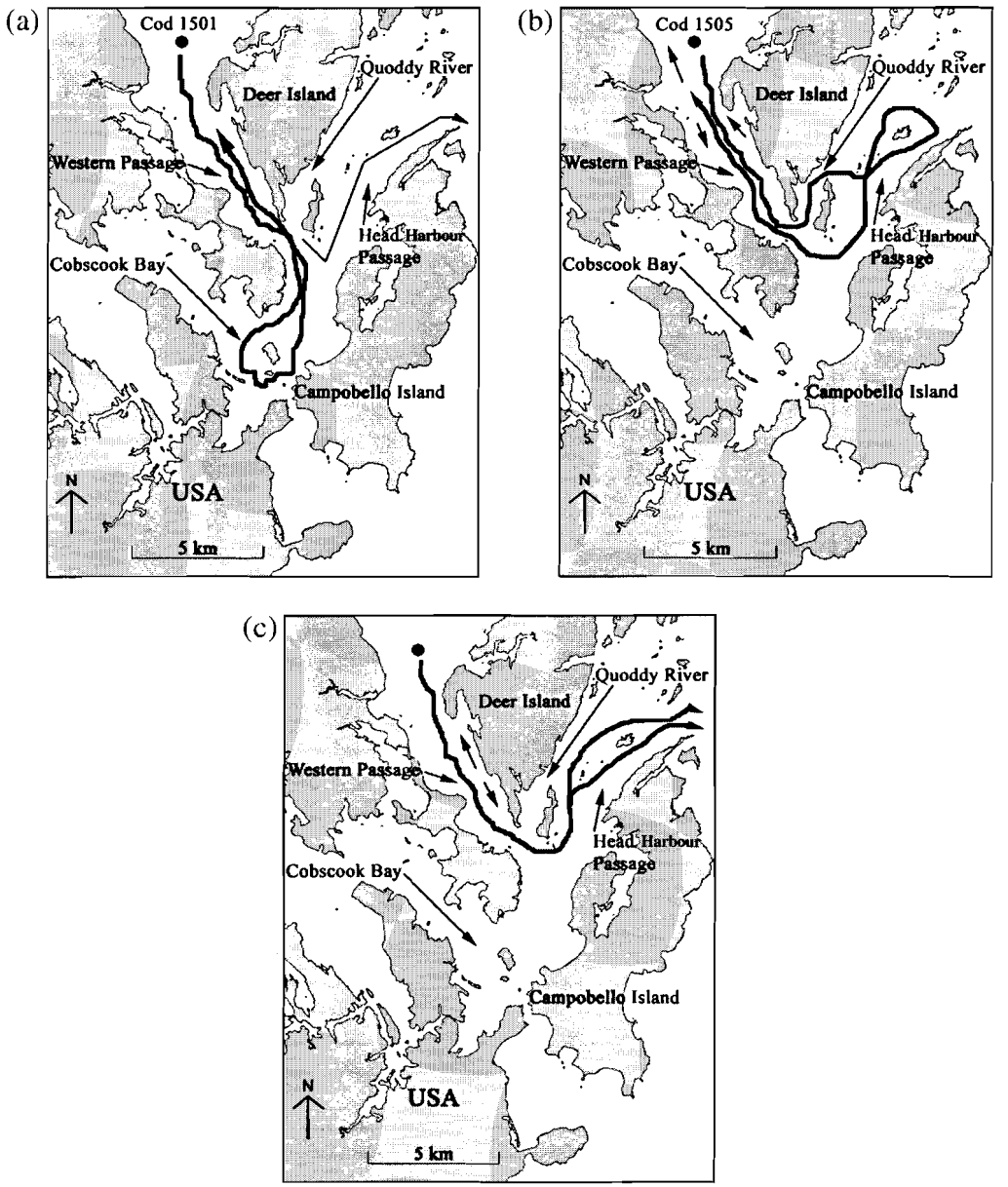

Figure 2. Examples of the movements of tagged cod following their release. The circle indicates the initial release site. (a) Course track of cod #1501 in bold within the first 54 h post-release. The lighter line indicates the exit route taken by this fish to the offshore region in November 2004. (b) Course tracks of resident cod #1505. The bold line indicates movements in the first 54 h post-release. The lighter lines indicate the local tidally driven movements in Western Passage. (c) The offshore migration paths of nine tagged cod during autumn 2004. The lighter lines indicate the local tidally driven movements in Western Passage.

returned to the wild. However, these "farmed" cod were slower to disperse from the release point and were caught at higher rates in fisheries than wild cod. It is not known how cod reared in culture for their entire life cycle will behave or reintegrate if they escape to the wild. There is increasing evidence, however, that cultured fish can learn survival skills from wild conspecifics (e.g. feeding and anti-predator behaviour) and that this social learning is a major adaptive force in fish populations (Brown and Laland, 2001, 2003).

The possible development of cod farming in the Quoddy region raises a number of concerns related to transmission of diseases, displacement of wild cod, and genetic introgression between farmed and wild cod. The behaviour of

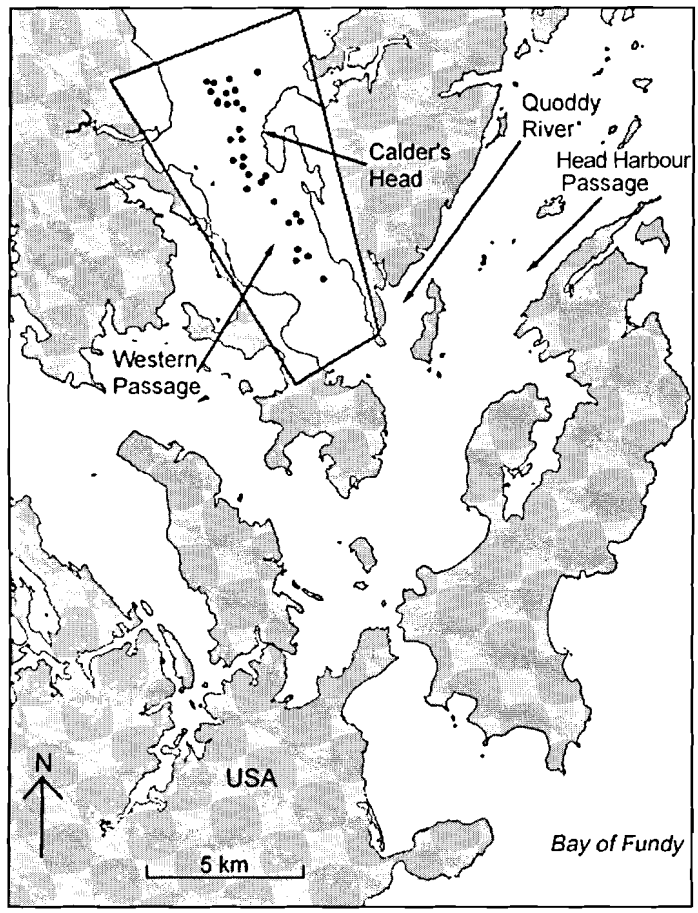

Figure 3. The area in which active tracking was conducted during autumn 2004. Transects were made within the highlighted box. Locations of the tagged cod are indicated by circles, each circle representing a single cod.

Table 2. The number of detections and percentage of total detections at each array from the time of release until 7 December 2004. No cod were recorded on the Passamaquoddy Bay or Letete Passage arrays.

	Western Passage North		Western Passage South		Head Harbour Passage		Lubec/Cobscook Bay	
COD ID	Number of detections	% of total detections	Number of detections	% of total detections	Number of detections	% of total detections	Number of detections	% of total detections
1501	8406	97	243	2	0	0	59	1
1502	2895	98	47	2	0	0	0	0
1503	18831	98	361	2	0	0	0	0
1504	3081	88	421	12	0	0	0	0
1505	3459	85	47	1	172	14	0	0
1506	5568	99	37	1	5	<1	0	0
1507	15	94	1	6	0	0	0	0
1508	10794	99	50	<1	0	0	0	0
1509	11059	99	89	<1	45	<1	0	0
1510	3522	96	23	1	118	3	0	0
Total	67630	97.5	1319	1.9	340	0.5	59	0.1

cod in cages differs from that of farmed Atlantic salmon in that they occupy positions close to the net and, therefore, are more likely to escape if the net is torn (WWF, 2005). Depleted wild cod stocks (Mayo, 1995; DFO, 2002; COSEWIC, 2003) may be particularly vulnerable to impact from escapees.

Previous studies have shown that most smolts leaving rivers draining into Passamaquoddy and Cobscock Bays do so in May and June through the Western Passage corridor (Lacroix and McCurdy, 1996; Lacroix *et al.*, 2004b). Of the ten cod tagged in this study, four were detected in the migration corridor of smolts at the time of their migration to the sea. Although cod are adapted for bottom feeding, they may spend considerable time near the surface (Scott and Scott, 1988) and can be a significant predator of Atlantic salmon smolts (Hvidsten and Møkkelgjerd, 1987; Hvidsten and Lund, 1988; O'Connell *et al.*, 1999). Further research is needed to confirm that escaped farmed cod behave in the same way as the tagged wild cod in this study and the degree to which the depth distribution of cod and salmon smolts overlap. Historically, cod populations may have been higher than at present, but in the Quoddy region, the local wild salmon populations are at critically low levels (Amiro, 2003; DFO, 2003; NRC, 2004) and may be particularly vulnerable to any increase in predation pressure. Cod farm site selection, equipment design, and deployment should consider the potential interactions between farmed and wild cod and other species, including Atlantic salmon.

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