Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences

C S A S | ***S C C S***

Canadian Science Advisory Secretariat | **Secrétariat canadien de consultation scientifique**

Research Document 2008/047 | **Document de recherche 2008/047**

Northern cod (*Gadus morhua*) 16 years after the moratorium: new information from tagging and acoustic telemetry

La morue du Nord (*Gadus morhua*), 16 ans après le moratoire : nouvelles données provenant du marquage et de la télémétrie acoustique

J. Brattey, B. Healey and D. Porter

Science Branch
Fisheries and Oceans Canada
PO Box 5667
St. John's NL A1C 5X1

ISSN 1499-3848 (Printed / Imprimé)

Canada

ABSTRACT

A combined tagging and acoustic telemetry approach was used to investigate the survival and migratory behaviour of a coastal population of northern cod, with emphasis on over-wintering cod in Smith Sound (SS), Trinity Bay, Newfoundland (NL). The home range, seasonal movements, fidelity to over-wintering areas, and survival (mortality) rates, of these cod were investigated. Movements patterns inferred from telemetry results were also compared with those based on recaptures of conventionally tagged cod. Following a pilot scale study, we released large numbers of cod (>100 per year) with surgically implanted coded transmitters (Vemco V16, 69kHz) and external (Floy) t-bar tags and deployed a "counting fence" of receivers (Vemco VR2) at the mouth of SS to provide detailed information about daily movements. We also deployed arrays of receivers along the northeast coast of NL to investigate migration patterns and dispersal, and determine if these cod were subsequently over-wintering in other inshore areas. Small numbers of cod ($\leq$20) with implanted transmitters were also released at other sites along the north east coast and their movements monitored. Survival of telemetred and tagged cod following release was only 66% for trawled cod from deep (190-225 m) water, compared to 96.4% for those caught with hand-lines in shallow (10-82 m) water. There was a clear seasonal pattern in movements that was repeated in three consecutive years (2005-07); most cod left SS in spring (March-June), remained outside SS during summer, dispersed mainly northward in Trinity Bay and Bonavista Bay, and returned during late autumn and winter (November-January); a small proportion of telemetred cod (0-20%) remained in SS throughout the year. Cod released in SS showed strong over-wintering site fidelity and return rates were: 9 of 9 (100%) in 2005, 64 of 77 (83%) in 2006, and 65 of 99 (65%) in 2007. Less than 10% of telemetred cod showed other behaviours, including over-wintering elsewhere in subsequent years, and returning to and leaving SS repeatedly during summer and fall. Ten percent of telemetred SS cod were captured in the fishery in 2006 and 9% in 2007, from reported landings of only a few thousand tons. Direct estimates of the minimum survival rate of two groups of telemetred cod were 80% (from 19 May 2006 to 29 January 2007) and 68% (from 31 May 2007 to 29 January 2008). Some cod released off Twillingate and in Newman Sound over-wintered in the deep inlets of inner Bonavista Bay, whereas those released in southern 3L stayed in the local area or moved south and some were captured in NAFO Subdiv. 3Ps the following winter. The results support the revised stock structure used in assessments of northern cod since 2005, and indicate a resident component in the central inshore region of 3KL, and a migratory component in southern 3L.

RÉSUMÉ

Nous avons employé une approche combinée de marquage et de télémétrie acoustique pour étudier la survie et le comportement migrateur d'une population côtière de morues du Nord, plus particulièrement celles qui passent l'hiver dans le détroit de Smith, la baie de la Trinité et au large des côtes de Terre-Neuve. Notre étude portait sur le domaine vital, les déplacements saisonniers, la fidélité aux zones d'hivernage ainsi que le taux de survie (mortalité) de ces morues et comprenait également une comparaison entre les profils migratoires basés sur les résultats de la télémétrie et les recaptures de morues marquées de la manière habituelle. Après une étude à petite échelle, le relâchement de grands nombres de morues (> 100 par an) munies d'un émetteur chirurgicalement implanté (Vemco V16, 69 kHz) et d'une étiquette en T (Floy) ainsi que la mise en place d'une « barrière de dénombrement » constituée de récepteurs (Vemco VR2) à l'embouchure du détroit de Smith nous ont permis d'obtenir de l'information détaillée sur leurs déplacements quotidiens. Par ailleurs, grâce à un réseau de récepteurs installés le long de la côte nord-est de Terre-Neuve, nous avons pu étudier les profils de migration et de dispersion de ces morues et déterminer si elles passaient l'hiver dans d'autres eaux côtières. Nous avons aussi relâché de petits nombres de morues (≤ 20) munies d'un émetteur et surveillé leurs déplacements dans d'autres sites le long de la côte nord-est de Terre-Neuve. Une fois relâchées, les morues marquées et munies d'un émetteur ont affiché des taux de survie de seulement 66 % pour les morues pêchées au chalut en eaux profondes (190-225 m) et de 96,4 % pour les morues capturées à la ligne à main en eaux peu profondes (10-82 m). Le déplacement des morues a affiché un profil saisonnier évident sur trois années consécutives (2005-2007) : la plupart des morues quittent le détroit de Smith au printemps (mars-juin), restent à l'extérieur du détroit de Smith pendant l'été, se dispersant principalement vers le nord dans la baie de la Trinité et la baie de Bonavista, puis retournent dans le détroit de Smith à la fin de l'automne et durant l'hiver (novembre-janvier). Dans une faible proportion, les morues munies d'un émetteur (0-20 %) restent dans le détroit de Smith tout au long de l'année. Les morues relâchées dans le détroit de Smith ont affiché un taux élevé de fidélité aux zones d'hivernage et y sont retournées dans les proportions suivantes : 9 sur 9 (100 %) en 2005; 64 sur 77 (83 %) en 2006; 65 sur 99 (65 %) en 2007. Moins de 10 % des morues munies d'un émetteur ont affiché d'autres comportements, comme passer l'hiver ailleurs au cours des années subséquentes et faire des allers-retours répétés depuis et vers le détroit de Smith pendant l'été et l'automne. Les morues munies d'un émetteur ont été capturées par des pêcheurs dans des proportions de 10 % en 2006 et de 9 % en 2007, d'après des débarquements déclarés de quelques milliers de tonnes seulement. Les estimations directes du taux minimal de survie de deux groupes de morues munies d'un émetteur ont été de 80 % (du 19 mai 2006 au 29 janvier 2007) et de 68 % (du 31 mai 2007 au 29 janvier 2008). Certaines morues relâchées au large de l'île de Twillingate et dans le détroit de Newman ont passé l'hiver dans les profondes échancrures de l'intérieur de la baie de Bonavista, tandis que celles relâchées dans le sud de la division 3L sont restées dans le secteur ou se sont déplacées plus au sud; certaines morues ont été capturées dans la sous-division 3Ps de l'OPANO l'hiver suivant. Les résultats soutiennent la structure des stocks révisée qui est utilisée dans les évaluations de la morue du Nord depuis 2005 et indiquent la présence de deux populations, à savoir une population résidente dans la région côtière centrale de 3KL et une population migratoire dans le sud de la division 3L.

INTRODUCTION

Acoustic telemetry technology has improved dramatically in the past decade and cost-effective, reliable systems are now available that can provide detailed information on the movements of many individual animals for several years. The behaviour of aquatic animals with attached or implanted transmitters can be monitored in various ways: either actively, by tracking and following individual animals, or repeatedly surveying specific areas with a mobile hydrophone deployed from a vessel; or passively, by mooring automated acoustic receivers at numerous locations throughout the study area and using them to record the movement of telemetred animals (Heupel et al. 2006; Heupel and Simpfendorfer 2002).

Most earlier telemetry studies on Atlantic cod (*Gadus morhua*) in eastern Canada employed the active approach and provided detailed behavioural information on a modest number of animals (Clark and Green 1990; Wroblewski et al. 1994; Green and Wroblewski 2000; Robichaud and Rose 2001, 2002; Cote et al. 2003; Windle and Rose 2005). More recently, two large scale studies using passive monitoring arrays and involving large numbers of Atlantic cod have been conducted. Comeau et al. (2002) monitored the movements of 126 Atlantic cod across a 160 km stretch of the Laurentian Channel off eastern Canada for 1 year using 69 subsurface receivers. Castonguay and co-workers (M. Castonguay, pers. comm.) deployed 80 bottom moored receivers and released 251 cod with transmitters to investigate stock mixing of Atlantic cod off the west and southwest coasts of Newfoundland during May 2004-July 2005.

Recent studies on other aquatic species have shown that acoustic telemetry can also be used quantitatively, to obtain direct estimates of natural, fishing, and total mortality rates (Heupel and Simpfendorfer 2002; Hightower et al. 2001). Estimates of the instantaneous rate of natural mortality (*M*) are critical for stock assessment, but are typically difficult to obtain (Vetter 1988, Quinn and Deriso 1999). An assumed value of *M* that is constant across all ages is often used, although the assumed value can change over time (Pinhorn 1975; Sinclair 2001). For the northern (2J+3KL) cod stock prior to the moratorium, an assumed value of $M = 0.2$ per yr was used. In the post-moratorium period, the rate of total mortality in the offshore has been extremely high, but the source of the mortality (fishing or natural) remains unclear (Lilly et al. 2006). Based on information from recent inshore tagging studies, the assumed value of *M* for coastal northern cod was initially set at 0.5 per yr, but this was subsequently reduced to 0.4 per yr (Lilly et al. 2005).

Under some circumstances, the telemetry approach can provide detailed information about mortality and survival rates, particularly when a large proportion of the stock concentrates in a well defined area. For example, survival rates of steelhead smolts have been studied using telemetry by deploying “counting fences” of receivers at river mouths and releasing large numbers of smolts with surgically implanted transmitters upstream (Welch et al. 2004). Arrays of receivers are also deployed in the marine environment at various distances away from the river mouth, and mortality rates can be determined by comparing counts of the number of smolts crossing each line of receivers.

In the present study we employed a combined tagging and acoustic telemetry approach to investigate the survival and migratory behaviour of a coastal population of northern cod that over-winters in Smith Sound (hereafter SS), Trinity Bay. Acoustic surveys conducted in SS during winter 1995-2007 provided biomass estimates ranging from a few thousand to >20,000 t (Rose 2003). Conventional tagging studies using Floy t-bar tags have shown that many of these cod leave SS in late spring and disperse around the northeast coast where they have been exploited to varying degrees by small-scale inshore fisheries (Brattey and Healey 2003, 2005, 2007).

The main objectives of the present study were: (1) to define the home range of cod over-wintering in SS; (2) explore seasonal movements and fidelity to over-wintering areas; (3) to estimate survival (mortality) rates; and, (4) to compare telemetry results with those from conventional tagging of cod. To achieve these objectives we released large numbers of cod (>100 per year) with surgically implanted transmitters and deployed a "counting fence" of receivers at the mouth of SS to provide detailed information about the numbers of cod leaving and returning daily. We also deployed arrays of receivers along the north east coast to investigate migration patterns and dispersal and determine if these cod were subsequently over-wintering in other inshore areas. Smaller numbers of cod ($\leq$20) with implanted transmitters were also released at other sites along the north east coast and their movements monitored. Initial findings from this ongoing study are reported here.

MATERIALS AND METHODS

STUDY SITE

The study area is a 350 km section of the inshore region off the northeast coast of Newfoundland, extending from Cape St. John in the north southward to Petty Harbour and up to about 8 km offshore (Fig. 1). Much of the study was focused in SS, a narrow (1-1.5 km wide) sheltered fjord approximately 30 km long, located in the northwestern portion of Trinity Bay and a known over-wintering area for cod. Water depths extend down to >200 m in several regions in the central and outer regions of the sound.

FIELD METHODS

Transmitters

Adult cod (>60 cm fork length) were caught using hand-lines equipped with feathered or baited hooks, rod and reel with lure, baited cod pots (fall 2006 only), or by bottom-trawling from a small (30 m) research vessel using a Yankee 36 otter trawl (spring 2006 and spring 2007). Captured cod in good condition were held in 400 L or 900 L tanks supplied with running ambient seawater. Individually coded transmitters (69Khz, Vemco Ltd., Nova Scotia) with long-life (>14 month) batteries were surgically implanted into the body cavity of cod using a standard procedure approved by the local committee of the Canadian Council for Animal Care. The V16 transmitters we used measure 16 mm by 95 mm, weigh 16 g in water, and have a power output of 165dB re 1uPa @ 1m; we implanted them in cod $\geq$60 cm fork length and weighing $\geq$2.0 kg. Prior to surgery, the fork length (FL) of each cod was measured, and two external t-bar anchor tags (Floy Tag Co. Ltd., Seattle, Washington) were inserted approximately 3 cm apart at the base of the first dorsal fin; these tags were identical to those used in our conventional tagging studies. The anterior tag was yellow and the posterior tag was pink, and both tags bore a unique number, a reward value ($10 for yellow, $100 for pink) and a return address. Cod were held for 30-60 min post-surgery or occasionally overnight, and then released close to the capture site. Transmitter function was confirmed using a receiver (VR100 or VR2) held in the holding tank during recovery.

During May 2005-July 2007 a total of 283 cod were captured and released with tags and transmitters in five areas (see Fig. 1, Table 1). These were: Twillingate (n=20); Newman Sound (n=4); Bonavista (n=13); Northwest Arm, Trinity Bay (n=2); and, Petty Harbour (n=18). In SS they were released during May 2005 (n=10), November-December 2005 and April-May 2006 (n=104), and during November 2006 and May 2007 (n=112). Within SS, cod were captured and released in batches at several widely dispersed sites (Fig. 2). Large numbers of cod tagged only with external t-bar tags were also released

simultaneously with each batch of fish with transmitters; details are given in Brattey and Healey (2007).

For analysis, we combined the cod released with transmitters in SS into three groups; a pilot-scale group which consisted of 10 cod released in May 2005, and two "over-wintering" groups, namely a fall 2005–spring 2006 group, and a fall 2006–spring 2007 group. We deliberately spread the releases of telemetred individuals in case there was temporal/spatial stock substructure among cod in SS during the over-wintering period.

Receivers

Arrays of 2-8 receivers (Vemco VR2 or VR2W) equipped with long-life (~14 month) batteries were moored at various locations throughout the coastal region to record the movements of cod with implanted transmitters (Fig. 1, Table 2). Mooring apparatus consisted of approximately 350 m of 6 mm polysteel rope weighted with equidistantly spaced concrete masonry blocks and 15 kg of heavy link chain at each end; the receiver was suspended at one end of the mooring line about 8-12 m off bottom on an 18 m vertical length of rope with a trawl float attached. The first receiver in an array was typically moored within 0.5 km of the shoreline, and subsequent ones spaced $\leq$1.8 km apart; the detection radius of the VR2 is approximately 1 km under optimum conditions. Pairs of receivers $\leq$1.8 km apart were also moored near the entrance to various narrow (<2 km wide) inlets of inner Bonavista Bay and in northwestern Trinity Bay to determine if and when cod entered and left these areas. Three receivers were also deployed longitudinally about 2.5 km apart near the mouth of SS from early May 2005 onwards to provide detailed information on movement of cod into and out of this location; two additional receivers were deployed in the inner reaches of SS during late fall 2006 to monitor movements within the sound. A further three receivers were moored in the mid-region of SS in mid-December 2007. Receivers were retrieved by dragging a grappling hook weighted with heavy chain that snagged the mooring line; they were retrieved periodically with a hydraulic winch, data downloaded, and new batteries inserted as required. A total of 85 receivers had been deployed by the end of 2007 (Table 2). Retrieval has been successful in most cases, although eight receivers have not been successfully retrieved to date (one off Cape St. John, one off Fogo, four off Cape Bonavista, one off East Random Head, and one off Petty Harbour). Batteries also failed on some units prior to replacement, resulting in possible missed detections from the date of failure until the next battery replacement date; however, data loss occurred mainly during winter and early spring months when most fish had returned to SS.

Several surveys to investigate local movement of telemetred cod within SS were conducted, using either a Vemco VR100 receiver equipped with an omni-directional hydrophone or a VR2 receiver suspended 8 m below a small (35 ft) fishing vessel. The detection radius of the receiver is approximately 1 km, although detection distance can be influenced by various environmental conditions and vessel noise. We constructed a fixed grid of 82 equidistant listening stations $\leq$0.75 km apart extending to the outer reaches of SS to longitude 53°30' W; we listened for 4-6 min at each station with the vessel engine and depth sounder turned off. These surveys were conducted to determine the general location and transmitter serial number of acoustically tagged cod, and to determine whether cod with transmitters had moved since release or since the previous survey. Lack of movement over a period of several months was assumed to indicate post-surgery mortality. Opportunistic surveys were also conducted at various other locations within the study area (off Melrose in May 2006, off Bonavista in June 2006, in southern Bonavista Bay in July 2006) using the same apparatus described above. During field work, we also deployed VR2's on temporary moorings equipped with surface floats in the vicinity of cod aggregations to determine if any cod with transmitters were in the immediate vicinity.

We used the detection data from the three receivers moored longitudinally near the mouth of SS (at Burn Point, Gooseberry Island, and Warwick Harbour, respectively; Fig. 2) to obtain precise identification and daily counts of the total number of telemetred cod exiting, returning, or entering SS. The width of SS at these locations is <1.9 km and Vemco VR2 receivers were reported to have a detection radius of 1 km under optimum conditions; thus, one purpose of these initial deployments was to test if a single receiver would detect cod leaving across the full width of the sound. Location and direction of travel of individual fish was determined from the sequence of timing of pings recorded by the three receivers. Location of individual telemetered cod at the end of each day after release was classified as being either within SS, among the three outer receivers, or outside SS.

Telemetry data

Our telemetry data were organized into three file types: transmitter and receiver deployment metadata, and receiver download files. We merged the data from these three file types into a single database to enable us to reconstruct a chronological detection history for each cod with a transmitter and to summarize detection results from various receiver arrays. We conducted extensive preliminary screening of the data as recommended by the manufacturer to eliminate false detections prior to analysis. The volume of data collected to date is considerable, with 1.6 million detection records available by the end of January 2008.

Conventional tagging

Recapture information from cod tagged with external Floy tags in Smith Sound and in NAFO Subdiv. 3Ps during 1997-2007 was summarized and compared with the telemetry data. Details of the conventional tagging experiments are described elsewhere (Brattey and Healey 2003, 2005, 2006, 2007).

RESULTS

SIZE DISTRIBUTION OF COD RELEASED WITH TRANSMITTERS

We implanted V16 transmitters in cod of a wide range of sizes. Among cod in SS, size (fork length) ranged from 60 cm to 105 cm, although most fish were <85 cm (Fig. 3); these fish would have been mostly sexually mature and typically $\geq$6 yrs old. There were no major differences in size frequency between cod released in 2005-06 or 2006-07 other than a slightly greater number of fish >82 cm in 2005-06; median length in both years was 74 cm. Size distributions of cod released at other sites were similar (not shown).

Pilot scale project

Data from the receivers moored at the mouth of SS confirmed that all 10 cod released in May 2005 were detected (on all three receivers) leaving SS later that spring. One was caught in a gillnet set for lumpfish (*Cyclopterus lumpus*) during June 2005 off Old Bonaventure (see Fig. 2) about 12 km outside SS. All of the remaining (nine) fish were detected, again on all three receivers, returning to SS during October-December 2005. These fish survived the winter and were detected again leaving SS the following spring before the transmitter batteries expired in July 2006. Based on these encouraging results we initiated a large-scale study during autumn 2005-spring 2006 and autumn 2006–spring 2007. We released cod with transmitters at various sites, including several batches within SS, and deployed arrays of receivers throughout the inshore off the northeast coast; five additional arrays were added in spring and early summer 2007 and a sixth in the central portion of SS in December 2007 (Fig. 1 and 2; Tables 1 and 2).

Survival of Smith Sound (SS) cod with transmitters immediately after release

Release of cod within an enclosed area such as SS has enabled us to quantify the proportion of cod with transmitters that survived the initial stress of capture, transmitter implantation and tagging. Repeated surveys of SS indicated that 11 of 20 cod caught with an otter trawl in deep (200-208 m) water in April 2006 and subsequently implanted with transmitters did not move after release and were assumed to have died; the remaining nine fish from this batch left SS and returned during late fall 2006. Similarly, 6 of 30 cod trawled in deep (190-225 m) water and released with transmitters in May 2007 did not subsequently move and were assumed to have died. In contrast, among cod caught with various gears in shallow (10-82 m) water and implanted with transmitters, 81 of 84 released in spring 2006 and 79 of 82 released in spring 2007 survived and left the area. Average survival was therefore only 66% for trawled fish from deep water, compared to 96.4% for those caught in shallow water. Transmitter implantation was typically conducted in spring or fall when the water column was uniformly cold (<5 C), as revealed by vertical CTD casts at the capture sites.

We investigated in detail the subsequent fate of the two groups of SS cod that survived the initial implantation procedure (i.e. 89 cod from the 2005-06 releases, and 103 from 2006 to 2007).

Movement of cod within Smith Sound

The receiver array at the mouth of SS provided detailed information about the timing and direction of movement of cod into and out of SS. Daily counts of the percent in SS from five separate batches of cod released within SS are shown in Fig 4; data from some batches of cod are not shown here (see Table 1), but these showed the same trends. Cod with transmitters that were captured in the fishery, or whose transmitters were beyond battery expiry dates, were subtracted from the total numbers available when calculating daily percentages. Our data indicated that many transmitters continued to function for several weeks after manufacturer's expiry dates; however, we omitted data from detections more than two weeks after expiry dates when calculating percentages. This procedure eliminated the potential confounding between movement away from receivers and battery failure which could have complicated interpretation of the results.

There was a clear seasonal pattern in movements that was repeated in three consecutive years (Fig. 4); most cod (84-100%) left during spring (March-June), remained outside SS during summer, and returned to SS typically during November-January. During late January until early March 2006 and 2007 there were only a few detections on the receiver array deployed in outer SS; no cod with transmitters either entered or left SS in this mid-winter period and cod were highly aggregated in the deep channel just north of the community of Petley in the vicinity of array # 16 deployed in the middle of SS in December 2007.

In some of the batches of cod released in SS, all individuals left SS in summer, but in others a small proportion (generally <20%) remained in SS during summer 2006 or summer 2007. The results also indicate synchronous movements of cod from different batches past the receiver array in spring; for example, during late December 2005 most cod from the 18-19 May 2005 batch and 13 December 2005 batch moved outside SS briefly then returned again in late January (Fig. 4). Similarly, during March 2006 about 75% of the cod from these two batches left SS during early March, and about 40% returned again during mid-April; most of these telemetred cod left again during April-June 2006 and did not return until the following autumn. Although the overall pattern of cod movement is outward on spring and return in late fall, these results indicate some

coordinated movement back and forth across the outer receiver array and not a simple unidirectional movement into or out of SS. In spring 2006 and 2007 some cod left SS as early as March. In 2007, from mid-March until early May the percentage in SS remained fairly constant, but cod began leaving again from May until early July (Fig. 4).

Overall, the cod released in SS showed strong over-wintering site fidelity. The numbers (percentages) of cod that left SS in spring and returned the next autumn (excluding those captured) were: 9 of 9 (100%) released in spring 2005, 64 of 77 (83%) released in autumn 2005-spring 2006, and 65 of 99 (65%) in autumn 2006-spring 2007.

Although most cod released in SS conformed to the general seasonal pattern of movement depicted in Fig. 4, a small proportion displayed different behaviours. Three fish released in 2005-06 and five fish released in 2006-07 did not leave SS during summer. Three cod that left SS in spring 2006 did not return to over-winter, but were subsequently detected on receivers outside SS the following summer, indicating they had over-wintered elsewhere; one over-wintered in deep water (300 m) close to a receiver moored off Grates Cove, Trinity Bay. Similarly, two cod that left SS in spring 2006 returned in August and October 2006, respectively, but left again in early December and over-wintered in Southwest Arm, Trinity Bay. Approximately 10% of the cod that left SS each year that were detected on receivers outside SS returned and left again one or more times during late summer and autumn before returning to over-winter in SS late in autumn.

Dispersal of cod outside Smith Sound

To investigate how many cod with transmitters that left SS in spring 2006 were subsequently detected on receivers outside SS, we computed the total number of cod with transmitters detected each month (including repeat detections) from March to December 2006 (Fig. 5). Detections on receiver array 14 at Bonaventure Head (Fig. 1) were omitted from this analysis as this array is close to the mouth of SS. The total numbers detected increased rapidly during April-June as cod left SS, but numbers declined after August to a minimum of only 6 in October. Numbers detected increased again in November and December as fish moved back towards SS. The maximum number of cod detected was 42 (in June), indicating that in each month at least 39% of the available fish with transmitters were not detected on the inshore receiver arrays.

Detection results for cod that left SS in spring 2007 were also compiled and the results, though preliminary, were similar to those for 2006. Numbers detected increased rapidly in June and July as cod left SS, but declined thereafter, partly because fewer data are available for this period as some receivers have not been retrieved and data uploaded. The maximum number of cod detected in any month in 2007 was 63 (July) again indicating that in each month a substantial fraction of the available cod with transmitters was not detected.

The cumulative percentage detected among cod that left SS in spring 2006 increased rapidly during April-August then leveled off and only a few additional telemetred cod were detected during September-December (Fig. 5). In total 77 of 85 (91%) were detected on at least one receiver outside SS in 2006. In 2007, the cumulative pattern is similar to that observed in 2006 and 67 of 99 (68%) have been detected. Note that the 2007 data are incomplete as all receivers have not yet been retrieved

To investigate the general dispersal pattern of SS cod we grouped the detections from adjacent receiver arrays into nine regions and computed the percentage of telemetred cod detected (Fig. 6); detections on receiver array 14 at Bonaventure Head (Fig. 1) were omitted as this array is close to the mouth of SS. Most of the detections were on receivers moored within about 100 km of SS, particularly at Melrose and

Bonavista, where 70% and 67% were detected, respectively. A small percentage of the cod were detected on receivers at the mouth of narrow inlets at the bottom of Bonavista Bay (7%) and in northwestern Trinity Bay immediately adjacent to but south of SS (11%). Small percentages were also detected in northern Bonavista Bay (5%) and off Baccalieu (6%). No cod from SS were detected northward to Notre Dame Bay or southward to Conception Bay.

Movements of cod released in other regions

Twillingate: Of the 20 telemetred cod released off Twillingate (Fig. 1) in early July 2006, seventeen have been detected to date on at least one receiver array. Eleven were detected locally on the Twillingate array (#2, Fig. 1) and most detections were during July and August 2006 with only one fish recorded in each of September and November, suggesting that cod did not over-winter in the local area. Five cod were detected eastward on the Fogo receivers (array # 4), mainly during August. Two fish passed southward through the narrow channels adjacent to Change Islands (array # 3). A total of six were detected in late autumn and early winter southward in Bonavista Bay, especially during November and December, and three made repeated incursions into the narrow inlets at the bottom of Bonavista Bay (array #'s 7, 8, 9, 10). One fish that over-wintered at the bottom of Bonavista Bay during 2006-07 was also detected at the bottom of Bonavista Bay in Sweet Bay and Newman Sound during June 2007, moved to SS in early December 2007, and has remained within SS during winter 2007-08. The receivers in the Twillingate area have not been retrieved since early summer 2007, so it remains to be determined if telemetred cod returned to the same area the following year.

One fish that disappeared from the Twillingate area after release in summer 2006 was relocated in the Strait of Belle Isle (Fig. 7, NAFO Div. 4R) in August 2007 approximately 250 km northward on VR2 receivers set by other researchers to intercept salmon.

Bonavista: During field work off Bonavista in early June 2006, we suspended receivers over cod aggregations in this area and detected several cod with transmitters that had been released in SS the previous winter (2005-06), indicating that many of the cod we were capturing had likely over-wintered in SS.

Thirteen cod with transmitters were released off Bonavista on 5 June 2006. All fish were subsequently detected on at least one receiver array. Detections were frequent on the Bonavista receiver array during June and July in both 2006 and 2007. Nine fish (69%) returned to SS and over-wintered there during 2006-07 and six of these returned again to over-winter in SS during 2007-08. Four were detected on receiver arrays at the bottom of Bonavista Bay during summer 2006. One cod made extensive migrations reaching as far north as the Twillingate and Fogo arrays during August 2006 before turning south past an array (#10) at the bottom of Bonavista Bay in September and across the receivers at Baccalieu and Cape St. Francis on 17th and 21st December 2006, respectively; this cod apparently migrated southward out of the study area; it was subsequently detected in the Strait of Belle Isle (NAFO Div. 4R) several hundred kilometers away during August 2007. One other fish was detected south of SS, on receivers at East Random Head and Northwest Arm in December 2006, although this fish over-wintered in SS in two consecutive winters. One of the 13 cod released off Bonavista was captured at the entrance to SS on 27 September 2007.

There were no detections on the Bonavista receiver array between mid-December and early June, suggesting that telemetred cod did not over-winter in the local area. Overall, the movement patterns of these cod were similar to those of fish released within SS, supporting our suggestion they were mostly of SS origin.

Newman Sound: Only 4 cod were released here, on 1 December 2005. Three were subsequently detected. One left Newman Sound in December 2005 and over-wintered in Chandler Reach from 5 December 2005 until 5 May 2006; this cod and one other moved northward and were recorded on the Greenspond array (#5) in northern Bonavista Bay during June, July and September 2006, and they returned to Newman Sound during November 2006 and February 2007, respectively. A third fish left Newman Sound in May 2006 but was not subsequently detected until November 2006 when it passed the array in Sweet Bay and subsequently over-wintered in Southern Bay from late November 2006 until late February 2007.

Northwest Arm: Two fish were released several kilometres inside the receiver array located at the mouth of Northwest Arm on 30 April 2006. Both fish were subsequently detected on several receiver arrays. One fish left Northwest Arm on 25 May and was detected briefly (4-5 June 2006) in SS, and was subsequently detected at Bonavista intermittently during 11 June –7 August 2006. The fish returned to SS on 30 November, over-wintered then left SS on 13 May and was detected off Bonavista for a second consecutive summer during 9-11 July 2007. The second cod left Northwest Arm on 10 May 2006, moved to SS during 23 May–14 June 2006, and appeared at Melrose (16-17 August 2006) and at Bonavista during 6-22 September 2006. Neither cod returned to Northwest Arm.

Petty Harbour: Eighteen cod were released at Petty Harbour during 18-19 July 2007 and these are the most southerly releases to date. Fifteen were subsequently located on receivers in the local area during summer and fall 2007. Three were caught in the fishery in 2007, two off the eastern Avalon about 20-40 km south of the release site, and the third was recaptured about 150 km southward in the neighbouring NAFO Subdiv. 3Ps stock management area. Three conventionally tagged cod released simultaneously with telemetred cod were also captured southward in 3Ps. To date, none of the telemetred cod released in Petty Harbour have been detected on receiver arrays located further northward, although the closest northward array at Cape St. Francis has not been retrieved since the cod were released at Petty Harbour.

Fishing mortality

A directed inshore fishery for cod was opened in the summer and fall of 2006 and again in 2007. Total landings each year are unknown because recreational fishery landings are uncertain, but reported landings from the stewardship fishery were 2,700 t in 2006 and 2,400 t in 2007 (DFO 2007, 2008).

Of the 89 cod from SS that survived the surgical implantation procedure in 2005-06, a total of nine (10%) were caught during the fishery in 2006. Two of these fish were caught inside SS and the remainder at various inshore locations in northwestern Trinity Bay and in Bonavista Bay. A further three were reported as recaptured in the fishery in 2007; one in Bonavista Bay, one in northwestern Trinity Bay, and one in SS.

Of the 103 cod from SS that survived the surgical implantation procedure in 2006-07, a total of nine (9%) were caught during the fishery in 2007. One was recaptured off Fogo, three in Bonavista Bay, two in northwestern Trinity Bay, and three in SS.

Of the 20 cod released with transmitters off Twillingate during early July 2006, a total of 5 (25%) were captured during the fishery in 2006; all were recaptured off Twillingate. None were reported as recaptured in 2007. One cod (of 13) released off Bonavista and three cod (of 18) released off Petty Harbour were also recaptured in 2007.

Survival rates

We used the detection data to estimate the minimum overall survival rate (expressed as a percentage) of the two groups of cod released in SS; these estimates are preliminary, particularly for fish released in 2006-07, as several receivers deployed in 2007 have not yet been retrieved and may yield more data.

Of the 89 telemetred cod available from SS in spring 2006, the receiver detections indicated that a minimum of 71 were still alive at the end of January 2007; these included 65 that returned to SS in late fall, three that did not leave SS, and three that did not return but reappeared on outside receivers in the summer of 2007. A total of nine cod (10%) were reported as captured in the fishery in 2006. Thus, our data give a minimum estimate of survival of 71/89=80% from the date the last batch of cod was released in SS (19 May 2006) until the end of January 2007. As of January 2007, there are nine telemetred cod that left SS whose fate is unknown; more information on the status of these fish may become available when the data from all the receivers deployed in the summer of 2007 are retrieved.

Of 103 telemetred cod from SS in spring 2007, a minimum of 70 were still alive at the end of January 2008; these included 65 that returned to SS in late fall and five that did not leave SS. A total of nine (10%) were captured in the fishery in 2007. Thus, our data give a minimum estimate of survival of 70/103=68% from the date the last batch of cod was released in SS (31 May 2007) until the end of January 2008. As of January 2008, there are 24 telemetred cod whose fate is unknown; these cod still have functioning transmitters and more information on the status of these fish may become available during the summer of 2008.

Comparison of telemetry with conventional tag returns

Since 1997, approximately 15,000 cod ($\geq$45 cm) have been tagged in SS with Floy tags and about 1,500 have been reported as recaptured, including >1,000 where exact recapture locations were given. The recapture positions of these tagged cod were plotted (Fig. 7) to compare them with the telemetry results depicted in Fig. 6 and described in the text. In addition, in Placentia Bay in the neighbouring stock (3Ps) area, approximately 39,900 cod have also been tagged during 1997-2007 and >10,000 recaptured, including 9,200 where exact recapture locations were given; these tag recaptures were also overlaid with those from SS (Fig. 7).

Although tag returns are strongly dependant on effort, the conventional tag returns for cod tagged in SS agree well with the telemetry data, with most recaptures of tagged fish taken around the Bonavista Peninsula and into Bonavista Bay (Fig. 7) where most telemetred cod were detected. The numbers of tagged cod recaptured north of Bonavista Bay or south into Conception Bay are small and these comprise <0.1% of the total recaptures. Small numbers of conventionally tagged cod from SS were also recaptured in 3Ps, but these represent an extremely small fraction of the total SS tagging recoveries. Furthermore, tagging in SS may have included some migrants from 3Ps that were recaptured when they migrated back to 3Ps.

The conventional tag returns also indicate some movement of cod from Placentia Bay into southern 3L, particularly into the eastern Avalon and Conception Bay, but rarely further north into Trinity Bay and Bonavista Bay. Overall, the telemetry data agree well with our previous conclusion from conventional tagging, that there is a resident coastal group of cod in the inshore of northern 3L and southern 3K, and that southern 3L is at least partly dependant on migrant cod from 3Ps. The telemetry data and tagging recaptures suggest that the resident coastal group in northern 3L are not strongly

represented in Notre Dame Bay, although small numbers of cod from SS were captured there in some years.

DISCUSSION

Our telemetry results reveal high over-wintering site fidelity for SS cod in three consecutive winters. Cod released in 2005, 2006 and 2007 showed return rates of 100%, 83% and 65% the following winter, when known recaptures were excluded from the calculations. The percentages returning are higher than the homing rates of 39% and 53% reported by Robichaud and Rose (2001) for telemetred cod at Bar Haven, Placentia Bay, during 1999 and 2000. The higher rates in our study may partly be due to the continuous monitoring that was possible with moored receivers, rather than periodic monitoring from mobile platforms which essentially reduces the probability of relocation. Green and Wroblewski (2000) found strong site fidelity (within 5 km^2 of initial tagging site) and year round residency of telemetred cod in Gilbert Bay, Labrador, despite unimpeded access to the open ocean. Bergstad et al. (2008) reported that only 40% of telemetred cod released within a fjord in southeastern Norway crossed a sill near the fjord mouth and made short excursions outside for only a few days; most fish remained close to the release site. Our return rates are comparable to the inferred homing rates of 71-92% for northeast Arctic cod and 72-79% for cod on spawning grounds off southwest Iceland, based on conventional tagging studies where return areas were much larger than those investigated here (Godø 1984, Jónsson 1996). Our findings also give evidence of a low rate of straying to other over-wintering areas, as some cod that over-wintered in SS moved to other deep (>200 m) inshore waters such as Southwest Arm and outer Trinity Bay in subsequent winters. Information on straying to other over-wintering areas is often impossible to obtain with methods such as conventional tagging because inshore fisheries are seasonal and during winter months there are no inshore fisheries and hence no tag returns.

Telemetry appears to be a useful method for estimating mortality of tagged cod immediately after release. With conventional tagging it is difficult to determine the fraction of tagged cod that survive and are available for subsequent recapture. Estimates of exploitation rate can be negatively biased if substantial fractions of tagged cod die immediately after release. Although telemetred fish were submitted to the additional stress of surgery, our study shows that initial survival was high (96%) among our tagged/telemetred cod captured in shallow water. Our initial survival estimates agree well with Brattey and Cadigan (2004) who reported 97% survival of conventionally tagged cod caught in shallow water and held in submersible enclosures. Initial survival was clearly lower (66%) among cod trawled in deep water, probably due to the stress of decompression and physical damage while the trawl was being retrieved. However, we felt it was important to include cod inhabiting deep water in our study as we intend to investigate whether these cod display different migratory behaviour from those inhabiting shallower depths.

Telemetry is becoming increasingly popular for estimating survival (or mortality) rates in fish populations (Hightower et al. 2001; Pollock et al. 2004). Our study provides one of the first direct estimates of the minimum survival rate for Atlantic cod, based on repeated measures of the same individuals in the population. We emphasize that our survival estimates are specific to cod >60 cm inhabiting SS and may not be applicable to cod in other regions even within the same stock area. Conventional tagging results suggest that recent survival rates of cod in the inshore of 3K are much lower (Cadigan and Brattey 2003). Similarly, analysis of trends in catch rates at age from trawl surveys suggest that the rate of total mortality among cod in the offshore of 2J3KL has been extremely high since the early 1990's, with few fish surviving beyond age 6 (Lilly et al. 2006). In contrast, cod >10 yr old are not uncommon in SS and the large size and broad length and age distribution of over-wintering cod in SS (Lilly et al. 2004) is consistent with

a higher survival rate than is evident in other regions within 2J3KL. Estimates of exploitation (harvest) rate from conventional tagging require an assumed value for the rate of natural mortality (Brattey and Healey 2007) and our telemetry data suggest that a value of *M* of 0.2 per year would be reasonable for over-wintering cod tagged in SS.

Only nine cod were not subsequently detected on outside receivers and disappeared from the study during 2006. For these fish it is not possible to distinguish between emigration, natural mortality, unreported fishing mortality, or transmitter failure. Modern transmitters are reliable, ours were tested prior to release, and we do not consider transmitter failure to be significant. Also, the fraction of unreported recaptures would likely be negligible as the reward is high for returning both tags ($110) and transmitters ($25) and the tagging program is well advertised. These nine cod may simply have migrated to or stayed in areas with no receivers, including deeper water within the inshore bays where we had relatively few receivers. Some cod may also have moved further out from the coast where we have no receivers. The total numbers of cod detected shows that a substantial fraction of telemetred SS cod are not detected in a given month, although in 2006 most encountered at least one receiver while outside SS and the majority of them returned to SS. In 2006, we deployed many of our receivers inside the mouth of narrow inlets in Trinity and Bonavista Bay to determine whether cod over-wintered in these areas. Our findings to date suggest that a small percentage of SS cod strayed to other areas. Furthermore, only 7% and 11% of telemetred cod from SS were detected in these inlets during the entire year, indicating that most of the telemetred cod were elsewhere. In future, to more accurately define the habitats occupied by these cod during summer it would be advantageous to extend receiver coverage and include deep water within the bays as well as further offshore, particularly off the headlands.

The monthly detection rates of cod on receivers outside SS during summer 2006 reveals a strong seasonal pattern, with a diminishing number of transmitters detected during August-October, although most of the cod eventually returned to SS. These findings may be reflecting subtle seasonal changes in the behaviour and movement patterns of cod during late summer. Lower mobility of cod or movement to deeper water in the latter part of summer could reduce the likelihood of telemetred cod passing in range of a receiver and reduce the numbers detected. Reduced detection range of receivers with the onset of poor weather and an associated increase in ambient noise during autumn, particularly in shallow water, may also be important and requires investigation. The influence of ambient conditions on receiver detection range is presently being explored by range testing experiments in various regions of the study area.

The fraction of telemetred cod captured during the fishery and returned to us was similar in both 2006 (10%) and 2007 (9%). These values are close to the estimated exploitation (harvest) rates of 10% and 7%, respectively, based on conventionally tagged cod released at the same time as telemetred cod (Brattey and Healey 2007; DFO 2008). Although total landings during the inshore fisheries in the past two years are unknown, the catch is likely to be in the range of a few thousand tons. The tagging estimates suggest that the inshore fishery, though small by historical standards, is removing a considerable proportion of the available stock, particularly in the Twillingate area in 2006, where 25% of telemetred cod were captured and conventional tagging indicated a harvest rate of 20%. Telemetry and conventional tagging indicate that cod that over-winter in SS are a significant component of the catch in some areas, most notably Trinity Bay and Bonavista Bay.

The telemetry and tagging results show that most of the cod that over-winter in SS are dispersed outside SS during summer and early autumn. Catch rates in the sentinel (1995-2007) and the commercial fishery (1998-2002, 2006-07) in the inshore of 2J3KL have consistently been highest in the inshore central area which includes Trinity Bay and

Bonavista Bay (DFO, 2008), especially around the Bonavista Peninsula (Lilly et al. 2006). The large numbers of telemetred cod detected on receivers as well as conventional tag returns from this area confirms that SS cod are contributing to these higher catch rates. In contrast, catch rates are generally lower in areas further north, i.e. from western Notre Dame Bay northward as well as southwards into Conception Bay and the eastern Avalon. The small numbers of tag returns and absence of detections of telemetred cod indicates that over-wintering cod from SS are not abundant in those areas during summer and fall. The lower catch rates also imply lower overall cod densities in these areas.

Although receivers in most areas did not detect telemetred cod during winter and early spring, the telemetry results show that some cod over-wintered in regions other than SS. Small numbers of cod released with transmitters in Newman Sound were recorded over-wintering in the deep inlets at the bottom of Bonavista Bay, and a small percentage (<2%) released in SS over-wintered in Southwest Arm, Trinity Bay and in the deep water (>300 m) in Trinity Bay off Grates Cove. In addition, three telemetred cod that did not return to SS reappeared on receivers the following summer and their over-wintering sites are unknown. More extensive coverage with receivers, particularly in the deep waters in the major bays, would be helpful to determine other inshore over-wintering sites of cod. Conventional tagging is not useful in this regard as fisheries are generally closed during the winter months. To date, we have avoided deploying receivers in the offshore because the area is vast and much of it is extensively fished by shrimp trawlers; receivers would likely be snagged by their fishing gear. However, in future it would be useful to deploy receivers in specific offshore areas where cod aggregate as straying to offshore areas may be an important component of stock rebuilding.

The telemetry results lend further support to the revised stock structure suggested for northern cod, which is based on results from inshore tagging studies conducted since the late 1990's (Brattey and Healey 2003, 2005, 2007). Since 2005, for assessment purposes the inshore region has been divided into three areas: 1) a northern area (2J and northern 3K); 2) a central area (southern 3K and northern 3L) where most of the resident inshore fish are located; and 3) a southern area (southern 3L) that is largely dependent on migrant fish, from 3Ps and possibly other offshore areas (Lilly et al. 2005). The detections of telemetred SS cod in the present study show that they dispersed widely into Trinity Bay and Bonavista Bay, and less frequently into Notre Dame Bay during summer and did not migrate north or south of the central inshore area. In addition, telemetred cod released in southern 3L remained in that area or migrated south, supporting the suggestion that this area is occupied by seasonally migrant cod from the neighbouring NAFO Subdivision 3Ps stock management area.

In summary, using a combination of conventional tagging and telemetry technology we have shown that cod show strong over-wintering site fidelity for SS, but in summer disperse around the coast, mainly into Trinity Bay and Bonavista Bay. Most cod leave SS, typically during March-June, and return during November-January, with a small percentage straying to other over-wintering sites in subsequent years. Survival of telemetred SS cod was high in 2006 (minimum estimate 80%) and 2007 (minimum 68%) although these numbers may be revised upward as more data becomes available. Telemetry results from cod released in various inshore regions of 3KL also support the revised stock structure proposed for northern cod. In the future we intend to direct some effort towards cod in the offshore regions of 2J3KL. Our preliminary results show that telemetry holds considerable promise for enhancing our understanding of various aspects of cod biology and population dynamics, and the relationship between inshore and offshore components of the northern cod stock.

ACKNOWLEDGMENTS

We thank the staff of the groundfish, fisheries evaluation, and sentinel fishery sections of DFO Science, Newfoundland and Labrador Region and the captains and crews of CCGS Shamook for help with tagging and deploying telemetry apparatus. Several harvesters and vessel operators assisted with field operations, particularly D. Ivany, B. Donovan, G. Penney, L. Burry, C. Coish, J. Negrijn, L. Philips, C. Dalley, G. Dalley, A. Payne, R. Tucker, T. Best and members of Petty Harbour fishers Co-operative. We also thank F. Whoriskey for providing data from our cod from receivers set for salmon. The study was funded through the Northern Cod Science and Stewardship Program (NCSSP) and the DFO Species at risk (SARA) program.

REFERENCES

Bergstad, O.A, Jørgensen, T., Knutsen, J.A., and Berge, J.A. 2008. Site fidelity of Atlantic cod *Gadus morhua* L. as deduced from telemetry and stable isotope studies. J. Fish. Biol. 72: 131-142.

Brattey, J., and Cadigan, N.G. 2004. Estimation of short-term tagging mortality of adult Atlantic cod (*Gadus morhua*). Fish. Res. 66: 223-233.

Brattey, J., and Healey, B.P. 2003. Exploitation rates and movements of Atlantic cod (*Gadus morhua*) in NAFO Divs. 3KL based on tagging experiments conducted during 1997-2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/032.

Brattey, J., and Healey, B.P. 2005. Exploitation and movements of Atlantic cod (*Gadus morhua*) in NAFO Divs. 3KL: further updates based on tag returns during 1995-2004. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/047.

Brattey, J., and Healey, B.P. 2006. Exploitation of Atlantic cod (*Gadus morhua*) in NAFO Subdiv. 3Ps: estimates from mark-recapture experiments for the October 2006 assessment. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/082.

Brattey, J., and Healey, B.P. 2007. Exploitation and movements of Atlantic cod (*Gadus morhua*) in NAFO Divs. 3KL: tagging results from the re-opened fishery in 2006. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/027.

Cadigan, N., and Brattey, J. 2003. Analyses of stock and fishery dynamics for cod in 3Ps and 3KL based on tagging studies in 1997-2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/037.

Clark, D.S., and Green, J.M. 1990. Activity and movement patterns of juvenile Atlantic cod, *Gadus morhua*, in Conception Bay, Newfoundland, as determined by sonic telemetry. Can. J. Zool. 68: 1434-1442.

Comeau, L.A., Campana, S.E., and Castonguay, M. 2002. Automated monitoring of a large-scale cod (*Gadus morhua*) migration in the open sea. Can. J. Fish Aquat. Sci. 59: 1845-1850.

Cote, D., Ollerhead, L.M.N., Scruton, D.A., and McKinley, R.S . 2003. Microhabitat use by juvenile Atlantic cod in a coastal area of Newfoundland as determined by 2-D telemetry. Mar. Ecol. Prog. Ser. 227-234.

DFO. 2007. Stock assessment of northern (2J+3KL) cod in 2007. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/018.

DFO. 2008. Stock assessment of northern (2J+3KL) cod in 2008. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2008/034.

Jónsson, J. 1996. Tagging of cod (*Gadus morhua*) in Icelandic waters 1948-1986. Rot. Fiskid. 14: 7-82.

Godø, O.R. 1984. Migration, mingling and homing of north-east Arctic cod from two seprated spawning grounds. *In* Reproduction and recruitment of Arctic cod. *Edited by* O. R. Godø and S. Tilseth. Institute of Marine Research, Bergen, Norway, pp 289-302.

Green, J.M., and Wroblewski, J.S. 2000. Movement patterns of Atlantic cod in Gilbert Bay, Labrador: evidence for bay residency and spawning site fidelity. J. Mar. Biol. Assoc. U.K. 80: 1077-1085.

Heupel, M.R., Semmens, J.M., and Hobday, A.J. 2006. Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Mar. Freshw. Res. 57: 1-13.

Heupel, M.R., and Simpfendorfer, C.A. 2002. Estimation of mortality of juvenile blacktip sharks, *Carcharhinus limbatus*, within a nursery area using telemetry. Can. J. Fish. Aquat. Sci. 59: 624-632.

Hightower, J.E., Jackson, J.R., and Pollock, K.H. 2001. Use of telemetry methods to estimate natural and fishing mortality of striped bass in Lake Gaston, North Carolina. Trans. Am. Fish. Soc. 130: 557-567.

Lilly, G.R., Murphy, E.F., Healey, B.P., Maddock Parsons, D., and Stead, R. 2004. An update of the status of the cod (*Gadus morhua*) stock in NAFO Divisions 2J3KL in March 2004. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/023.

Lilly, G.R., Brattey, J. Cadigan, N.G., Healey, B.P., and Murphy, E.F. 2005. An assessment of the cod (*Gadus morhua*) stock in NAFO Divisions 2J3KL in March 2005. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/018.

Lilly, G.R., Murphy, E.F., Healey, B.P., and Brattey, J. 2006. An assessment of the cod (*Gadus morhua*) stock in NAFO Divisions 2J3KL in April 2006. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/043.

Pinhorn, A.T. 1975. Estimates of natural mortality for the cod stock complex in ICNAF Div. 2J, 3K, and 3L. ICNAF Res. Bull. 11: 31–36.

Pollock, K.H., Jiang, H., and Hightower, J.E. 2004. Combining telemetry and fisheries tagging models to estimate fishing and natural mortality rates. Trans. Am. Fish. Soc. 133: 639-648.

Quinn, T.J., II, and Deriso, R.B. Quantitative fish dynamics. 1999. Oxford University Press, Oxford, UK.

Robichaud, D., and Rose. G.A. 2001. Multiyear homing of Atlantic cod to a spawning ground. Can. J. Fish. Aquat. Sci. 58: 2325:2329.

Robichaud, D., and Rose, G.A. 2001. The return of cod transplanted from a spawning ground in southern Newfoundland. ICES J. Mar. Sci. 59: 1285-1293

Rose, G.A. 2003. Monitoring coastal northern cod: towards an optimal survey of Smith Sound, Newfoundland. ICES J. Mar. Sci. 60: 453-462.

Sinclair, A.F. 2001. Natural mortality of cod (*Gadus morhua*) in the Southern Gulf of St Lawrence. ICES J. Mar. Sci.: Journal du Conseil. 58: 1-10.

Vetter, E.F. 1988. Estimation of natural mortality in fish stocks: a review. Fish. Bull. 86: 25-43.

Windle, M.J.S., and. Rose, G.A. 2005. Migration route familiarity and homing of transplanted Atlantic cod (*Gadus morhua*). Fish. Res. 75: 193-199.

Welch, D.W., Ward, B.R., and Batten, S.D. 2004. Early ocean survival and marine movements of hatchery and wild steelhead trout (*Oncorhynchus mykiss*) determined by an acoustic array: Queen Charlotte Strait, British Columbia. Deep-Sea Res. 51: 897-909.

Wroblewski, J.S., Bailey, W.L., and Howse, K.A. 1994. Observations of Atlantic cod (*Gadus morhua*) over-wintering in nearshore waters of Trinity Bay, Newfoundland. Can. J. Fish. Aquat. Sci. 51: 142-150.

Table 1. Details for Atlantic cod, *Gadus morhua*, implanted with ultrasonic transmitters and released at various sites off the northeast coast of Newfoundland (see Figure 1 and 2) during 2005-07.

Date of release	Capture depth (m)	NAFO Unit area	Location	Number of cod
1 July 2006	35	3Ki	off Twillingate	2
3 July 2006	27	3Ki	off Twillingate	13
3 July 2006	38	3Ki	off Twillingate	2
3 July 2006	35	3Ki	off Twillingate	3
1 Dec 2005	48	3La	Newman Sound	4
5 June 2006	20	3La	Cape Bonavista	13
18 May 2005	10	3Lb	Burn Point, Smith Snd.	2
18 May 2005	10	3Lb	Nut Cove, Smith Snd.	3
19 May 2005	10	3Lb	Green's Bight, Smith Snd.	3
19 May 2005	12	3Lb	west Bluff Head, Smith Snd.	2
16 Nov 2005	40	3Lb	Nut Cove, Smith Snd.	7
16 Nov 2005	22	3Lb	Petley, Smith Snd.	5
13 Dec 2005	82	3Lb	Burgoyne's Cove, Smith Snd.	7
13 Dec 2005	73	3Lb	Petley, Smith Snd.	5
26 Apr 2006	20	3Lb	Petley, Smith Snd.	4
27 Apr 2006	23	3Lb	Dalton's Head, Smith Snd.	16
28 Apr 2006	24	3Lb	Smith Point, Smith Snd.	20
29 Apr 2006	200	3Lb	Hickman Islands, Smith Snd.	2
30 Apr 2006	202	3Lb	off Lance Cove, Smith Snd.	5
1 May 2006	208	3Lb	Hickman Islands, Smith Snd.	13
19 May 2006	22	3Lb	Aspen Cove, Smith Snd.	20
25 Nov 2006	40	3Lb	Smith Point, Smith Snd.	25
26 Nov 2006	40	3Lb	Bluff Head, Smith Snd.	25
7 May 2007	190	3Lb	Clifton, Smith Snd.	24
7 May 2007	225	3Lb	Lance Cove, Smith Snd.	6
30 May 2007	24	3Lb	Green's Bight, Smith Snd.	24
31 May 2007	28	3Lb	Tilton Head, Smith Snd.	12
30 Apr 2006	18	3Lb	NW Arm, Trinity Bay	2
18 July 2007	30	3Lj	Petty Harbour, eastern Avalon	12
19 July 2007	30	3Lj	Petty Harbour, eastern Avalon	6

Table 2. Details of acoustic receiver deployments (BB=Bonavista Bay, TB=Trinity Bay). See Figure 1 and 2 for locations.

*Array	NAFO area	Location	Number of receivers	Deployment depth (m)	Deployment date	Last retrieval date
1	3Kh	Cape St John	6	78-193	2-Jul-2006	1-Jul-2007**
2	3Ki	Long Point, Twillingate	4	42-180	20-Jun-2006	30-Aug-2007
3	3Ki	Change Island	4	44-55	29-Jun-2006	30-Jun-2007
4	3Ki	Gappy Island, Fogo	2	56-150	5-Jul-2006	30-Jun-2007
5	3La	Greenspond, BB	5	75-200	4-Jun-2006	29-Jun-2007
6	3Lb	Little Denier Isl., BB	3	85-120	19-May-2007	7-Nov-2007
7	3La	Newman Sound, BB	2	88-100	30-Nov-2005	7-Nov-2007
8	3La	Chandler Reach, BB	2	90-92	21-Nov-2005	8-Nov-2007
9	3La	Southern Bay, BB	2	45-81	21-Nov-2005	6-Nov-2007
10	3La	Sweet Bay, BB	2	81-113	21-Nov-2005	6-Nov-2007
11	3La	Tickle Cove, BB	2	39-74	19-May-2007	6-Nov-2007
12	3La	Cape Bonavista	10	20-326	3-Apr-2006	5-Nov-2007
13	3Lb	Melrose, TB	4	64-220	15-May-2006	11-Sep-2007
14	3Lb	Bonaventure Head, TB	3	88-245	18-Jan-2006	30-Jan-2008

Cont'd.

Table 2. Cont'd.

*Array	NAFO area	Location	Number of receivers	Deployment depth (m)	Deployment date	Last retrieval date
15	3Lb	outer Smith Sound, TB	3	152-210	18-May-2006	29-Jan-2008
16	3Lb	inner Smith Sound, TB	2	60-144	26-Nov-2006	29-Jan-2008
16	3Lb	middle Smith Sound, TB	3	88-194	19-Dec-2007	29-Jan-2008
17	3Lb	East Random Head, TB	2	175-193	29-Nov-2006	10-Nov-2007
18	3Lb	NW Arm TB	2	78-150	29-Sep-2005	11-Sep-2007
19	3Lb	SW Arm, TB	2	179-206	29-Sep-2005	10-Sep-2007
20	3Lb	Bellevue, TB	4	30-184	3-May-2007	11-Nov-2007
21	3Lb	Grates Cove Point, TB	2	91-337	12-Apr-2006	24-May-2007
22	3Lf	East Baccalieu Island	2	59-138	1-Jul-2007	not retrieved
23	3Lf	Baccalieu Tickle	2	110-124	12-Apr-2006	24-May-2007
24	3Lj	Cape St. Francis	4	50-210	6-Sep-2006	17-May-2007
25	3Lj	Petty Harbour	4	81-165	2-Jul-2007	15-Nov-2007

* see Fig. 1 for locations.
** not redeployed after retrieval.

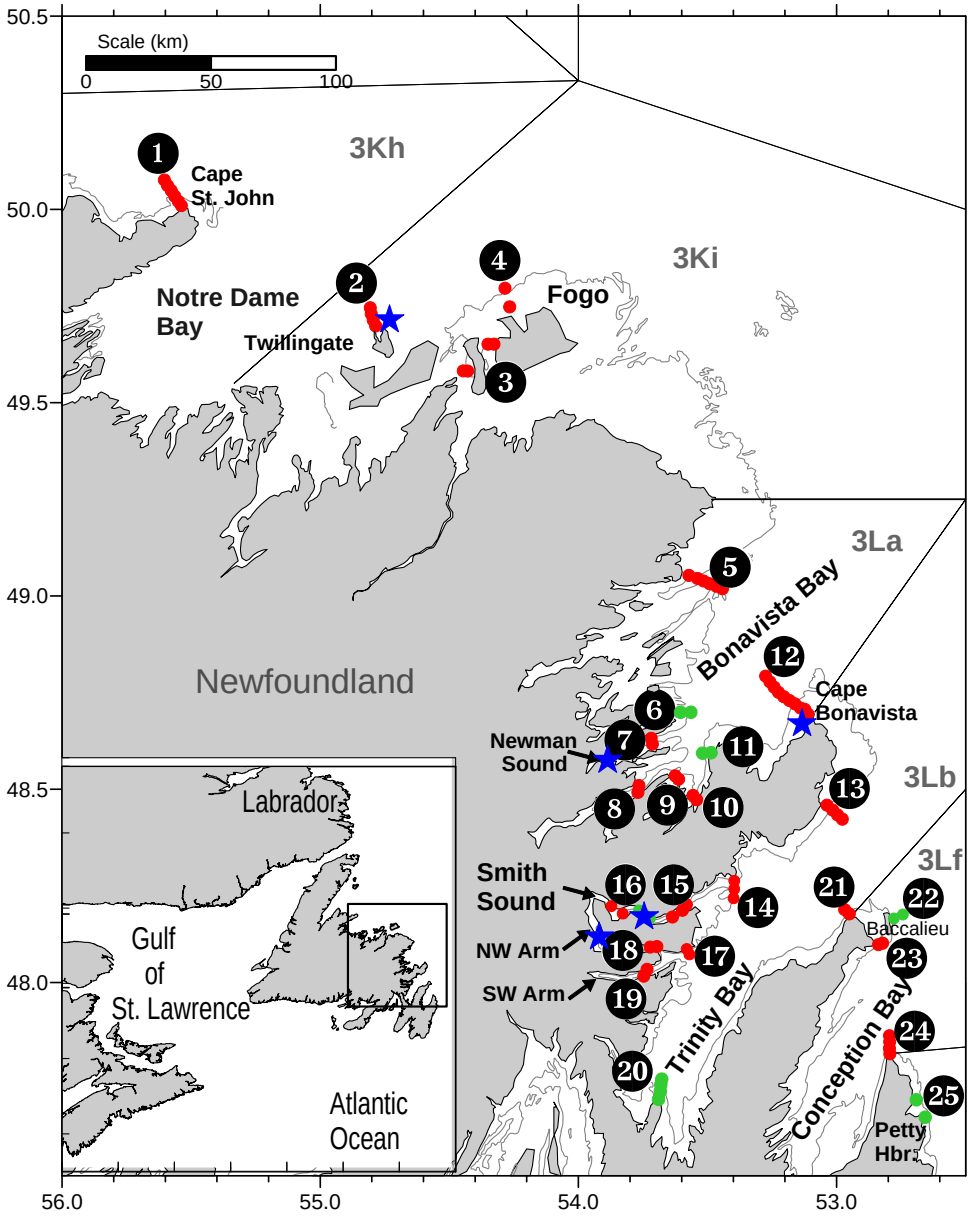

Figure 1. Northeast coast of Newfoundland showing locations of receiver arrays deployed in 2005-06 (red dots), 2007 (green dots), and release sites of cod implanted with transmitters (stars). Solid lines are boundaries of NAFO statistical unit areas. Grey line is 100 m depth contour. 1=Cape St. John, 2=Twillingate, 3=Change Islands, 4=Fogo, 5=Greenspond, 6=Little Denier Isl., 7=Newman Snd., 8=Chandler Reach, 9=Southern Bay, 10=Sweet Bay, 11=Tickle Cove, 12=Cape Bonavista, 13=Melrose, 14=Bonaventure Hd., 15=outer Smith Sound, 16=inner and middle Smith Sound (see Figure 2 for more detail), 17=East Random Head, 18=Northwest Arm, 19=Southwest Arm, 20=Bellevue, 21=Grates Cove Pt., 22=East Baccalieu Isl., 23=Baccalieu Tickle, 24=Cape St. Francis, 25=Petty Harbour.

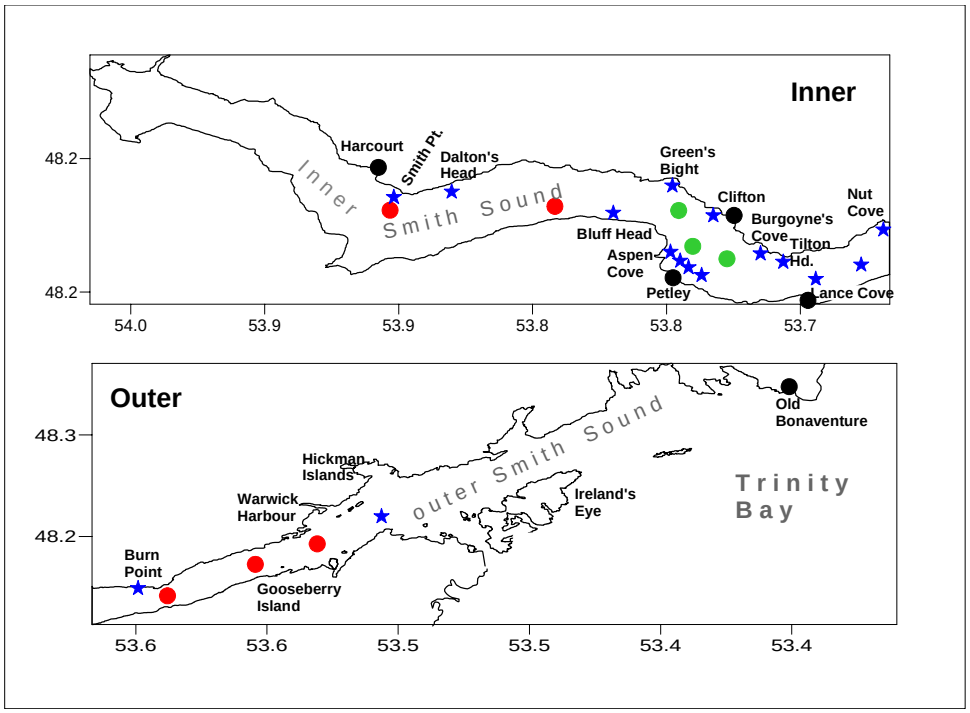

Figure 2. Details of locations where receivers were deployed in 2005-06 (red dots), 2007 (green dots), and release sites for cod with transmitters (stars) in the inner (upper panel) and outer (lower panel) regions of Smith Sound, Trinity Bay. The three receivers in the lower panel were used to monitor the daily movements of cod into and out of Smith Sound.

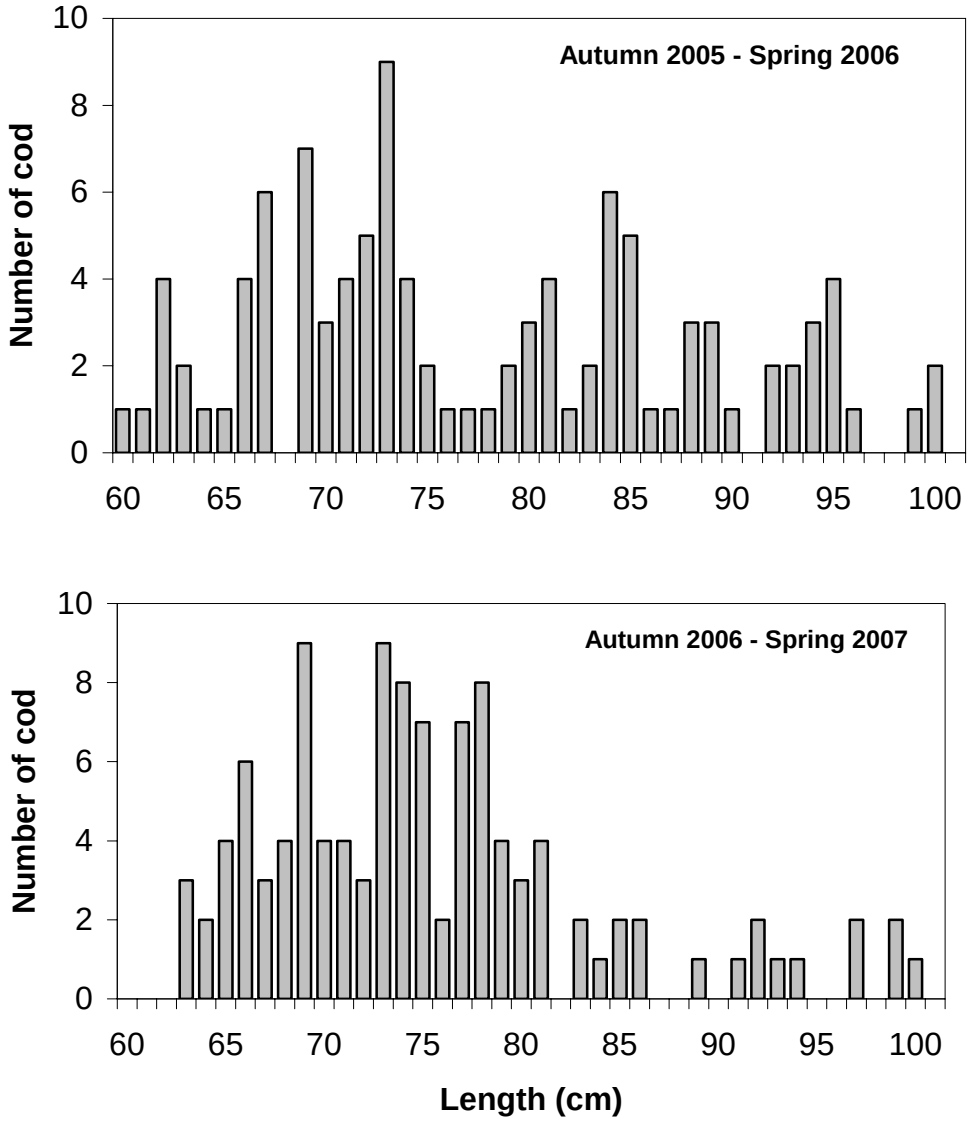

Figure 3. Length distribution of cod released in Smith Sound with external tags and implanted transmitters.

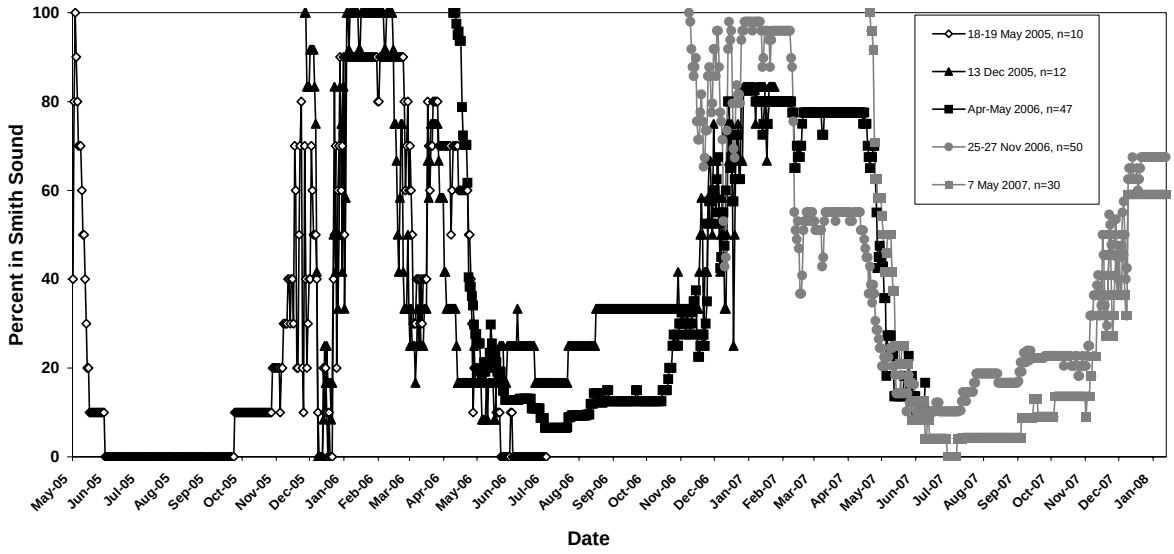

Figure 4. Seasonal changes in the numbers of cod with transmitters in Smith Sound (SS), Trinity Bay. Results from five batches of cod, released inside SS at various intervals from 18-19 May 2005 to 7 May 2007, are shown.

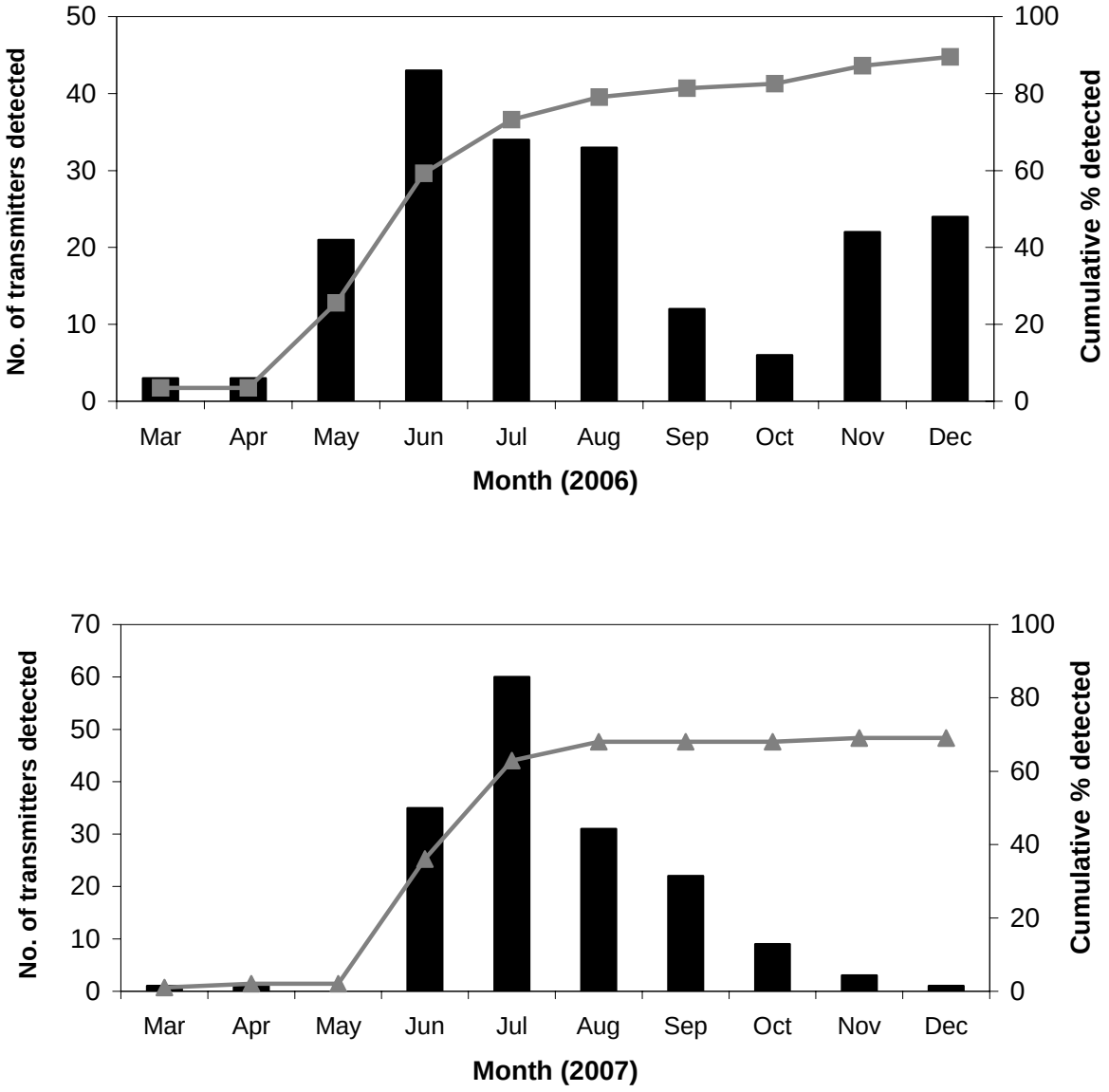

Figure 5. Monthly totals (bars) and cumulative percentage of cod with transmitters from Smith Sound detected on receiver arrays moored around the inshore off northeastern Newfoundland during March-December 2006 (upper panel) and 2007 (lower panel). A maximum of 85 and 99 cod with transmitters were available for detection in 2006 and 2007, respectively (see text for details). Data for 2007 are preliminary.

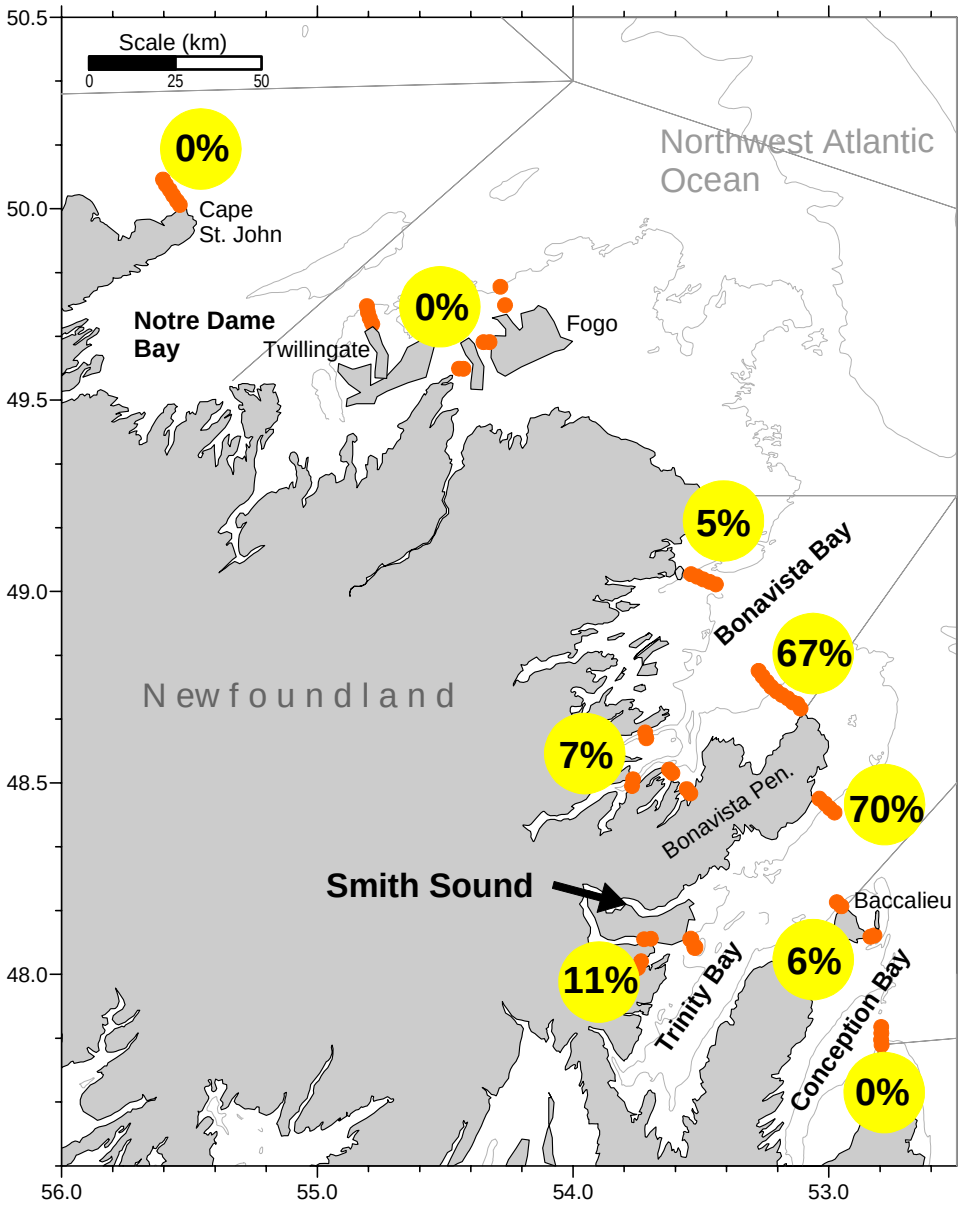

Figure 6. Percentage of cod detected on groups of receiver arrays moored in coastal waters off the northeast coast of Newfoundland during 2006. Values are based on 86 cod released with transmitters in Smith Sound during winter/spring 2005-06. Dots indicate locations of receiver arrays. Scale is approximate.

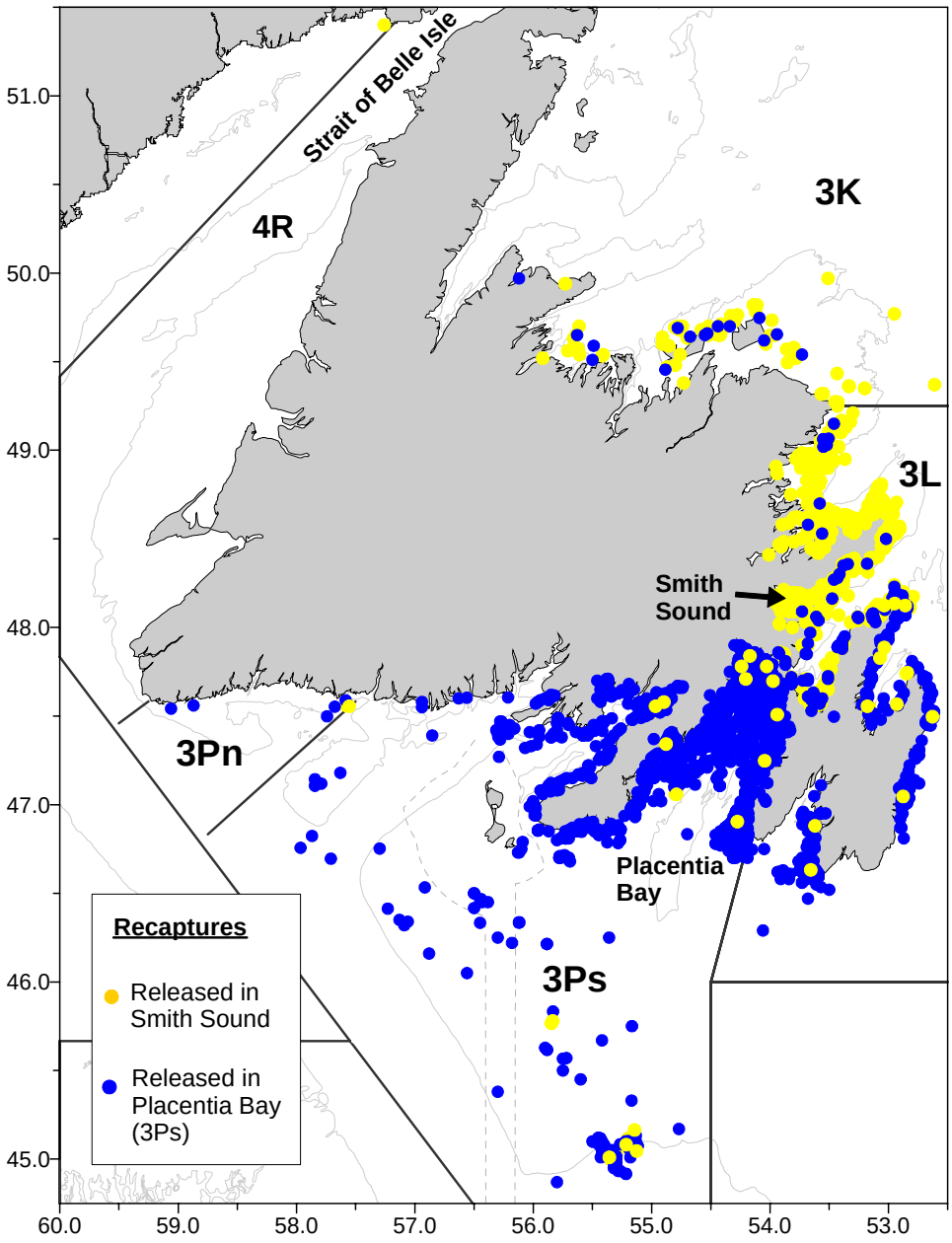

Figure 7. Reported recapture positions for cod tagged and released in Smith Sound, Trinity Bay (NAFO Div. 3L) and Placentia Bay (NAFO Subdiv. 3Ps) during 1997-2007.