Marine Biology (1996) 124: 619–627

J. S. Wroblewski · R. K. Smedbol · C. T. Taggart
S. V. Goddard

Movements of farmed and wild Atlantic cod (*Gadus morhua*) released in Trinity Bay, Newfoundland

Received: 8 May 1995/Accepted: 26 June 1995

Abstract Fishery scientists and managers are investigating the feasibility of enhancing annual recruitment to the northern Atlantic cod (*Gadus morhua* L.) stock complex off Labrador and northeastern Newfoundland through the release of farmed fish back into the sea. Release of newly matured fish and adults with farm-advanced fecundity would increase the spawning biomass. Enhancement efforts might be measurably successful in major bays that are year-round habitats for cod. To determine if farmed cod would remain and spawn in Trinity Bay, 14 fish with surgically implanted transmitters were released in November 1992. Sonic tracking confirmed that farmed cod released on the western side of Trinity Bay overwintered within the bay, and integrated with wild cod approaching spawning condition in April 1993. Blood plasma antifreeze levels confirmed that these wild cod had overwintered inshore in subzero waters. A spawning aggregation was found in July 1993, providing evidence that northern cod reproduce in Newfoundland bays. These findings suggest that it may be possible to increase the number of cod spawning inshore through the release of farmed fish.

Communicated by J.P. Grassle, New Brunswick

J.S. Wroblewski (✉) · R.K. Smedbol
Fisheries Oceanography Group, Ocean Sciences Centre,
Memorial University of Newfoundland,
St. John's, Newfoundland A1B 3X7, Canada

C.T. Taggart
Canada Department of Fisheries and Oceans, Science Branch,
Northwest Atlantic Fisheries Centre, P.O. Box 5667,
St. John's, Newfoundland A1C 5S7, Canada

S.V. Goddard
Marine Sciences Research Laboratory, Ocean Sciences Centre,
Memorial University of Newfoundland,
St. John's, Newfoundland A1C 5S7, Canada

Introduction

The northern Atlantic cod (*Gadus morhua*) fishery has recently experienced the most severe decline in the history of Newfoundland and Labrador (Lear and Parsons 1993; Hutchings and Myers 1994; Taggart et al. 1994). Stock abundance, which exceeded a million tonnes several decades ago, is currently so low that it cannot be estimated with confidence. Spawning biomass may be below 20 000 tonnes (Bishop et al. 1993). Rebuilding the resource is now the prime concern (Fisheries Resource Conservation Council 1994). The intent of the current moratorium on fishing is to allow the cod stocks to recover naturally; however, an additional management option is intervention to increase the spawning biomass.

The Canada Department of Fisheries and Oceans and the Provincial Government of Newfoundland and Labrador have been investigating the feasibility of enhancing annual recruitment to the northern cod stock through the release of farmed fish back into the sea (Working Group on Cod Enhancement 1994). Laboratory experiments have shown that the onset of maturity in fish is generally related to nutritional condition (Scott et al. 1991). Experimental cod farming has demonstrated that immature cod, kept in a pen and fed frequently, will reach sexual maturity earlier than wild cod (J. Moir, Seaforest Plantations Co. Ltd., St. John's, unpublished data). Releasing these newly matured cod back into the ocean would increase the numbers of spawning fish. The capture and "grow-out" of adult cod could also supplement the spawning biomass. As fecundity is a function of body size (May 1967), adult cod that are farmed may have a higher fecundity relative to wild cod of the same age because of faster growth. With a severely depressed wild stock, the contribution to annual recruitment by released farmed cod could be significant.

Enhancement efforts might be measurably successful in major bays of Newfoundland that are year-round habitats for cod. Most northern cod living off eastern Newfoundland and Labrador spawn over the continental shelf in the spring (Hutchings et al. 1993), and then migrate inshore during the summer to feed along the coast (Lear and Green 1984). Cod gradually move back offshore during the fall to overwinter in warm (2 to 4 °C) waters near the shelf edge (Templeman 1979; Wroblewski et al. 1995b). The nearshore zone constitutes the summer feeding ground for adults and the nursery ground for developing juveniles, which eventually move into deeper offshore waters with increasing age (Templeman and Fleming 1956; Taggart et al. 1994). It has long been suspected, however, that some adult cod remain year-round in the larger bays, such as Trinity Bay and Bonavista Bay (Thompson 1943).

Wroblewski et al. (1994) observed adult northern cod overwintering in the Random Island region of Trinity Bay (Fig. 1). Why these fish remained inshore is unknown. They may have been part of an inshore–offshore migration where some individuals simply remained behind at the coast; or, they may have been members of a stock of northern cod that spawns inshore. Templeman's (1979) migration model presumes that the winter–spring location of mature cod is the spawning area. While there have been reports of cod in spawning condition nearshore (Hutchings et al. 1993), the existence of "bay stocks" has not been established.

The objective of the present study was to determine if farmed cod released in Trinity Bay would remain and spawn there, as a first step in determining the feasibility of enhancing annual recruitment. Fourteen cod that had been trapped in Trinity Bay and kept with several thousand others in a sea cage for 6 mo were sonically tagged and released in November 1992. Their position was determined by acoustic tracking in January and April 1993. Wild cod were sampled in Trinity Bay in April and July 1993 to determine their reproductive condition and their blood antifreeze glycoprotein levels as a physiological indictor of group overwintering behaviour.

Methods

Farming of experimental cod, *Gadus morhua* L.

Between 8 June and 9 July 1992, several thousand cod of various sizes were caught near East Random Head, Trinity Bay (Fig. 2), using a Japanese cod trap. Every second or third day the trap catch was transferred to a pen approximately 11 m × 12 m × 5 m deep, moored at 18 m depth in Gooseberry Cove. These fish were held in the pen and fed fresh capelin (occasionally herring) three times a week. The fish were offered food until feeding activity nearly ceased. During the summer and fall, the farmed cod increased in weight and length. Although the growth of individual fish was not measured, the total weight of the fish in the pen increased from ~5000 kg in early July to nearly 11 000 kg on 2 October 1992. Comparable weight gains in *Gadus morhua* farmed under similar conditions have been reported by Clark et al. (1995).

Sonic tagging of farmed cod

In November 1992, 14 experimental fish were removed from the pen, tagged with pinger transmitters, and released into Trinity Bay. The sonically tagged cod ranged in fork length from 56 to 77 cm, and weighed 2.5 to 5 kg (Table 1). Fultons condition factor (mean ± SE) was calculated as whole weight g/length $(cm)^3 \times 100$. The cod were anesthetized (Jolly et al. 1972) and fitted with Vemco Ltd. V3-6HI sonic transmitters (9 cm long × 1.6 cm diameter, weighing 34 g in air) implanted in the body cavity using surgical procedures (Templeman and Fleming 1962). The V3-6HI transmitter is powered by a lithium battery designed to emit signals for 165 d. Individual fish were identified by frequency (either 60, 65, 69 or 76 kHz) and pulse period (between 1000 and 1158 ms) of the transmitter signal. Ten fish were released into the waters near Random Island, and four near Heart's Content (Fig. 1). A reward for recapture of a sonically tagged cod was announced on local radio and in regional newspapers.

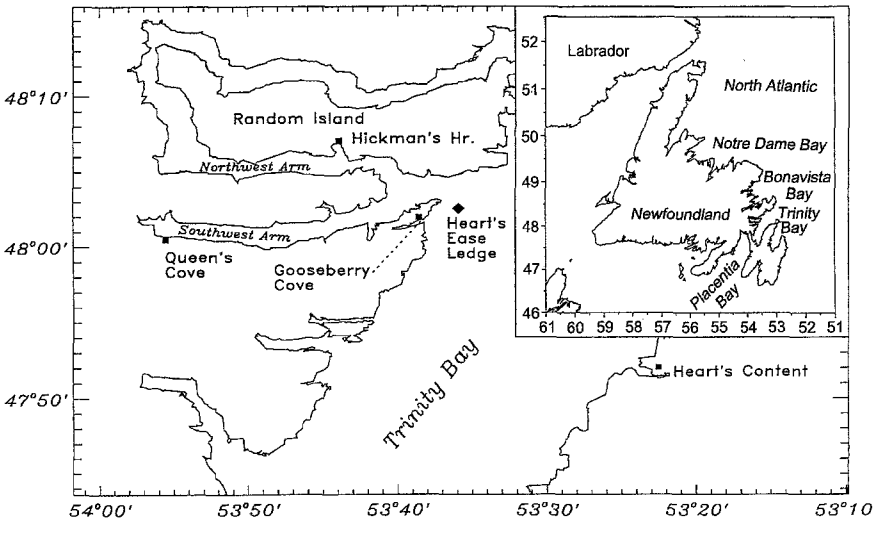

Fig. 1 Maps of study area, Trinity Bay, Newfoundland

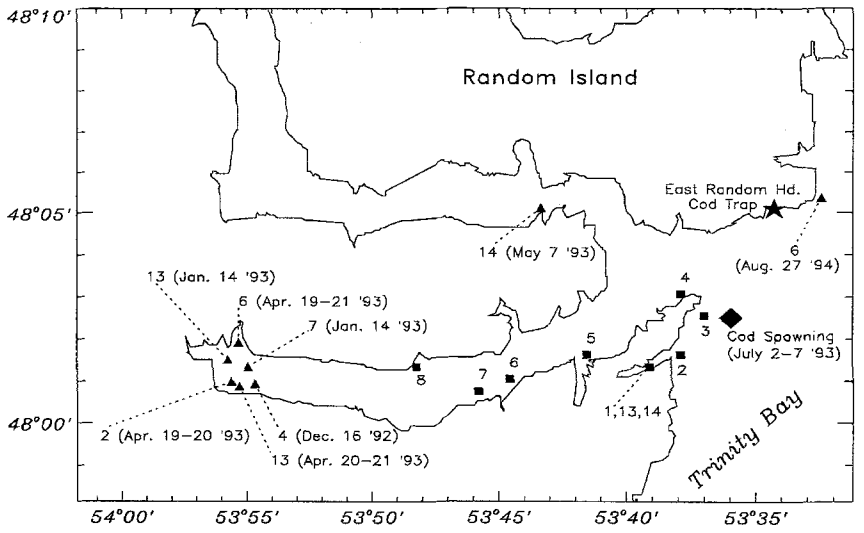

Fig. 2 Sites of release from the cod farm in Gooseberry Cove, Trinity Bay (■) and relocation (▲) of sonically tagged fish. Fish #1, #13 and #14 were released near the pen. *Star* marks location near East Random Head where cod were originally trapped during June/July 1992. *Diamond* marks Heart's Ease Ledge where cod were spawning in July 1993

Table 1 *Gadus morthua.* Information on 14 sonically tagged fish released from the cod farm in Trinity Bay. Experimental cod #1–8 were released 17 Nov 1992, and cod #9–14 were released 26 Nov 1992. See Fig. 2 for release sites and relocations. All fish except #4, #6 and #14 were still at large as of April 1995

Fish #	Length (cm)	Weight (kg)	Release site	Dates relocated	Place relocated
1	77.0	5.0	cod farm	–	–
2	69.0	3.0	Gooseberry Cove	19, 20 Apr '93	Southwest Arm
3	61.5	2.5		–	–
4	65.0	3.0	Southwest Arm	16 Dec '92	Southwest Arm
5	65.0	3.0		–	–
6	62.0	3.3		19–21 Apr '93; 27 Aug, '94	Southwest Arm; E. Random Hd.
7	59.0	2.5		14 Jan '93	Southwest Arm
8	56.5	2.3		–	–
9	61.5	2.8	Heart's Content	–	–
10	60.0	2.5		–	–
11	72.0	4.0		–	–
12	66.0	3.0		–	–
13	65.0	3.1	cod farm	14 Jan; 20, 21 Apr '93	Southwest Arm
14	67.0	3.0		7 May '93	Northwest Arm

Acoustic tracking of farmed cod released in Trinity Bay

Fish were tracked with a Vemco Ltd. V-10 directional hydrophone attached to the end of an aluminium pole that was rotated by hand. On 14 January 1993 sonically tagged cod were relocated by lowering the hydrophone through a hole in land-fast ice covering Southwest Arm. From 14 to 23 April 1993, a commercial fishing longliner, "Northern Quest", was chartered to conduct a search for the released cod. If a signal was detected, the boat was maneuvered to the site of strongest signal reception. The position of the fish was determined using landmarks, depth soundings and navigational charts. The position was verified using the ship's Global Positioning System (GPS). The maximum range of detection using a V-10 directional hydrophone and a VR-60 receiver was approximately half a nautical mile when the transmitters were first activated. The decrease in transmitter performance was monitored as follows. The transmitter recovered from fish #4 on 16 December 1992 (see "Results" section) was kept at Memorial University's Marine Science Research Laboratory in a tank supplied with running sea water pumped from Logy Bay. Each week the tank temperature was recorded and the transmitter tested for emission of signals. On 14 April 1993 the range of this transmitter was determined by fastening it to a mooring at 10 m depth. The range had decreased to 0.25 nm during the 5 mo since activation, as battery power diminished.

Measurement of sea-water temperature

A Vemco Ltd. Sealog-TD (temperature–depth) logger with fast response option was used to record the water temperature profile to within 1 m of the sea bottom at each site where a sonically tagged fish was located. The instrument recorded temperature with 0.1 °C resolution. On 21 April 1993 eight stations with 4-km spacings were occupied along the centre axis of Southwest Arm, and on 24 April 1993 four stations (48°09'N, 53°08'W; 48°07'N, 53°19'W; 48°06'N, 53°25'W; and 48°05'N, 53°31'W) were occupied across Trinity Bay. The Sealog-TD logger was deployed along with a Sea-Bird Electronics Inc. Seacat SBE 19-03. The latter instrument measures ocean temperature with 0.001 °C resolution.

Experimental fishing

Experimental fishing was conducted in the Random Island region during April and July 1993. On 20 and 21 April, five gillnets each 91.5 m (50 fa) in length with 14 cm (5.5″) mesh were deployed overnight in Southwest Arm near Queen's Cove. Length and weight data were recorded for 77 cod caught in the nets. Blood samples (1 to 2 ml) were taken from 71 cod and processed using the method of

Goddard et al. (1992). Samples were subsequently analyzed for the presence of antifreeze proteins (Kao et al. 1986). The method used to quantify antifreeze activity in a plasma sample involves measuring the freezing and melting points of that sample. The antifreeze glycoproteins act primarily to inhibit ice formation, and thus they have a strong depressing action on the freezing point. However, they have only a weak effect on the melting point. The more antifreeze there is in a sample, the greater the difference between the sample freezing and melting points. This difference is termed thermal hysteresis (°C) and is used as a direct measure of antifreeze activity. In adult cod, the primary stimulus for antifreeze production is exposure to subzero temperatures, and antifreeze levels reflect the length of time spent below 0 °C (Goddard et al. 1994). In the present study, antifreeze analysis was used as an indicator of inshore overwintering behaviour, since this is what is suggested by the presence of high mean antifreeze levels in a sample population at the end of winter (Goddard et al. 1994). Fish surviving capture by experimental fishing were released with T-bar anchored, spaghetti tags attached externally under the anterior dorsal fin. Non-surviving fish were examined internally to determine their reproductive state and staged according to the criteria of Morrison (1990).

In July 1993 an aggregation of cod over Heart's Ease Ledge was detected hydroacoustically using a Simrad EQ100 38 kHz echosounder. The school was sampled by jigging the fish on 2, 3, 6 and 7 July. The gonads were examined to determine the state of reproduction. Blood samples for antifreeze analysis were taken from 26 cod in spawning condition. Tissue samples from 33 fish in spawning condition were used in a genetic analysis (Carr et al. 1995).

Results

Movements of farmed cod

At the time of release in November 1992 the body condition of the farmed *Gadus morhua* appeared to be excellent. The condition factor for the 14 experimental fish was 1.12 ± 0.03. In April 1993 it was determined that all 14 sonically tagged fish had departed from their release sites. Evidently each experimental fish survived the tagging procedure. Six of the ten fish released in the Random Island region were relocated at least once (Table 1). The four fish released on the eastern shore of Trinity Bay near Heart's Content were not relocated. Fig. 2 displays the positions where the experimental fish were found.

Fish #4 was jigged by a recreational fisherman on 16 December 1992 in Southwest Arm near Queen's Cove at 72 m depth. On 14 January 1993, signals from fish #7 and #13 were detected near Queen's Cove by lowering the hydrophone through land-fast ice (Fig. 2). The sea-water temperature at this location increased from −1.7 °C immediately under the ice, to 0.9 °C near the bottom at 42 m. In the same area where fish #7 and #13 were detected, numerous cod were caught by recreational fishermen by jigging through the ice. Several catches were examined. These cod ranged in fork length from 35 to 65 cm.

Loose pack ice was present in Trinity Bay on 16 April 1993. Southerly winds caused the ice to drift out of the bay over the next 2 d. The 21 to 24 April 1993 survey of Southwest Arm and Trinity Bay indicates solar warming had established a spring thermocline from the surface down to 10 m. Surface temperature was ~1 °C. Below 10 m sea-water temperatures were subzero. A temperature minimum (−1.5 to −1.7 °C) occurred between 50 and 150 m. Waters in the bay deeper than 400 m were 0 to 0.2 °C.

Fish #2, #6, and #13 were relocated in Southwest Arm during 19 to 21 April (Fig. 2). On 7 May 1993, 2 wk after search operations were completed, fish #14 was caught in Northwest Arm near Hickman's Harbour by a fisherman (Fig. 2). The cod and its transmitter were returned to us. The skin around the incision for transmitter implantation had healed. The transmitter was inactive when tested on 10 May.

On 27 August 1994 fish #6 was caught on a baited hook during recreational fishery for cod, ~21 mo after its release in Southwest Arm. The cod was recaptured near East Random Head, where it had been trapped in June 1992 (Fig. 2). The fisherman reported the fish was in healthy condition. The transmitter was attached to the body cavity wall by connective tissue.

Cod overwintering in Trinity Bay

The lengths of 77 cod caught by experimental fishing in Southwest Arm near Queen's Cove during 21 to 22 April 1993 are presented in Fig. 3A. Both juvenile and adult fish were sampled. The condition factor for these fish was 0.95 ± 0.01, $n = 77$. The reproductive states of the 23 fish examined internally are presented in Fig. 3B. All but two were either ripening or near spawning condition; no fish had yet spawned. Ocean temperatures at the capture site decreased from 0 °C at the surface to −0.7 °C near the bottom (22 m). Of the 71 cod sampled 68 had high levels of antifreeze activity in the plasma. The mean (±SE) value of thermal hysteresis was 0.31 ± 0.02 °C, indicating several weeks exposure to subzero water temperatures (Goddard et al. 1994). The mean (±SE) plasma freezing point was depressed from the usual summer value of approximately −0.7 °C, to -1.14 ± 0.02 °C.

Movement of cod between bays

Of the 77 cod caught by experimental fishing on 21 to 22 April near Queen's Cove in Southwest Arm, 54 were released with external spaghetti tags. Two of these fish were recaptured several months later in an adjacent bay to the north, Bonavista Bay. In mid September 1993 a 76 cm, 4 kg cod was caught in 11 m of water, and on 4 December 1993 a 64 cm, 2.5 kg cod was jigged at a depth of 48 m.

Cod spawning in Trinity Bay

The lengths and stages of sexual maturity of 114 cod sampled from a spawning aggregation in early July

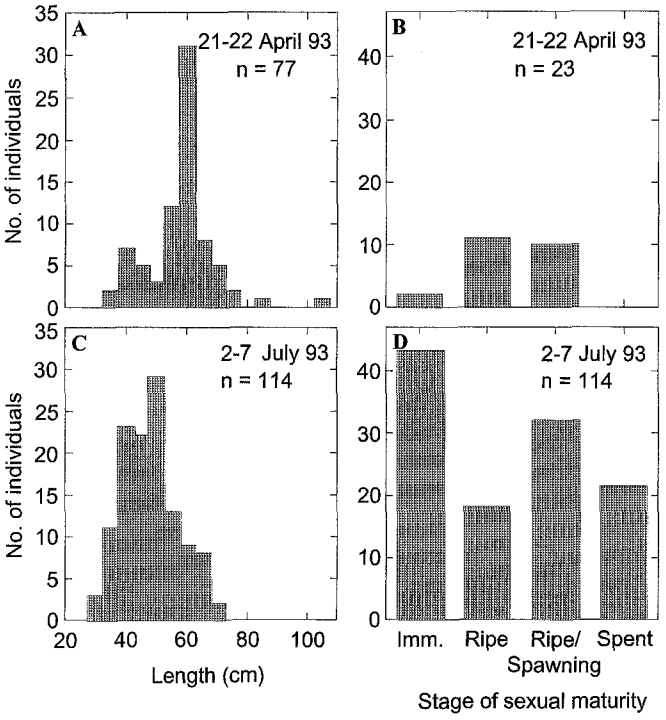

Fig. 3 *Gadus morhua*. **A** Length distribution of cod caught by experimental fishing, 21 to 22 April 1993 in Southwest Arm near Queen's Cove. **B** Stages of maturity of cod from Southwest Arm examined 21 to 22 April 1993 (descriptive criteria of Morrison 1990). No fish had yet spawned. **C** Length distribution of cod sampled 2 to 7 July 1993 from a spawning aggregation over Heart's Ease Ledge. **D** Stages of maturity of cod from Heart's Ease Ledge examined 2 to 7 July 1993. Many adult fish were actively spawning; some were spent

1993 over Heart's Ease Ledge near Gooseberry Cove (Fig. 1) are presented in Fig. 3C, D, respectively. Both juvenile and adult cod were present in the school. The length (mean $\pm$ SD) at sexual maturity was estimated by probit analysis (SAS 1988) to be 47 ± 10 cm, $n = 114$. This was the minimum length at which 50% of the fish in this sample could be assumed to be adults. Taggart et al. (1994) reported a mean length at maturity value of 47 cm for female and 38 cm for male cod sampled on the northern Grand Banks in 1993. Cod in the Heart's Ease Ledge aggregation were actively spawning. Males had running milt and females had streaming eggs. The number of spent fish in the daily sample increased between 2 and 7 July. The condition factor for the 114 fish from the aggregation was 0.78 ± 0.02. This relatively low value reflects the presence of spent fish in the sample.

Water column temperature measured over Heart's Ease Ledge on 2 July declined from 8 °C near the surface, to 2 °C near the bottom at 40 m depth. Blood samples were taken from 26 cod in spawning condition. No measurable antifreeze activity was found in any of the plasma samples (mean thermal hysteresis = 0.08 ± 0.01 °C, mean plasma freezing point = -0.85 ± 0.01 °C).

Discussion

The results of the present study suggest that the farmed cod were able to integrate back into the wild *Gadus morhua* population in Trinity Bay. Fish set free at the cod farm (#1, #13 and #14) were observed moving away from the pen on the day of release. One might have expected farmed cod to have become domesticated after several months of feeding. Fish #2, #4, #6, #7, #13 and #14 were all relocated amongst other cod. Several farmed cod (#2, #4, #6, #7 and #13) were found in association with a group of wild cod overwintering in Southwest Arm. Their movements are consistent with previous sonic tracking observations of cod overwintering in the Random Island region during the winter of 1990/91 (Wroblewski et al. 1994). The antifreeze levels in wild cod found in Southwest Arm on 21 to 22 April 1993 indicate that these fish had overwintered in subzero temperature waters, most likely within Trinity Bay (Goddard et al. 1994). Levels were similar to those found in cod in the Random Island region during April/May of 1991 and 1992 (Goddard et al. 1994), and provide further evidence that an overwintering group of adult cod is a regular feature within Trinity Bay.

The four farmed cod which were found in the spring (fish #2, #6, #13 and #14) were among those released in the Random Island region. Fish released along the eastern shore of Trinity Bay were not relocated. Degradation of the transmitters' range made a thorough search of the bay impractical. These fish may have been simply missed during search operations, or they may have moved to other regions.

The recapture of fish #6 almost two years after release suggests the complete recovery of this experimental cod. Wroblewski et al. (1994) demonstrated the long term survival of *Gadus morhua* released with a surgically implanted transmitter. Our results support the findings of Marty and Summerfelt (1986) and Tyus (1988) that the effects of implants on fish behaviour and mortality are minimized when transmitter weight is <2% of the fish's weight.

Habitat of bay cod

Whether or not farmed cod will remain where released may depend upon the characteristics of the local habitat. Random Island cod overwinter in deep water sounds, where prey is available. Schools of capelin and herring are commonly observed in the region during the winter and spring months. Howse (1993) reported mysids, euphausiids, crab, herring, capelin and cod in the stomach of adult cod in Southwest Arm during the winter of 1990/91. Random Island cod do not avoid subzero water temperatures during the winter. Cod have been observed near the shoreline in waters < -1.5 °C (Wroblewski et al. 1994; present study).

If Trinity Bay is representative of other Newfoundland bays, then one would expect the presence of cod overwintering in areas with similar deep water bathymetry and biota (Richard and Haedrich 1991). Indeed there is evidence from recreational fishing that cod overwinter in Notre Dame Bay, Bonavista Bay, and Placentia Bay. Reports of adult cod jigged through the ice are common from bay areas with deep trenches connected to the open ocean, similar to the Random Island region of Trinity Bay. These areas may be the end points of inshore migration "highways" (Rose 1993). Inshore migrating cod may follow depressions in the continental shelf bathymetry into the bays, and some cod may remain to occupy the bay habitat during the winter.

Non-migration behaviour of Random Island cod

Cod commonly move along the coast of Newfoundland from one bay to an adjacent one (Templeman 1979). In the present study, two cod tagged in Southwest Arm on 22 April 1993 were caught several months later in Bonavista Bay. However, the non-migration (absence of offshore migration) behaviour exhibited by six sonically tagged cod and wild cod observed in Southwest Arm is consistent with the results of tagging studies of Random Island cod by the Canada Department of Fisheries and Oceans (Taggart et al. 1995).

During the periods of 27 to 28 March 1988, 24 to 29 March 1990 and 20 to 27 January 1991, live cod were collected by otter trawl at an average depth of 224 m ($\pm$29 m SD) along the length of Southwest Arm in Trinity Bay, where the bottom temperatures ranged between -0.7 and 1.5 °C (mean = 0.0 °C). A total of 5021 (692, 1639, and 2690 in 1988, 1990 and 1991, respectively) of these cod, having an average length of 44 cm ($\pm$8 cm SD), were marked with sequentially numbered, T-bar anchored, spaghetti tags and released in the immediate vicinity of capture.

As of 1 January 1995, a total of 1398 of these tagged cod had been captured by the commercial and recreational fisheries, the tags had been returned to the Department of Fisheries and Oceans Northwest Atlantic Fisheries Centre in St. John's. A total of 1160 tags had accompanying information on at least the month and year for the date of capture as well as the location of capture. By the end of the first post-release, winter–spring period (end of May) 471 of these tagged cod had been recaptured; 95% of them within 30 nm of the release location, and all but one within 60 nm (Fig. 4). By the end of the first post-release, summer–autumn period (end of November) a further 548 tagged cod had been captured of which 83% were within 30 nm of the release site. All but 12 (2%) of these cod were reported from locations <60 nm from the release location.

A similar pattern was observed in the following year, when by the end of the second winter–spring period an additional 49 of the tagged cod had been captured of which 40 (82%) were within 60 nm of the release location (Fig. 4). At least nine of these cod (18%) had migrated offshore to the shelf break sometime during the first 12 to 14 mo following their release. By the end of the second post-release, summer–autumn period a further 63 cod were captured, and again the majority were from the local region (70% within 30 nm of the release location and 91% within 60 nm). Offshore migration was indicated by one cod caught on the continental shelf off Labrador. This pattern of returns for cod tagged and released in the Southwest Arm area continued through the end of the third winter–spring and summer–autumn periods (8 of 10 and 8 of 11 tagged cod reported from within 60 nm, respectively), and through the end of the fourth winter–spring and summer–autumn periods (2 of 2 and 4 of 5 from within 30 nm, respectively).

These tagging studies indicate that there is a relatively high probability that cod released during the January to March period in the Southwest Arm region will subsequently be captured in the local area, even three or more years later, consistent with the concept of local residency at coastal-bay scales (30 to 60 nm). Even if the tags reported from these studies during the first 6 to 12 mo following release are dismissed due to post-release time bias in their availability, it remains that 68% of all subsequent tag returns were reported within 30 nm of the release location and 83% were within 60 nm. We were able to dismiss the possibility that part of the differences observed between inshore and offshore locations resulted from differences in tag reporting rates between regions. This was achieved by assessing the results from offshore tagging studies conducted in winter and inshore tagging studies conducted in summer (Taggart et al. 1995). Both clearly showed the majority of tags recaptured during the winter periods in the years subsequent to release were reported from offshore locations. Random Island cod exhibit a behaviour similar to coastal cod in northern Norway, which occupy fjord habitats year round (Jakobsen 1987; Salvanes and Ulltang 1992).

Inshore spawning of Random Island cod

Farmed cod (fish #2, #6 and #13) were found amongst adult cod approaching spawning condition in Southwest Arm during April 1993. The presence of adult cod in Southwest Arm was also observed in April 1991 (Wroblewski et al. 1994). The size distributions of cod observed in 1991 and 1993 were similar, with a number of fish > 60 cm in both samples. The stage of reproduction of fish examined in April 1993 was also similar to that observed in 1991. Most males and females were ripening, but none had yet spawned.

Our observation of a spawning aggregation over Heart's Ease Ledge near Random Island in July 1993 is

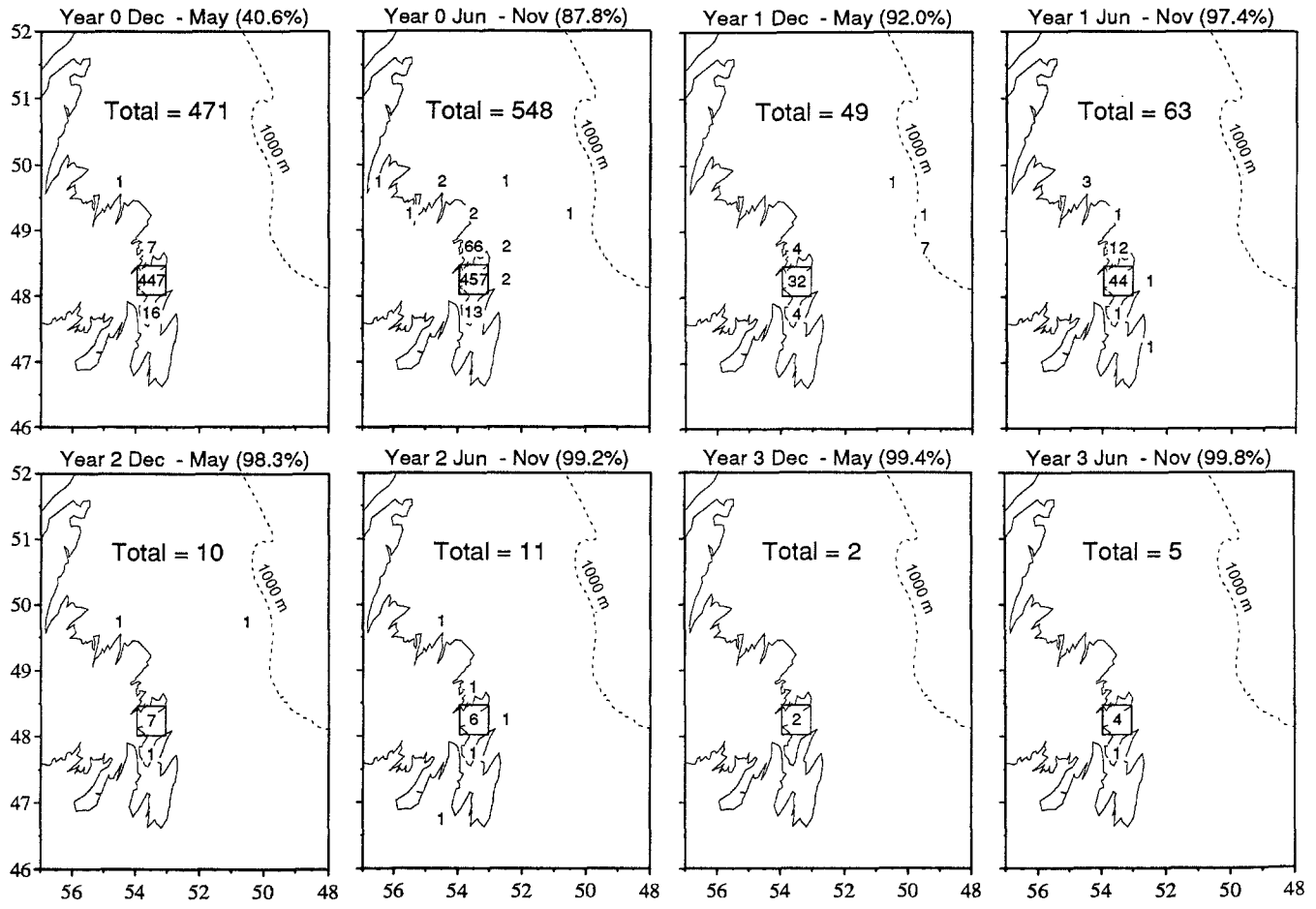

Fig. 4 Charts (coastline and 1000 m isobath) of Newfoundland region and Grand Bank showing location (*outlined box*) where 5021 cod were tagged and released in winter–spring (December–May) of 1988, 1990 and 1991, and where tags were reported captured in subsequent summer–autumn (June–November) and winter–spring periods (Years 0, 1, 2, and 3). Each chart provides cumulative % of all tags reported to date, total number of tags reported during period illustrated, and location of recaptures within 30′ N × 30′ W grid squares

clear evidence that northern cod reproduce in Newfoundland bays. Heretofore, only the presence of cod in spawning condition had been reported (Hutchings et al. 1993). In the past, bays have been primarily regarded as the nursery ground for offshore spawning cod, their developing eggs and larvae having been carried to the coast by the currents (Lear and Green 1984). As northern cod also reproduce in Trinity Bay, some of the juvenile cod found in the bay (Methven and Bajdik 1994) are likely the offspring of inshore spawning cod.

It is not known if farmed cod were among the Heart's Ease Ledge spawning cod, since signals from the surgically implanted transmitters had ceased by May. However, the close proximity (within 4 nm) of the spawning site to the location where fish #6 was caught in August 1994, suggests it was possible. Neither the genetic analysis of tissue samples taken from the Heart's Ease Ledge spawning aggregation, nor the antifreeze protein analysis of blood samples from spawning fish provided conclusive information on where these fish overwintered. Heart's Ease Ledge specimens did not show any significant mitochondrial DNA sequence variation from cod sampled offshore (Carr et al. 1995). The absence of antifreeze proteins in the plasma of these spawning cod does not imply that these cod overwintered offshore in warm ($> 0\,^{\circ}C$) waters. Indeed, it would be surprising to find cold-adapted cod in warm waters during summer, since thermal hysteresis levels in cold-adapted bay cod decrease quickly once the cod enter seasonally warmed waters (Fletcher et al. 1987; Goddard et al. 1994). It is quite likely that these cod overwintered in Trinity Bay, but then lost their antifreeze upon entering the spring thermocline (Wroblewski et al. 1995a).

In the fjords of northern Norway inshore spawning grounds are occupied in spring by year-round residents, and subsequently by Barents Sea cod which migrate to the coast to spawn (Godø 1984; Jakobsen 1987). Cod found spawning in Trinity Bay may also be a combination of local residents and late-spawning individuals that arrive from the continental shelf.

Based on the results of the present study, an effort to increase the number of spawning cod in the Random

Island region through the release of farmed fish would appear to be ecologically reasonable. The data reported here also suggest, however, that not all released fish would remain in Trinity Bay. As with wild cod, some farmed cod might move to adjacent bays, while others might join the offshore migration. Now that it has been established that farmed cod behave similarly to wild cod upon release, the next step is the development of a pilot enhancement project, where large numbers of sexually mature cod are released from farms. It remains to be demonstrated that farmed cod will contribute significantly to annual recruitment in bays.

Acknowledgements We thank W. Bailey, A. Collier, F. Davidson, B. Dean, C. George, K. Howse, C. Seward, G. Seward, Capt. G. Best and the crew of the C.F.V. "Northern Quest", and Capt. C. Scott and the crew of the R.V. "Shamook", for assisting in field operations. M. Kao performed the antifreeze protein analysis. P. Penney assisted in tagging data analysis. F. Perry prepared the figures. Funding for this research was provided by the Canadian Centre for Fisheries Innovation, the Newfoundland and Labrador Department of Fisheries, the Natural Sciences and Engineering Research Council of Canada (NSERC) with Fishery Products International Ltd. and National Sea Products Ltd. under NSERC's Research Partnerships Program, by OPEN (the Ocean Production Enhancement Network), one of the Networks of Centres of Excellence supported by the Government of Canada, and by the Interim Funding Research Program.

References

Bishop CA, Murphy EF, Davis MB, Baird JW, Rose GA (1993) An assessment of the cod stock in NAFO Divisions 2J + 3KL. N Atlant Fish Orgn (NAFO) scient Coun Stud 93/86, Ser No N2271: 1–51

Carr SM, Snellen AJ, Howse KA, Wroblewski JS (1995) Mitochondrial DNA sequence variation and genetic stock structure of Atlantic cod (*Gadus morhua*) from bay and offshore locations on the Newfoundland continental shelf. Molec Ecol 4: 79–88

Clark DS, Brown JA, Goddard SJ, Moir J (1995) Activity and feeding behaviour of Atlantic cod in sea pens. Aquaculture, Amsterdam 131: 49–51

Fisheries Resource Conservation Council (1994) Conservation – stay the course. 1995 conservation measures for Atlantic groundfish. Report to the Minister of Fisheries and Oceans. Fisheries Resource Conservation Council, Ottawa, FRCC 94.R4E

Fletcher GL, King MJ, Kao MH (1987) Low temperature regulation of antifreeze glycopeptide levels in Atlantic cod (*Gadus morhua*). Can J Zool 65: 227–233

Goddard SV, Kao MH, Fletcher GL (1992) Antifreeze production, freeze resistance, and overwintering of juvenile northern Atlantic cod (*Gadus morhua*). Can J Fish aquat Sciences 49: 516–522

Goddard SV, Wroblewski JS, Taggart CT, Howse KA, Bailey WL, Kao MH, Fletcher GL (1994) Overwintering of adult northern Atlantic cod (*Gadus morhua*) in cold inshore waters as evidenced by plasma antifreeze glyco protein levels. Can J Fish aquat Sciences 51: 2834–2842

Godø OR (1984) Cod (*Gadus morhua* L.) off Møre – composition and migration. In: Dahl E, Danielssen DS, Moksness E, Solemdal P (eds) The propagation of cod (*Gadus morhua* L.) Flødevigen rapportser 1: 591–608

Howse KA (1993) A modified migration model for Atlantic cod, *Gadus morhua*, off the northeast coast of Newfoundland. MSc Thesis, Dept of Biology, Memorial University of Newfoundland, St. John's, Newfoundland

Hutchings JA, Myers RA (1994) What can be learned from the collapse of a renewable resource? Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. Can J Fish aquat Sci 51: 2126–2146

Hutchings JA, Myers RA, Lilly GR (1993) Geographic variation in the spawning of Atlantic cod, *Gadus morhua*, in the northwest Atlantic. Can J Fish aquat Science 50: 2457–2467

Jakobsen T (1987) Coastal cod in northern Norway. Fish Res 5: 223–234

Jolly DW, Mawdesley-Thomas LE, Bucke D (1972) Anaesthesia of fish. Vet Rec 91: 424–426

Kao MH, Fletcher GL, Wang NC, Hew CL (1986) The relationship between molecular weight and antifreeze polypeptide activity in marine fish. Can J Zool 64: 578–582

Lear WH, Green JM (1984) Migration of the "northern" Atlantic cod and the mechanisms involved. In: McCleave JD, Arnold GP, Dodson JJ, Neill WH (eds) Mechanisms of migration in fishes. Plenum, New York, NY, pp 309–315

Lear WH, Parsons LS (1993) History and management of the fishery for northern cod in NAFO Divisions 2J, 3K and 3L. In: Parsons LS, Lear WH (eds) Perspectives on Canadian marine fisheries management. Can Bull Fish aquat Sciences 226: 55–89

Marty GD, Summerfelt RC (1986) Pathways and mechanisms for expulsion of surgically implanted dummy transmitters from channel catfish. Trans Am Fish Soc 115: 577–589

May AW (1967) Fecundity of Atlantic cod. J Fish Res B Can 24: 1531–1551

Methven DA, Bajdik C (1994) Temporal variation in size and abundance of juvenile Atlantic cod (*Gadus morhua*) at an inshore site off eastern Newfoundland. Can J Fish aquat Sciences 51: 78–90

Morrison CM (1990) Histology of the Atlantic cod, *Gadus morhua*: an atlas. Part 3. Reproductive tract. Can Spec Publ Fish aquat Sciences 110

Richard JM, Haedrich RL (1991) A comparison of the macrozooplankton faunas in two Newfoundland fjords differing in physical oceanography. Sarsia 76: 41–52

Rose GA (1993) Cod spawning on a migration highway in the north-west Atlantic. Nature, Lond 366: 458–461

Ruzzante DE, Taggart CT, Cook D, Goddard S (1996) Genetic differentiation between inshore and offshore Atlantic cod (*Gadus morhua*) off Newfoundland: microsatellite DNA variation and antifreeze level. Can J Fish aquat Sciences (in press)

Salvanes AG-V, Ulltang Ø (1992) Population parameters, migration, and exploitation of the cod (*Gadus morhua* L.) in Masfjorden, western Norway. Fish Res 15: 253–289

SAS (1988) SAS/STAT User's Guide, release 6.03. SAS Institute, Inc, Cary, North Carolina

Scott AP, Sumpter JP, Kime DE, Rolfe MS (1991) Proceedings of the Fourth International Symposium on the Reproductive Physiology of Fish, FishSymp 91, Univ of East Anglia, Sheffield

Taggart CT, Anderson J, Bishop C, Colbourne E, Hutchings J, Lilly G, Morgan J, Murphy E, Myers R, Rose G, Shelton P (1994) Overview of cod stocks, biology, and environment in the Northwest Atlantic region of Newfoundland, with emphasis on northern cod. ICES mar Sci Symp 198: 140–157

Taggart CT, Penney P, Barrowman N, George C (1995) The 1954–1993 Newfoundland cod-tagging database: statistical summaries and spatial–temporal distributions.

Templeman W (1979) Migration and intermingling of stocks of Atlantic cod, *Gadus morhua* the Newfoundland and adjacent areas from tagging in 1962–66. Res Bull int Commn NW Atlant Fish 14: 5–50

Templeman W, Fleming AM (1956) The Bonavista longlining experiment, 1950–1953. Bull Fish Res B Can 109

Templeman W, Fleming AM (1962) Cod tagging in the Newfoundland area during 1947 and 1948. J Fish Res B Can 19: 445–487

Thompson H (1943) A biological and economic study of cod (*Gadus callarias* L.) in the Newfoundland area including Labrador.

Research Bulletin No 14, Newfoundland Government Dept Natural Resources, St. John's

Tyus H (1988) Long-term retention of implanted transmitters in Colorado squawfish and razorback sucker. N Am J Fish Mgmt 8: 264–267

Working Group on Cod Enhancement (1994) Cod enhancement – operational plans. Report of the working group on cod enhancement. Published by the Canadian Centre for Fisheries Innovation, Memorial University, St. John's

Wroblewski JS, Bailey WA, Howse KA (1994) Observations of adult Atlantic cod (*Gadus morhua*) overwintering in nearshore waters of Trinity Bay, Newfoundland. Can J Fish aquat Sciences 51: 142–150

Wroblewski JS, Goddard SV, Smedbol RK, Bailey WL (1995a) Movements of Atlantic cod (*Gadus morhua*) within the spring thermocline in Trinity Bay, Newfoundland. J mar biol Ass UK 75: 265–284

Wroblewski JS, Kulka DW, Narayanan S, Oake AM, Collier AG, McGrath BD (1995b) Winter distribution and movement of northern Atlantic cod (*Gadus morhua*) along the Newfoundland–Labrador continental shelf edge derived from observations on commercial trawlers. Fish Oceanogr 4: 128–146

Note added in proof. Ruzzante et al. (1996) found that cod overwintering inshore in Trinity Bay are genetically distinct from cod overwintering offshore.