Gear-independent patterns of variation in catch of juvenile Atlantic cod (*Gadus morhua*) in coastal habitats

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**Abstract:** Habitat and size of juvenile Atlantic cod (*Gadus morhua*) change substantially during the first 3 years after settlement, and hence, cohort size cannot be followed using a single gear. We investigated whether catch could be calibrated across gear types by deploying pairs of gears repeatedly in the same habitat. As expected, size selectivity differed substantially among gears. Trawls and seines generally collected individuals <200 mm. Gillnets and jiggers collected individuals >150 mm. Size modes, corresponding to age-classes, were common to catches of most gears. Highest catches were taken by trawls and seines. Gillnet catches were orders of magnitude lower. Standardized catches could not be calibrated across pairs of gears deployed in the same habitat at approximately the same time. However, it was possible to identify spatial depth gradients and diel changes in catch that were independent of gear. Consistent spatial and temporal patterns across gears were interpreted as characteristic of fish populations, not just of gears. Density in coastal habitats was higher at night and was higher at 4–7 m than at greater depths. These results, in conjunction with other studies, establish that coastal depths of 4–7 m represent the centre, and not the edge, of the distribution of age 0 cod in Newfoundland during autumn. Hence nursery areas during the early 1990s, a time of historically low spawning stock biomass, must be identified as the coastal zone, not offshore.

**Introduction**

Recruitment variability and its prediction are important and longstanding problems in fisheries studies. Research has focused on early life stages because it is often theorized that year-class strength is established during a relatively brief critical period early in the life of fishes. Hjort (1914, 1926) hypothesized that year-class variability is related to a critical period in larval life when mortality is increased due to depletion of yolk and onset of starvation. Support for the critical period concept and for estimating recruitment from egg and larval surveys has not always been strong (May 1974; Cushing 1981; Petersen et al. 1988). An alternative view is that recruitment variability and cohort size are modified throughout the pelagic stage (Sette 1943) and continue to be modified during the first few years of life (Sissenwine 1984). This view places greater emphasis on tracking cohort strength throughout the juvenile stage.

Early juvenile stages of many marine fishes inhabit both pelagic and demersal environments where they are often segregated from adults (Harden Jones 1968). Consequently, a variety of sampling gears, some specifically designed, are required to measure juvenile abundance. In pelagic habitats, sampling early life stages of Atlantic cod (*Gadus morhua*) requires relatively few gears, some of which have been quantitatively compared (Schmack 1973; Solemdal and Ellertsen 1984; Suthers and Frank 1989; Potter et al. 1990). Such
Comparisons have not been made for demersal stages, especially in coastal habitats where juvenile cod are often concentrated. Several difficulties arise when comparing catches among demersal samplers. These include differences between active and passive samplers (Hayes 1989; Hubert 1989), restrictions due to habitat type (Godø et al. 1989), and difficulties relating sampling effort to a standard unit (Ricker 1975, p. 19).

The initial objective of our study was to determine if catches of juvenile cod from contrasting coastal habitats could be calibrated among demersal gears (i.e., catch of one gear estimated from catch of a second gear). We used pairwise comparisons of standardized catches between simultaneously deployed gears in the same habitat to determine if calibration was possible. If catches can be calibrated across gears, it becomes possible to estimate losses from cohorts by sampling with different gear as individuals grow, become more mobile, and change habitat. A second objective was to test whether size modes were common across all gears. Early findings led to additional objectives where we tested whether spatial gradients of depth and temporal changes in catches were comparable across gears on a relative scale. If gradients are comparable, then pattern can be interpreted as characteristic of fish populations, not just of gear.

**Methods**

Most sampling was conducted at several shallow (usually <30 m) coastal sites using a 6-m open boat powered by a 45-hp outboard motor. Instrumentation included a speedometer ($v$, kilometres per hour through the water), depth sounder ($z$, metres), and clock (seconds). Cod caught by all sampling gears were counted and measured for standard length (SL, millimetres). All sampling gears are described in the Appendix and include several seines with different methods of deployment (9-, 14-, 22.9-, and 30.5-m seines), bottom trawl, gillnets, jigger, and visual observations by SCUBA divers. Depth was determined as the average of the depth at the start and finish locations for the bottom trawl and each gillnet and SCUBA dive. Depth was recorded as the maximum depth sampled for all of the seines, regardless of method of deployment.

### Table 1. Description of sampling sites and gear deployment in 1991 for comparisons of catches among gears.

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Exposure</th>
<th>Gear</th>
<th>Depth (m)</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bellevue</td>
<td>47°38' N, 53°43' W</td>
<td>Sheltered</td>
<td>1, 2, 3, 4, 5</td>
<td>1.5–4.0</td>
<td>Pebble, cobble, sand in deeper water</td>
</tr>
<tr>
<td>3. Beach</td>
<td>47°38' N, 53°46' W</td>
<td>Intermediate</td>
<td>1, 2, 4</td>
<td>7–12</td>
<td>Pebble, broken shells</td>
</tr>
<tr>
<td>4. Trap</td>
<td>47°39' N, 53°43' W</td>
<td>Exposed</td>
<td>1, 2, 4</td>
<td>5–30</td>
<td>Boulder, bedrock, sand in deeper water</td>
</tr>
<tr>
<td>5. Master’s Head</td>
<td>47°43' N, 53°50' W</td>
<td>Intermediate</td>
<td>1.6</td>
<td>6–10</td>
<td>Coarse sand to cobble</td>
</tr>
<tr>
<td>6. Bald Pt. Beach</td>
<td>47°50' N, 53°52' W</td>
<td>Intermediate</td>
<td>1.6</td>
<td>6–25</td>
<td>Pebble, cobble, boulders in deeper water</td>
</tr>
<tr>
<td>7. Little Mosquito Cv.</td>
<td>47°50' N, 53°53' W</td>
<td>Sheltered</td>
<td>1.6</td>
<td>3–8</td>
<td>Pebbles, mud</td>
</tr>
<tr>
<td>8. Deep</td>
<td>47°39' N, 53°46' W</td>
<td>Exposed</td>
<td>1.2</td>
<td>18–35</td>
<td>Sand</td>
</tr>
</tbody>
</table>

**Note:** Gears: 1, gillnets; 2, trawl; 3, 9-m seine; 4, SCUBA; 5, 30.5-m seine; 6, 14-m seine. Site Nos. are those used throughout the text.

### Table 2. Gear characteristics for comparisons of catches among gears in 1991.

<table>
<thead>
<tr>
<th>Gear</th>
<th>$A$ (m$^2$)</th>
<th>$t$ (h)</th>
<th>$n$</th>
<th>$N_A$</th>
<th>$N_LG0$</th>
<th>$N_LG1$</th>
<th>$N_LG2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5-m seine</td>
<td>73.2</td>
<td>0.08</td>
<td>1</td>
<td>0.78</td>
<td>3.90</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>9.0-m seine</td>
<td>8.2</td>
<td>0.05</td>
<td>2</td>
<td>4.15</td>
<td>4.15</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>14-m seine</td>
<td>21.0</td>
<td>0.06</td>
<td>3</td>
<td>6.34</td>
<td>3.43</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Gillnets</td>
<td>54.9</td>
<td>15.00</td>
<td>3</td>
<td>0.00001</td>
<td>0.00082</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>SCUBA</td>
<td>9.0</td>
<td>0.36</td>
<td>1</td>
<td>3.31</td>
<td>2.82</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>4.9-m trawl</td>
<td>5.5</td>
<td>0.17</td>
<td>2</td>
<td>4.93</td>
<td>4.40</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** $A$ is the effective fishing area of a gear (m$^2$), $t$ is the total time (h) gears were deployed ($t$ was constant for beach seines and variable for other gears), and $n$ is the number of nets (i.e., gillnets) deployed or, alternatively, the number of tows (i.e., trawls or beach seines) conducted for each gear comparison. Mean standardized catches (fish m$^{-2}$ h$^{-1}$) are given for length groups of juvenile cod (LG0, LG1, LG2) as defined in the text.

$N = A \cdot t \cdot n$ for a catch of 20 cod from two tows of a bottom trawl ($A = 5.5$ m$^2$, $t = 10$ min, $n = 2$) would be $10 \times (5.5 \times 10 \times 2) = 1057$ cod m$^{-2}$ h$^{-1}$. In all cases, $A$ is the effective fishing area of the gear, not the horizontal area swept by the gear. Table 2 summarizes the characteristics of each gear.

Pearson product-moment correlation coefficients were calculated to determine if a linear relationship existed for catches between pairs of gears. Catches were only compared for gears that were deployed at the same site and at the same time (within 2 h). Sampling gears included two beach seines (9 and 30.5 m) deployed from shore, a 14-m beach seine deployed from a boat, a 4.9-m bottom trawl, 22.9-m gillnets, and visual observations by SCUBA divers along three fixed transects (Table 1). Sampling was conducted primarily during hours of darkness. Standardized catches from the 14-m beach seine and gillnets deployed at sites 5, 6, and 7 were the only ones compared during daylight.

The catch from each gear was standardized for the amount of time the gear was fishing (hours), the size of the gear (square metres), and the number of tows or nets deployed. Units of standardized catch (number per square metre per hour) were therefore the same for both passive (gillnet) and active (trawl, seine) gears. The standardized catch (SC) for each gear was calculated as

$$SC = N \cdot A^{-1} \cdot t^{-1} \cdot n^{-1}$$

where $N$ is the number of cod caught, $A$ is the unit of effective fishing area of the gear (square metres) through which fish must pass to be caught, $t$ is the time (hours) each gear was deployed, and $n$ is the number of units deployed at one time (e.g., number of gillnets). Alternatively, $n$ can represent the number of times a gear was deployed for a particular comparison (e.g., two trawl tows). For example, SC for a catch of 20 cod from two tows of a bottom trawl ($A = 5.5$ m$^2$, $t = 10$ min) would be $20 \times (5.5 \times 10 \times 2) = 1067$ cod m$^{-2}$ h$^{-1}$. In all cases, $A$ is the effective fishing area of the gear, not the horizontal area swept by the gear. Table 2 summarizes the characteristics of each gear.
Table 3. Summary of fishing effort for study of size selectivity among gears.

<table>
<thead>
<tr>
<th>Gear</th>
<th>Months</th>
<th>Site</th>
<th>No. of times gear deployed</th>
<th>No. of fish measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5-m seine</td>
<td>Sept.–Nov. 1991</td>
<td>1</td>
<td>5</td>
<td>153</td>
</tr>
<tr>
<td>14-m seine</td>
<td>Oct.–Nov. 1991</td>
<td>5, 6, 7</td>
<td>7</td>
<td>387</td>
</tr>
<tr>
<td>4.9-m trawl</td>
<td>Aug.–Dec. 1991</td>
<td>1, 3, 4, 8</td>
<td>64</td>
<td>1 593</td>
</tr>
<tr>
<td>Jigger</td>
<td>Oct. 1991</td>
<td>8</td>
<td>1</td>
<td>135</td>
</tr>
</tbody>
</table>

Note: Sites 34 and 58 are located in Trinity (48°23′N, 53°22′W) and Notre Dame (49°31′N, 54°48′W) bays, respectively. misc., 24 sites in Trinity and Conception bays; rhg, rock hopper gear.

Comparison of size selectivity among gears

Data for the comparison of size selectivity among gears were mostly collected at seven sites in southern Trinity Bay from July to December each year (Table 3). Sampling gears included a 25-m beach seine, a fishing jigger, and the 4.9-m bottom trawl (modified with rock hopper gear) in addition to the gears listed previously. Comparisons of size selectivity among gears were based on sampling conducted at various times of the day or night. We recorded the method of capture for all gillnetted cod as entangled either around the mouth or around the gills and body as reported by Hovgård (1987).

Size selectivity was examined from cumulative length frequency plots for each gear by the Kolmogorov–Smirnov (K–S) test statistic $d_{max}$ (Sokal and Rohlf 1995). In this study, $d_{max}$ was the maximum absolute difference in the relative cumulative length frequency distributions of juvenile cod between two sampling gears. Length data were apportioned into 4-mm length-classes, i.e., the number of cod in each 4-mm length-class was determined and a cumulative length frequency made for each gear. Length-classes of 4 mm were chosen as a compromise that minimized the number of empty cells containing zero cod and maximized the total number of cells upon which comparisons were based. Multiple comparisons by the K–S tests were conducted at an adjusted $\alpha$ of 0.01 criteria of significance as calculated by the Dunn–Šidák method (Sokal and Rohlf 1995) for five ($i$–$v$) sets of planned gear comparisons: ($i$) 1 versus 5 and 7, ($ii$) 2 versus 6*, 3, 5, 6, and 6*, ($iii$) gillnets only 38.1 versus 25.4- and 50.8-mm meshes, ($iv$) mouth38.1 versus gill38.1, and ($v$) mouth50.8 versus gill50.8. Gear codes in $i$ and $ii$ are listed in Table 1. Significance criteria were adjusted to $\alpha = 0.01$ because multiple comparisons lack independence. If the outcome of a single gear comparison is significant, the outcomes of subsequent comparisons might more likely be significant as well (Sokal and Rohlf 1995). Probability values were calculated by solving eq. 11 of Miller (1956, p. 118) for the adjusted $\alpha$ given a known sample size and critical value of $d_{max}$. This equation was solved for $\alpha$ using only the first two terms which, depending on sample size, produced $p$-values accurate to two or three decimal places. This method of comparing length frequencies independent of site and year assumes that cod were randomly distributed with all length groups being equally available to all gears. The small number of shallow (<30 m) coastal sites sampled (less than nine sites for all gears except the rock hopper trawl, Table 3) and the relatively high number of tows conducted for most gears (mean >50 tows per gear type, Table 3; but note that three gears were deployed <10 times) suggest that observed differences in catches among gears were not due to a few unrepresentative catches and that this method of comparing length frequencies is appropriate.

Spatial gradients and temporal changes in catches among gears

We examined small-scale depth gradients in catches to determine if these were independent of gears. Depth gradients were calculated for the bottom trawl, SCUBA surveys, 25-m beach seine, and gillnets, all of which were deployed over a relatively wide range of depths (2.5–30 m). Spatial gradients were defined as the difference in catch at two locations relative to the separation (Schneider 1994). The vertical spatial gradient $\Delta C$ (cod per metre) was calculated as

$$\Delta C = C_2 - C_1$$

where $C_1$ is the mean catch at depth interval $z_1$ and $C_2$ is the mean catch at the next depth interval. For example, a mean catch ($C_1$) of 10.5 fish at depth interval 10.1–12.5 m and a mean catch ($C_2$) of 22.5 fish at the next depth interval (12.6–15.0 m) yields a spatial depth gradient of $\Delta C = (22.5 - 10.5) / (2.5) = 5 \text{ cod m}^{-1}$. Spatial gradients were calculated at a resolution of 2.5 m. The vertical resolution (2.5 m) was chosen as a compromise between the number of depth classes and interpretability of the depth gradient pattern.

A further test of the relationship between depth and catch was conducted using gillnets at two coastal sites with contrasting offshore depth profiles. At site 4 near Bellevue (Table 1), bottom depth increased rapidly with distance offshore such that the depth at 400 m offshore averaged 37.3 m. This contrasts with Hant’s Harbour (48°01′N, 53°16′W) in northeast Trinity Bay where the mean depth at 400 m offshore averaged 20.7 m. Seven nets formed a right-angle pattern that ran parallel to the shoreline (nets 1–3) and then away from the coast (nets 4–7). Three nets (1–3), with 100 m between each net, were set along the shore. Four additional nets (4–7), with 100 m between each net, were set in an offshore direction. Net 4, located at the junction of the longshore and cross-shore nets, was therefore common to both series of nets. Gillnets were set late in the afternoon, fished overnight, and then retrieved shortly after dawn the following day. Sampling was repeated four times (i.e., 4 days) at each site with a total of 7 nets-day$^{-1}$ $\times$ 4 days-site$^{-1}$ $\times$ 2 sites $= 56$ nets set.

We also examined small-scale temporal changes in catches to determine if day and night differences in catches were independent of gears. Site 4 was sampled eight times on 23–24 August 1993 with gillnets. Three gillnets were deployed at the same site for 3 h before being retrieved and replaced with three new nets. Site 3 was sampled on 13–15 October 1992. Two 5-min tows by the bottom trawl were conducted at 3-h intervals at this site.
Results

Comparison of standardized catches among gears

Both the Shapiro–Wilks statistic and plots of residuals indicated that residuals were not normally distributed when standardized catches (transformed and nontransformed) were examined for significant differences among gears by ANOVA. We therefore used randomization tests (Manly 1991) on nontransformed data to test for significant differences in catches among the gears listed in Table 2. Standardized catches differed significantly among gears for each length group (LG0: \( p = 0.005 \), LG1: \( p < 0.0001 \), LG2: \( p = 0.015 \)).

Gillnet catches were orders of magnitude lower than for all other gears (Table 2).

We tested whether catches could be calibrated across gears by plotting catches of one gear against a second gear within each length group. Results for LG1 cod for all paired gear comparisons (Fig. 1) are typical for other length groups. There was only one significant correlation (out of a total of 22 comparisons): LG1 cod in gillnets were significantly correlated with LG1 cod in the 9-m beach seine (\( r = 0.771, n = 7, p = 0.0446 \)). The lack of correlation in more than one out of 22 comparisons indicated that standardized catches could not be calibrated across gears on an absolute scale.

Comparison of size selectivity among gears

Gillnets and jiggers primarily collected individuals >150 mm SL whereas trawls and beach seines with 9-mm stretch mesh generally collected juvenile cod <200 mm SL (Fig. 2). Length frequencies from most trawls and seines contained one or two clear size modes at about 60–75 and 120–140 mm SL (Fig. 2). Consequently, many of the multiple comparisons of cumulative length frequencies among trawls and beach seines (Fig. 3) were not significantly different at the adjusted \( \alpha \) of 0.01. For example, length frequencies of juvenile cod taken by the trawl and by the same trawl modified with rock hopper gear did not differ significantly (\( d_{\text{max}} = 0.2445, n = 42, p = 0.0111 \)). Length frequencies among the trawl and 9- and 14-m beach seines also did not differ significantly (\( d_{\text{max}} < 0.2038, n > 37, p > 0.2000 \), in all cases). In general, the trawl and beach seines caught a very similar size range of juvenile cod (35–200 mm SL) with either one or two size modes being present. Cumulative length frequencies from gillnets and the fishing jigger always differed significantly from all other gears and from each other (\( p < 0.0001 \)) because these gears generally sampled much larger cod (Figs. 2 and 3).

Three clear size modes of juvenile cod were observed in gillnet catches (Fig. 4). These were LG1 (148–190 mm SL), LG2 (190–270 mm SL), and possibly LG3 (270–370 mm SL). The individual size modes do not correspond to the three different mesh sizes (i.e., the 148–190 mm mode from the 25.4-mm mesh, the 190–270 mm mode from the 38.1-mm mesh, and the 270–370 mm mode from the 50.8-mm mesh) because the 25.4-mm mesh was ineffective at catching cod (Fig. 4) and accounted for only 36/3143 = 1.1% of the total gillnet catch. Size selectivity of gillnets appeared to be related to method of capture (gill and mouth) in addition to mesh size. The two size modes present in each of the 38.1-mm (148–190 and 205–280 mm SL) and 50.8-mm (190–250 and 250–370 mm SL) meshes correspond to method of capture, with cod being meshed around the body or gills or, alternatively, entangled near the mouth (Fig. 4). Mouth-caught cod were generally larger than gilled cod within each of these mesh sizes (Fig. 4). There were no significant differences between cumulative length frequencies of cod taken by the 25.4- and 38.1-mm meshes (\( d_{\text{max}} = 0.3584, n = 19, p = 0.0119 \)) or between the 38.1- and 50.8-mm meshes (\( d_{\text{max}} = 0.2112, n = 53, p = 0.0153 \)) of gillnets at the adjusted \( \alpha \) of 0.01 (Figs. 3 and 4). Differences did occur between the 25.4- and 50.8-mm meshes (\( d_{\text{max}} = 0.5728, n = 16, p < 0.0001 \)) as well as between gill- and mouth-caught cod taken by the 50.8-mm mesh (\( d_{\text{max}} = 0.7635, n = 29, p < 0.0001 \)). Cumulative length frequencies of gill- and mouth-caught cod from the 38.1-mm mesh were not significantly
different ($d_{max} = 0.4966, n = 9, p = 0.0168$). Very few cod <150 mm were collected by gillnets and jiggers, even though cod of this size were routinely collected by trawls and beach seines deployed in the same area at the same time. The three size modes represented in the gillnet catches (148–190, 190–270, and 270–370 mm SL) likely correspond to the upper size limit of LG1 (148–190 mm SL), LG2 (190–270 mm SL), and possibly LG3 cod (270–370 mm SL).

Spatial gradients and temporal changes in catches among gears

Spatial gradients in catches were examined to determine whether these were specific to individual gears or, alternatively, if patterns were independent of gears. Plots of catch at depth (0.1-m resolution) and of spatial depth gradients (2.5-m resolution) show that highest catches occurred at shallow depths of about 5 m for LG0, LG1, and LG2 cod taken by bottom trawl, SCUBA, 25-m beach seine, and gillnets (Fig. 5). All gear caught fewer fish at depths >27–30 m.

A further test of the relationship of catch to depth was conducted using gillnets at site 4 and at Hant’s Harbour, two sites that differed in offshore depth profiles. Based on the depth-related pattern of catches described above (Fig. 5), we expected that catch would decline with increasing depth offshore. This was the pattern we observed at site 4 where depth increased from 6.7–8.3 m nearshore to 37 m at 400 m offshore (Fig. 6). At Hant’s Harbour, a site with a more uniform cross-shore depth gradient (range 12.0–20.7 m, Fig. 6), cross-shore

Fig. 2. Length frequency distributions of juvenile cod (4-mm length intervals) collected at several sites along the northeast coast of Newfoundland. Gears are described in the text. rhg, rock hopper gear.
catches of gillnetted cod were similar to longshore catches and consequently did not show the decline that was evident with depth at site 4 (Fig. 6). Catches differed significantly between longshore and cross-shore gillnets at site 4 (ANOVA, $F_{1,95} = 15.16, p = 0.0002$) but not at Hant’s Harbour (ANOVA, $F_{1,95} = 0.83, p = 0.3637$), again indicating the importance of depth to the distribution of juvenile cod in the nearshore zone.

Temporal patterns in catches among gears were compared for two 24-h collections, one by bottom trawl (11–14 m, site 3) and the other by gillnets (4–17 m, site 4), to determine whether diel patterns were specific to individual gears or if patterns were independent of gears. At the temporal scale of day versus night, a strong pattern was evident with 91.6% (trawl) and 73.8% (gillnets) of all juvenile cod caught at night.

**Discussion**

Repeated deployment of several demersal sampling gears in different coastal habitats showed that (i) catches could not be calibrated across gears deployed simultaneously at the same site, (ii) size modes of juvenile cod were independent across gear, similar among trawls and beach seines, but contrasted with the larger cod taken by gillnets and jiggers, and (iii) standardized catches differed among gears, with gillnet catches being orders of magnitude lower than for all other gears. Early findings led to the formulation of additional objectives that investigated whether spatial gradients of depth and temporal changes were comparable across years. Spatial gradients and diel changes in catches were comparable across gears, with highest catches occurring close to shore in 4–7 m of water during hours of darkness.

Substantial effort was devoted in this study to matching gear by time and location to reduce error in calibration. Despite this, it proved impossible to calibrate standardized catches across gears. However, it was possible to identify a series of length modes that were consistent across most gears. Modes occurred at about 50–77, 120–140, and approximately 200–300 mm SL. The smallest mode, best sampled by beach seines and trawls with 9-mm mesh, was age 0 cod that settled in autumn (Pinsent and Methven 1997). Cod between 200–300 mm were best sampled by gillnets and were in the size range (22–27 cm) of 2-year-olds (Fleming 1960). The size mode in between age 0 and age 2 cod ($\approx 120–140$ mm SL) likely represents age 1 cod that have overwintered, but there...
appears to be no confirmation of this for cod from Newfoundland based on ages determined from otoliths. Caution should be taken when assigning ages to individual gillnetted cod based solely on length frequency modes. Peaks in the size distributions of gillnetted cod are not only influenced by mesh size selection but are also related to the way cod were meshed (gill or mouth). Thus, it is important to distinguish between the two smallest size modes (50–77 and 120–140 mm SL) sampled by small-mesh trawls and seines that apparently correspond to the size distribution of the population and the larger mode (200–300 mm) caused by the mesh selection of the gillnets.

Patterns of relative change in abundance with time of day and with depth could be identified independently of gear type. The different types of gear (passive, active, and visual observations by divers) used to sample juvenile cod over a 24-h period at the same site in this and other studies (Keats 1990; Methven and Bajdik 1994; Gibson et al. 1996) all show higher catches at night, indicating that this pattern is independent of gear and characteristic of coastal populations of LG0 and LG1 cod. We interpret this pattern to be due more to an inshore movement at dusk or night than to a substantial change in catchability (Methven and Bajdik 1994; Gibson et al. 1996). Rapid inshore and offshore movements at dusk and dawn by a variety of fishes (Helfman 1993) indicate that collections taken at these times may not be representative of typical daytime densities.

Spatial depth gradients were also similar across gears when averaged across sampling sites. Highest catches occurred at shallow (4–7 m) depths close to the coast. This pattern is not unique to LG0 and LG1 cod in Newfoundland waters. Catches of 0-group cod off the English and Welsh coasts taken by a 2-m beam trawl were highest at about 6 m (Riley and Parnell 1984). Highest catches of age-1 cod sampled by gillnets off southwestern Greenland were taken at 3–10 m. Catches were lowest at depths <3 m and >20 m (Hansen and Lehmann 1986; Hovgård and Nygaard 1990). Gibson et al. (1996) reported that highest catches of juvenile cod in Scotland occurred at 5 m over the range 0.5–5.0 m. Acoustic surveys in Finnmark, northern Norway, showed that most juvenile cod occurred at depths <35 m, with highest densities occurring closest to the coast where the vessel could not sample (Olsen and Soldal 1989). These studies, conducted across a variety of habitats, depths, and gears, indicate that the coastal distribution of 0-group cod occurs at shallow depths and that larger juveniles occur at progressively deeper depths and distance from the coast (Hansen 1966; Hislop 1984; Riley and Parnell 1984; Tremblay and Sinclair 1985; Dalley and Anderson 1997). This positive relationship between size and depth is characteristic of many species and implies an ontogenetic movement towards deeper water with increasing size (Macpherson and Duarte 1991). This was first described by Heincke (1913) for plaice (Pleuronectes platessa) and was referred to as Heincke’s Law (Wimpenny 1953). Relative to the adult stages,
larvae and juveniles of many temperate demersal fish species occur in shallow and hence relatively well-lighted water.

At a scale of hundreds of kilometres, LG0 and LG1 cod are presently (mid-1990s) confined to the coast of Newfoundland during autumn (Dalley and Anderson 1997). Our study extends this result to a finer scale of tens of metres within the coastal zone where LG0 and LG1 cod reached maximum densities at depths of 4–7 m. This confirms observations of Lear and Green (1984) that nursery areas for LG0 cod are located along the coast. The prevailing southward flow of the Labrador Current will tend to carry eggs and larvae toward the coast due to Coriolis forces, although this tendency is episodically reversed at the surface by strong wind events from the southwest (Templeman 1966; Frank and Leggett 1982; Rose and Leggett 1988; Schneider and Methven 1988; Ings et al. 1997a). A physical model of egg and larval drift (Helbig et al. 1992) showed that eggs spawned offshore generally remained offshore, but more recent models (Davidson and de Young 1995; Pepin and Helbig 1997) showed that coastal transport was possible for particles seeded along the shelf break to the north but not to the east of Newfoundland. These observations, together with the current absence of LG0 cod away from the coast (Dalley and Anderson 1997), a spawning failure of the offshore components of the 2J3KL Newfoundland–Labrador cod stock (Dalley and Anderson 1997), and well-documented spawning along the northeast coast of Newfoundland (Thompson 1943; Hutchings et al. 1993; Laprise and Pepin 1995; Smedbol and Wroblewski 1997), are consistent with a coastal origin for many of the newly settled cod collected along the coast in shallow (4–7 m) water. In the past, coastal areas may have served as nursery areas for both inshore and offshore spawning fish (Lear and Green 1984). Concentration of newly settled

Fig. 5. Number of cod in relation to depth (0.1-m resolution) and depth gradients (2.5-m resolution). Depth gradients are defined in the text.
demersal cod in the horizontal dimension can be achieved either by (i) an active migration towards the coast, possibly in response to depth, and factors that covary with depth such as light, salinity, or food gradients (Riley and Parnell 1984; Tremblay and Sinclair 1985; Heessen 1991; Angel 1992) or (ii) from wind-induced coastal upwelling where demersal juveniles can be moved toward the coast in bottom water drawn shoreward during upwelling.

To explain this pattern of vertical distribution, we propose that shallow waters act as traps for vertically migrating pelagic cod that settle upon encounter with suitable bottom habitat and that undergo increasingly extensive vertical migration as they increase in size before settling. Vertical migration begins during the pelagic stage, as juveniles ascend towards the surface during darkness and descend during daylight (Koeller et al. 1986; Perry and Neilson 1988). On Georges Bank, these diel vertical migrations kept cod in contact with their pelagic prey (Neomysis americana, Tisbe sp., and Pagurus larvae) at thermally stratified and nonstratified sites (Perry and Neilson 1988). As the length of individual cod increases, the vertical extent of the pelagic migration increases (Perry and Neilson 1988) until individuals eventually encounter the bottom. A positive relationship between length of cod and the extent of diel vertical migration is reported for another gadid, walleye pollock (Theragra chalcogramma, Bailey 1989), and for fish in general (Neilson and Perry 1990). This trapping mechanism is testable.

Predictions are that (i) size of individual cod at settlement will be less on shallow banks and coastal areas than on deeper banks, (ii) shallow sites will have a higher proportion of smaller cod than deeper sites, and (iii) recently settled cod will be more aggregated than their pelagic counterparts because shallow banks (and especially coastal areas) act as traps that concentrate settled cod. This trapping mechanism is consistent with ultimate, or evolutionary, factors favouring settlement of juvenile cod in coastal habitats. These factors include reduced predation and maintaining contact with a familiar and relatively abundant pelagic food supply. Both factors increase survival. Predation is reduced because larger (predatory) fishes tend to occupy deeper water (Helfman 1978; Macpherson and Duarte 1991). Coastal sites also provide abundant fleshy macroalgae, a preferred habitat that, in addition to cobble, provides juvenile cod with cover from predation (Keats et al. 1987; Gotceitas et al. 1995). Settlement in shallow water also helps maintain contact with pelagic food in the surface layer until cod reach 60–100 mm, the size at which they make the transition to predominately benthic prey (Lomond et al. 1998).

The high densities observed in shallow water contrast with the distribution of newly settled cod off Nova Scotia and New England where LG0 and LG1 cod were either not collected in shallow water or attained maximum densities at depths greater than the 4–7 m observed in this study (Targett and McCleave 1974; McCleave and Fried 1975; Macdonald et al. 1984; Horne and Campana 1989; Lough et al. 1989; Black and Miller 1991; Hanson 1996; but see Tupper and Boutilier 1995). Water temperature may be an important variable that restricts 0- and 1-group cod to deeper water south of Newfoundland, and in Norway where in the southern Gulf of St. Lawrence, age 0 cod are absent at depths <10 m (Hanson 1996) and along the Skagerrak coast of Norway, age 1 cod occur in deeper water during summer when subsurface temperatures are too warm (Danielsson and Gjøsæter 1994). A second possibility relates to spawning locations south of Newfoundland. If spawning occurs primarily offshore and passive eggs and larvae are not advected towards the coast, then extensive settlement may not occur at the coast. For example, similarity in the patterns of egg and larval distributions offshore on the Scotian Shelf at any one time, as well as the persistence of the larval distributions over certain offshore banks led O’Boyle et al. (1984) to suggest that eggs and larvae were retained by gyral circulation associated with offshore banks and that the spawning and nursery grounds are often located within the same geographical area offshore (Gagné and O’Boyle 1984).

At present (1992 onward), the coastal zone nursery area for LG0 cod is the only confirmed source of recruits in Newfoundland. Our study, in conjunction with Dalley and Anderson (1997), establishes that shallow coastal depths represent the

Fig. 6. Number of cod collected by individual gillnets set about 100 m apart in a line along the shore (locations 1–4) and in a line in an offshore direction (locations 4–7) at two sites (upper and lower panels) with contrasting offshore depth profiles. Mean depth (z, m) of four gillnets is indicated immediately above each panel over the longshore and cross-shore location to which it refers. Seven gillnets, one at each location, were set overnight on each of four occasions (i.e., four lines of data) for each site in August 1992. The seven gillnets set at any one time for each site formed a right-angle shaped pattern, with the gillnet at location 4 being common to both the longshore series and the cross-shore series of nets.
centre, and not the edge, of the distribution of LG0 cod off eastern Newfoundland. These results indicate that a coastal survey (e.g., Schneider et al. 1997; Ings et al. 1997b) together with an inshore–offshore survey (e.g., Dalley and Anderson 1997) in deeper water are required to track annual changes in distribution and abundance of juvenile cod off eastern Newfoundland during the 3 years prior to recruitment to the fishery. Each survey has disadvantages. Coastal surveys with bottom-sampling seines do not sample large (>200 mm) juvenile cod well, likely because of gear avoidance and the preference for deeper water (Gregory and Anderson 1997). Coastal surveys (e.g., Tveite 1984; Ings et al. 1997b) are also restricted to relatively smooth bottom habitats near the coast. Consequently, they may not be a good indicator of cod abundance in deeper water. Offshore demersal surveys conducted from large ships (e.g., Dalley and Anderson 1997) cannot sample the immediate nearshore zone where density of LG0 cod was highest at 4–7 m. In addition, offshore surveys generally do not catch as many 0-group cod compared with 1-group cod, due possibly to no sampling near the coast. Neither survey by itself can accurately represent the abundance and distribution of juvenile cod. Both a coastal survey and an offshore survey are required to track relative cohort strength of demersal cod during the first 3 years of life.

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Appendix. Description of sampling gears

Beach seines

9-m seine
The 9-m by 1.5-m-deep beach seine with 9-mm stretch mesh and its method of deployment are described in Methven and Bajdik (1994).

14-m seine
The 14-m beach seine was constructed of 15-mm stretch mesh with a codend liner of 9-mm stretch mesh. This seine sinks to the bottom and sampled from the bottom to about 1.5–2.0 m above the bottom. It did not sample from the surface to the bottom as the 9- and 30.5-m seines. The 14-m seine was deployed by boat to a distance of 55 m offshore and was hauled towards shore by towing lines. Retrieval of the 14- and 25-m beach seines is described in Lear et al. (1980).

25-m seine
Specifications and deployment of the 25-m beach seine are described in Schneider et al. (1997).

30.5-m seine
The 30.5-m by 2.4-m-deep beach seine had a 2.4-m³ collection bag and was constructed entirely of 9-mm stretch mesh. One person remained onshore holding a pole attached to the end of the seine while the other end was taken offshore by a person wearing chest waders. This seine was fished in one arclike sweep such that an area of about a quarter of a circle was sampled.

Bottom trawl
The trawl was a 4.9-m semiballoon bottom trawl with a 5.2-m headrope and a 6.4-m footrope. The footrope was fitted with eight 7.6 × 12.7 cm rollers spaced evenly with 69-cm centres between which hung with one loop of galvanized chain. The mesh in the wings, top, belly, and codend was 32–38 mm stretch with a 9-mm stretch mesh liner in the codend. Thread size was No. 12 in the body and No. 18 in the codend. Chaffing gear of 63.5-mm stretch mesh was attached to the underside of the net and codend. Trawl doors were made of wood with metal runners and measured 76 cm long by 38 cm deep. Each door weighed about 7 kg. The amount of towing warp was three to four times the water depth. Tows were usually limited to 5–10 min each at a speed of 2.5–3.0 km·h⁻¹. The foot gear of the trawl was modified to include rock hopper gear (see Gunderson 1993) in 1992 and 1993. This consisted of groups of four 7.5-cm-diameter rubber discs that were evenly spaced every 10.2 cm by metal spacers. The net was attached to a 4-mm-diameter wire (that ran through the discs to prevent them from rolling) by three links of chain. Each link of chain was 25 mm long, thus ensuring that the space between the rock hopper gear and the net was minimized.

SCUBA
SCUBA surveys were conducted by divers after dusk along rope transects that were anchored to the bottom. Transects started in shallow water close to shore and extended offshore for 61 m (site 1), 118 m (site 3), and 113 m (site 4). The start and finish depths were 1.7–4.4 m (site 1), 6.9–10.0 m (site 3), and 4.5–14.5 m (site 4). All cod observed within 3 m of either side of the transect and within about 1.5 m of the bottom were counted. Visibility at night depended on the dive site but usually exceeded 4 m with an underwater light. Divers recorded all information on plastic slates. Five underwater transects were conducted by divers who recorded cod on underwater video (H18 mm camcorder, Sony model V101, enclosed in an Amphibico housing with two 50-W lights). Juvenile cod did not appear to be either attracted to or repulsed by divers (see Keats et al. 1987; Keats 1990) or underwater lights.
**Gillnets**

Gillnets were 22.9 m by 2.4 m deep and contained three 7.6-m panels, each of different size mesh (25.4-, 38.1-, and 50.8-mm stretch mesh). The floatline was made of foamcore, a flexible styrofoam core running through the centre of a 9.5-mm nylon rope. The footline was 6.4-mm-diameter lead line that was attached to building bricks, as weights, at each end of the net. Meshes were made of No. 69 monofilament line (0.28 mm thick). Gillnets were set perpendicular to the coast in a line from shallow to deep water (sites 3 and 4) or along the shore (sites 1, 6, and 7) so as not to interfere with boat traffic. Nets were usually set shortly before dusk and were retrieved by 08:00–10:00 the next day. Soak time was about 15 h.

**Jigger**

The fishing jigger is known locally as a Norwegian-style jigger and is manufactured by Sølvkroken. It is silver in colour, 21 cm long, weighs 498 g, and has a single treble hook with red plastic around the shaft.