ICES mar. Sci. Symp., 198: 140–157. 1994

Overview of cod stocks, biology, and environment in the Northwest Atlantic region of Newfoundland, with emphasis on northern cod

C. T. Taggart, J. Anderson, C. Bishop, E. Colbourne, J. Hutchings, G. Lilly, J. Morgan, E. Murphy, R. Myers, G. Rose, and P. Shelton

Taggart, C. T., Anderson, J., Bishop, C., Colbourne, E., Hutchings, J., Lilly, G., Morgan, J., Murphy, E., Myers, R., Rose, G., and 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.

Total landings of cod in the Newfoundland region (NAFO Divisions 2GHJ, 3KLMNO, and Subdivision 3Ps) increased from ~1 × 10^5 metric tonnes (t) in 1800 to ~4 × 10^5 t in 1950. Landings then increased to >1 × 10^6 t in 1968 and then declined to <2 × 10^5 t by 1978. Landings again increased to 3.5 × 10^5 t in the 1980s and after 1988 dropped to <1 × 10^5 t. By 1993 the cod fishery throughout the majority of the region was closed. Northern cod (2J+3KL) spawner population estimates follow a temporal pattern similar to landings; current levels are at a record minimum of <1 × 10^8 and have been paralleled by a collapse in the size and age structure of the stock. Under the prevailing levels of fishing mortality, recruitment per spawner was below replacement from 1983 onwards, paralleling the stock decline. Recruitment determination is consistent with a parent stock-recruitment relationship. Widespread distributions of age 5+ cod, typically seen in the 1980s, became more aggregated toward the offshore, culminating in very few major aggregations along the shelf break in 1992. Winter–spring spawning throughout the region is protracted (3–4 months) and may be more frequent in inshore regions and on banks than has been previously perceived. The overall physiological condition of northern cod in more northerly regions has been decreasing since 1988, and only in the most recent years have capelin been virtually absent from the stomachs of cod in northerly regions. Lengths at 50% maturity have been declining since the early 1980s, particularly in northerly regions. Fishing mortality for northern cod was consistently >0.4 in the mid-1970s. The reduction of F to <0.4 during 1977 to 1980 was paralleled and followed by increases in the abundance of the spawner population. Slowly increasing fishing mortalities after 1980 accelerated after 1987. The combined effects of fishing mortality on spawning population size and reduction in length and age reduced fecundity contributions of older individuals. A recent examination of a salinity–recruitment relationship shows that with the addition of spawning-stock biomass estimates, recruitment estimates can be well modelled. A series of years characterized by better than average environmental conditions will likely be required to provide the good recruitment necessary to rebuild the stock size and length/age structure.

C. T. Taggart, Science Branch, Canada Department of Fisheries and Oceans, Northwest Atlantic Fisheries Center, PO Box 5667, St John's, NF, Canada A1C 5X1.

Introduction

The critical status of Atlantic cod (*Gadus morhua* L.) in the Newfoundland and Labrador region of the Northwest Atlantic, particularly northern cod in the Northwest Atlantic Fisheries Organization (NAFO) Divisions 2J+3KL, was recognized in the late 1970s (Kirby, 1982), again in the mid-1980s following a severe decline in the inshore fishery (Alverson, 1987), and more recently in 1989 (Harris, 1990). Since then, cod stock levels have become so low that Canadian commercial cod fishing is now banned throughout most of the region (Divisions 2J+3KLNO and Subdivision 3Ps) and long-term prospects for rebuilding the northern cod stock are such that "recovery of the spawning stock biomass is unlikely before the year 2000 at the earliest" (Anon., 1993, p.16). At the same time a considerable effort has been mounted to examine more closely the nature of catch statistics, fishing effort, population size, distribution and structure, spawning and recruitment, feeding, growth, maturity, and condition, etc., as well as variations in the climate and the physical environment. The majority of these efforts, which have primarily focused on the "northern cod" of NAFO Divisions 2J+3KL, are ongoing, and some of those results are presented elsewhere in this ICES Cod and Climate Change Symposium volume.

The goal of this article is to compile from these sources some of the more important aspects of the findings in order to provide a timely, though primarily descriptive, overview of the cod stocks, their biology and surrounding environment in the Newfoundland region, focusing mainly on northern cod over the last 10 to 20 years. In doing so, we hope to provide for general and future insights to analytical comparisons with the other Atlantic cod stocks and to provide a general background for the more specific and analytical studies on cod from the Newfoundland region that are contained within this volume.

Landings, population estimates and distribution

Landings

Atlantic cod have been exploited in the Newfoundland region (NAFO Divisions 2GHJ, 3KLMNO and Subdivision 3Ps) since the late 1400s. Total reported commercial landings by all Canadian and Newfoundland fleets and gear increased from about 1×10^5 metric tonnes (t) in 1800 to around 4×10^5 t in 1950 (Fig. 1). Subsequent to 1950, and with the extension of long-distance foreign fleets (primarily European and Soviet) into the Northwest Atlantic, total reported landings increased dramatically to $>1 \times 10^6$ t in 1968 and then declined just as sharply to $<2 \times 10^5$ t by 1978, a trend which helped stimulate the introduction of total allowable catch (TAC) limits in 1974 and the extension of Canada's economic management zone to 200 miles in 1977 (Fig. 1). In the mid-1980s, landings increased to $\sim 3.5 \times 10^5$ t, paralleling the introduction and increased exploitation by the Canadian offshore trawler fleet. After 1988 landings dropped sharply to $<1 \times 10^5$ t in 1992, partly a result of the early closure of parts of the Canadian offshore cod fishery, and later the inshore fishery. Later in 1992 Canada closed all commercial cod fishing within the Canadian economic management zone throughout 2J+3KL (northern cod). The closure has since expanded to include Divisions 3NO and Subdivision 3Ps. Exploitation by foreign fleets outside the Canadian economic management zone (the "nose" and "tail" of the Grand Bank and Division 3M – Flemish Cap) is under NAFO jurisdiction, and although not limited by the Canadian closure, NAFO has subsequently endorsed the cessation of commercial cod fishing on the "nose" and "tail" of the Grand Banks, but not on the Flemish Cap (Division 3M).

Since 1950, Newfoundland and Labrador cod stocks have been managed more-or-less as stock "components" according to the NAFO Divisions, i.e. 2GH (northern Labrador cod), 2J+3KL (northern cod), 3NO (southern Grand Bank cod), and 3Ps cod. More recently (since 1987) TAC management for northern cod (2J+3KL) has reflected a one-third allocation among each of the Divisions (2J, 3K, and 3L) for the offshore fishery, although the stock is assessed as a unit. Divisional landing statistics show a high degree of variation within and among Divisions (Fig. 2). Landings were highest in all Divisions during the 1960s (reflecting foreign exploitation), though relatively low ($\sim 5 \times 10^4$ t) and stable in the most southern region (3Ps) and in the most northern region (2GH), with the exception in the latter of increased exploitation (again primarily foreign) during 1965 to 1970 (Fig. 2). The highest landings have been consistently and conspicuously derived from the "northern" cod stocks in 2J+3KL, particularly the southern Labrador banks (2J) and the northern Grand Bank (3L) throughout the 1960s and early 1970s (Fig. 2).

Population estimates

Sequential population analysis (SPA) estimates of spawners (ages 6+ in this section of the paper) in the Newfoundland region from the mid-1950s to 1993 follow a temporal pattern similar to that seen in the total landings, with the maximum estimates of $>1 \times 10^9$ in 2J+3KL in the early 1960s declining by one order of magnitude to $\sim 1 \times 10^8$ in 1977 (Fig. 3). Subsequent increases to $>3 \times 10^8$ in 1987 in 2J+3KL were soon followed by a sharp decrease to a record minimum of less than 1×10^8 in 1993 (Fig. 3). The temporal pattern seen in the age 6+ population estimates is also apparent, though less pronounced, in the historically much smaller (always $<1 \times 10^8$) 3NO and 3Ps estimates (Fig. 3).

SPA recruitment estimates of age 3 cod also show a pattern similar to that seen in both the landings and spawner population estimates (Fig. 3). The general correlation ($r^2=0.54$) between spawner and recruit estimates for 2J+3KL cod is indicative of a stock–recruit relationship (see Myers *et al.*, 1993a) and is further addressed below.

The reduction in population size of 2J+3KL cod has been paralleled in recent years by a reduction in the average size and age of the population. The interquartile

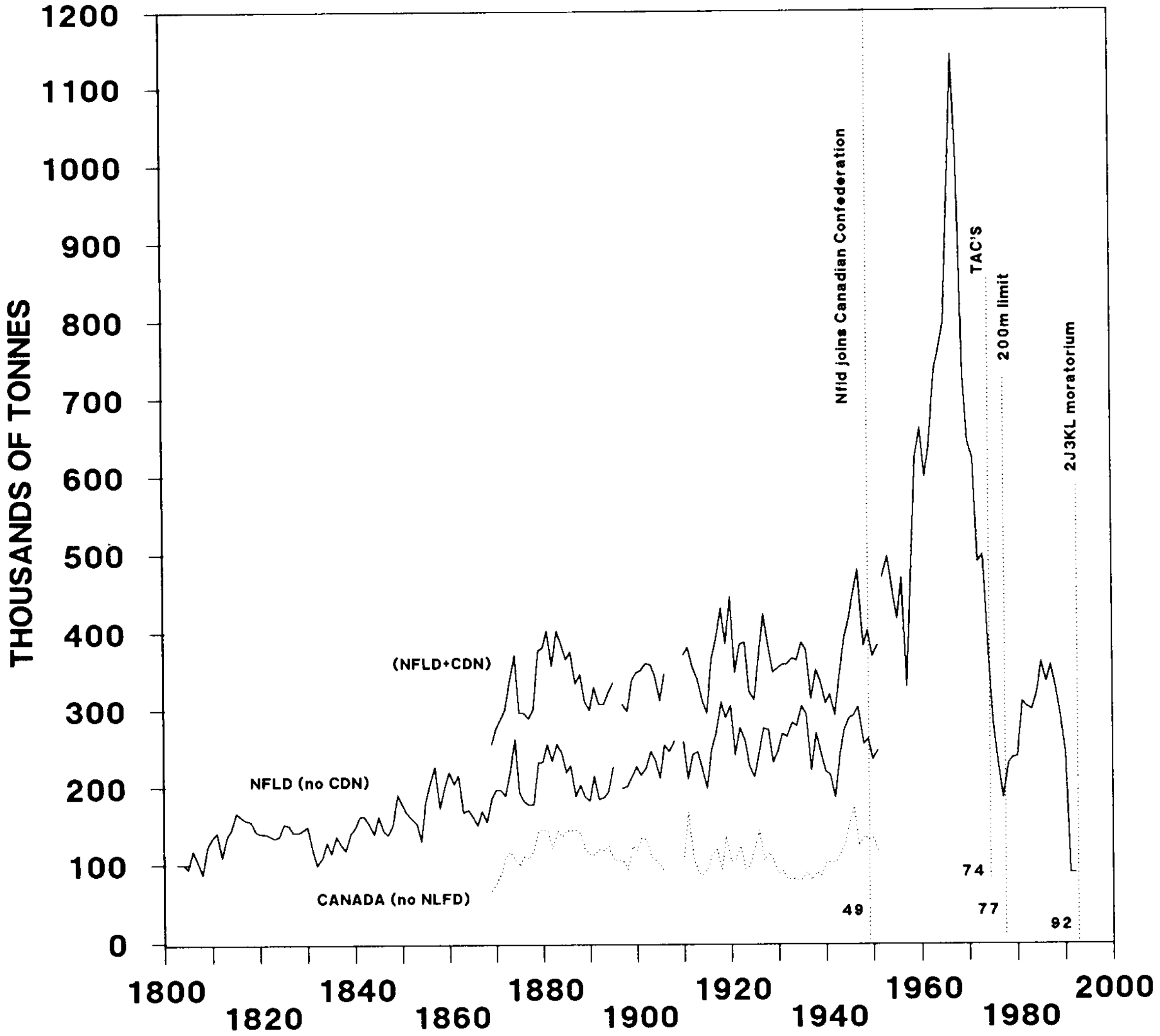

Figure 1. Total reported commercial landings (t) of cod in the Newfoundland region (NAFO Divisions 2GHJ, 3KLMNO, and Subdivision 3Ps) since 1800 for all gear sectors. Reported landings to 1950 for pre-confederation Newfoundland (NFLD-no CDN) include NAFO Areas 2 and 3 only and exclude Canadian and foreign landings. Reported landings to 1950 for Canada (Canada-no NFLD) include only NAFO Area 3 and exclude Newfoundland and foreign landings. Total reported landings subsequent to 1950 include all Canadian and foreign fleets and gear in NAFO Areas 2 and 3. Major management changes are noted in 1950 (following Newfoundland joining Canadian Confederation in 1949), 1974 (introduction of Total Allowable Catches), 1977 (extension of Canadian economic management zone to 200 miles), 1992 (Canadian moratorium on domestic commercial catch in 2J+3KL). Data are derived from ICNAF (1959–1978) and NAFO (1978+) Statistical Bulletins and Anon 1981. Post-1989 data are considered provisional.

length ranges of cod in migrating aggregations declined from 45–57 cm in June 1990 to 42–48 cm in June 1992 (Bishop *et al.*, 1993; Rose, 1993). The average age in 1993, derived from research vessel (RV) survey data, was ~4 years and was bounded by a relatively narrow age distribution (Fig. 4).

Adult distributions

Abundance distributions of cod in the Newfoundland and Labrador region, derived from annual RV surveys in the early 1980s, can be considered "typical" (see Bishop *et al.*, 1993 for greater temporal detail) and show

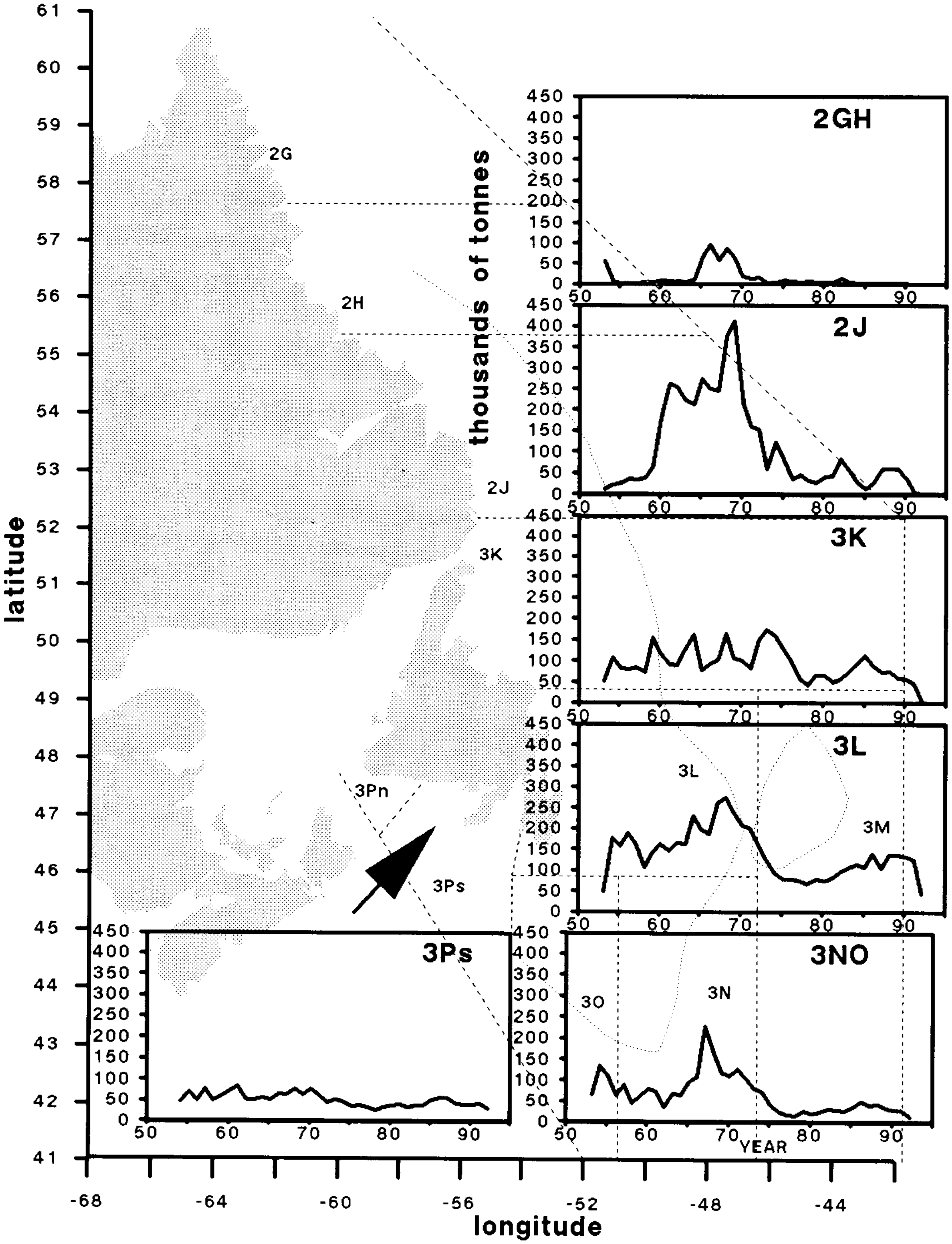

Figure 2. Total reported commercial landings (t) by all fleets and all gear (foreign and Canadian) of cod for the period 1953 to 1992 in the Newfoundland and Labrador region of the Northwest Atlantic by NAFO Division. Times series are overlaid on the Divisional chart (- - - -), which also shows the 1000 m isobath outlining the shelf break and the Flemish Cap (. . . . .). Data are from Anon. (1981), ICNAF (1959–1978) and NAFO (1978+) Statistical Bulletins. Post–1989 data are considered provisional.

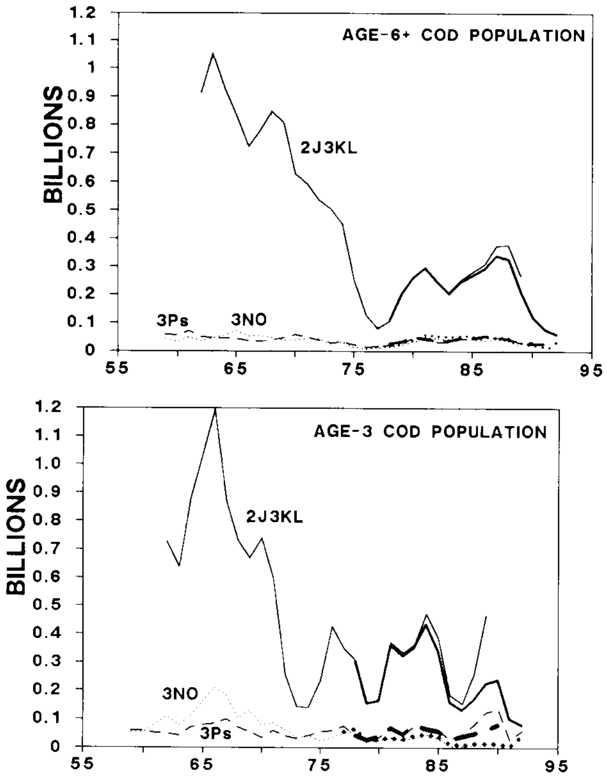

Figure 3. Population assessment estimates of age 6+ spawners and age-3 recruits for Newfoundland cod in NAFO Divisions 2J3KL, 3NO, and 3Ps for the period 1958 to 1993. Note the illustrations are offset by 3 years to align the age-3 estimates with the spawner population at year of birth. Fine-traced estimates are derived from the 1990 and 1991 sequential population estimates (after Baird *et al.*, 1990 and Bishop *et al.*, 1991) which included Canadian research vessel survey estimates, commercial catch rate information, and the French research survey data for 3Ps. Post-1977 estimates traced in bold are from 1993 sequential population estimates calculated using research vessel survey estimates only (after Bishop *et al.*, 1993).

frequent, widespread catches of age 5+ cod ranging from 10 to 100 per 1/2 h standard tow (Fig. 5). During the late 1980s and early 1990s catches became progressively more contagious, and relative to the earlier period high catches were more frequent in a southerly direction and were closer to the offshore shelf break. This progression culminated in 1992 with severely reduced survey catch rates in the majority of sets (≪10 per 1/2 h tow) throughout the region, except for one large aggregation along the shelf break at the border between 3K and 3L and two smaller aggregations near the shelf break in Subdivision 3Ps (Fig. 6). An examination of some of these distributional changes and associated variations in water temperature is provided in Rose *et al.* (1994).

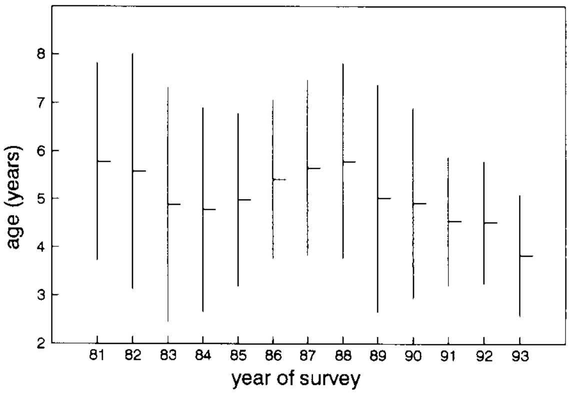

Figure 4. The average age (years ± 1 s.d.) of cod in NAFO Divisions 2J+3KL for the period 1981 to 1993 calculated from autumn research vessel survey catch data weighted by survey stratum area.

Juvenile distributions.

Investigations of the distributions of demersal juvenile cod during the period 1981 to 1992 (Anderson, 1993) show that age 1+ juveniles are concentrated primarily along the coastal regions of northern Newfoundland and Labrador and further offshore on the Grand Banks (Fig. 7). This pattern is, in part, consistent with distributions of 0-group pelagic juveniles, at least for the years 1991 and 1992, when the 0-group was primarily concentrated in the inshore regions (Anderson and Dalley, 1993). The nearshore concentrations appear to be a recent pattern and not consistent with historical observations which show 0-group pelagic juveniles widely distributed over the shelf region (Anderson *et al.*, in press). Nevertheless, with increasing age, juveniles during the period 1981 to 1992 were found progressively further offshore on the shelf (Fig. 7), a pattern strikingly similar to that seen for the older age groups during the 1980s (Fig. 5) and consistent with the observation that by age 4 the juveniles are beginning to adopt the distributional and migratory behaviour of the mature age classes (Rose, 1993).

Spawning, egg, and larval distributions

Myers *et al.* (1993b) have concluded that cod spawning throughout the 2GHJ and 3KL Divisions is protracted (3–4 months); generally beginning and ending earlier in the north (Jan–Jun) and later and more protracted (Feb–Sep) in the south. Spawning in the more southerly Divisions of 3NO and 3Ps reaches its maximum in Apr–May and there is no significant latitudinal trend in the average spawning time (Myers *et al.*, 1993b).

Historically, cod eggs and early stage larvae in the

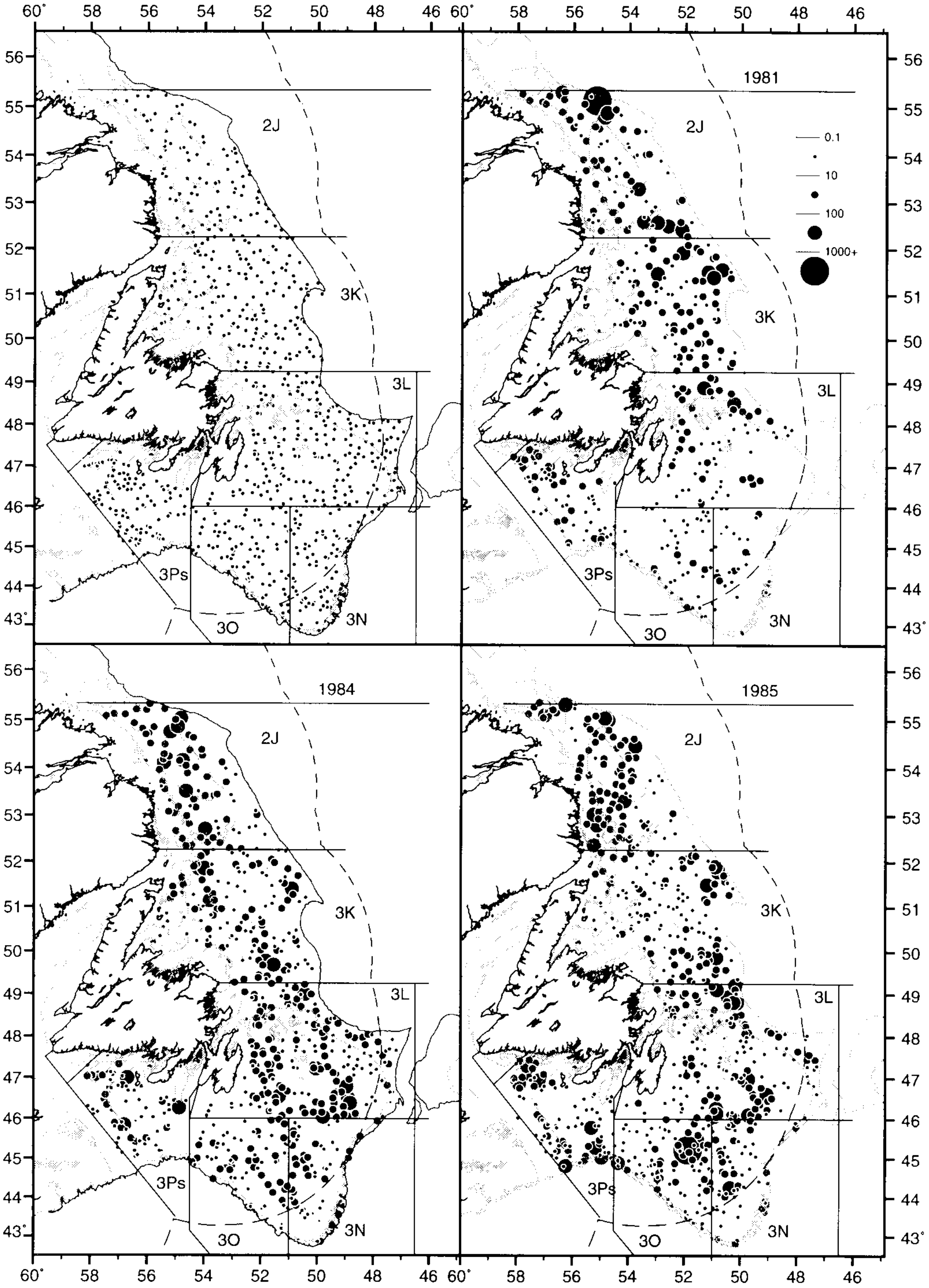

Figure 5. Research survey $\log_{10}$-scaled abundance (number per 1/2 h tow) distributions of age-5+ cod in NAFO Divisions 2J+3KL (Sep. to Nov. of year), Subdivision 3Ps (Feb. of year+1), and 3NO (April of year+1) during the period 1982 to 1984 (after Bishop *et al.*, 1993). Note: only non-zero catches are plotted. Set concentration for a typical annual survey is illustrated in the upper left panel.

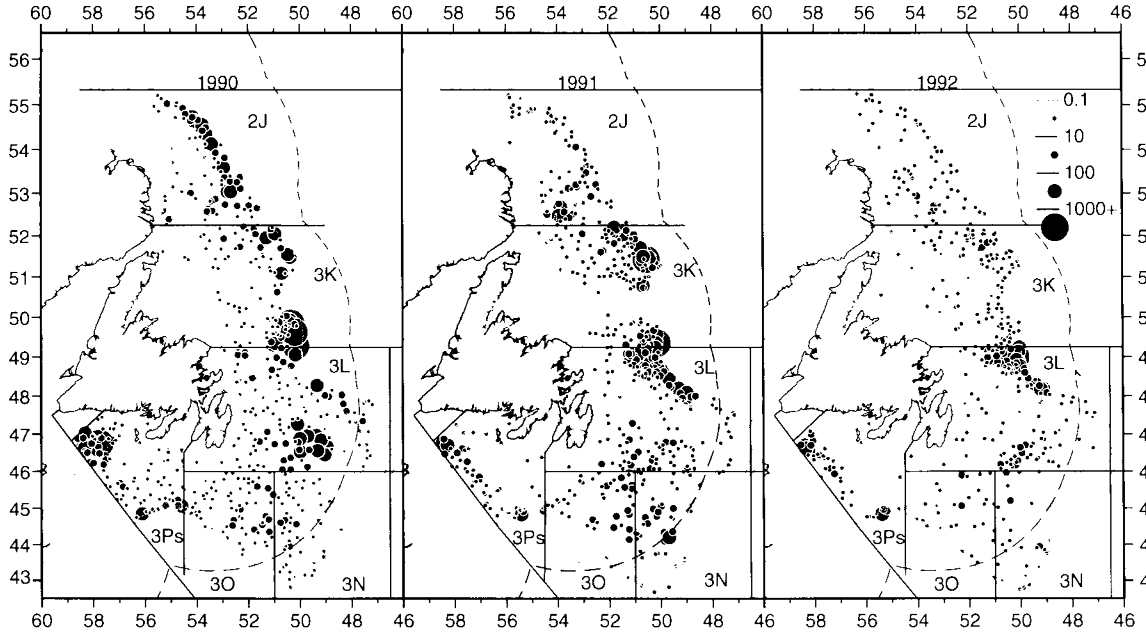

Figure 6. Research survey log$_{10}$-scaled abundance (number per 1/2 h tow) distributions of age-5+ cod in NAFO Divisions 2J+3KLNO (Sep. to Nov. of year) and Division 3Ps (Feb. of year+1) during the period 1990 to 1992 (after Bishop *et al.*, 1993). Note: only non-zero catches are plotted. Set concentration for a typical annual survey is illustrated in the upper left panel of Figure 5.

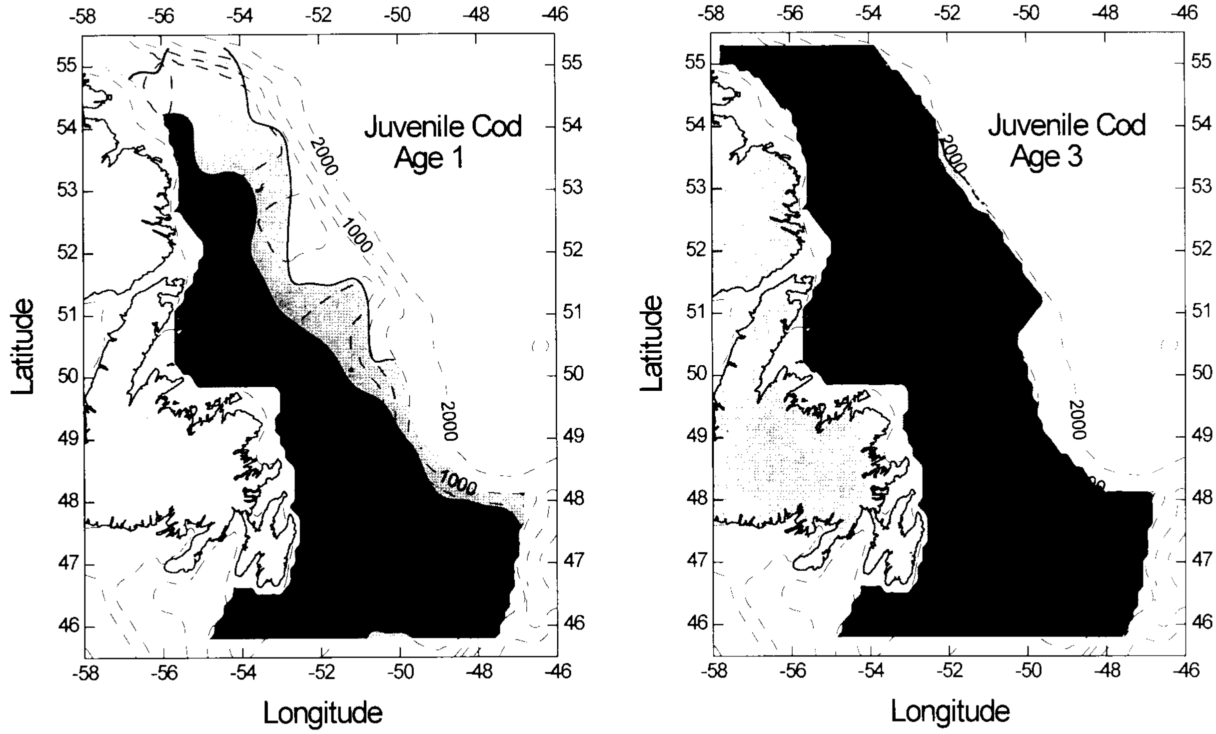

Figure 7. Catch probability isopleths of Age 1 and Age 3 demersal cod from juvenile cod research surveys over the shaded region during the period 1981 to 1992. For Age 1 the grey scale grades from <0.2 to >0.2<0.3 and to >0.3. For Age 3 the grey scale grades from <0.3 to >0.3<0.5 to >0.5<0.7 and to >0.7. After Anderson (1993).

offshore have been concentrated on and along the shelf break of the Labrador Shelf and Grand Banks, particularly in the more northern regions (Serebryakov 1965, 1968). Data compiled by Fitzpatrick and Miller (1979) suggested spawning was concentrated along the shelf break of Hamilton, Belle Isle and Funk Island Banks in 2J+3K, the southern shelf break of the Flemish Cap (3M), the southwest and southeast shelf break of the Grand Banks (3NO), and the shelf break of St Pierre Bank in Division 3Ps (Fig. 8). However, recent analysis by Hutchings *et al.* (1993) of cod maturity data collected during the period 1946–1992 suggest that spawning may be more prevalent in inshore regions, along western (landward) edges of offshore banks, as well as the interior of the Grand Bank (Fig. 8), spawning on the shelf, in northern Division 3L, has been documented in 1991 and 1992 (Rose, 1993).

Stock health

Body condition indices

The overall average body condition index (Kf = gutted weight × length^{-3}) of age 3 to 11 cod in Divisions 2J+3KL during the period 1979 to 1992 is 0.77, and older individuals (age 9+) are generally in better than average condition relative to the younger age classes (Fig. 9). However, the youngest age group (ages 3–5) in (3L) is often at or below average condition, whereas the same age group in the more northerly (2J) region is generally above average, except most recently (Fig. 9). It is apparent from these data that the average condition in all age groups in 2J and 3K has been decreasing since 1988 (see also Bishop and Baird, 1993).

It is possible that the body condition index (Fig. 9) may be size-dependent, as shown by general increases in condition with age (and therefore generally with length) in all three divisions. Thus, we calculated the liver condition index (Kl = liver weight × gutted weight^{-1}) for four different length groups (27–35, 45–53, 63–71, and 90–98 cm) of 2J+3KL cod as opposed to the age groups. Some aspects of the patterns observed in Kf among Divisions and age groups are generally reflected in the liver condition index (Fig. 10). The overall age Kl for the period 1979 to 1992 for the length groups considered is 0.066 and the larger length classes are generally in better condition than the smaller length classes. As seen in the Kf condition index, the larger length classes in the more northerly Divisions (2J+3K) are in above average condition, except in the most recent years in Division 2J, where a decreasing trend, starting in 1989, is apparent. Although similar short-term trends were apparent in previous years, the recent trend in 2J is toward record low levels. In contrast, the three smallest length classes in the most southerly region (3L) have been consistently below the overall average Kl, except subsequent to 1988, when the Kl's show monotonic increases that appear to be approaching record high levels in all the length classes considered (Fig. 10).

Three different processes may explain the observed variation in condition indices. The first, and perhaps simplist, is that generally "good" condition cod have moved from more northerly regions (2J) to more southerly regions (3L), thereby influencing the apparent recent increases in condition in 3L. This explanation is consistent with the observed changes in the survey-based distribution of cod seen in the most recent years (Fig. 6). However, if this was the only process, a similar change would be expected in the condition of 3K fish and this is not readily apparent.

A second possible explanation is that both conditional indices (Kf and Kl), each derived from seasonally fixed annual survey samples, have recently become progressively aliased with respect to normal seasonal cycles in cod physiology that are dependent on temperature and feeding success. Jangaard *et al.* (1967) have shown that the oil content (and a variety of lipid constituents) in cod livers on the Scotian Shelf has a pronounced seasonal cycle that peaks in late autumn and early winter following seasonal increases in temperature and feeding. This seasonal cycling is consistent with that shown for liver weights in Norwegian cod (Eliassen and Vahl, 1982). Condition indices compiled from several years of data for Division 3L on the Grand Bank show that Kl cycles around the overall average Kl of 0.066 estimated above (Fig. 11). Because temperature patterns, expressed as physiological degree-days, have become progressively shifted in recent years in the Newfoundland region, particularly in northward regions where anomalously cold environmental conditions exist (see below), it is reasonable to hypothesize that the normal physiological cycle, as expressed in condition factors, has shifted. Thus a time series of annual estimates can result in apparent anomalous trends, because the sampling for the indices has not been adjusted for the physiological shift. The potential for this effect may be further compounded by the fact that survey data for condition indices are collected at different times (spread over 1 to 3 months) among the different regions during the Autumn survey period.

A third explanation for the variation in condition factors may be found in feeding performance as estimated from partial fullness (capelin and other prey) indices for cod (Fig. 12). Although the data have not been standardized for sampling effort (see Lilly, 1993, 1994), it is apparent that in the most recent years (1991 and 1992) capelin have been virtually absent from the stomachs of cod collected in Division 2J, consistent with the recent declines in Kf and Kl. These findings are also consistent with the virtual absence of capelin in Division

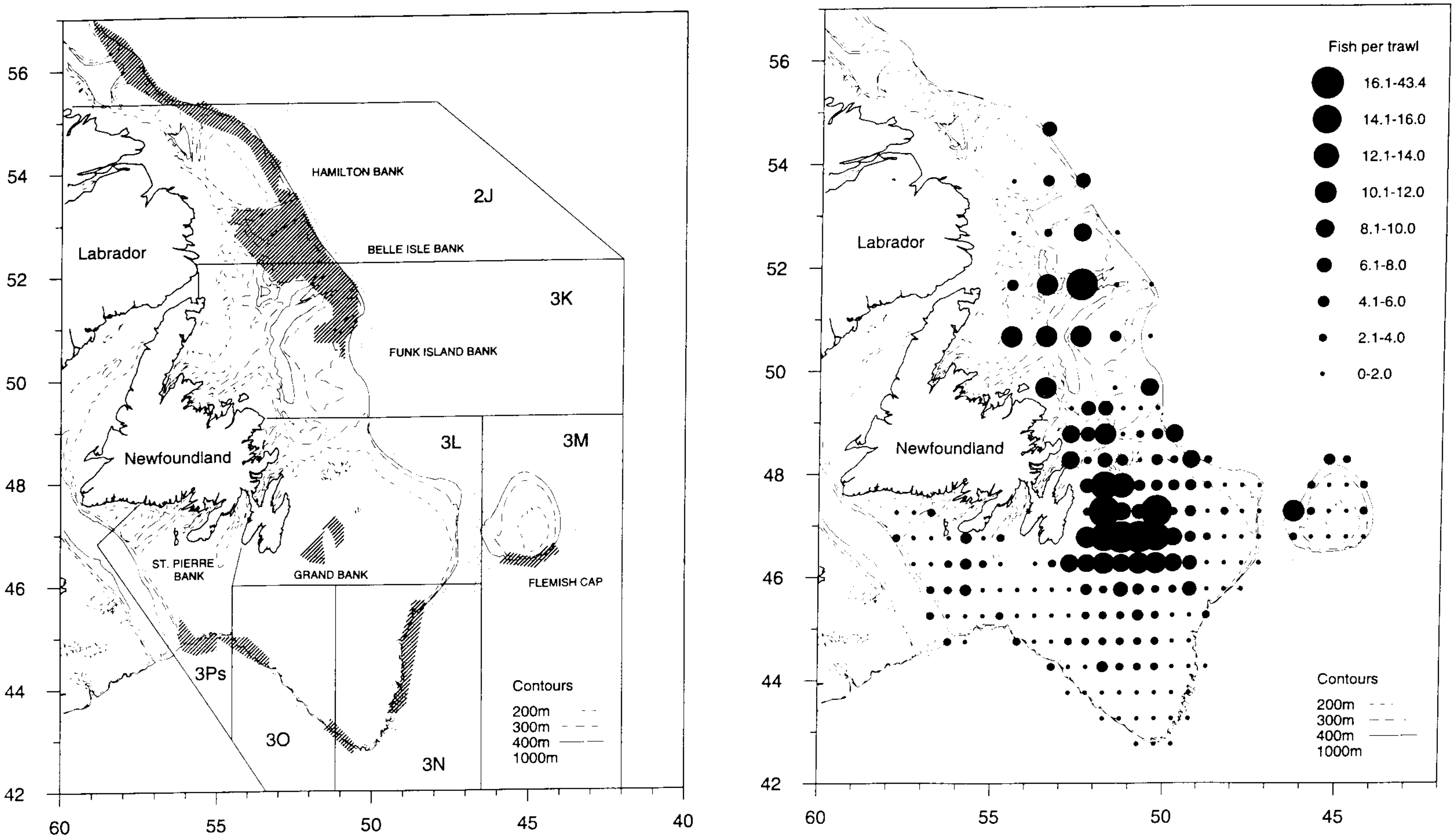

Figure 8. Distributions of cod spawning areas in the Newfoundland region based on spawning maturity data compiled by Fitzpatrick and Miller (1979) as shown by hatching in the left panel, and as compiled by Hutchings *et al.* (1993) as shown by numbers of fish per trawl in spawning condition in the right panel. After Hutchings *et al.* (1993).

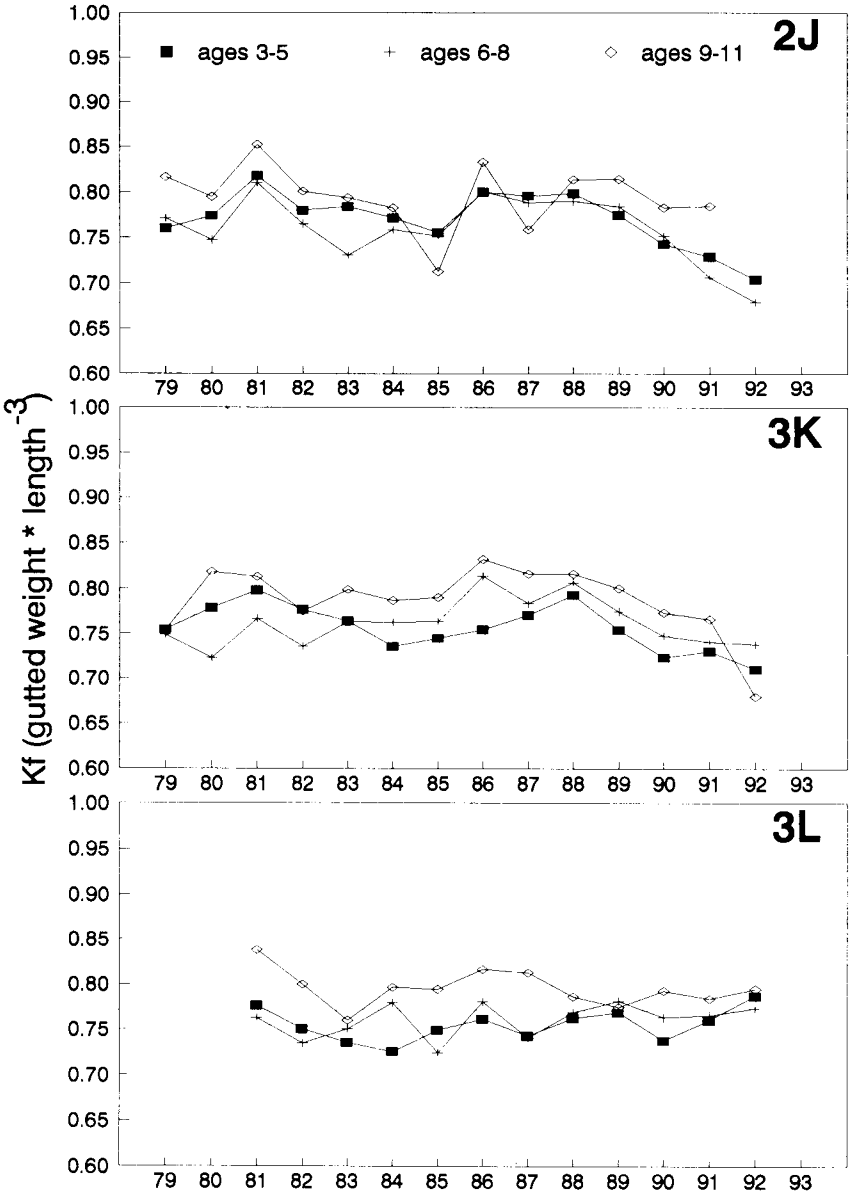

Figure 9. Average body condition indices (Kf = gutted weight × length^{-3}) for cod in NAFO Divisions 2J, 3K, and 3L averaged over three different age groups (3–5, 6–8, 9–11) sampled during autumn research surveys over the period 1979 to 1992. The dotted line at 0.77 reflects the overall (all ages, all Divisions, all times) average condition. Data from Bishop and Baird (1993).

2J in recent years, at least during the autumn capelin research surveys (Miller and Lilly, 1991; Miller, 1993). In contrast, stomach fullness indices for cod in Division 3L in 1990 through 1992 are the highest on record and show a greater proportion of capelin than for any previous estimate (Fig. 12), a pattern that is also consistent with the apparent recent increases in Kl in Division 3L. Finally, fullness indices for Division 3K have been consistently at or above average since 1986, a pattern that is not reflected in the Kf and Kl estimates. However, it is unclear at this time how the changing geographic distributions of cod and their prey through time may be influencing the fullness indices (see Lilly, 1994).

Length and age of maturity

Lengths at 50% maturity in both female and male cod throughout Divisions 2J+3KL have been trending

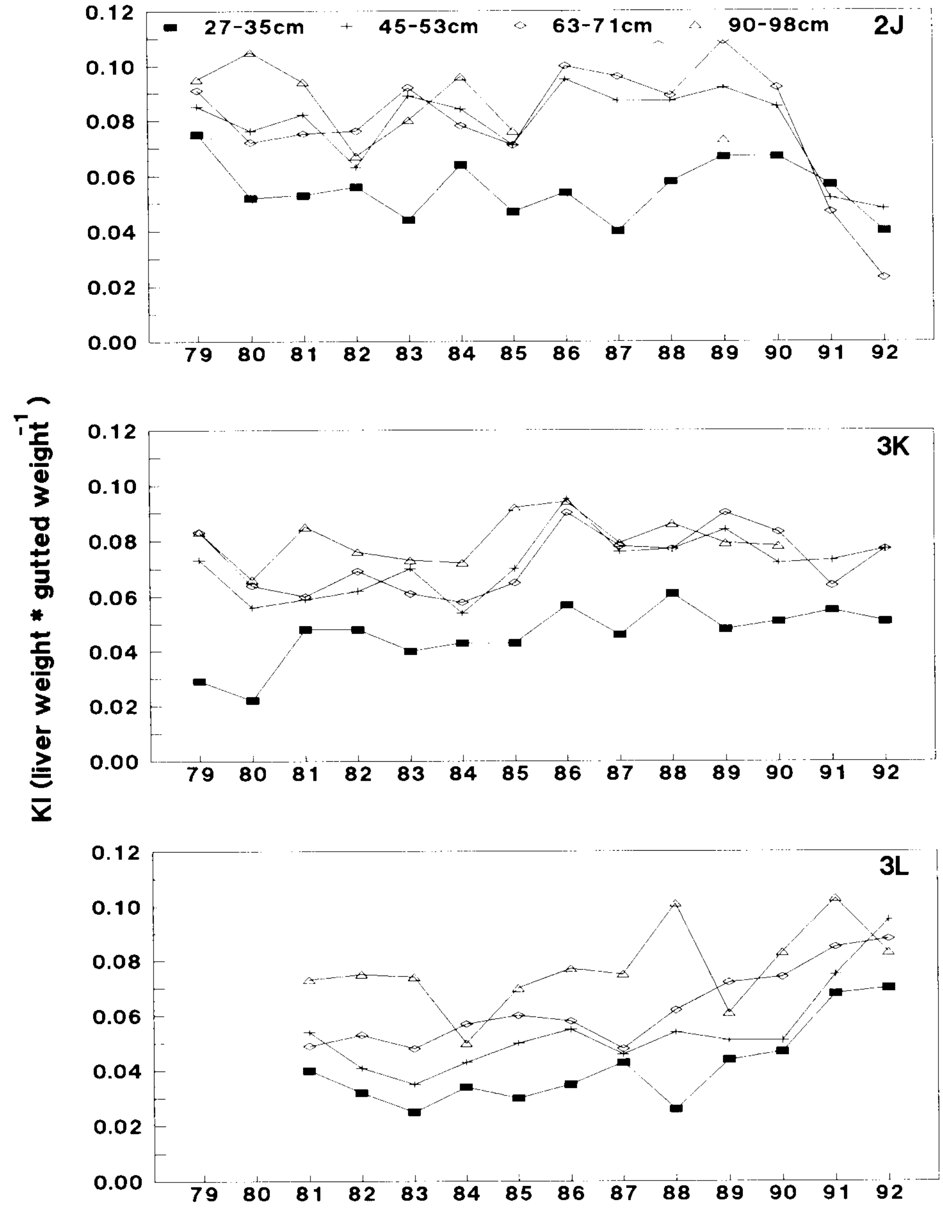

Figure 10. Average liver condition indices (KI = liver weight × gutted weight $^{-1}$) for cod in NAFO Divisions 2J, 3K, and 3L averaged over four different length groups (27–35 cm, 45–53 cm, 63–71 cm, and 90–98 cm) sampled during autumn research surveys over the period 1979 to 1992. The dotted line at 0.066 reflects the overall average KI for the length groups (all Divisions, all times).

downward since the early 1980s (Fig. 13a, b). The declining trend is most pronounced and least variable in 2J fish (slowest growing), while more variable and less pronounced in the more southerly and faster growing 3L fish. The overall declines calculated from the combined ogives amount to ~ 10 cm in the females (Fig. 13a) and ~8.5 cm in the males (Fig. 13b). Decreases in length at maturity are consistent with size selective exploitation. Changes in the average age at 50% maturity of female and male cod from the same Divisions over the same period (Fig. 13c) did not show a downward trend until the late 1980s; females and males are now showing the youngest ages at 50% maturity (age 5.4 and age 4 respectively) in the 1979 to 1993 record. Model-based

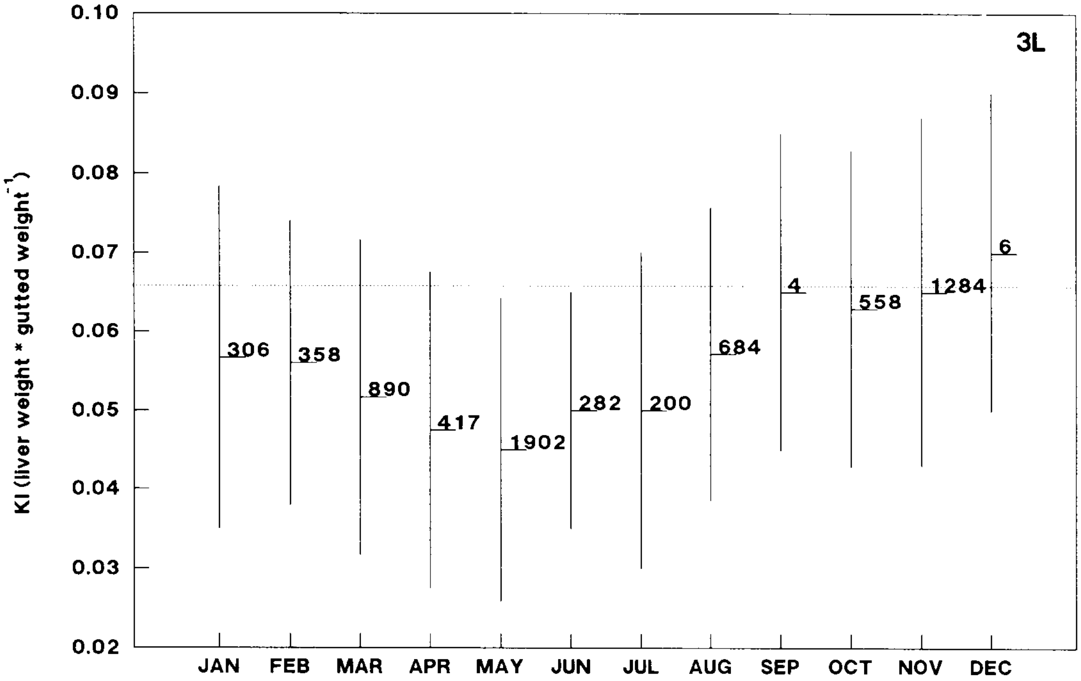

Figure 11. The seasonal cycle in the average (±1 s.d.) of annual monthly averages (when available) of the cod liver condition index (KI = liver weight × gutted weight $^{-1}$) for NAFO Division 3L compiled for the period 1978–1992. The sample size for each monthly average is highly variable and is noted beside each. Note: not all years are represented for all months. The dotted line at 0.066 reflects the overall average KI for the Divisional length groups shown in Figure 10.

estimates of maturity at age also show a trend in increasing proportions mature for cod aged 5, 6, and 7 years since 1986 (Shelton and Morgan, 1993a, b, in press).

Fishing mortality and spawner biomass replacement

Fishing mortality estimates (F) for cod in Divisions 2J+3KL examined recently by Shelton and Morgan (1993a, b, in press), derived from SPA estimates in Bishop *et al.* (1993), were consistently >0.35 in the mid-1970s, at times exceeding 1.0 in the older (9–11) age classes (Fig. 14a). High Fs occurred during the precipitous decline in landings (Figs. 1, 2), and in estimates of the size of the spawner population and age 3 recruitment (Fig. 3). During the 1977 to 1980 period, following the extension of Canada's economic management zone to 200 miles in 1977 (see Fig. 1), there was a reduction in F to below 0.4 in all age classes (Fig. 14a). This period of reduced exploitation was paralleled by increases in the size of the spawner population and subsequent recruitment from 1978 to 1982 (Fig. 3). However, from 1980 to 1991 (after which severe catch restrictions and fishing closures began) there was a consistent increasing trend in fishing mortality (Fig. 14a) with a particularly marked increase during the final stage of the precipitous decline in landings (Figs. 1, 2). It must be noted that the SPA population and fishing mortality estimates are derived under the assumption of a fixed natural mortality. Nevertheless, despite the reduced F estimates in the late 1970s and early 1980s (Fig. 14a), landings in 2J showed a limited increase to a recent (post-1977) maximum in 1984 (Fig. 2). Increased landings were more pronounced in 3K to a recent maximum in 1985, and in 3L to recent maxima in 1985 and 1988 (Fig. 2). Increased landings were associated with increasing fishing mortalities after 1980 (see also Hutchings and Myers, in press).

The combined effects of fishing mortality on the spawning population size of northern cod, and the resulting reduction in length and age structure of the populations, has reduced the fecundity contributions of the older (larger, more fecund) individuals and can have a dramatic influence on recruitment (Hutchings and Myers, 1993). Changes in weights and proportions mature at age have acted in concert with changes in fishing mortality to influence the amount of recruitment required to replace the spawner stock (Shelton and Morgan, 1993a, b, in press). Calculations of recruitment per spawner show that annual values were below replacement levels in the mid-1970s, rose briefly above replace-

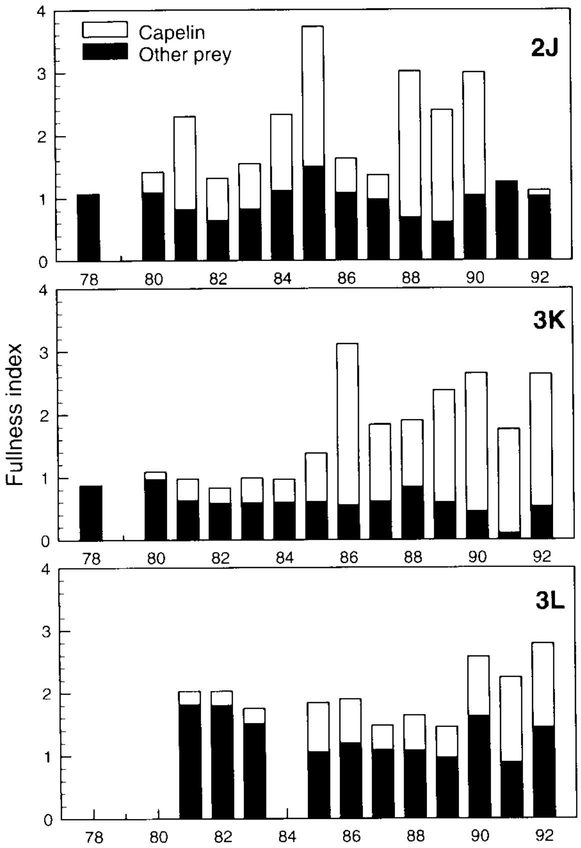

Figure 12. Average fullness index for cod stomachs partitioned into capelin and "other" prey species sampled during Autumn over the period 1978 to 1992 in NAFO Divisions 2J, 3K, and 3L. Zero (baseline) indices indicate no data available. From Lilly (1993, 1994).

ment levels in the late-1970s and early 1980s, and remained below replacement levels from 1983 onward (Fig. 14b), paralleling the stock decline. Even when the effect of fishing mortality is removed from the calculations of replacement, the combined effect of changes in weights and proportions mature at age cause the level of recruitment required to meet spawner biomass replacement to increase steadily from 1980 onward (Fig. 14b). Values of recruit per spawner for the apparently poor year classes of 1988 and 1989 (see Fig. 3) were very close to the replacement level, i.e., the level of recruitment below which the population can go extinct even in the absence of fishing. Thus, despite the apparent increased size of the spawner population in 1987 (Fig. 3), the required replacement recruitment remained high, recruitment per spawner has remained low and parallels recent and continuing declines in length and age of maturity and some indices of condition.

Recruitment and the environment

Recruitment in northern cod has been at, or near, record minima subsequent to the formation of the 1982 year class (age 3 in 1985, Fig. 3). Although the size of the spawning stock plays a role in determining recruitment (Myers *et al.*, 1993a), recruitment appears to have been negatively influenced by extreme environmental conditions (anomalously cold) since 1983, with a brief respite in 1986 and 1987, as indicated by a variety of strongly correlated oceanic and atmospheric indices (Fig. 15 and see Colbourne *et al.*, 1994). Of the 36 correlations possible among 9 different environmental variables, including various measures of the wind and pressure fields (Fig. 15), ice conditions, water temperatures throughout the water column, and the volume and extent of the cold intermediate layer overlying the Newfoundland and Labrador shelf regions (Fig. 15), a full 28 (78%) are each independently significant at $\alpha = 0.05$ (Table 1). Correction for the simultaneous correlations requires $p < 0.0013$ and thus 44% remain significant. The Labrador air temperature and the Winter–Spring ice-extent anomalies are significantly correlated with most of the other indices (Table 1) and perhaps represent the best measures of the overall environmental conditions in the Newfoundland and Labrador region. It was only during 1986 and 1987 that there was a marginal increase in recruitment of northern cod (Fig. 3), similar to the increases seen in the period 1978 to 1982 when environmental conditions were also warmer than average (Fig. 15). Thus it appears that recruitment variability in the recent past is determined, in part, by environmental conditions. The persistence of the extremely cold conditions suggests that future recruitment, at least for northern cod, will not reach the levels estimated in the 1960s (Fig. 3b), particularly given the limited size of the spawner population.

Recruitment levels in northern cod may also be determined by the distributional pattern of the spawners (at least offshore) and ocean climate variations. For example, deYoung and Rose (1993) have hypothesized that northerly distributions of spawners are necessary for relatively high recruitment levels, and will likely occur during relatively warm periods (see Rose *et al.*, 1994). However, the relationship between water temperature and recruitment is unclear (see deYoung and Rose (1993) and Hutchings and Myers (in press)), and although Helbig *et al.* (1992) have suggested that other factors, such as storm tracks, may have a significant impact on egg and larval drift and subsequent settlement distributions and recruitment, these same authors conclude that no convincing relationship has been demonstrated between recruitment in northern cod and the available climatic indices.

Of the various environmental indices available, early

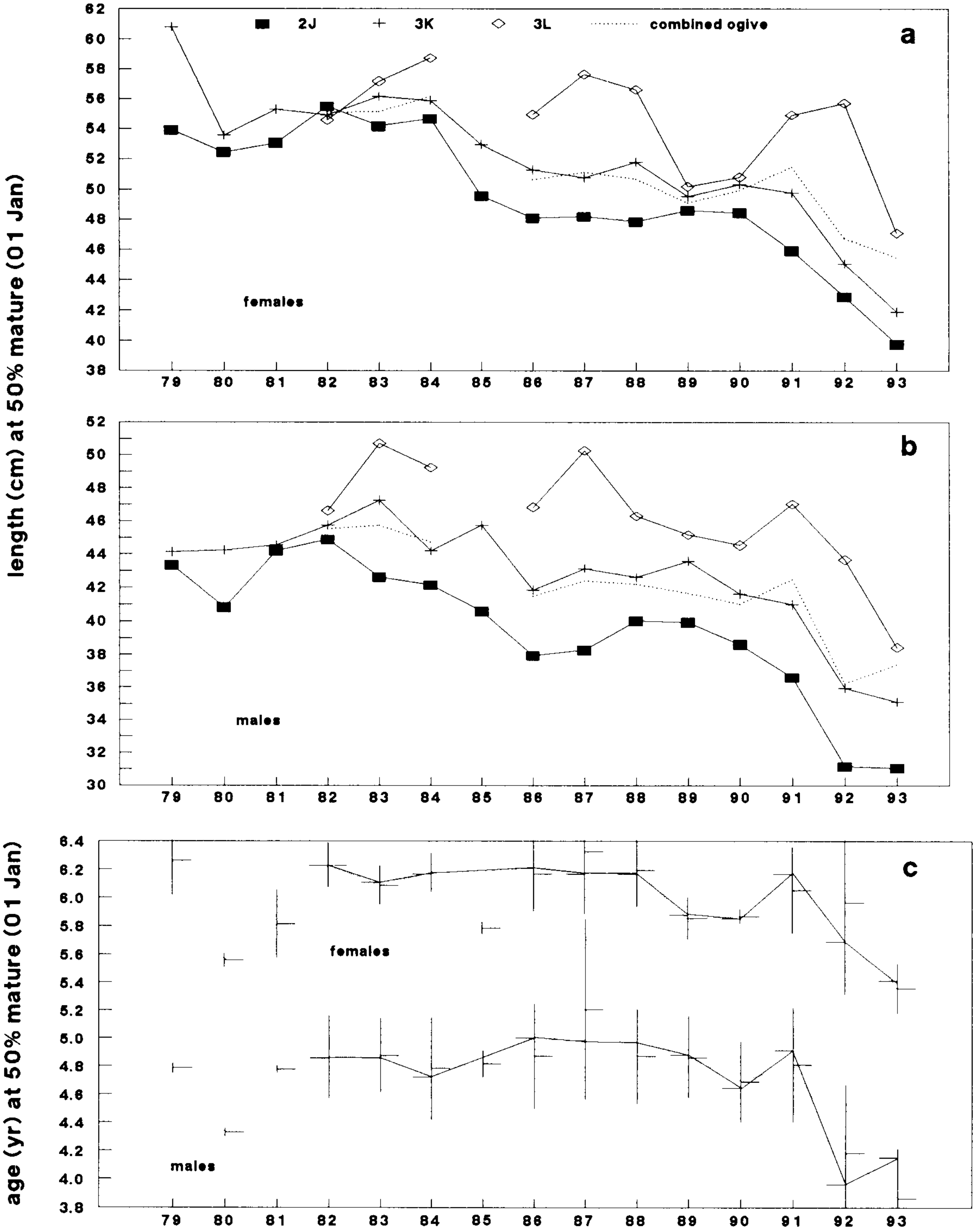

Figure 13. Average length (cm) at 50% mature estimates for cod females (a) and males (b) in NAFO Divisions 2J, 3K, and 3L, and (c) average age (years ± 1 s.d.) at 50% mature for females and males combined for all three Divisions during the period 1979 to 1993. Estimates of the combined ogives are shown with the dotted line. Data from Morgan *et al.* (1993).

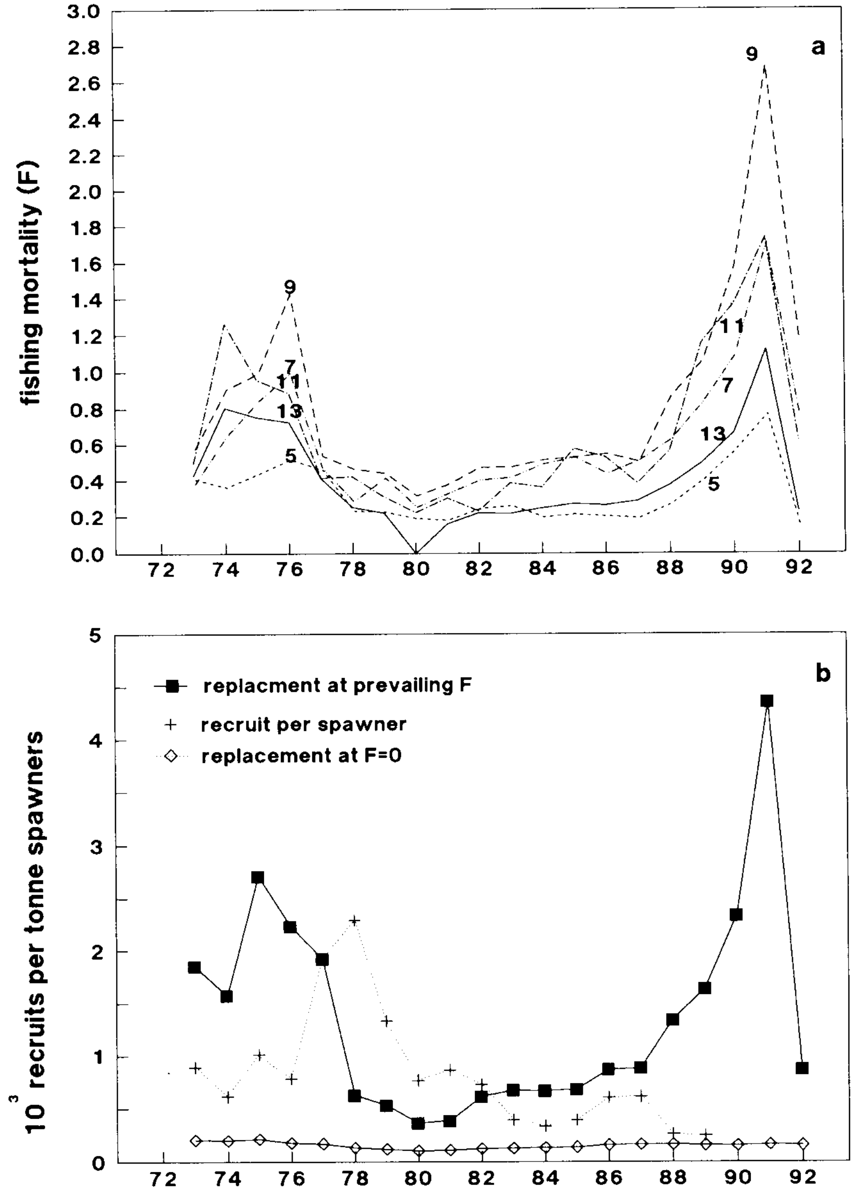

Figure 14. (a) Estimates of fishing mortality (F) for ages 5, 7, 9, and 13 in NAFO Divisions 2J+3KL for the period 1972 to 1992, and (b) annual values of recruitment (10^3 individual) per spawner (t) and spawner biomass replacement levels calculated at the prevailing fishing mortality (F) and at F = 0 over the period 1972 to 1992. After Shelton and Morgan (1993a,b, in press), and data from Bishop *et al.* (1993).

work by Sutcliffe *et al.* (1983) showed that variations in northern cod recruitment could be explained by variations in depth-averaged (0–50 m), summer salinity measurements at Station 27 in Division 3L. A recent examination of the salinity–recruitment relationship by Myers *et al.* (1993a) has generally confirmed those initial findings and shows that the salinity variations can reproduce recruitment fluctuations during the period 1962 to 1988, although the mechanism(s) accounting for the modelled relationship remains elusive. Although the salinity-based model was able to capture the fluctuations in recruitment variations, it was unable to capture the long-term trend from high recruitment (and high-spawning biomass) in the 1960s to low recruitment (and low-spawning biomass) in the 1970s and 1980s. With the addition of spawning-stock biomass estimates to the

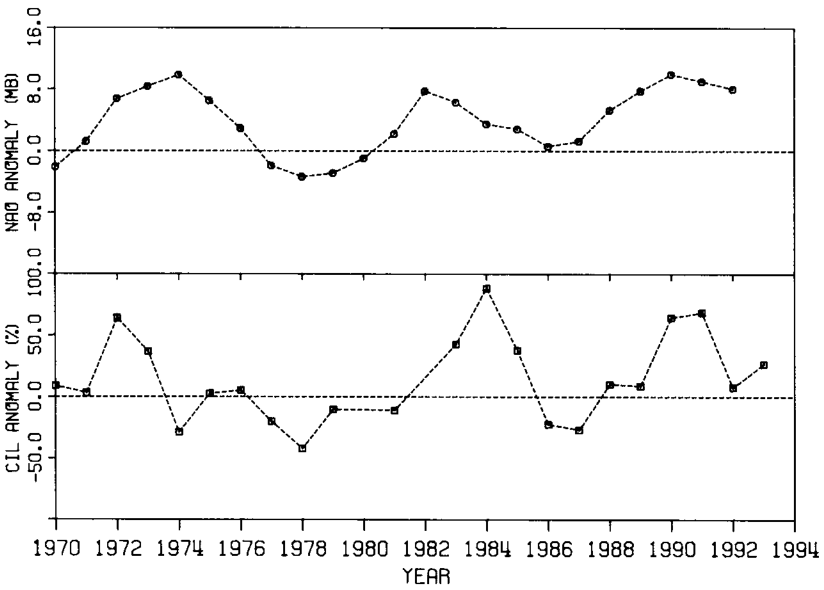

Figure 15. Time series of atmospheric pressure differentials using the annual North Atlantic Oscillation (NOA) anomaly index (positive values infer poor environmental conditions), and the percentage difference from the average cross-sectional area of water <0.0°C in the cold intermediate layer (CIL) of the Newfoundland Shelf (NAFO Divisions 3K+3L). After Colbourne *et al.* (1994).

Table 1. Correlation matrix of coefficients of determination and significance values for annual estimates of oceanic and atmospheric variables (1970 to 1993) in the Northwest Atlantic region of Newfoundland. CIL ( ) refers to the cross-sectional area of the −1, 0, and 1 degree isotherms of the cold intermediate layer in summer on the continental shelf; NAO ANOM is the North Atlantic oscillation (pressure differential) annomaly relative to the 1951–1980 average; CIL(MIN) CORE-T is the minimum summer core temperature of the cold intermediate layer; NW WIND FREQ is the frequency of winter NW winds measured in Labrador; AIR-T ANOM is the Labrador air temperature anomaly referenced to the 1960 to 1985 average; SELF ICE ANOM is the winter and spring areal ice cover relatived to a 25-year average; and STN-27 BT is the bottom temperature anomaly at Station 27 referenced to the 1946–1993 average. Shaded values are significant at a = 0.05. See Colbourne *et al.* (1994) for greater detail.

	CIL(0) AREA SUMMER	CIL(−1) AREA SUMMER	CIL(1) AREA SUMMER	NAO ANOM 51−80	CIL(MIN) CORE−T SUMMER	NW WIND FREQ LAB.	AIR−T ANOM LAB.	SHELF ICE ANOM NFLD
CIL(−1) AREA	0.884 0.000							
CIL(1) AREA	0.965 0.000	0.787 0.000						
NAO ANOM	0.515 0.017	0.538 0.012	0.411 0.064					
CIL(MIN) CORE−T	−0.582 0.005	−0.680 0.001	−0.515 0.014	−0.332 0.142				
NW WIND FREQ	0.263 0.263	0.311 0.183	0.192 0.418	0.746 0.000	−0.253 0.281			
AIR−T ANOM	−0.647 0.003	−0.628 0.004	−0.564 0.012	−0.847 0.000	0.571 0.011	−0.784 0.000		
NFLD ICE ANOM	0.780 0.000	0.743 0.000	0.764 0.000	0.720 0.000	−0.716 0.001	0.528 0.017	−0.852 0.000	
STN−27 BT	−0.438 0.042	−0.520 0.013	−0.409 0.059	−0.662 0.001	0.235 0.292	−0.492 0.020	0.699 0.000	−0.851 0.000

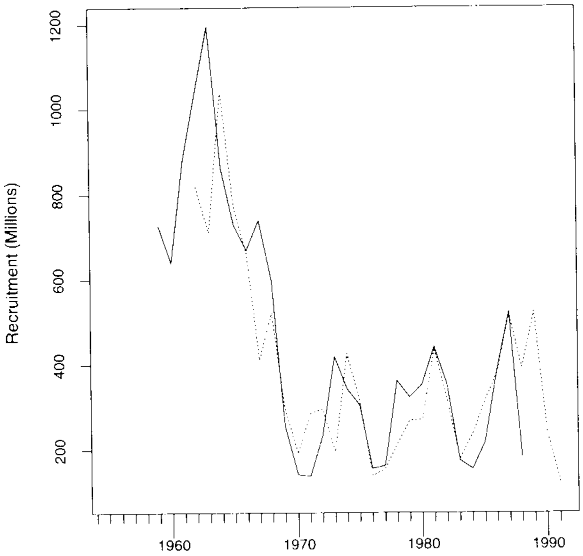

Figure 16. Time series of survey-based estimates of recruitment (solid line) and modelled recruitment (dotted line) using annual 0–50 m summer salinity averages at Station 27 (NAFO Division 3L) and annual survey-based spawning stock biomass estimates. After Myers *et al.* (1993a).

model (Myers *et al.*, 1993a), the long-term trend and short-term fluctuations in northern cod could be reproduced (Fig. 16), reflecting both the stock size and environmental influences on recruitment. Model predictions indicate recruitment will be at a record low in 1991, simply reaffirming the quotation in our introduction that "recovery of the spawning stock biomass is unlikely before the year 2000 at the earliest" (Anon., 1993, p.16).

Conclusions

It is apparent from the variety of information presented that intense fishing, particularly on northern cod in Divisions 2J+3KL in the 1960s reduced the Newfoundland stocks to a point where long-term average recruitment was reduced by ~50%, partly in response to decline spawning stock size, but also as expressed through the equally precipitous decrease in the fecundity contribution by older age groups as the size and age structure was compressed.

Although the estimated spawner biomass increased in the late 1970s, changes in weights and proportions mature at age, together with increasing fishing mortality, imply that from the early 1980s onward an ever-increasing amount of recruitment per spawner was required to exceed replacement and permit population growth. In addition, poor environmental conditions have apparently had an additive effect in further limiting potential recruitment.

Persistence of poor environmental conditions into the 1990s will likely continue to influence the distribution and physiological conditions of adults. This may have further negative effects on fecundity and recruitment. However, the Canadian moratorium on cod fishing should help to protect the remaining stock. Continuance of a poor environment may also limit recruitment, even if the most recent recruitment serves to increase the spawner population. The above suggests that a series of better than average environmental years is needed if the chances for a series of good recruitment years rebuilding the stock size and length/age structure are to be increased. The long-term record suggests that this may only occur: (1) if fishing pressure remains at or near zero; (2) if the size of the spawner population increases significantly (at least to some level exceeding that of 1987); (3) if the lengths at 50% maturity rebound to the early 1980 levels; and (4) if the current, offshore distributional patterns of the adults changes to resemble the distributions seen in the 1980s.

Acknowledgments

We thank our colleagues at the Northwest Atlantic Fisheries Center (NWAFC), at the Bedford Institute of Oceanography, and at the 1993 ICES Cod and Climate Change Symposium in Reykjavík for their support, discussions, and criticisms, and equally so to a great number of technical and office support staff at NWAFC who contributed their efforts in compiling the information presented here. We also thank J. Carscadden and an anonymous reviewer for their critical insights, which led to an improved manuscript. The Canada Department of Fisheries and Oceans Northern Cod Science Programme provided a large proportion of the research funding to support the suite of initiatives reviewed in this paper.

References

Alverson, D. L. (Chair). 1987. A study of trends of cod stocks off Newfoundland and factors influencing their abundance and availability to the inshore fishery. Report of the Task Group on Newfoundland Inshore Fisheries. 101 pp. +appendices.

Anderson, J. T. 1993. Distributions of juvenile cod in NAFO Divisions 2J3KL during fall, 1981–1992, in relation to bathymetry and bottom temperatures. NAFO SCR Doc., 93/68. Ser. No. N2252. 18 pp.

Anderson, J. T., and Dalley, E. 1993. Inshore/offshore distributions and abundance of pelagic 0-group cod in NAFO Divisions 3K and 3L in Fall of 1991 and 1992. NAFO SCR Doc., 93/32. Ser. No. N2212. 12 pp.

Anderson, J. T., Dalley, E. L., and Carscadden, J. E. (in press). Pelagic 0-group cod in Newfoundland waters: inshore vs offshore. Can. J. Fish. aquat. Sci.

Anon. 1981. The place of northern cod in Newfoundland's development. Prepared for the Government of Newfoundland and Labrador by the Newfoundland Oceans Research and Development Corporation (NORDCO). Jefferson Printing Ltd. St John's, NF. 211 pp.

Anon. 1993. Report on the status of groundfish stocks in the Canadian Northwest Atlantic. Fisheries Resource Conservation Council. Canada. Working Copy, July 1993. 128 pp.

Baird, J. W., Bishop C. A., and Brodie, W. P. 1990. The assessment of the cod stock in NAFO Divisions 2J, 3K and 3L. CAFSAC Res. Doc., 90/18. 89 pp.

Bishop, C. A., and Baird, J. W. 1993. Spatial and temporal variability in condition factors of 2J3KL cod. NAFO SCR Doc., 93/56. Ser. No. N2239. 15 pp.

Bishop, C. A., Baird, J. W., and Murphy, E. F. 1991. An assessment of the cod stock in NAFO Subdivision 3Ps. CAFSAC Res. Doc., 91/36.

Bishop, C. A., Murphy, E. F., Davis, M. B., Baird, J. W., and Rose, G. A. 1993. An assessment of the cod stock in NAFO Divisions 2J+3KL. NAFO SCR Doc., 93/86. Ser. No. N2271. 51 pp.

Colbourne, E., Narayanan, S., and Prinsenberg, S. 1994. Climatic changes and environmental conditions in the Northwest Atlantic, 1970–1993. ICES mar. Sci. Symp., 198: 311–322.

deYoung, B., and Rose, G. A. 1993. On recruitment and distribution of Atlantic cod (*Gadus morhua*) off Newfoundland. Can. J. Fish. aquat. Sci., 50: 2729–2741.

Eliassen, J-E., and Vahl, O. 1982. Seasonal variations in biochemical composition and energy content of liver, gonad, and muscle of mature and immature cod, *Gadus morhua* (L.) from Balsfjorden, northern Norway. J. Fish Biol., 20: 707–716.

Fitzpatrick, C., and Miller, R. J. 1979. Review of spawning times and location for some commercial fin fish on the Newfoundland and Labrador coasts. Fish. Mar. Serv. Tech. Rep., 905. 14 pp.

Harris, L. (Chair). 1990. Independent review of the state of the northern cod stock. Report prepared for the Minister of Fisheries. Communications Directorate, Canada Department of Fisheries and Oceans, Ottawa. 154 pp. +appendices.

Helbig, J., Mertz, G., and Pepin, P. 1992. Environmental influences on the recruitment of Newfoundland/Labrador cod. Fish. Oceanogr., 1: 39–56.

Hutchings, J.A., and Myers, R.A. 1993a. Effect of age on the seasonality of maturation and spawning of Atlantic cod, *Gadus morhua*, in the Northwest Atlantic. Can. J. Fish. aquat. Sci., 50: 2468–2474.

Hutchings, J. A, Myers, R. A., and Lilly, G. R. 1993. Geographic variation in the spawning of Atlantic cod, *Gadus morhua*, in the Northwest Atlantic. Can. J. Fish. aquat. Sci., 50: 2457–2467.

Hutchings, J. A., and Myers, R. A. (in press). What can be learned from the collapse of a renewable resource? Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. Can. J. Fish. aquat. Sci.

Jangaard, P. M, Ackman, R. G., and Sipos, J. C. 1967. Seasonal changes in fatty acid composition of cod liver, flesh, roe and milt lipids. J. Fish. Res. Bd Can., 24:613–627.

Kirby, M. J. (Chair). 1982. Navigating troubled waters: a new policy for the Atlantic fisheries: report of the task force on the Atlantic fishery. Canada. Task Force on Atlantic Fisheries. 379 pp.

Lilly, G. R. 1993. The food of cod in Divisions 2J, 3K and 3L during the autumns of 1978–1992. NAFO SCR Doc., 93/55, Ser. No. N2238. 14 pp.

Lilly, G. R. 1994. Predation by Atlantic cod on capelin on the southern Labrador and Northeast Newfoundland shelves during a period of changing spatial distribution. ICES mar. Sci. Symp., 198: 600–611.

Miller, D. 1993. Observations and studies in SA2 and Div. 3K capelin in 1992. Dept. Fish. Oceans Atl. Fish. Res. Doc., 93/10. 10 pp.

Miller, D., and Lilly, G. 1991. Observations and studies in SA2 and Div. 3K capelin in 1990. CAFSAC Res. Doc., 91/11. 30 pp.

Morgan, M. ., Bishop, C., and Baird, J. W. 1993. Temporal and spatial variation in age and length at maturity in 2J3KL cod. NAFO SCR Doc., 93/57. Ser. No. N2240. 8 pp.

Myers, R. A, Drinkwater, K. F., Barrowman, N. J., and Baird, J. W. 1993a. Salinity and recruitment of Atlantic cod (*Gadus morhua*) in the Newfoundland Region. Can. J. Fish. aquat. Sci., 50: 1599–1609.

Myers, R. A., Mertz, G, and Bishop, C. A. 1993b. Cod spawning in relation to physical and biological cycles of the northern North-west Atlantic. Fish. Oceanogr., 2(3/4): 154–165.

Rose, G.A. 1993. Cod spawning on a migration highway in the north-west Atlantic. Nature, 366: 458–461.

Rose, G. A., Atkinson, B. A., Baird, J. W., Bishop, C. A., and Kulka, D. W. 1994. Atlantic cod distribution changes and thermal variation in Newfoundland waters, 1980–1992. ICES mar. Sci. Symp., 198: 542–552.

Serebryakov, V. P. 1965. Some results of Soviet research work on ichthyoplankton in the northwest Atlantic: eggs and larval cod. ICNAF Spec. Publ., 6: 425–431.

Serebryakov, V. P. 1968. Cod reproduction in northwest Atlantic. Fish. Res. Bd Can., Transl. Ser. No. 1133, 53 pp. (Trudy PINRO 1967, 20: 205–242.)

Shelton, P. A., and Morgan, M. J. 1993a. Assessing the risk of failing to achieve replacement recruitment. ICES CM 1993/D: 54. 20 pp.

Shelton, P. A., and Morgan, M. J. 1993b. An analysis of NAFO Division 2J3KL cod spawner biomass and recruitment. NAFO SCR Doc., 93/37. 14p.

Shelton, P. A., and Morgan, M. J. (in press). An analysis of replacement in the northern cod stock. NAFO Sci. Coun. Stud.

Sutcliffe, W. H., Loucks, R. H., Drinkwater, K. F., and Coote, A. R. 1983. Nutrient flux onto the Labrador Shelf from Hudson Strait and its biological consequences. Can. J. Fish. aquat. Sci., 40: 1692–1701.