Relative effects of trap versus trawl fisheries on population dynamics of the northern cod (*Gadus morhua*) stock

L. Fahrig, S.E. Pope, K.M. Henein, and G.A. Rose

Abstract: We compared the effects of the inshore trap and the offshore trawl fisheries on the population dynamics of the northern cod (*Gadus morhua*) stock using data analyses and simulation modelling. We first statistically characterized the catch versus stock biomass relationships for the two fisheries (1977–1986). We found a significant ($P < 0.0001$) relationship between the trawl catch at time t and the stock biomass at time $t - 2$. No temporal lag was evident in the trap catch versus stock biomass relationship. The variability in these two relationships was similar. We then modelled the catch and stock biomass dynamics of the two fisheries in parallel, incorporating the observed catch versus stock biomass relationships, but assuming equal mean catches, to examine the effects on cod population dynamics of the temporal lag and variability in the catch versus stock biomass relationships. The results suggest that, for the same amount of fish taken, a quota-based trawl fishery presents a much greater risk of collapse to the cod stock than does an inshore trap fishery. Current management methods overestimate the "safe" catch for the trawl fishery because they do not incorporate the consequences of the lag in the relationship between stock biomass and trawl catch.

Résumé : Pour comparer les effets de la pêche côtière aux trappes et de la pêche hauturière au chalut sur la dynamique des populations de la morue franche (*Gadus morhua*) du Nord, nous avons analysé des données et utilisé des modèles de simulation. Nous avons d'abord statistiquement caractérisé les relations entre les prises et la biomasse du stock des deux pêches (1977–1986). Nous avons constaté une relation significative ($P < 0{,}0001$) entre les captures au chalut au temps t et la biomasse du stock au temps $t - 2$. La relation entre les prises aux trappes et la biomasse du stock ne comportait aucun effet à retardement. Les deux relations présentaient la même variabilité. Nous avons ensuite construit un modèle représentant la dynamique des prises et de la biomasse des stocks des deux pêches en parallèle; nous y avons appliqué les relations entre les prises et la biomasse observées, mais en supposant des prises moyennes égales, afin d'examiner comment l'effet à retardement et la variabilité des relations entre les captures et la biomasse des stocks pouvaient influer sur la dynamique des populations de morues. D'après les résultats, il se pourrait que, pour des prises quantitativement identiques, la pêche au chalut avec quotas pose un risque beaucoup plus grand d'effondrement pour le stock de morue que la pêche côtière aux trappes. Avec les méthodes de gestion actuelles, on surestime les captures « sans danger » dans la pêche au chalut parce qu'on ne tient pas compte de l'effet à retardement dans la relation entre la biomasse des stocks et les prises.
[Traduit par la Rédaction]

Introduction

A rapid decline in abundance of the northern cod (*Gadus morhua*) stock of Newfoundland and Labrador resulted in closure of the Canadian fishery in 1992 (Bishop et al. 1993; Hutchings and Myers 1994). The historical annual catch of northern cod ranged between 150 000 and 300 000 t from the mid-nineteenth to the mid-twentieth century, jumped sharply to a maximum of 810 000 t in 1968, and then declined to 140 000 t by 1977 (Harris 1990). Canadian management of the stock began in 1977, and the reported catch increased to 267 000 t by 1988. However, by early 1989, it had become apparent that the stock was not increasing as had been believed; quotas were reduced until a full moratorium on fishing was imposed within the Canadian zone in 1992 (Bishop et al. 1993; Atkinson et al. 1997).

During the period of Canadian management of the stock, the two main sectors of the fishery were the inshore trap fishery during the summer and the otter trawl fishery that operated primarily during winter and spring on the offshore wintering and spawning grounds (Pinhorn 1976). There were important differences between the two fisheries in terms of their timing, spatial dynamics, and management.

The trap fishery acted as a passive "sampler" of fish that entered the traps during their summer feeding migration northward along the coasts of Newfoundland and Labrador (Rose and Leggett 1989; Rose 1993). Until the present moratorium, the inshore fishery, including the trap catch, was effectively unrestricted. There were no quotas but an annual allotted "allowance" that was never fully taken (Anonymous 1989). Between-year variation in the trap catch was high and occurred

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for two major reasons: variation in the stock itself and variability in the trap catch versus stock biomass relationship, related to environmental factors affecting the probability of fish entering traps (Lear et al. 1986; Rose and Leggett 1988; Rose 1992).

The mobile trawl fishery, on the other hand, was an active, "hunting-type" fishery prosecuted on a relatively stationary, highly aggregated population. Hence, the trawl fishery was not a passive sampler of the population; fishing on the wintering and spawning aggregations was continuous. From 1978 to 1991, the Canadian trawl fishery was controlled by quotas. Over this period, the Canadian landings represented, on average, 70% of the total offshore catch. Unlike the trap fishery, the degree to which the trawl catches reflected variation in the stock biomass depended mainly on the degree to which the quota itself reflected the stock biomass.

We speculated that these differences between the trap and trawl fisheries in their catch versus stock relationships could result in different risks to the northern cod stock, independent of the relative amounts of fish taken by the two fisheries. This difference in risk could occur for either or both of two major reasons. First, the higher the variation in a catch versus stock relationship, the greater the probability that fishing would, by chance, push the biomass below some threshold (Sissenwine et al. 1988). We hypothesized that this random variation in catch versus stock relationship was greater in the largely unregulated trap fishery than in the offshore trawl fishery. Second, when quotas control a fishery, a lag in the catch versus stock relationship is likely because there is a time delay between when the stock biomass is assessed (for setting the quota) and when the fish are actually caught. In a retrospective analysis, Rivard and Foy (1987) described 2-year lags in 18 stocks in the Northwest Atlantic. These lags resulted from the practice of calculating the total allowable catch for the coming fishing season based on data collected in the previous season (Rivard and Foy 1987). Such lags increase the amplitude of fluctuations in the stock (and catch), again increasing the likelihood that the stock will reach a lower threshold (Pimm et al. 1988). We hypothesized that there was a lag in the catch versus stock relationship for the offshore trawl fishery but no lag in the relationship for the trap fishery.

The objective of this study was to compare the effects of the inshore trap and the offshore trawl fisheries on the population dynamics of the northern cod stock. We evaluated whether the probability that the stock biomass would drop below a threshold value and the duration of any such declines differed between the two fisheries. Our approach was first to statistically characterize the catch versus stock relationships for the two fisheries. In doing so, we tested the hypotheses that (*i*) the variability in the catch versus stock relationship was higher for the trap than for the offshore trawl fishery and (*ii*) a lag was present in the catch versus stock relationship for the offshore trawl fishery but not for the trap fishery. We then constructed a simulation model of the catch and stock biomass dynamics for the two fisheries separately, incorporating the observed catch versus stock biomass relationships, but assuming equal mean catches for the two fisheries. We assumed equal mean catches for the two fisheries to examine the effects on population dynamics of observed temporal lag and variabilities in the catch versus stock relationships, independent of mean catch of the two fisheries.

Data analysis

Data used in the statistical analysis

We wished to consider the relationship between the trawl catch and the stock biomass for the period over which the trawl catch was limited by the quota and the relationship between the trap catch and stock biomass for the period for which data were available. In 1977 the 200-mile limit was instituted and a more effective quota for the trawl fishery was established (Harris 1990). For the trap fishery, which was not limited by quotas (Rose 1992), the time period of our study is limited only by the data available.

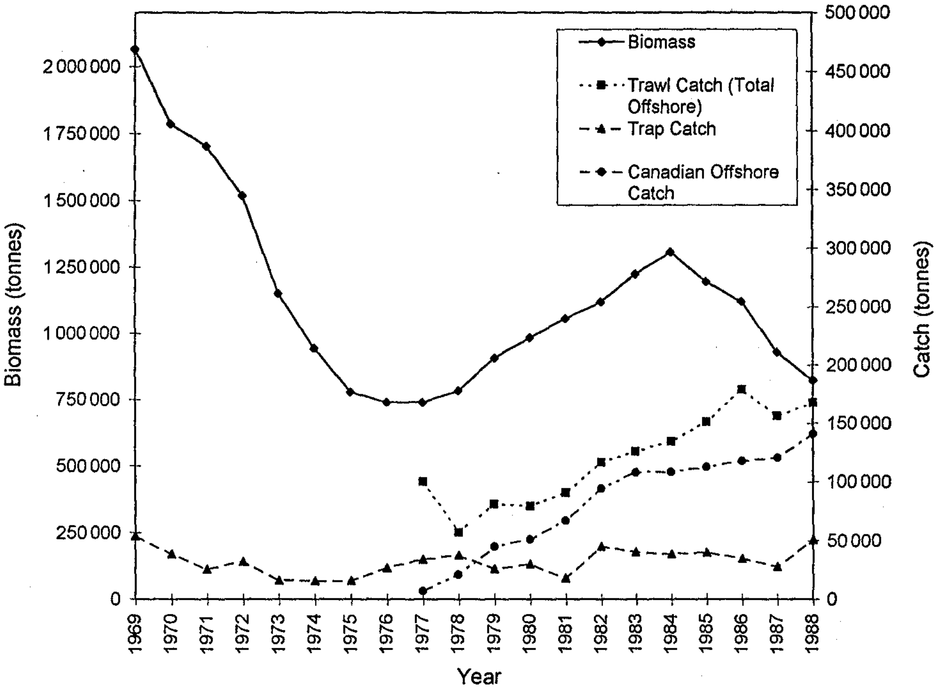
Our primary data source for stock biomass estimates was the 1993 assessment of the cod stock in NAFO divisions 2J + 3KL, the "northern cod stock" (Bishop et al. 1993). The assessment gave stock size in terms of numbers of fish, and we converted this to biomass by multiplying by weight-at-age data from the commercial fishery (Bishop et al. 1993). In all our analyses, total stock biomass is the summed biomass of the fish aged 3–13.

The 1993 assessment provides an estimate of stock size derived from sequential population models (SPA) and calibrated using research vessel survey data. Because the research surveys began in 1978, population estimates in the 1993 assessment are given only for 1978 on. However, population estimates extending back to 1962 are available in the 1991 assessment (Baird et al. 1991). Both research vessel survey and catch-per-unit-effort (CPUE) data were used to establish these earlier estimates (Baird et al. 1991). Population estimation, calibrated using research vessel survey data only and not including CPUE data, has been demonstrated to be more accurate (Baird et al. 1992). We therefore used the 1993 data for population estimates from 1978 on and extended the series back using adjusted values from the 1991 assessment for the period 1969–1977. We calculated a conversion factor between the 1991 and 1993 assessments, based on the time period for which the 1991 and 1993 assessments overlapped. For the 1969–1977 estimates, we used the values in the 1991 assessment multiplied by this conversion factor (see below: Extending the stock biomass estimates back past 1978).

Although SPA estimates from the most recent period are highly sensitive to the assumed number of survivors in the last year of the time series, those from earlier years are not, provided that fishing mortality is sufficiently high (Pope 1972, cited in Sinclair et al. 1990). Figure 1 in Sinclair et al. (1990) suggests qualitatively that this is a problem for only the most recent six years in the northern cod stock assessments. We therefore did not include the six most recent years (1987–1992) in the data analyses. Because we were working with data from the 1993 (Bishop et al. 1993) and 1991 (Baird et al. 1991) assessments, removing six years for convergence meant that we had available population estimates up to and including 1986.

Data on the total offshore trawl catches covered the period 1977–1986 and were taken from Baird et al. (1991, table 1: Total offshore mobile gear). We also ran the analyses using the Canadian-only portion of the offshore catch (Baird et al. 1991, table 1: Total Canada – Total fixed gear). The data for the trap catch were from Harris (1990) and covered the period 1969–1986 (see Fig. 1.)

Fig. 1. Stock biomass and catch values used in the statistical analyses. Data up to and including the year 1986 were used; the data for 1987–1988 are included for illustrative purposes only (see Data used in the statistical analysis section for details).



SPA estimates of stock size were calculated using two methods, ADAPT and Laurec/Shepard, in the 1993 assessment (Bishop et al. 1993). For the converged portion of the series (1978–1986) the Laurec/Shepard and ADAPT estimates are nearly identical. Only the ADAPT method was used in the 1991 assessment. We based our analyses on the population estimates calculated using the ADAPT method.

Extending the stock biomass estimates back past 1978

Stock biomass estimates from the 1993 assessment (Bishop et al. 1993) are consistently higher than the estimates from the 1991 assessment (Baird et al. 1991). This difference is due to the fact that the estimates in the 1993 assessment were calibrated using only the research vessel data whereas in the 1991 assessment, both offshore CPUE and research vessel data were used.

We "extended" the stock size estimate back to include the period 1969–1978 using adjusted values of the 1991 assessment (Baird et al. 1991). We removed 6 years (i.e., 1985–1991) for convergence of the 1991 estimates and then regressed the 1993 ADAPT estimates on the 1991 estimates for the years 1978–1984 to calculate a conversion factor (model $R^2 = 0.9895$). We then adjusted the stock biomass values for 1969–1977 using this conversion factor on the 1991 estimates. (See Fig. 1 for the full biomass series used in our analyses.)

Characterizing the catch versus stock relationships

Trawl fishery

We regressed the total trawl catch on the stock for the same year, for the same year with no intercept, and on the stock lagged 1, 2, 3, and 4 years. In all models, we used the converged stock biomass estimates (1977–1986) and the catch estimates shifted forward by the number of years in the lag. For example, for the model with a 2-year lag, we used the catch estimates from 1979–1988. We also tried each of these models with logged values of the trawl catch. There was no improvement of the model fit or of the distribution of the residuals using the logged values.

The best single-term model related the total trawl catch in year t to the stock biomass in year $t - 2$. The model was highly significant ($P < 0.0001$) and explained 90% of the variation in the trawl catch. This 2-year-lagged model was a statistically significant improvement over both the unlagged model which explained 49% of the variation in the trawl catch and the 1-year-lagged model which explained 74% of the variation. The results for the Canadian-only portion of the offshore fishery were very similar.

We also evaluated the total trawl catch versus stock relationship for the period prior to the institution of the catch quota (1969–1976). The unlagged and 2-year-lagged models were both significant ($P < 0.01$) but had similar model R^2 values of 0.85 and 0.82, respectively. Whereas over the period after the implementation of the quota, a 2-year-lagged model was a substantial improvement over the unlagged model, over the earlier time period the unlagged model of the catch versus stock relationship explained as much variation as did the model built with a 2-year lag. This suggests that the imposition of the quota is the cause of the lag in the trawl catch versus stock relationship.

To characterize the variability of the trawl catch versus stock relationship, we used the variance of the residuals of the 2-year-lagged regression model of the total offshore catch. The residuals were normal (SAS Institute Inc. 1990), homogeneous over the range of stock biomass estimates used in the model, and showed no autocorrelation (SAS Institute Inc. 1990; StatSci. 1991). The residual variance was 1.1×10^8 (mean catch = 1.12×10^5 t).

Trap fishery

We regressed the trap catch (1969–1986) on the stock biomass for the same year, for the same year with no intercept, and on the stock biomass lagged 1, 2, 3, and 4 years. We also tried each of these models with logged values of the trap catch. The best single-term model related the trap catch in year t to the total stock biomass in year t. The model explained 24% of the variation in the trap catch ($P < 0.05$). There was no improvement of the model fit or of the distribution of the residuals using the logged values.

To characterize the variability of the trap catch versus stock relationship, we used the variance of the residuals of the unlagged regression model. The residuals were normal (SAS Institute Inc. 1990), homogeneous over the range of stock biomass estimates used in the model, and showed no autocorrelation (SAS Institute Inc. 1990; StatSci. 1991). The variance was 8.8×10^7 (mean catch = 3.16×10^4 t), slightly less than the residual variance for the trawl catch versus stock relationship.

Although the residual variances of the catch versus stock relationships were very similar for the trap and total offshore trawl fisheries, the mean catch of the trawl fishery was 3.5 times the mean catch of the trap fishery. Since positive mean–variance relationships are very common (McArdle and Gaston 1992), it was possible that this similarity in variances of the two fisheries would not have occurred if the mean catches had been more similar. The variance of the trap fishery might have been greater had the catches been higher.

To estimate the maximum possible effect of variance in the trap catch versus stock relationship, we used the observed variance in catch during the period 1900–1928 from data in Harris (1990). During this period the trap fishery constituted a large proportion of the northern cod fishery (Harris 1990; Rose 1992), and offshore trawling had not yet become a significant component of the fishery (Harris 1990). The calculated variance was 1.6×10^9 (mean catch = 2.67×105 t), or about 18 times the variance calculated above for the trap catch versus stock relationship. This variance is inflated by variance due to actual changes in stock size during the period 1900–1928. Also, the stock is believed to have been much larger in the early 1900s than in the 1970s and 1980s which should result in larger variance in the catch versus stock relationship. Note that we cannot correct for these inflation factors because there is no separate estimate of stock biomass (independent of catch) for the period 1900–1928.

Model analysis

General model structure

We built a stochastic model to simulate independently the effects of the inshore trap fishery and the offshore trawl fishery on the dynamics of the northern cod stock. We conducted separate model runs over a range of fishing mortalities from 0.2 to 0.8; in each run, the trap and trawl fisheries were modelled separately for 100 years, beginning from the same initial conditions. Although the model was stochastic, differences between the output from the two modelled fisheries at the same fishing pressure resulted only from the observed differences in the variances of the catches and the observed 2-year lag in the trawl catch versus stock relationship (see below).

The model was not age structured. Stock biomass changes due to recruitment, natural mortality, and fishing mortality were incorporated. Individual growth was not incorporated, since this would have required an age-structured model. Instead, recruitment biomass was added by assuming that recruited fish had attained the mass of an average-sized fish taken in the catch (i.e., 1.54 kg). A single time step in the model corresponded to 1 year.

Recruitment

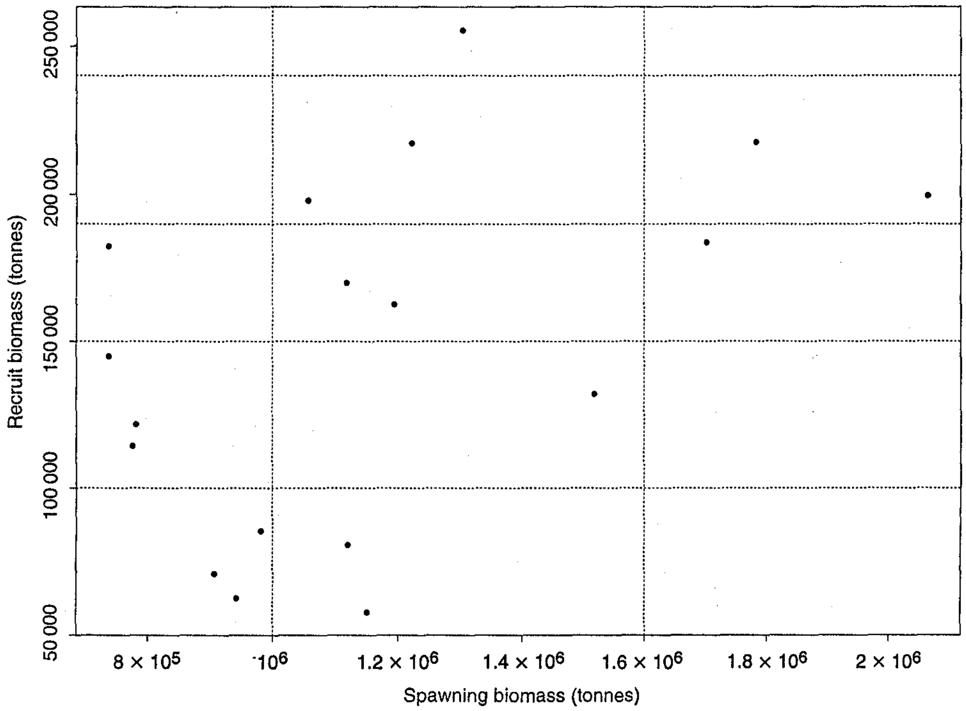
Recruitment is the dominant and most variable component of fish production and can vary from a factor of 3 to more than 2 orders of magnitude from year to year in response to environmental variation (Cushing 1988). The response of recruitment to changes in the spawning stock can be obscured by this variability and by measurement error, unless the stock is at a very low level (Cushing 1995). Shepard (1988) contended that when techniques that avoid spurious correlations are used in fitting statistical models to the stock–recruitment relationship, the parameters obtained depend as much on the fitting technique as anything else.

Despite this variability, deterministic stock–recruitment relationships predominate in the application of mathematical models to analysing fisheries management problems and computing maximum sustainable yields (Getz and Swartzman 1981). Deterministic models have not been useful for modelling many stock–recruitment problems because of their failure to reproduce variability that occurs over the full range of parental stock sizes (Overholtz et al. 1986). Getz and Swartzman (1981) advocated a transition matrix approach. This method is not subject to problems such as inappropriate model choice or poor fits to the data, and it removes or ignores the problems of autocorrelation (Overholtz et al. 1986). A drawback of the matrix method is that it requires a large number of years in the data set. We had 18 years available, which is less than the 30 years recommended as a minimum by Hilborn and Walters (1992); this introduced additional uncertainty in the relationship.

We developed a stock–recruitment matrix for the northern cod (Getz and Swartzman 1981) (Fig. 2). We used age 3 as the age of recruitment to the fishable population; this assumes knife-edged recruitment to the fishery. Note that in the simulation model the recruitment biomass is grown stochastically to reflect the fact that all fish are assumed to be 6 years old, the average age of a caught fish. Total stock biomass was used as a surrogate for the spawning biomass, as the simulation model is not age structured. Although this procedure may have introduced additional variation into the model, we do not expect this to alter the qualitative results of the study, since the effect is equally applied to the trap and trawl simulations.

The matrix arrayed the total stock biomass in year t against the recruitment biomass in year $t + 3$ for the years 1969–1986 (Fig. 2). We have previously described our method for extending the 1993 total stock biomass estimate back to 1969; the same procedure was followed for the 1993 recruitment series. We partitioned the total stock biomass into three spawning biomass classes and the recruitment biomass into five classes (Fig. 2). Note that the largest biomass class includes all biomass values greater than 1.6×10^6 t. We set the probabilities

Fig. 2. Spawning–recruitment matrix. Data points cover the period 1969–1986. Total stock biomass (ages 3–13 inclusive) is used as a surrogate for spawning biomass (ages 7–13). Gridlines separate the data into the categories used in the simulation model.



of falling into each recruitment class given a particular spawning class according to the observed stock–recruitment data points for the years 1969–1986 (Getz and Swartzman 1981). Actual recruitment was then calculated as a uniform random number within the bounds of the recruitment class. The same sequence of random numbers was used in the two fisheries over the 100 years of each simulation. We did this to ensure that differences between the trap and trawl fisheries were due to differences in their catch versus stock relationships, and not to chance differences in recruitment.

Fishing mortality

Fishing mortality is typically reported in the literature in terms of the numbers of fish caught in a particular age-class. Our model requires an overall value for fishing mortality, since it determines the catch based on total stock biomass. Given a particular fishing mortality, the model then calculates catch based on the Baranov catch equation:

$$C = B\cdot(F/(F+M))\cdot(1 - \exp(-(F+M)))$$

where C is the catch, B is the stock biomass, M is natural mortality, and F is fishing mortality. The Baranov catch equation is equally applicable to total rather than age-class-specific population estimates and can be calculated using biomass instead of numbers as long as there is a linear relationship between these two population estimates. To test this assumption, we regressed the total number of fish (ages 3–13, Bishop et al. 1993, table 29) on the total biomass of fish for the years 1978–1986. The model R^2 was 0.9899. The model indicated that, on average, one fish weighs slightly more than 1 kg (e.g., the 1981 average mass was 1.209 kg). The variance of the residuals was fairly constant, and the residuals were normal (SAS Institute Inc. 1990) with no autocorrelation (SAS Institute Inc. 1990; StatSci. 1991), suggesting that a linear relationship between stock biomass and numbers was appropriate.

Once a catch had been calculated for the fishery in question, we added variance by sampling from a normal distribution (Hammersley and Handscomb 1964) with mean zero and variance as determined from the statistical analysis of the catch versus stock relationships for each fishery. Additional runs were conducted for the trap fishery using the maximum variance estimate. We used the same sequence of random numbers in applying variability in the catch versus stock relationship for the trap and trawl fisheries over the 100 years of each simulation. Therefore, differences in the dynamics of the two fisheries were due to differences in the absolute magnitudes of the variance in their catch versus stock relationships and the lag in the trawl catch versus stock relationship.

Natural mortality

Natural mortality is dynamic for groundfish, depending on fish age, abundance of predators, prey, and other factors (Sinclair et al. 1990). All estimates of natural mortality are associated with such wide confidence intervals that they would be disregarded were it not for the necessity of some estimate to proceed with analysis (Garrod 1988). However, natural mortality is not usually estimated in SPA (Sinclair et al. 1990). A reasonable value of natural mortality is often assumed to be between 0.2 and 0.3. Natural mortality is consequently an additional assumption of the model, and not a real parameter (Sinclair et al. 1990). However, Garrod (1988) contends that natural mortality is simply a scalar value that has no bearing on the result of an analysis, provided natural mortality does not change between treatments under consideration.

We used a constant of 0.2 with no variance for natural mortality in our simulation model. Since total population numbers and biomass are linearly related (as described above), the Baranov equation for natural mortality applies equally to numbers as to biomass:

$$D = B \cdot (M/(M + F)) \cdot (1 - \exp(-(F + M)))$$

where D is death due to natural mortality, B is the current stock biomass, M is natural mortality, and F is fishing mortality.

We assumed that natural mortality acts equally on all ages in the fishery and, therefore, that the average weight of a fish lost to natural causes is equivalent to the average weight of fish in the population. This may not be a biologically sound assumption, but not enough is known about natural mortality after recruitment to assume otherwise.

Threshold

To compare the effects of the trap and trawl fisheries on stock biomass, we developed a reference value based on the modelled unexploited stock. By running the model for 200 years from an initial biomass of 400 000 t without fishing but with natural mortality and recruitment as described above, we were able to calculate the level the stock would reach in the absence of fishing (Fig. 3). We took as our threshold 20% of the average stock size at this level (Beddington and Cook 1983). Changing the initial biomass to 200 000 or 600 000 t did not change the reference threshold obtained.

Running the model

Each run began with an initialization period of 8 years that was identical for the trap and trawl runs. Fishing began in the ninth year. For the first 4 of the initial 8 years, recruitment was based on a stock biomass of 400 000 t. For the remaining 4 of the initial 8 years, and for all subsequent years in the simulation, recruitment was based on the stock biomass in year $t - 3$.

Random values were generated to produce random variation in recruitment biomass, growth, and catch during the 100 years of the simulation. As described above, for each procedure, the same set of random numbers was used for the two fisheries. This effectively ensured that fluctuations due to environmental factors were constant between the two fisheries. Therefore, all differences observed in the population dynamics were attributable to differences in the catch versus stock relationships of the trap and trawl fisheries. Below, we describe the change in the stock biomass, for one year in the model.

Each year t was modelled in two stages. In the first stage, recruitment was added to the stock biomass from the end of the preceding year, and in the second stage, natural and fishing mortality were applied. Therefore, there were two stock biomass calculations in each year, labelled Br_t (stock biomass following recruitment in year t) and Bm_t (stock biomass following mortality in year t). Recruitment was based on the stock biomass (following recruitment) in year $t - 3$, with random variation applied as described above:

$$\mathrm{Br}_t = \mathrm{Bm}_{t-1} + R_t$$

where R is recruitment.

The proportion lost from the stock each year to natural mortality (D) was calculated from the Baranov equation (as described above) and was applied to the new stock biomass for year t:

$$D_t = \mathrm{Br}_t \cdot (M/(M + F)) \cdot (1 - \exp(-(F + M)))$$

where D is death due to natural mortality, M is natural mortality, and F is fishing mortality.

The statistical analyses revealed a 2-year lag in the relationship between catch taken by the trawl fishery and the stock biomass upon which that catch was based. We therefore calculated the catch for year t from the stock biomass in year $t - 2$ before mortality and fishing were applied ($\mathrm{Br}_t - 2$) using the Baranov equation

$$C_t = (\mathrm{Br}_{t-2}) \cdot (F/(F + M)) \cdot (1 - \exp(-(F + M)))$$

Because there was no lag in the trap catch versus stock relationship, as discussed above, the trap catch in the model was based on the stock present at the time of fishing, using the Baranov equation

$$C_t = \mathrm{Br}_t \cdot (F/(F + M)) \cdot (1 - \exp(-(F + M)))$$

where C is catch.

The stock biomass remaining at the end of year t was calculated by subtracting the natural mortality and the catch from the stock biomass (including recruitment biomass) present at the beginning of the year:

$$\mathrm{Bm}_t = \mathrm{Br}_t - D_t - C_t.$$

Simulation results

We first ran the model for 200 years with no fishing to develop a picture of the dynamics of an unexploited stock (Fig. 3). The stock stabilized at between 2.4×10^6 and 3.2×10^6 t. The threshold value for the simulation was calculated as 20% of the mean: 5.5×10^5 t.

We varied fishing pressure from 0.2 to 0.8 by 0.2 intervals (Fig. 4). Note that although the model is stochastic, multiple model runs were not required because the stochastic fluctuations in recruitment and catch versus stock relationships for trap and trawl fisheries were intentionally correlated, as described above. Therefore, differences observed in the long-term dynamics of the two fisheries were attributable solely to differences in absolute variance in the catch versus stock relationships and (or) the lag in the trawl catch versus stock relationship.

Stocks in the two fisheries tracked each other most closely (i.e., variance was most similar) at 0.2. In all cases, variability of the stock biomass was greater for the trawl fishery than for the trap fishery, resulting in higher probabilities of crossing the threshold or of dropping to zero stock biomass in the trawl fishery. Variability of the stock biomass decreased for the trap fishery as fishing pressure increased whereas that for the trawl fishery increased.

When variances in the catch versus stock relationships for the two fisheries were both set to the trap value and the lag was present for the trawl fishery, differences remained evident between the two fisheries (Fig. 5A). When the lag in the trawl catch versus stock relationship was not incorporated but the observed variances were, only small differences existed in stock sizes between the two fisheries (Fig. 5B). Therefore the lag was the major contributor to the differences in stock variability.

When the maximum variance in the trap catch versus stock biomass relationship (18 times the observed variance; see above) was applied to the trap fishery and the 2-year lag to the

Fig. 3. Simulated unexploited stock biomass from an initial stock of 400 000 t.

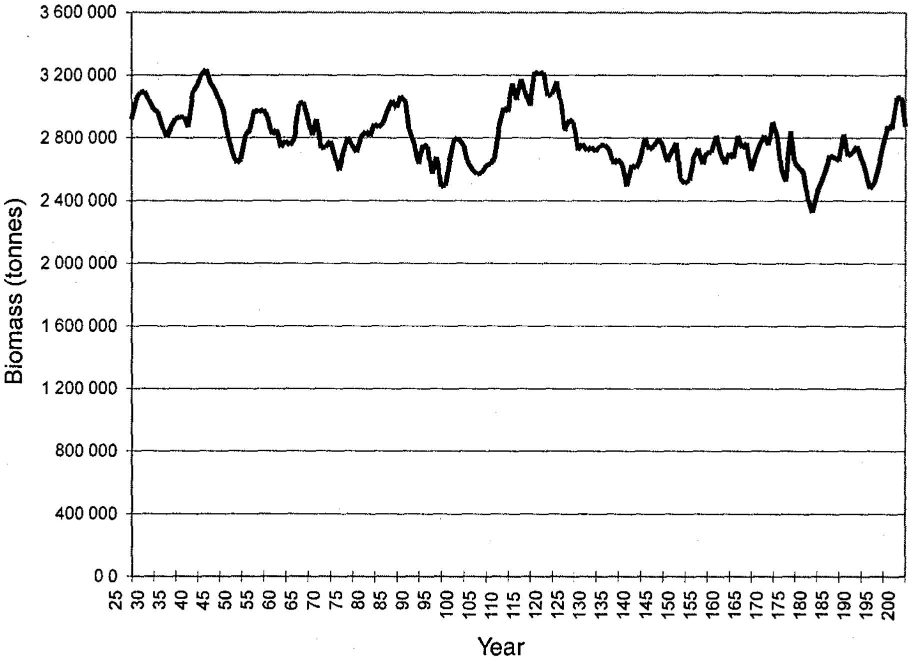


Fig. 4. Simulated stock biomass under a fishing regime based on residual variance for the trap fishery, residual variance and 2-year lag for the trawl fishery, and fishing mortality of (A) 0.2, (B) 0.4, (C) 0.6, and (D) 0.8.

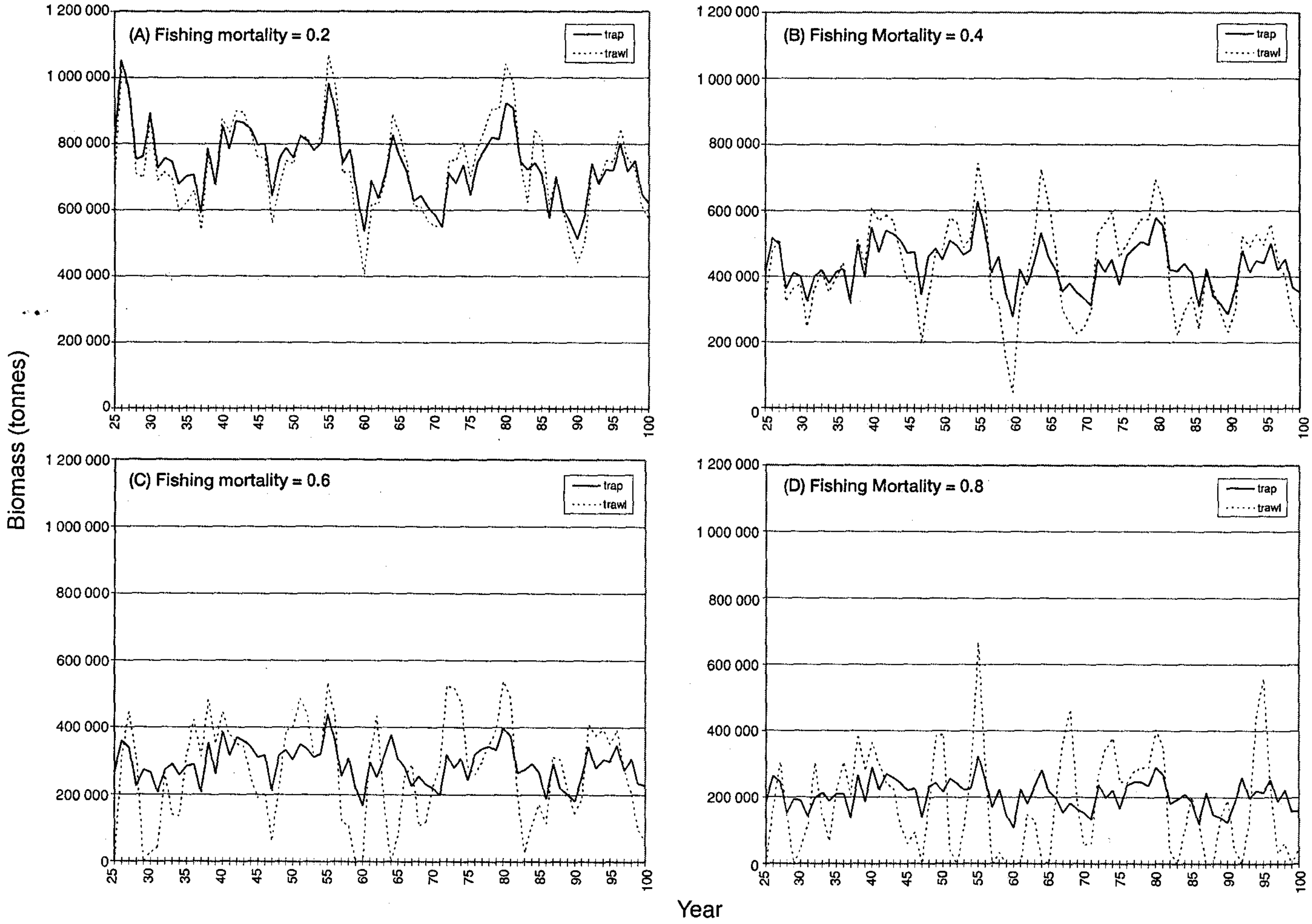


Fig. 5. Simulated stock biomass under a fishing regime based on a fishing mortality of 0.4 and (A) equal variance for the trap and trawl fisheries and a 2-year lag for the trawl fishery and (B) residual variance for the trap and trawl fisheries and no lag for the trawl fishery.

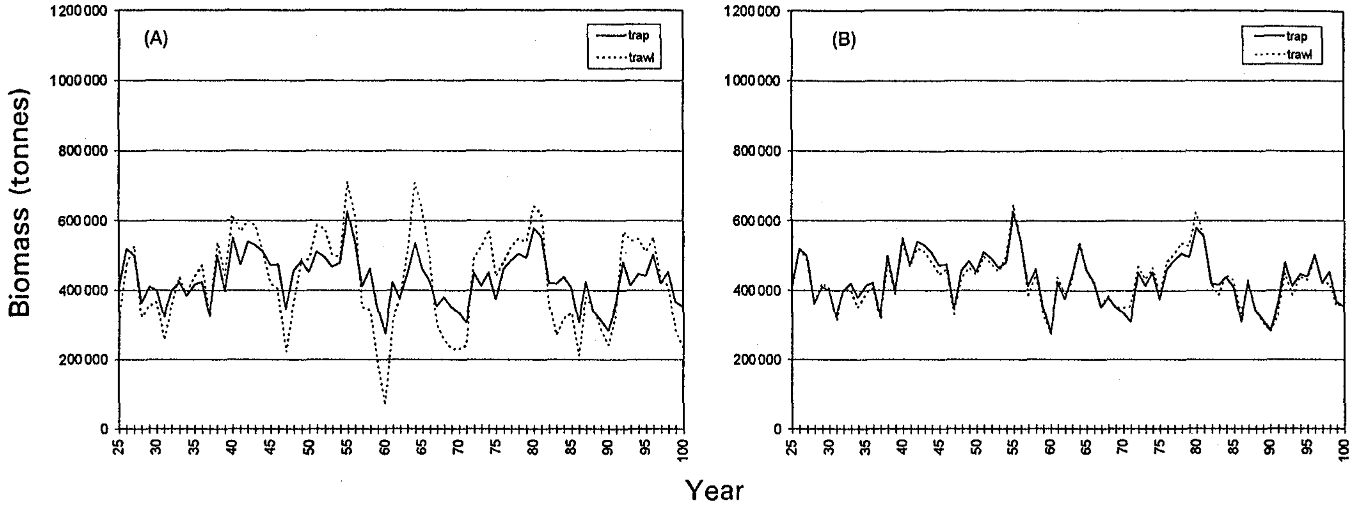
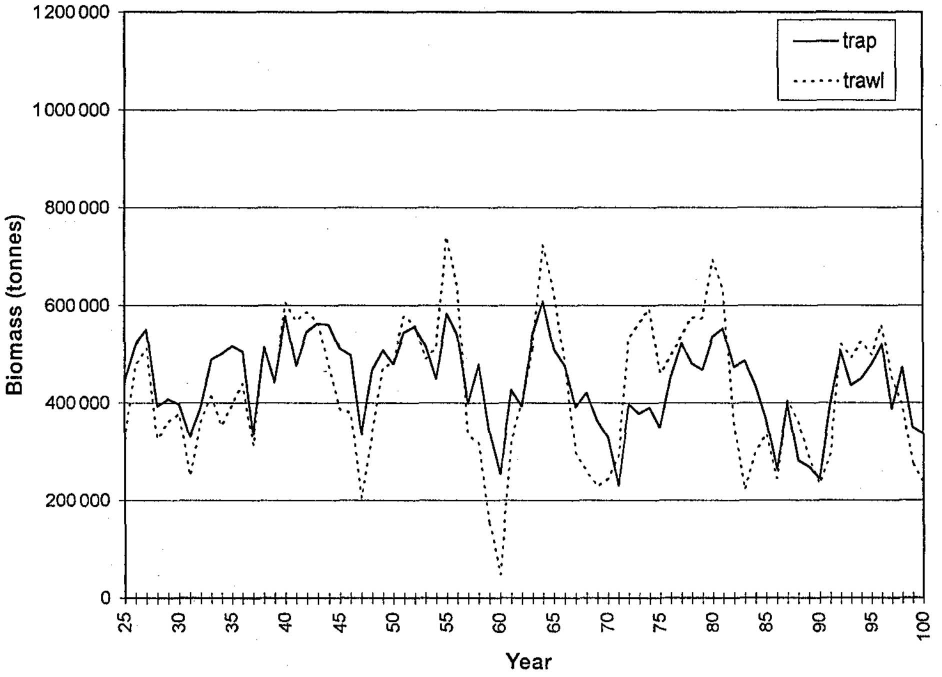


Fig. 6. Simulated stock biomass under a fishing regime based on the historical variance for the trap fishery, residual variance and a 2-year lag for the trawl fishery, and a fishing mortality of 0.4.



trawl fishery, the stock under the trawl fishery was still more variable than was the stock under the trap fishery (Fig. 6). This indicated that the effect of the lag in the offshore trawl catch versus stock relationship outweighed any possible effect of higher variability in the trap catch versus stock relationship.

Discussion

Our study suggests that the effects of fishing on the medium- to long-term state of a fish stock depend on interactions between the type of fishery prosecuted and the management scheme, and not simply on the amount of fish caught. In particular, for the northern cod stock, a quota-based otter trawl fishery presents a much greater risk of collapse to the stock than does an inshore trap fishery. This result holds even for the hypothetical situation in which the two fisheries harvest the stock at the same rate within the range of historical fishing levels. The greater risk from the trawl fishery results from the 2-year lag in the catch versus stock relationship evident for that fishery for the period of management by quota.

The statistical analyses of the trawl catch versus stock biomass relationships before and after the institution of the quota implicated the quota as a significant factor in the development of the lag. The lag occurred because the quota applied in year *t* was based on projections of the stock made in year *t* – 1 using data collected in year *t* – 2 (Rivard and Foy 1987).

Lags are particularly problematic in resource management when the resource being harvested is declining. If the stock is declining, the quota is based on a past population that is higher than the current population. Therefore, a catch that fills the quota will invariably exceed the management goal (e.g., $F_{0.1}$). The problem is most acute at the inflection point, when a population begins a downturn. At that point, the catch will be set based on an estimate of a population that is perceived to be increasing whereas, in reality, the population is decreasing. Quotas set around a downturn point in the population trend thus have the potential to accelerate the decline in the population. Such a downturn appears to have occurred in the northern cod stock in 1984 (Fig. 1). We hypothesize that the lag in the trawl catch versus stock relationship for northern cod accelerated the stock decline in the years following 1984.

In both our statistical analyses and our simulation modelling, we were working with stock biomass estimates that were as free from bias and error as possible: in the statistical analyses by working only with the converged stock biomass estimates and in the model by not including any bias or error in the stock biomass values. The simulations, therefore, did not address the cause of the lag; they addressed only the consequences.

In reality, both the estimates of the population in the recent past and the projections forward are subject to error (Rivard and Foy 1987) and also frequently bias (Rivard and Foy 1987; Bishop et al. 1993; Hutchings and Myers 1994). To remove the negative impact of the trawl catch on the population dynamics would require that the quota be set based on the population size on which the fishery is actually prosecuted. The trap fishery appears to exhibit this property without much management. The catch of the trap fishery reflected current population levels, although with much variability; the R^2 value for the trap catch versus stock model was only 24%, as compared with 90% for the trawl catch versus stock model. This variability is thought to be caused mainly by ocean conditions and migration variations, which affect movement of fish into traps (Lear et al. 1986; Rose and Leggett 1988, 1989; Rose 1992). Variability in the relationship may also have been affected by changes over time in effort in the trap fishery.

In contrast with the more passive trap fishery, the trawl catch is not naturally regulated by the size of the fish population. Otter trawl fisheries almost invariably catch the full quota because they are mobile "hunting-type" operations in which fleets of vessels are cooperatively dispatched to fish on aggregations of fish located with sonar devices. Indeed, such fisheries are economical only when fish are highly aggregated (Laevastu and Hayes 1981), which for cod is the wintering, spawning, and postspawning migration period (Rose 1993). During this period, aggregation properties of cod tend to be more dependent on behaviour than on population levels (Rose 1993; DeBlois and Rose 1995). It has long been suspected and more recently confirmed that such fisheries might sustain high catch rates even under population declines (Paloheimo and Dickie 1964; Templeman 1966; Houghton and Flatman 1981; Crecco and Overholtz 1990; Rose and Leggett 1991).

The trap fishery for cod has often been criticized because the minimum size of fish taken is smaller, and therefore the catches include more immature fish than those of alternative gear. The trap fishery has also been criticized for being too seasonal to sustain a viable economy in rural areas (Shrank et al. 1992). In fact, problems of selectivity and seasonality in the trap fishery contributed to the growth of the trawler fleets in the first place. However, by increasing the minimum allowable mesh size, by adopting fishing practices that release small and possibly very large fish (traps catch fish live with less damage to the animal), and by implementing holding and feeding pens to extend the season and increase the yield per fish, these problems of the trap fishery could be effectively ameliorated.

A much more robust assessment and management regime would be required to reduce the risk from a regulated trawl fishery to levels comparable with that from a trap fishery. It is no coincidence that an unregulated fishery, composed predominantly of traps and other passive gear, sustained high levels of catch (>150 000 t/annum) for nearly a century in Newfoundland and Gulf of St. Lawrence waters with little evidence of stock or catch depletion until the introduction of trawlers by the European fleet in the 1960's (Harris 1990). To attain equivalent sustainability, fishing rates from a trawl fishery would require reduction to levels well below the $F_{0.1}$ target level suggested by current management methods (Doubleday et al. 1984; Deriso 1987).

The "safe" catch for the trawl fishery on the northern cod stock was overestimated because methods for stock estimation did not incorporate the consequences of the lag in the trawl catch versus stock relationship. Risk of stock collapse was therefore underestimated. It might be argued that better survey and assessment methods would reduce this risk by closing the lag between quotas and stock biomass. However, as it is unlikely that the lag can be completely removed, the trawl fishery will remain more risky than the trap fishery for equivalent catch levels. Where a fishery is capable of catching the quota regardless of errors in the stock biomass projections, as for an otter trawl fishery, it may not be feasible to reduce the risk imposed by such fisheries on cod stocks to levels near those of more passive gear such as the cod trap, for the same fishing mortality. Our results suggest that the fishing mortality from a trawl-only fishery would need to be lower than the fishing rate for a trap-only fishery to produce the same risk of stock collapse.

Our findings have several implications for future fisheries on this stock. Under present systems of stock assessment and quota management, an otter trawl fishery poses a substantial risk to the population. Should the cod stocks off Newfoundland reach sufficient size to warrant reopening the fishery, we recommend beginning with a reduced shore-based fishery using passive gear traditionally used in the region (traps and (or) long lines) and no trawl fishery. If monitoring indicates no ill effects, the passive fishery could be enlarged. Consideration should be given to reinstating the trawl fishery only if the stocks prove robust to the passive, shore-based fisheries. In this event, the lag in the stock biomass versus quota relationship must be addressed, and the calculated quota should be reduced to compensate for the negative effects of the lag on stock states. Our results suggest that the trawl fishery is more risky than the trap fishery on a per kilogram of fish caught basis. To avoid stock collapses in future, management of the trawl fishery will need to be significantly more risk-averse than management of the trap fishery.

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