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Recent Research on the Role of Seals in the Northwest Atlantic Ecosystem

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Abstract

A review of the current state of our knowledge on the potential impact of seals on fish stocks in the northwest Atlantic was presented to the NAFO Scientific Council in 2007. Since that time, only limited research has been carried out. In 2008, a symposium, sponsored by NAFO, ICES and NAMMCO and attended by approximately 70 scientists from around the world, was held to explore how marine mammals interact with other components of their ecosystem. Presentations addressed the biological and environmental factors affecting life histories, foraging strategies and energetic requirements, marine mammal- fisheries interactions and theoretical considerations on apex predators and multispecies models. In addition to research highlighted at the symposium, studies have continued to determine the impact of harp seal predation on 2J3KL cod. Consumption was estimated by integrating information on abundance, age specific energy requirements, seasonal distribution and diet of harp seals in the Newfoundland area. The diet of harp seals was estimated using reconstructed stomach contents, a multinomial regression approach and fatty acid signatures. Although specific diets varied with season, location, year and method of estimation, forage fish such as capelin, Arctic cod, sandlance (sand eel) and herring were the primary prey consumed. Using these three methods of estimating diets resulted in very different estimates of cod consumption, although all were highly imprecise. Based upon the average diet obtained from reconstructed hard parts in the stomachs, cod consumption was estimated to be approximately 80,000t since the mid 1990s. Using the diet estimated from the multinomial regression method resulted in estimates of cod consumption approximately three times higher while only 1,000t of Atlantic cod are estimated to have been consumed by harp seals based upon the diets obtained from the fatty acid signatures. Incorporating these different estimates into a bioenergetic-allometric biomass dynamic model that incorporates seal predation, capelin availability, and fisheries catches as external drivers of the Northern cod dynamics, indicated that consumption of cod by harp seals does not appear to be an important driver of 2J3KL cod dynamics during the study period. The model that best fit the data was one including capelin and fisheries catches, but without seal consumption. In 2008, DFO sponsored a workshop to summarize available data on the impact of seals on cod stocks in Canada. They found that although the reasons for the lack of recovery vary between stocks, elevated natural mortality of adult cod is an important factor for many stocks. Seals, particularly grey seals, may be a contributing factor in some areas, but there is still considerable uncertainty in the factors affecting cod dynamics and in the magnitude of stock-specific seal predation mortality on cod. After reviewing recent advances in multispecies modelling and techniques for estimating marine mammal diets and/or consumption, a NAMMCO working group concluded that current models are not sufficient to address management questions such as the impact of changes in the abundance of certain marine mammal populations on allowable catch levels for commercial fish species.

INTRODUCTION

The impact of marine mammals, particularly seals, on the recovery of depleted fish stocks is a controversial issue and the focus of significant research efforts. Three species of seals are considered important predators in the northwest Atlantic, harp, hooded and grey seals. Harp and hooded seals are seasonal migrants that have shown little or no increase in abundance over the past decade. Grey seals are residents of temperate waters that, after a number of decades of exponential growth, are beginning to show signs of density dependent reductions in growth rates. A review of the available data on consumption and impact of these three species on fish stocks in the Northwest Atlantic was reviewed in Stenson (2007). He found that harp seals are important predators in Divisions 2J3KL and 4RS while grey seals are the most important pinniped predator in 4T and 4VsW. Hooded seals feed primarily in 2J3KL and 3M. A number of studies designed to determine the impact of seals on fish stocks in the northwest Atlantic, particularly the impact of harp and/or grey seals on Atlantic cod, concluded that although seals consume substantial amounts of commercial fish species and important forage species, the impact of these removals on the current fish stocks is difficult to determine. Seals are important predators of both large and small cod and could be playing a role in the non-recovery of cod stocks, but seal predation can not account for a large component of mortality in most areas and therefore, the total impact of seal predation cannot be determined. Often, estimates of age specific cod consumption by seals are inconsistent with the high mortality observed among older age groups. Little is known about the functional response of seals to changes in abundance of prey, other sources of mortality, or possible ecosystem effects such as competition for forage fish and positive feedback through seal predation on piscivorous fish. No research has been carried out to determine the potential impact of seals on fish stocks in the NRA outside of the Canadian continental shelf and slope.

NAFO/ICES/NAMMCO SYMPOSIUM ON THE ROLE OF MARINE MAMMALS IN THE ECOSYSTEM

Only a limited amount of research on the impact of seals on commercial fish stocks in the northwest Atlantic has been carried out since the review of Stenson (2007). In September 2008, NAFO (North Atlantic Fisheries Organization), ICES (International Council for the Exploration of the Sea) and NAMMCO (The North Atlantic Marine Mammal Commission) sponsored a Symposium on the Role of Marine Mammals in the Ecosystem of the 21st Century (Stenson and Haug 2009). At this symposium, attended by approximately 70 marine mammal and fisheries scientist from 11 countries, over 45 papers were presented describing recent research on how marine mammals are affected by their environment and how they influence other components of their ecosystem. Participants presented new findings on the syntheses of information over ecosystem components, on biological and physical aspects of the environment, and on new research approaches to understanding the role of marine mammals. The symposium was divided into four sessions dealing with 1) Biological and environmental factors affecting life history, 2) Foraging strategies and energetic requirements, 3) Marine mammal- fisheries interactions and 4) theoretical considerations on apex predators and multispecies models. Although many of the papers presented at the symposium described research that took place in other parts of the world, many of the approaches used can be applied to species found in the Northwest Atlantic. For example, Norwegian research on methods to estimate prey selection by harp seals and quantify competition between baleen whales and pelagic fish in the Barents Sea should be applied to similar situations in the NRA. Also, a study in the southern Ocean illustrated the important role of marine mammals in transferring nutrients within marine systems which has not been considered in the northwest Atlantic.

A simulation study to determine the impact of incorporating a factor for increased pup mortality in years of poor ice conditions indicated that our perception of the population dynamics of northwest Atlantic harp seals may be incorrect if this mortality is not accounted for. Because total abundance is estimated using estimates of pup production that are carried out every 4-5 years, a series of poor ice years may result in a significant reduction in total abundance before the impact is identified.

Preliminary estimates of consumption by cetaceans along the Canadian continental shelf (~1.7 million tonnes) suggest that predation by whales and dolphins may be an important component of the ecosystem that must be accounted for. This predation may have significant controlling effects on the biomass of other consumers as well as the prey.

Comparing body condition of harp and hooded seals collected in the northwest Atlantic during the 1980s and 1990s indicated that the condition of both species was lower in the more recent time period. This appears to be reflected in lower reproductive rates in both of these species.

A study of the diets of Atlantic cod, Greenland halibut and harp seals found that all three predators relied heavily on capelin, but that the cod diet showed a higher consistency over time. This suggests that cod have less trophic plasticity than Greenland halibut or seals. This lack of trophic flexibility could be a contributing factor in the lack of recovery of cod. It also suggests that other generalist predators like Greenland halibut, and possibly seals, may be better positioned to utilize a changing resource base.

During a general discussion on the current state and future of research on improving our understanding of the ecological role marine mammals, participant indicated that significant progress has been made, often as a result of new technologies such as satellite telemetry and alternate methods of estimating diets. Also, the statistical approaches being used are much more sophisticated and improve the way in which uncertainty is incorporated. Generally, there is a more holistic approach to the questions being asked with multi-disciplinary studies, especially those including oceanographers, advancing our understanding significantly. However, in many regions, significant progress is still needed to involve fisheries scientists in collaborative projects.

THE IMPACT OF HARP SEALS ON 2J3KL COD

Estimating diet and consumption of 2J3KL cod by harp seals

Consumption of Atlantic cod by harp seals off the east coast of Newfoundland in NAFO Divisions 2J3KL was estimated in 2001 using data available up to the late 1990s (Stenson and Perry 2001MS). Since that time, a number of studies have been carried out to update data on abundance, movements and diets in this area. Recent consumption by harp seals was estimated by integrating information on the numbers at age, age specific energy requirements, seasonal distribution and diet of harp seals in the Newfoundland area. Abundance was estimated using a population model integrating pup production between the late 1970s and 2004 (Fig 1), annual estimates of reproductive rates from 1954-1998 and data on age specific removals from 1952-2008. Energy requirements of the population were estimated using a simple allometric model based on body mass obtained from monthly, sex specific growth curves. The proportion of energy obtained in 2J3KL was estimated using data obtained from satellite telemetry and traditional tagging studies. The diet of harp seals in nearshore and offshore waters during winter (October – March) and spring (April – September) was determined by reconstructing the wet weight of stomachs collected in 1982 and 1986-2007. The impact of different diet determination methods was explored by estimating consumption based upon the proportion of cod in the diet obtained using a multinomial regression approach and fatty acid signatures. Uncertainty in the consumption estimates was approximated by incorporating the uncertainty in the numbers at ages, diets, energy requirements and seasonal distribution.

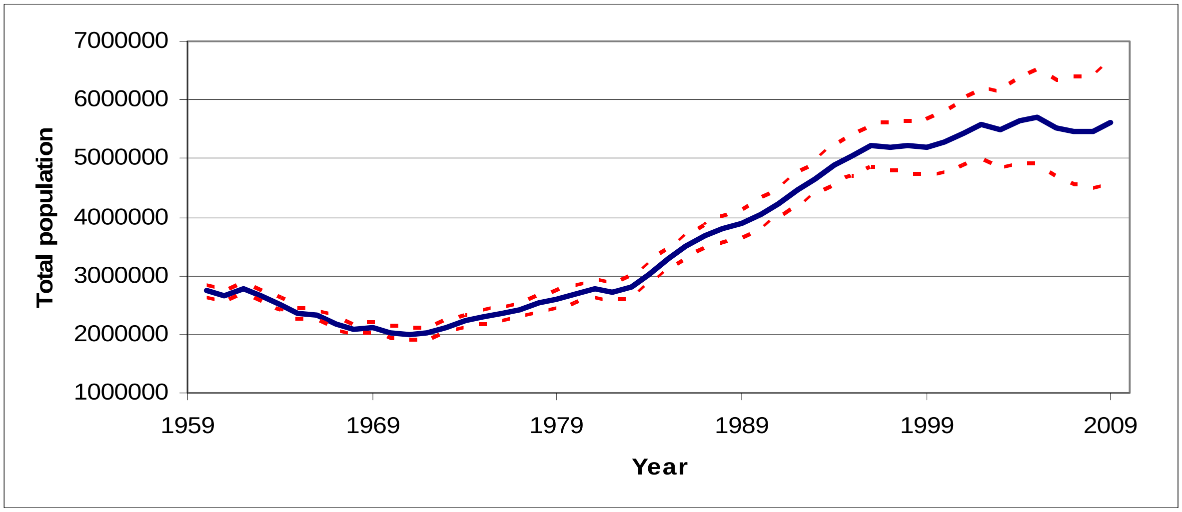

Figure 1. Estimated abundance of the Northwest Atlantic harp seal population between 1960 and 2009. Mean ±se. From Hammill and Stenson (2008MS)

The total population of Northwest Atlantic harp seals was estimated to be 5.6 million (95% C.I. 3.9-7.2 m) in 2008 (Hammill and Stenson 2008MS). Of their total energy requirement, approximately 20% and 19% were obtained in the Newfoundland areas during the winter and spring periods, respectively.

Although specific diets varied with season, location, year and method of estimation, forage fish such as capelin, Arctic cod, sandlance and herring were the primary prey consumed. Incorporating data obtained from the reconstruction of stomach contents collected up to 2007 resulted in significant changes in the average diet compared to previous estimates (Fig 2). Reduced proportions of American Plaice and other Pleuronectids were observed, along with lower proportions of Arctic cod in the nearshore diets and capelin in offshore diets. In contrast, higher proportions of shrimp were observed, particularly in the offshore, while the proportion of Atlantic cod was slightly higher.

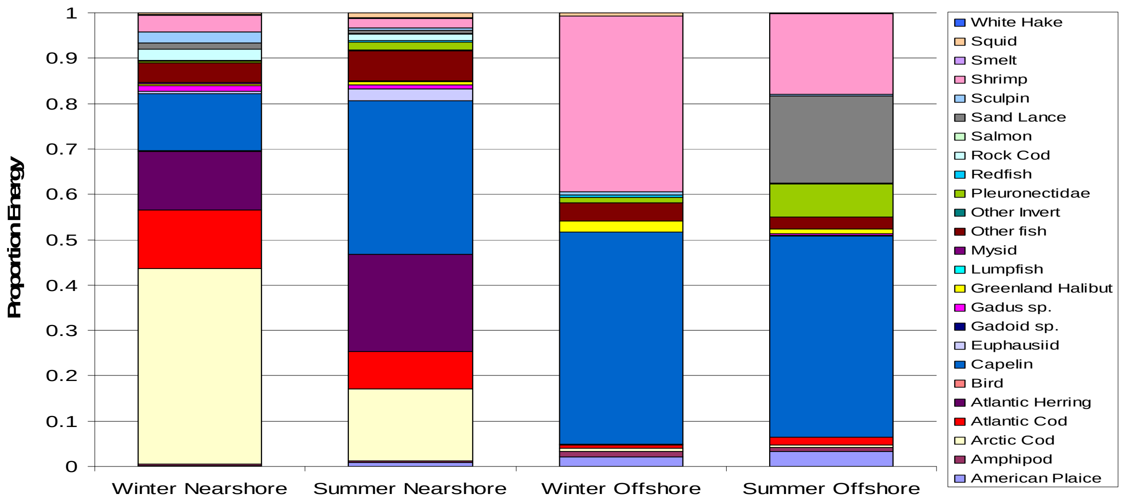

Figure 2. Diet of harp seals in 2J3KL determined from reconstruction of stomach contents of seals collected between 1986 and 2007.

We also estimated diet based upon a multinomial regression technique. This 'two tier' method estimates diet composition in biomass which, on one hand, allows to statistically testing the effects of different factors on diet composition, and on the other hand, provides a tool for reconstructing diet composition. The two-tier structure of this approach evolves from realizing that the classical calculation of proportion by weight in the diet can also be obtained by considering the probability of finding a given prey in a stomach and the mean weight of that prey in the stomach when it is present. For example, if N is the total number of predators in a sample, n_x is the number that actually contains a given prey x, and B_x is the total biomass of x in the collection, then the relative proportion of x in the diet (w_x) can be calculated as:

$$w_x = \frac{B_x}{\sum_I B_i} = \frac{(B_x/N)}{\sum_I (B_i/N)} = \frac{[(n_x/N)(B_x/n_x)]}{\sum_I [(n_i/N)(B_i/n_i)]} = \frac{p_x m_x}{\sum_I p_i m_i}$$

with

$$p_i = n_i / N \quad \text{and} \quad m_i = B_i / n_i$$

where p_x is the probability of finding prey x in a stomach and m_x is the mean weight of x in a stomach when x is actually present. Based on this reparameterization, the proportion in biomass can be calculated from independent estimates of p_i and m_i.

If each prey species in a stomach is consumed independently, using the above parameterization when considering all prey species in a stomach or just one of them should render similar results if the sample size is large enough. This idea was empirically supported by the comparison of harp seal diets obtained from classical diet analysis and the one obtained by only considering the most important prey in biomass in each stomach (Fig. 3). Since each stomach can be conceived as the individual realization of a multinomial experiment (one prey species is selected as main prey from a finite set of potential prey), the probability p_i can be estimated using multinomial regression models (a.k.a. multicategory logit models) (Agresti 2002). The use of these statistical models to estimate p_i allows including in the analysis several potential factors that may affect diet composition (e.g. age, year, area, sex, etc) and assess if they are actually significant for the case in question. Furthermore, these regressions can be used for estimating the p_i for combinations of factors not necessarily observed in the data, and hence, filling observation/sampling gaps. These probabilities, in conjunction with estimated (or reasonably approximated) m_i values can be used to reconstruct the predator diet. If time is one of the significant factors in these regressions, then the expected changes in diet over time can also be visualized (Fig. 4). The robustness of this multinomial regression approach to fill data gaps was explored by comparing predicted diets estimated from the full database with those obtained by fitting the model to reduced datasets (i.e. where blocks of data were removed). The results indicated that the method performed well at filling data gaps when interpolating within the database. In order to compare with the classical stomach content analysis, a tailor made randomization test was implemented. The results from this analysis suggested that for realistic coefficient of variations in the diet (CV=0.25), and if moderate to large sample sizes are available (n>90), the multinomial regression approach provides similar results to the classic diet analysis although difference may occur when samples sizes are small or when trying to estimate occurrence of rare prey.

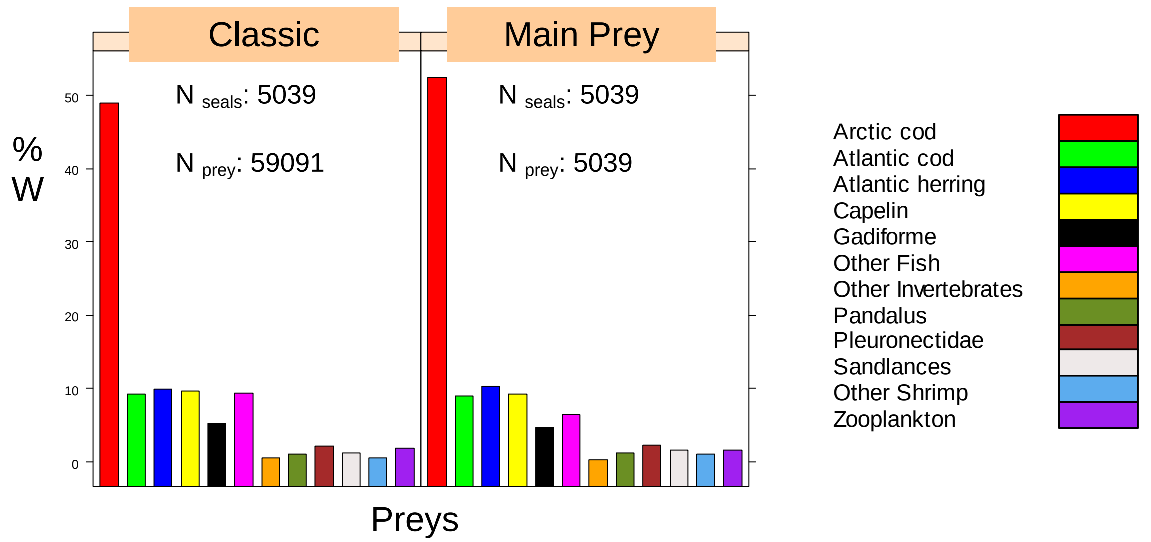

Figure 3. Comparison between the prey proportions by weight in the diet of harp seal from Newfoundland, Canada, using classical diet analysis and using only the main prey (see text for details).

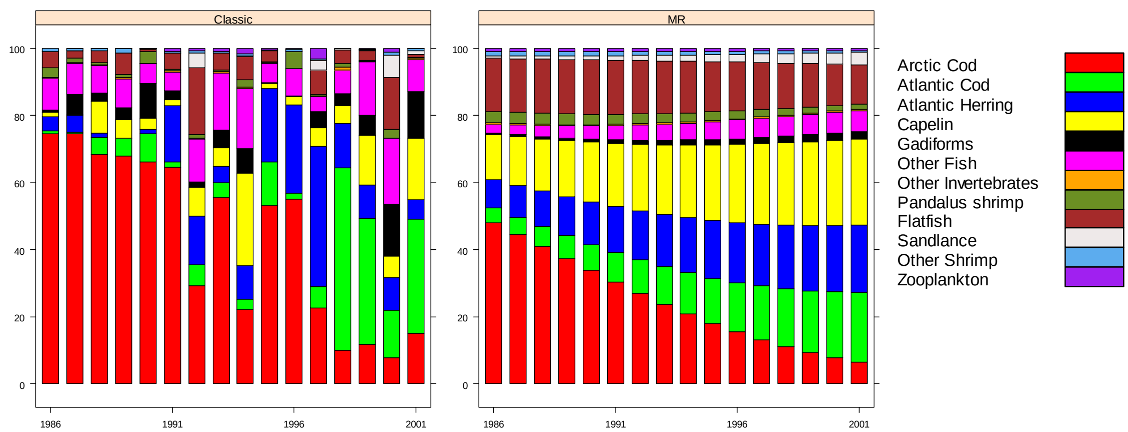

Figure 4. Predicted change over time for adult harp seals in the inshore waters of Newfoundland as estimated using the multinomial regression approach (MR) in comparison with the classic diet analysis.

Unlike the classical method, however, this method also resulted in estimates of significant proportions of Atlantic cod in the offshore diets. In contrast, diets estimates based on fatty acid signatures showed extremely low levels of Atlantic cod in the diet and none in offshore diets (Fig 5, Tucker et al. 2009). Diets of seals collected in different areas and seasons obtained from fatty acids were more similar than those estimated from reconstructed hard parts, likely as a result of the longer integration period represented by this method. This method also resulted in higher estimates of sandlance, redfish and amphipods, and lower estimates of Arctic cod, capelin and Atlantic herring.

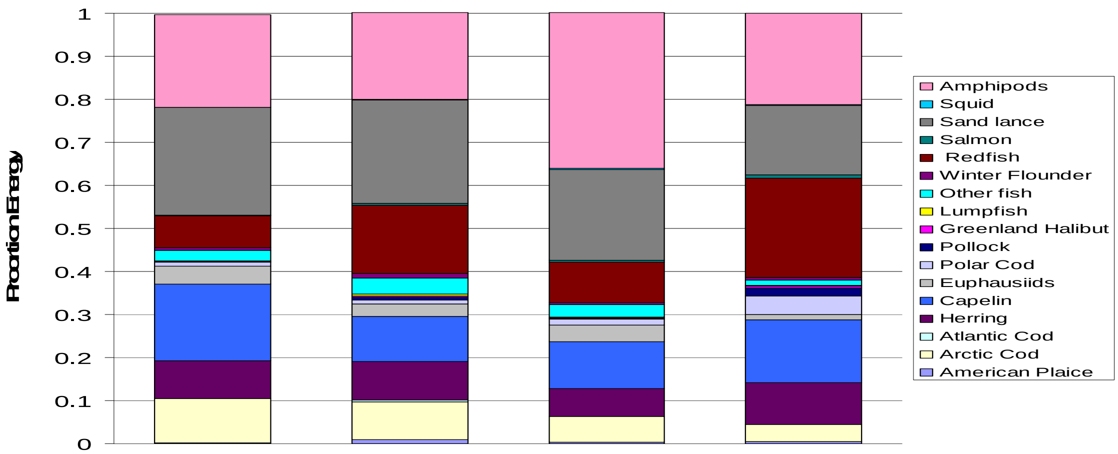

Figure 5. Diet of harp seals in 2J3KL determined from analysis of fatty acid signatures of blubber (from Tucker et al 2009).

Using these three methods of estimating diets resulted in very different estimates of cod consumption, although all were highly imprecise. Based upon the average diet obtained from reconstructed hard parts in the stomachs, consumption of Atlantic cod increased from approximately 40,000t in 1960 to over 80,000t by the mid 1990s (Fig 6). Since then it has remained relatively constant. Dividing the diet into northern and southern areas resulted in slightly higher estimates.

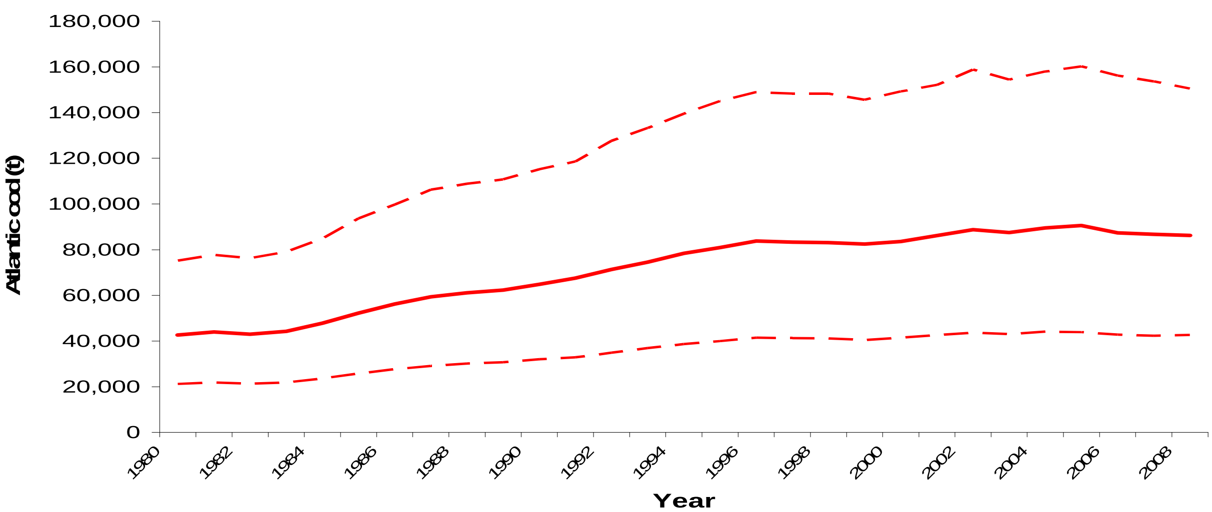

Figure 6. Estimated consumption of 2J3KL Atlantic cod by harp seals based upon the average proportion of cod in the diet from reconstructed stomach contents.

Using the diet estimated by the multinomial regression method resulted in estimates of cod consumption approximately 3 times higher, primarily due to the higher proportion of cod in all components of the diet (Fig. 7). Unlike the average diet, cod consumption was estimated to be increasing in recent years. In contrast to diets based on hard part analysis, only 1,000t of Atlantic cod are estimated to have been consumed by harp seals based upon the diets obtained from the fatty acid signatures (Fig 8). The length of cod consumed was estimated from the otoliths; samples collected in the 1980s and 1990s indicated that the vast majority of cod consumed were between 5 and 15 cm in length. Samples collected since 2000, however, indicate that larger cod have been consumed in recent years.

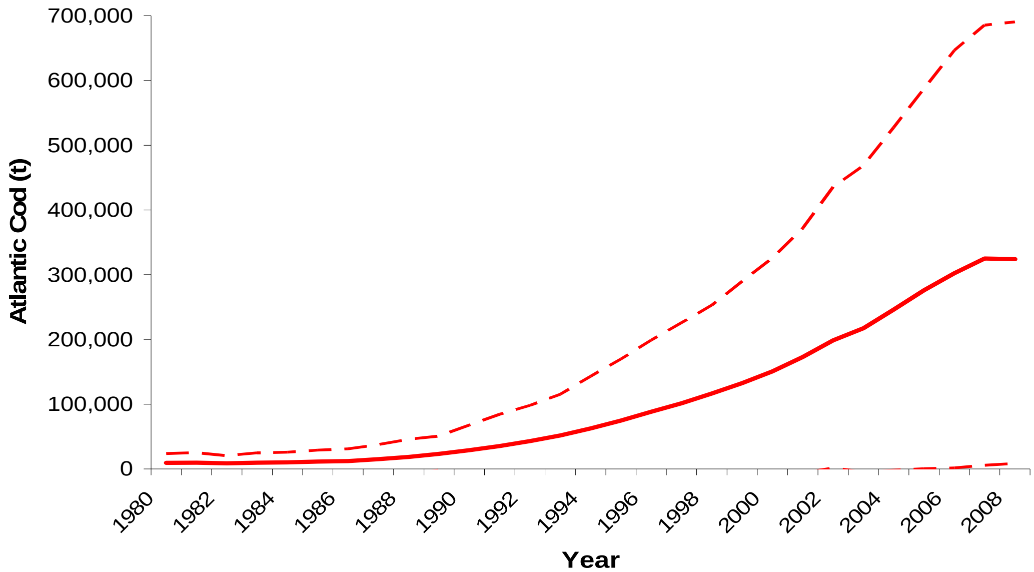

Figure 7. Estimated consumption of 2J3KL Atlantic cod by harp seals based upon the average proportion of cod in the diet using a multinomial regression technique.

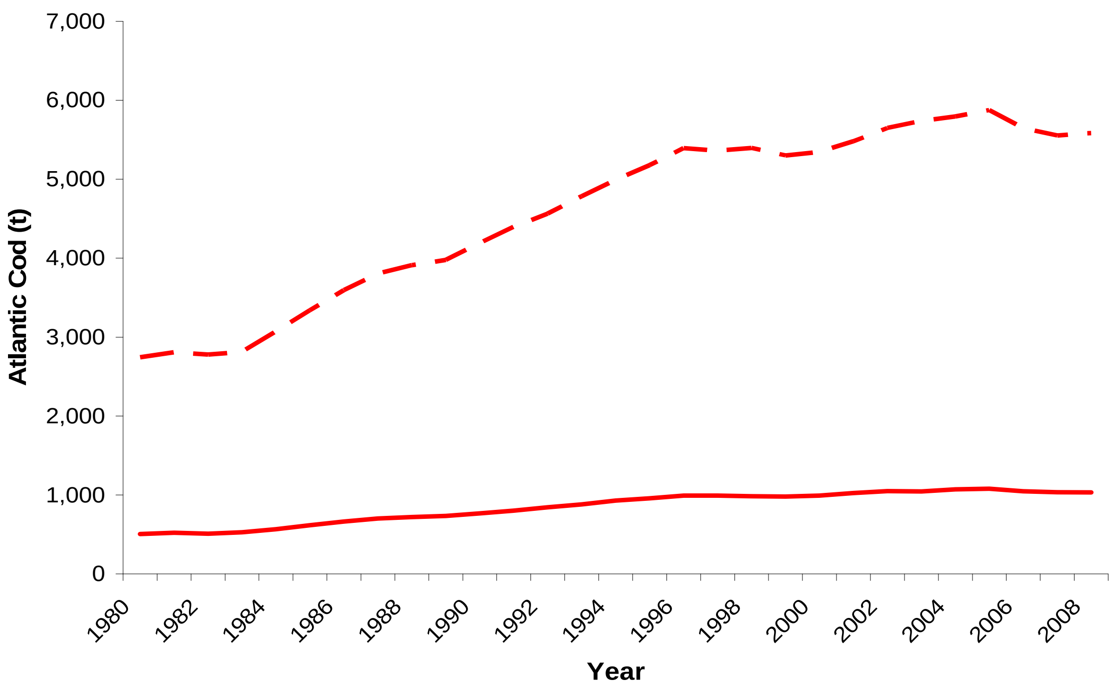

Figure 8. Estimated consumption of 2J3KL Atlantic cod by harp seals based upon the average proportion of cod in the diet using fatty acid signatures.

Interactions between cod, capelin and harp seals in 2J3KL

In order to explore common hypotheses about the non-recovery of the northern cod stock, the effects of harp seal predation, capelin availability, fisheries catches and physical environment (temperature) should be tested simultaneously and their relative empirical support weighed. However, this is an extremely complex problem and so as a first step, we explored the effects of predation, fisheries, and capelin availability, leaving the other components for further developments. We implemented a bioenergetic-allometric (Yodzis and Innes 1992) cod biomass dynamic model, where fisheries catches, consumption by seals, and capelin (food) availability were included as external forcers of the model. Fisheries catches were obtained from DFO and NAFO, the effects of capelin were incorporated by making the cod population growth rate a function of capelin availability (assumed proportional to DFO acoustic index) and the harp seal consumption of cod was estimated as described above using two different diet compositions: 1) 'classic' description based on classic stomach content analysis, and 2) reconstructed diet taking a multinomial regression approach. On the basis of this generic model, scenarios were explored by fitting different versions of the model to the observed DFO RV survey series for northern cod. These scenarios resulted from a combination of a) removing each forcer from the model independently and b) using the different estimates of harp seal consumption derived from the two diet descriptions considered. Due to their high uncertainty, consumption time series were also allowed to scale up or down according to an *ad hoc* scaling parameter estimated during the fitting process. The resulting models were ranked according using the Akaike Information Criterion corrected for sample size (AICc) (Burnham and Anderson 2002). The scenario that performed best was the one that did not include seal predation (Fig. 9). Based on the differences in AIC between models, all other scenarios can be dismissed (Table 1). These results suggest that for the study period, the consumption of cod by harp seals does not appear to be a significant driver of the stock. On the other hand, fisheries and availability of food emerged as significant drivers for northern cod. If these results hold after further scrutiny, having a healthy capelin stock would be a necessary element for a sustained rebuilding of the northern cod stock. This current model is being refined to determine if these preliminary results are supported.

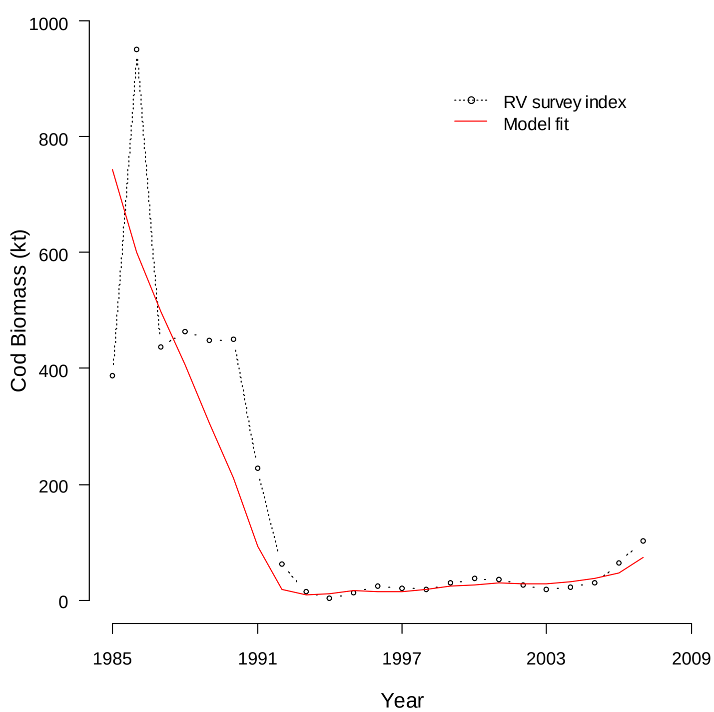

Fig. 9. Fit of the scenario 'No seals'.

Table 1. Model selection statistics

Scenario	$\ln[\mathscr{L}(\theta)]$	Number of fitted parameters	AICc	Δ AICc
No Seals	272.07	6	561.39	0.00
No capelin, classic, ASC	279.24	6	575.73	14.34
All effects, classic, ASC	281.15	7	583.77	22.37
All effects, MR, ASC	282.98	7	587.42	26.03
No capelin, MR, ASC	285.57	6	588.38	26.99
All effects, classic	288.61	6	594.47	33.08
No fishery, classic, ASC	288.22	7	597.91	36.52
No fishery, MR, ASC	288.42	7	598.31	36.92
All effects, MR	291.08	6	599.41	38.02

Classic means that the diet of harp seals was described using a classic approach.
MR means that the diet of harp seals was described taking a multinomial regression approach
ASC stands for 'adjusted seal consumption': the cod consumption was scaled by an estimated factor ˜ This allowed us to explore a wide range of potential consumptions (e.g. the consumption in 2007 was allowed to vary between 10 and 400 kt)
All effects means that the effects of food availability, and removals by fisheries and seals were included in the model
No seals means that the effect of cod consumption by seals was removed from the model.
No fishery means that the effect of fisheries catches was removed from the model.
No capelin means that the effect of food availability was removed from the model.

DIET OF HOODED SEALS IN THE NORTHWEST ATLANTIC

Hooded seals are the second most abundance pinniped in the northwest Atlantic. Reconstructing the stomach contents of hooded seals collect in the waters off the coast of Newfoundland and southern Labrador, Canada indicated that diets vary spatially and temporally (Stenson unpublished data). The main prey species in nearshore waters were squid (*Gonatus* sp.) and Greenland halibut, while the main prey species identified in a small sample of seals collected in offshore areas (n=40) were flatfish (Pleuronectidae), Atlantic cod and squid. Greenland halibut and redfish were also important prey.

Tucker et al. (2009) estimated the diet of hooded seals using fatty acid signatures obtained from the blubber. This method integrates diets over the period of blubber deposition, a period of 1-3 months. Generally, the diets of adult males and females were similar, but differed from those of juveniles. During the pre breeding period, adult hooded seals fed primarily upon redfish, amphipods, capelin and Atlantic argentine. Juveniles fed mainly upon capelin although argentine, sandlance (sand eel), amphipods and herring were also eaten. During the post breeding period, redfish were the most important prey for adult hooded seals. Lower proportions of capelin, argentine and longfin hake were also consumed. In contrast to data obtained from hard part analyses, fatty acids suggest that amphipods and argentine are important prey for hooded seals. The latter species has never been seen in the stomach contents although this may be due to its off-shelf distribution.

IMPACT OF SEALS ON ATLANTIC COD IN CANADA

DFO sponsored two workshops to review the evidence on impacts of seals on Atlantic cod stocks in eastern Canadian waters. The first workshop, held in Halifax November 12-16, 2007, reviewed what is known about seal-cod interactions and identified 1) gaps in our understanding, 2) analyses that could be completed for review at the second workshop, and 3) longer term research needs (Bowen et al 2008MS). The second workshop, held in November 2008, reviewed additional analyses relevant to cod-seal interactions and examined evidence for and against various hypotheses for the cause of elevated natural mortality of cod (Bowen et al 2009MS). During this meeting 24 presentations were given on the potential impacts of seals on fish stocks in Eastern Canada. These presentations, for the most part, were of new analyses and model results of research identified at the first Workshop that participants felt could be done with existing data. The meeting was attended by 33 invited ecologists and modellers from Canada, Norway, and France and members of the fishing industry in eastern Canada and north-eastern United States of America.

Industry has a strong view that seals are having a significant impact on cod recovery. Representatives stated that fishermen feel that grey seals pose a direct threat to depleted cod stocks and indirectly affect the industry through the transmission of the sealworm parasite to commercial species across an expanding geographic range. Fishermen also suspect that spawning success of cod is being negatively affected as grey seals find it profitable to prey on spawning aggregations on shallow banks.

There is considerable uncertainty in the factors affecting cod dynamics and in the magnitude of stock-specific seal predation mortality on cod. Preliminary results were presented from bioenergetic allometric and statistical catch-at-age models to evaluate the effects of seal predation, food competition and environmental variability on the dynamics of several cod stocks. These and previous multi-species models underscore the importance of considering seal predation in a broader ecosystem context as the effects of predation may often be conditional on the presence of competitors and quality of the environment for cod. Several studies underscored the importance of the proportion of cod in the diet and the size frequency distribution of cod eaten on estimates of seal predation mortality. Restricted sample collection (in both time and space) and the method used to estimate the diet can affect both the estimated proportion and size of cod eaten by seals.

Monte Carlo simulations were used to estimate the probability that different diet compositions of seals could explain natural mortality (M) for southern Gulf of St. Lawrence cod, white hake and winter skate. Results suggested that: 1) to explain elevated M seals must consume cod and white hake that are larger than indicated by the available stomach contents data; 2) whole fish consumption by seals is likely to explain less than 40% of M in white hake and cod, but can easily explain elevated M in winter skate, and 3) if seals consume some groundfish by belly-feeding, the probability that seal predation explains a substantial component of M becomes much more likely.

Harp seals are estimated to consume 28,000 t of 3Pn4RS cod, predominantly (56%) pre-recruits under 3 years of age. Grey seals were estimated to consume 14,000 t of 3Pn4RS cod in 1996, with a preference for larger cod than harp seals (25-35 cm versus 10-15 cm). Modelling indicates harp seal predation on juvenile cod could have significant impact on recruitment, under good conditions. Under poor oceanographic conditions other factors limiting recruitment are more important than harp seal predation (Chassot et al 2009).

There are temporal and spatial corrections between the abundance of grey seals and changes in natural mortality of cod in the southern Gulf of St. Lawrence (4T). Estimates of consumption indicate that significant amounts of 4T cod are being consumed (10,000-12,000 tonnes) but the stomach content data indicate that the diet is dominated by fish smaller than 35 cm long which is inconsistent with M is high for larger adult cod. Although the causes of elevated M in this stock remain unknown, , spatial and temporal correlations between grey seal abundance and estimated cod M support the hypothesis that grey seal predation is an important cause of the elevated M, whereas other hypotheses for the elevated M of 4T cod are not supported by the correlations between M and the hypothesized forcing factor.

Grey seals may also play an important role in the recovery of 4VsW cod. A large proportion of the NW Atlantic grey seal population used this area throughout the year where they are known to consume cod. However, estimates derived from fatty acids indicate only a small fraction (~2%) of the diet is cod while historical estimates based on otoliths indicate that cod account for a higher (~12%) proportion. Based on diets estimated by fatty acids, grey seal predation is considered to be a minor factor in the lack of recovery of cod; however, given the uncertainties in the diet, a more important contribution to the lack of recovery cannot be ruled out.

A small, but seasonally variable proportion (9-20%) of the grey seal population uses the 4X area. Grey seals presumably contribute directly to the mortality of 4X cod, but the level of this contribution is unknown due to a lack of diet data for 4X. Assuming the diet indicated by fatty acids for 4VsW, the effect would be negligible.

The impact of seals on 3Ps cod has not been examined. Although harp seals are known to consume cod in this area, they are transient and resident for only short periods. The use of this area by other seal species (e.g., grey seals) appears to be relatively minor. Similarly, impacts of seals on 3NO cod are thought to be insignificant because relatively few seals use this area.

The impact of cetaceans on cod has not been examined. Significant numbers occur in many of these areas and although the diet of most cetaceans species in the region are unknown, data from harbour porpoise and cetaceans in other areas indicate that Atlantic cod are consumed. Therefore, the recovery of cod may be impacted by cetaceans with through direct predation or competition for food.

However, two key uncertainties that can be applied to all areas are the true proportion of cod in the diet of seals and the age distribution of cod eaten by seals. Together these aspects of diet have a large effect on the putative impact of seal predation on the dynamics of cod. Furthermore, despite their importance, estimating the diet of seals is extremely difficult, given the challenges in obtaining representative samples from large, mobile and widely distributed seal populations.

Factors affecting cod dynamics

A number of hypotheses have been proposed to explain the lack of recovery of cod in Canadian waters. For most of the cod stocks that have not recovered, natural mortality remains above the ‘normal’ value of 0.2. Specifically, natural mortality is especially high in all stocks south of the Laurentian Channel. A number of factors may be contributing to the high M including: unreported catch (i.e., the mortality is due to fishing, not natural mortality), disease, contaminants, starvation (i.e., poor condition), life-history changes, impacts of seal predation, predation by other species, parasites, and other impacts. Bowen et al (2009MS) list evidence to evaluate the likelihood that various factors may have or are currently contributing to the elevated of natural mortality of cod for a number of stocks in Canada to place seal predation in a broader context. The summaries prepared for 2J3KL and 3NO cod are presented in Appendix I.

NAMMCO WORKING GROUP ON MARINE MAMMAL AND FISHERIES INTERACTIONS

In 1996 the North Atlantic Marine Mammal Commission (NAMMCO) struck a Working Group (WG) to examine research on the feeding ecology of minke whales, harp and hooded seals and methods of estimating consumption (NAMMCO 2009MS). It also considered the use of multi-species models to assess species interactions in the Barents Sea and Central North Atlantic. They concluded that minke whales, harp seals and hooded seals in the North Atlantic might have substantial direct and/or indirect effects on commercial fish stocks. Since then the WG has met a number of time to examine new research and identify ways to advance our understanding.

The most recent meeting of the WG took place in April 2009. The objectives of this meeting were to monitor progress made in multi-species modelling and in the collection of input data to decide if enough progress had been made to warrant further efforts in this area. A number of papers describing efforts to estimate diet and consumption by marine mammals in the North Atlantic and off Japan were presented, including the work on harp seals in 2J3KL discussed above. Of particular interest to the working group were the descriptions of new methods of estimating diet, particularly fatty acid signatures. The NAMMCO WG recognized the potential of fatty acid (FA) analysis for the determination of the qualitative and quantitative aspects of the diet of marine mammals, especially given the longer integration time. However, the methodology has to be further developed and validated as there are indications that the assimilation rates of prey fatty acids in the blubber vary among species and among fatty acids. Furthermore, the destination of the dietary fatty acids in the blubber profile and the differential utilization of the blubber profile by different species needs to be considered. In addition to continued research on the potential biases associated with the use of fatty acid signatures, NAMMCO (2008) also recommended additional research on the energy requirements of marine mammals, particularly harp seals, and that the regular gathering of data on predator and prey distribution and density, as well as diet data should be continued.

A number of modelling efforts were described to the Working Group. The Scenario Barents Sea Model developed in Norway over the past decade has many attractive features, both in its structure, not the least the functional response part, and in that a rather comprehensive handling of uncertainty was attempted. However, this model was originally designed to explore interactions among minke whales, cod and herring. Inclusion of the harp seal in the model made it difficult to estimate the parameters, most likely due to the weak data on harp seal feeding ecology, and the fact that the harp seal is a major top predator in the system. The model was simply not sufficiently stable and provided simulation results that were implausible. A possible reason for this is that important feed-back mechanisms are lacking.

More promising is the Icelandic GADGET (Globally applicable Area-Disaggregated General Ecosystem Toolbox) model. This model is currently being used for several species within Icelandic waters, the Barents Sea, the Celtic Sea, North Sea herring, the Tyrrhenian Sea and the Bay of Biscay. In spite of known problems, the program is currently used for assessments in several cases where no alternatives exist to account for known important processes within the system. Planned work includes setting up the GADGET data base for minke whales in Icelandic waters. Subsequently the minke whale model will be linked to updated models for cod.

In addition to these two models from the northeast Atlantic, a bulk biomass model (*Ecopath* with *Ecosm*) and a broad scale multispecies model of the Antarctic ecosystem (Mori and Butterworth 2006) were also presented.

The participants agreed that current efforts to model ecosystems are not sufficient to provide management advice. The multispecies modelling required in order to address management questions such as the impact on allowable catch levels for some commercial fish species of changes in the abundance of certain marine mammal populations is complex and in some circumstances different models, whose merits cannot be distinguished given existing data, can provide very different answers to such a question. Therefore, they proposed to initiate a study where at least three different modelling approaches are used to describe the same ecosystem. Potential modelling approaches include the Minimal realistic model (GADGET, a bulk biomass model (*Ecopath* with *Ecosim),* a time series regression technique developed in Norway and/or the simple biomass-based model such as one described above for 2J3KL. Possible ecosystems under consideration are the Barents Sea and the region around Iceland.

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APPENDIX I: Summaries of available information on factors affecting mortality in Canadian cod stocks (from Bowen et al. 2009).

NORTHERN COD (NAFO DIV. 2J3KL)

Estimates of the rate of total mortality (Z) of cod in 2J3KL are available from catch-at-age data from the autumn survey of the offshore portion of the 2J3KL stock area. Estimates are based on standard method of log ratio of the catch at age n versus age n+1 and are computed as an average for ages 4-6. Estimates for younger ages are not available as these are not fully recruited to the survey gear, and for older ages because there were too few cod > age 6 in survey catches in the post moratorium period. Estimates for Z were consistently high in 12 consecutive autumn surveys after the 1993 moratorium. The average annual value for Z (instantaneous rate) in the 1996-2007 period was 0.87, which corresponds to an annual death rate of 58% per year including a period when there was no directed cod fishery. In the most recent period (after 2003) Z seems to have declined substantially (Fig. 23). This change in Z is not expected to be related to survey coverage. Movements of cod to outside the survey area are not likely – deep waters have been fished sporadically during surveys but have not revealed significant quantities of cod. Movement inshore (other than seasonally) is also unlikely and most data suggest an ontogenic movement towards offshore as cod get older. Furthermore, there is evidence from several independent sources that corroborate the recent decline in Z in the offshore (e. g. increased by-catch of older cod in northern 3L turbot fishery, increased catch of cod in DFO spring survey of 3L, acoustic-trawl survey of offshore 3KL found significant aggregation of cod along shelf edge in 2007 and 2008, broadening of age structure).

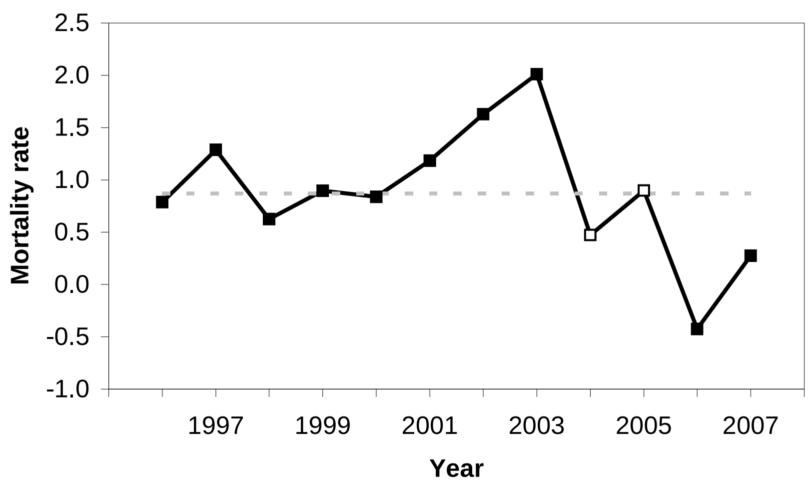

Figure A1: Total mortality rate (Z) of cod aged 4-6 calculated using data from the autumn RV surveys in the offshore of 2J3KL. For example, the value in 1996 is the mortality experienced by the 1991-1989 year-classes from ages 4-6 in 1995 to ages 5-7 in 1996. The dashed line is the average (Z=0.87, which corresponds to 58% mortality each year). Open symbols indicate estimates based on an incomplete survey in 2004.

Hypotheses

1) Catch: The high rate of Z is unlikely to be due to fishing; non-Canadian fishing occurs on the nose of the Grand Banks (3L), but estimates of foreign catch of cod have been < 80 t and declining in recent years. Estimates of mortality due to domestic shrimp trawling offshore are also low based on observer based sampling scaled up to the whole shrimp fleet. The decline of Z in the most recent period (after 2003) has occurred at the same time an inshore fishery for cod was reopened suggesting that the rate of natural mortality has declined substantially (i.e. F has increased but Z has still continued to decline). In reference to unreported catches, available data suggests that it cannot account for the high Z levels prior 2003. ***Conclusion: Unreported catches are not thought to be a significant source of mortality.***

2) Diseases and Parasites: There are no reports of significant incidence of disease related mortality incidents in northern cod, but no formal surveillance or study of aquatic animal health is available. ***Conclusion: This possibility can not be ruled out due to lack of evidence one way or another.***

Regarding parasites, *Lerneaocera branchialis* is a parasitic copepod found on the gills of cod, mostly inshore on juveniles (ages 1-3) and it is rare in offshore and in older fish. The copepod feeds on the hosts' blood and infection is associated with lower body condition; it can infect a considerable percentage of small cod in some area (~15%). ***Conclusion: This parasite may kill some small cod, but is not thought to be a major source of mortality in the stock as a whole.***

3) Contaminants: Yeats et al (2003) is the only known examination of contaminant loads and it provides no indication that they are abnormally high. Although this source of mortality cannot be ruled out, it is assumed that contaminant loads are lower than the North Sea (or Baltic) levels where no M changes have been reported. ***Conclusion: Contaminants are not thought to be significant source of mortality.***

4) Starvation/poor condition:

Condition: Time-series information on 2J3KL cod condition comes mainly from sampling during autumn RV surveys. There is a strong seasonal cycle in cod condition with lowest values typically in spring after spawning and highest values in autumn; consequently, lowest condition levels would not be necessarily evident in the data available. Based on autumn surveys, cod condition was lower in 2J in early 1990s compared to 1980s, and has recovered somewhat but remains lower than was seen in the 1980s. Condition in 3K has been variable with some decline in the early 1990s with current values close to the long-term average. Condition in 3L has been variable but did not undergo the decline seen further north.

Growth: Length at age was higher in the late 70s/early 80s than currently, particularly among older fish. The trend towards lower mean length at age reversed from the low point in 1990s. The decline was greatest in 2J, and in last few years values of length at age are around the average for the whole 1978-2005 period. Fish with age 6+ disappeared from 2J during 1991-2005 so results for these older fish cannot be compared. Overall there was more of a decline in 2J, less of a decline in 3K but same overall trend, and no decline seen in 3L. The apparent lack of a strong improvement in growth rates in spite of greatly reduced population size suggests that the stock is not as productive as it was in the past (with much lower cod density better growth might be expected).

Conclusion: The biological data based on sampling during the autumn research surveys indicate that aspects of stock productivity such as growth and condition have improved over values in the 1990s, but are below the peak values observed in the early part of the time series, especially in the north (2J). The impact of these changes on M is not clear.

Productivity: Productivity of the cod stock has been reduced since the mid-1980s but some aspects of productivity appear to be improving in recent years (after 2003). In the offshore, numbers (abundance) and biomass have increased by about 30% per year and 60% per year, respectively, since 2003, but the increases are taking place mainly in one region, along the 3K-3L border. The increases appear to be due to improved survival and growth of the 2000-2002 year-classes and not due a pulse of recruitment which remains low. There is a suggestion that this trend in cod appears to be linked to the availability of food resources (capelin). Specific information to support this suggestion was not available at the cod assessment, although a general improvement in the status of capelin was noted. Although the improvement in capelin indicates that this stock is in better shape than observed in the mid-1990s, it is still way below the level observed in the late 1980s. The time series of information of capelin abundance is poor and for the recent period mostly based on acoustic surveys in only a portion of the stock area of 2J3KL cod.

Conclusion: Ongoing analyses from a simple biomass-based model exploring the impact of several factors on cod dynamics (harp seals predation, capelin availability and fisheries) are consistent with the notion that changes in productivity (i.e. capelin availability) appear to be an important factor in explaining the lack of recovery of this stock and may be contributing to the high M inferred previously.

5) Life history changes: The age at maturity dropped rapidly in the mid to late 1980s and remains low (~4.9 yr for females) in the recent period and has not shown signs of improvement. The age structure of the population has been highly contracted in the offshore component as a result of the high Z, with very few cod older than age 6 in the offshore up to 2005. Rose and Fudge (2008) suggest cod in north spawn much earlier, produce many more eggs than they used to, and then die at a much higher rate, implying a much higher post-spawning mortality rate. ***Conclusion: Age-at-maturation remains low and values for the most recent cohorts are among the lowest observed but the relationship to changes in M is unknown.***

6) Seals: Estimates of Atlantic cod consumption by harp seals are imprecise and dependent upon the diet assumed. If annual estimates of diet are considered (instead of average diet over time), the amount of cod consumed increases since the late 1980s due, primarily, to an increased occurrence of Atlantic cod in near shore diet samples. Earlier model results using Ecopath with Ecosim and presented in 2001 indicated that harp seals may have an impact on the recovery of 2J3KL cod. However, preliminary results from a recently developed biomass-based model explicitly implemented to simultaneously explore the impact of several factors on Northern cod dynamics (seal consumption, fisheries and prey availability) suggested that harp seal predation has not being a significant factor in the lack of recovery to date. Although these later results are still preliminary, the model already considered a wide range of consumption scenarios to accommodate the large uncertainty around consumption estimates. Although this contradiction can be traced back to several of the structural differences and assumptions between the two models, in practical terms it highlights the high level of uncertainty which truly surrounds the impact of seal consumption on cod dynamics. ***Conclusion: expectations of clear-cut, direct relationship between seals and cod are not supported by the available evidence.***

Beside predation, other possible interaction between harp seals and cod is competition for prey. The more recent model indicated that capelin is a significant factor in cod productivity and capelin is also an important prey for harp seals. However, detecting competitive effects is even more complex than predation effects and the possibility of competition for prey has not been properly examined to date, although there are ongoing efforts directed to explore this possibility. ***Conclusion: the impact of competition between cod and seals is unknown but may be a non-trivial contributing factor to the level of M experienced by cod.***

The impact of other seal species like hooded seals on Atlantic cod has not been examined to date, although they are abundant in offshore areas and known to consume Atlantic cod.

7) Other predators and/or competitors:
Although seals probably are the most visible candidate to have predation and/or competitive effects on cod, there are several other predators which could also have significant impacts on cod. Recent aerial surveys indicated that there are significant numbers of cetaceans in the region. Diets of most cetacean species in the area are unknown although data from harbour porpoise and cetaceans in other areas indicate that Atlantic cod are consumed. Furthermore, trends in abundance of the vast majority of cetaceans are also unknown although Humpback whales have been shown to have increased since whaling ended.

Fish predators can also have an impact on cod. A comparative study of the diets of cod, Greenland halibut and harp seals suggested that both predators are potential competitors of Atlantic cod, but the diet of Greenland halibut bears a higher resemblance to the diet of cod than harp seals does. Also many cetaceans and sea birds are known to feed on capelin and therefore may compete for food with cod.

Conclusion: The impact of consumption and/or competition between cod and predators other than seals is unknown but may be a plausible contributor to the observed levels of M.

8) Environmental forcing:
Physical environment may have an impact on the population dynamics of Atlantic cod that may affect mortality either directly or through other factors. Cod are generally less productive during cold periods (grow more slowly) and recruitment may be less successful. In addition, there have been incidents of direct mortality associated with extreme cold water. For example, cold water has been suggested as the causative factor in a mortality event observed in Smith Sound in April 2003. This was a local event –associated with extreme temperatures (-1.6 C) at a known over-wintering location of cod. Approximately 800 t of dead and dying cod were harvested in March-April 2003. Underwater video and trawling did not indicate substantial amounts of dead cod on the bottom. This event occurred during a period when the inshore stock was declining, mostly due to a resumption of fishing as tag return information indicated that fishing mortality was high in spite of the relatively small catch (4,000 to 8,300 t

annually). The overall impact on the inshore stock could not be evaluated but based upon tag returns from the harvested cod it did not appear to represent more than 5% of the available tagged cod.

Several other isolated mortality events were observed in the inshore of 3KL during 1997-2003 where dense schools of cod were observed very close to shore, often in association with harp seals, ice, and/or herring. These events were observed in Notre Dame Bay and Bonavista Bay. Some predation by seals was observed directly, and in at least one incident (at Virgin Arm) several thousands of pounds of dead cod were observed on the bottom, but it was not clear if this was due to predation or fatal harassment where cod were herded into extremely cold water, or they followed herring and were trapped by cold water masses.

Conclusion: Mortality due to environmental forcing may have contributed to higher mortality in some local areas but there is no evidence of significant mortality in recent years.

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COD (NAFO DIV. 3NO)

There is no evidence suggesting that M has increased in this stock. No change in M is assumed in the post-moratorium period from the customary value of 0.2.

1) Catch: Although this stock is under moratorium, bycatch levels are high and imposing fishing mortality levels comparable to years where fishing was allowed. ***Conclusion: Significant by-catch (Canadian and foreign) is thought to be a major source of mortality and is impeding recovery of this stock.***

2) Disease: There are no reports of significant incidence of disease but no formal surveillance or monitoring of aquatic animal health takes exists for this stock. ***Conclusion: This possibility can not be ruled out due to lack of evidence one way or another.***

3) Contaminants: Again, Yeats et al (2003) is the only known examination of contaminant loads and it provides no indication that they are abnormally high. ***Conclusion: Although it cannot be ruled out, it is assumed that contaminant loads are not a problem for this stock.***

4) Starvations/poor condition:

Condition:

Condition was not evaluated at the most recent assessment of 3NO cod

Growth:

Beginning of the year weight-at-age from sampling of commercial catches indicates that values in the more recent period tend to be slightly higher than in the pre-moratorium period.

Productivity:

The 2007 assessment concluded based on deterministic projections and analyses using ADAPT that the average recruits per spawner from 2004-2006 was 0.14 compared to a historical average of 0.72 for the 1959-2006 time series, indicating that the stock is not as productive as it was in the past.

Conclusion: Lower productivity may be affecting the population dynamics of this stock although growth does not appear to be lower than in the past.

5) Life history changes: The age at maturity dropped rapidly in the mid to late 1980s and remains low, similar to the trend observed in other cod stocks.

6) Seals: Consumption of cod by harp and/or grey seals has not been examined. Harp seals are only occasionally observed in this area; but the few diet samples examined do not indicate that Atlantic cod is consumed. Based on satellite tracking, available data indicates that grey seals do not go to this region. ***Conclusion: Although consumption buy seals has not been estimated, it is thought to be small.***

7) Other predators and/or competitors: Like in other areas, recent surveys indicate significant numbers of cetaceans in the region. Similarly, the diets of most cetacean species in the region are unknown. ***Conclusion: Although it is expected that some consumption on Atlantic cod occurs, there is no information to assess this potential impact.***

9) Environmental forcing: Although it would be expected that it may have an impact on the population dynamics of Atlantic cod that may affect mortality either directly or through other factors, there is no directed studies on this issue for this specific stock.