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## Chapter 35

# The Rise and Fall (Again) of the Porbeagle Shark Population in the Northwest Atlantic

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### Abstract

A comprehensive population dynamics analysis of porbeagle shark (*Lamna nasus*) in the Northwest Atlantic indicates that the population has collapsed for the second time in its 43-year fishing history. The virgin population in the early 1960s supported annual catches of over 9,000 metric tons (t) before the fishery collapsed in 1967. After a partial recovery over the next 25 years, annual catches of 1,000–2,000 t throughout the 1990s appear to have once again driven the population to record-low numbers. Both the size and the age composition of the catch have declined markedly since 1990, with relatively few large sharks left in the population. Commercial catch rates are now only 10–30% of those in the early 1990s. Both Petersen calculations based on tag recaptures and an age- and sex-structured population model suggest that recent biomass is 10–20% of that present in the virgin population. Porbeagle have a low pup production rate and mature considerably after the age at which they first appear in the fishery. In light of the very low numbers of mature females now found in the population, it is unlikely that even the strict quota management that has been implemented will allow the population to rebuild quickly. However, a 75% reduction in fishing mortality, accurate monitoring of catch, effort, and size composition, and area closures to protect mating aggregations have all been put into place to allow population recovery.

**Key words:** porbeagle, *Lamna nasus*, overfishing, population dynamics, stock abundance.

### Introduction

The porbeagle shark (*Lamna nasus*, Lamnidae) is a large, cold-temperate pelagic species that occurs on both sides of the North Atlantic Ocean, as well as in the South Atlantic and South Pacific Oceans. In the Northwest Atlantic, the species range extends from Newfoundland to New Jersey and possibly to South Carolina, but it is most abundant off the eastern coast of Canada between the Gulf of Maine and Newfoundland (Templeman,

1963). It is the only large shark species for which a directed commercial fishery exists in Canadian coastal waters (Hurley, 1998).

Even though surprisingly little is known of the biology of this species (Aasen, 1963; Francis and Stevens, 2000) and almost nothing of its population dynamics, the porbeagle population in the Northwest Atlantic has often been cited as a clear example of stock collapse in an elasmobranch (Anderson, 1990; Walker, 1998; Stevens *et al.*, 2000). This widely accepted conclusion is based on the detailed catch records of the Norwegian longliners who first arrived in the Northwest Atlantic to fish the virgin (previously unfished) population in 1961. By 1967, the fishery had almost disappeared because of low catch rates and "unprofitable sizes" (Myklevoll, 1989). At the time it was clear that the fishery had suffered an economic collapse. What was not so clear was whether there had been a corresponding population collapse.

In recent years, an increasing number of countries have considered legislation to protect endangered elasmobranch populations, highlighted by the Food and Agriculture Organization's (FAO) International Plan of Action for the Conservation and Management of Sharks, which noted that many of the world's shark species are severely depleted (FAO, 1998). Numerous authors have documented the low productivity of elasmobranchs compared to teleosts, largely owing to their low fecundity and delayed age at sexual maturation, and have suggested that only a handful of fast-growing, fecund species are able to sustain a fishery (Cortés, 1998; Walker, 1998; Musick, 1999; Stevens, 1999). Because the porbeagle collapse has received such widespread attention, it is important that the fishery collapse and any subsequent recovery be documented and understood. This chapter presents the first complete analysis of the past and present status of porbeagle population dynamics in the Northwest Atlantic. It builds upon a recent population dynamics analysis by Campana *et al.* (2002b). New to the current analysis are direct estimates of the natural mortality rate, virgin population biomass, and yield per recruit, and a comprehensive age- and sex-structured population model. The analysis concludes with an evaluation of the likelihood of population recovery after a period of unsustainable exploitation.

## **Fishery and population dynamics**

### ***The fishery***

The fishery for porbeagle sharks in the Northwest Atlantic (NAFO areas 3–6) started in 1961 when Norwegian vessels began exploratory fishing on what was then a virgin population. These vessels had previously fished for porbeagle in the Northeast Atlantic, and they were joined by vessels from the Faroe Islands during the next few years. Reported landings in the Northwest Atlantic rose from about 1,900 t in 1961 to over 9,000 t in 1964, and then fell to less than 1,000 t in 1970 (Fig. 35.1). Although the fishery remained unrestricted, landings were less than 500 t until 1989. Reported landings rose to about 2,000 t in 1992 as a result of increased effort by Faroese vessels and the entry of Canadian vessels. Faroese participation was phased out of the directed fishery by 1994, at which time total landings by three Canadian offshore pelagic longline vessels and a number of inshore vessels was about 1,600 t. Since that time, the fishery has been almost exclusively

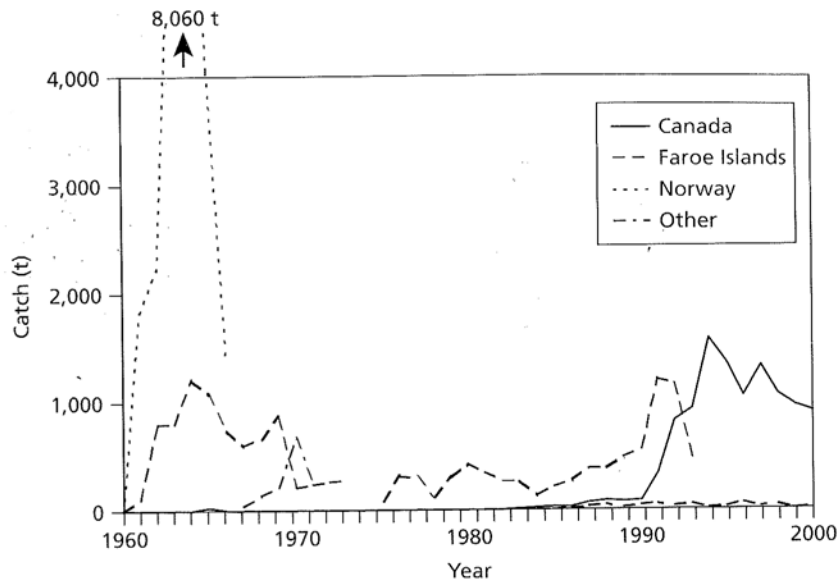
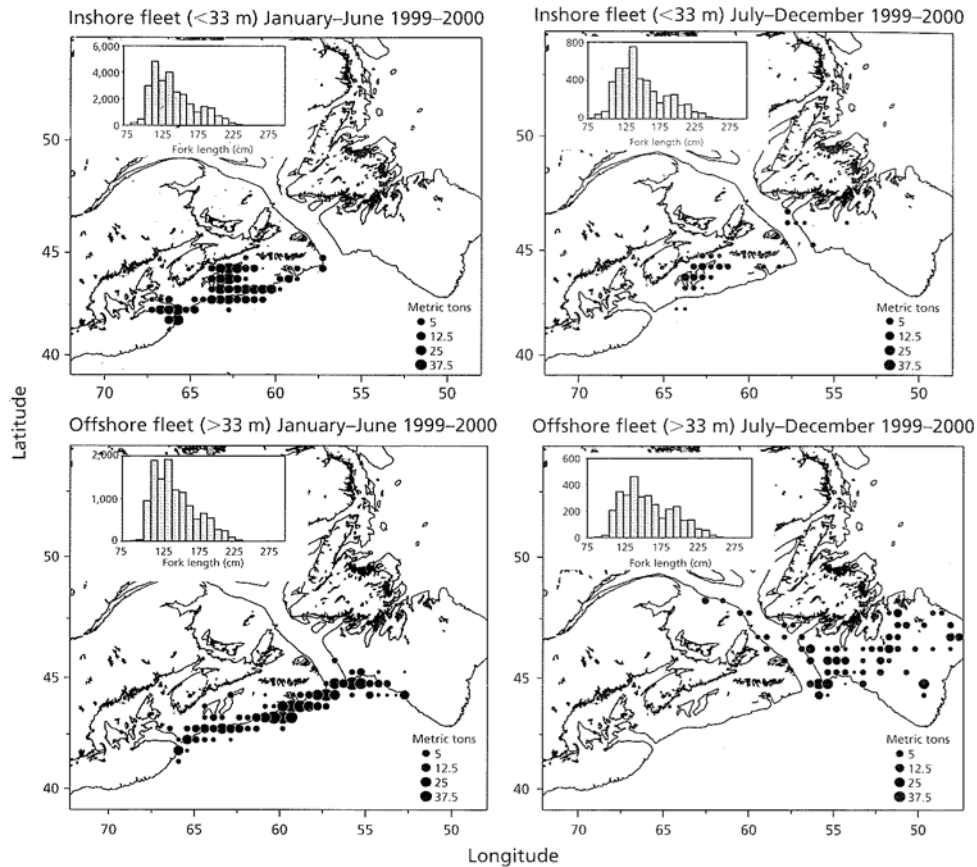


Fig. 35.1 Reported landings (in metric tons) of porbeagle in the Northwest Atlantic by country.

Canadian, with landings declining gradually to 1,066t in 1998. Landings from 1998 to 2001 were restricted by quota control to below 1,000t, and further restricted to 250t beginning in 2003. Detailed landings data were presented in Campana *et al.* (2002b).

The first fishery management plan for any pelagic shark species in Atlantic Canada was implemented in 1994. The plan provided for the collection of catch and effort data through the completion and submission of logbooks, and for collection of sampling data (species, sex, length, weight) for each shark landed through a dockside monitoring program. In 1997, a more comprehensive plan was released to govern the exploitation of all large pelagic shark species through the maintenance of a biologically sustainable resource and a self-reliant fishery. Conservation was not to be compromised and a precautionary approach was to guide decision making. All licenses issued under the plan were to be considered exploratory while scientific information was collected and the sustainability of the resource was evaluated. The management plan of 2000–2001 was the first to be based on the new scientific data and the accompanying analytical stock assessment for porbeagle (Campana *et al.*, 1999). In addition to a reduced quota, the plan restricted access to porbeagle mating grounds off southern Newfoundland. Relying on additional scientific information and an improved stock assessment, the management plan of 2002 reduced allowable catches of porbeagle by a further 70% and eliminated access to the mating grounds (Campana *et al.*, 2001). Further details of the shark management plan and of porbeagle management history are presented in Campana *et al.* (1999, 2001).

Porbeagle sharks are taken almost exclusively by a Canadian directed longline fishery that focuses on largely immature porbeagles on the Scotian Shelf in spring and on larger, primarily mature animals off Newfoundland and the Gulf of St. Lawrence (NF-Gulf) in the fall (Fig. 35.2). Both inshore and offshore fleets fished the Shelf in the spring of



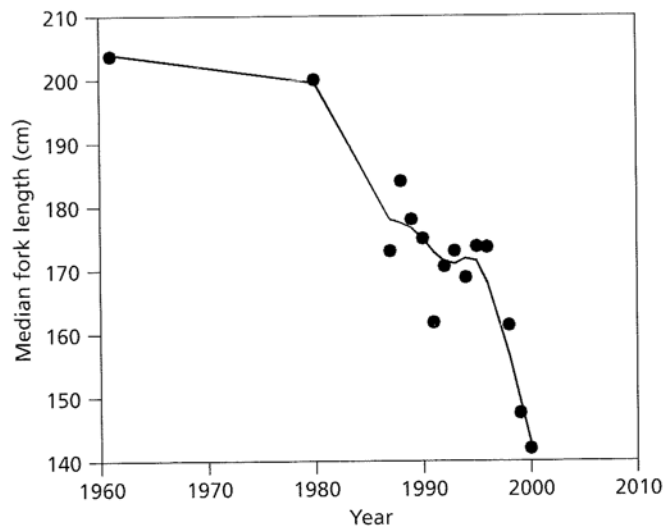
**Fig. 35.2** Catch location and associated length composition for Canadian inshore (<33 m) and offshore (>33 m) vessels in spring (January–June) and fall (July–December) of 1999–2000. The size of the symbol is proportional to the size of the catch.

recent years, although the offshore fleet tended to fish near the edge of the continental shelf while the inshore fleet fished well onto the Shelf. Fishing by both fleets was minimal in the summer. In the fall, the small amount of catch taken by the inshore fleet was mainly from the Scotian Shelf, while the much larger offshore catches were made in the Gulf of St. Lawrence, off southern Newfoundland, and on the Grand Banks (Fig. 35.2).

Porbeagle bycatch in the Canadian swordfish (*Xiphias gladius*, Xiphiidae) longline fishery, the Japanese tuna (*Thunnus* spp., Scombridae) longline fishery, and various inshore fisheries is minimal, seldom exceeding 40 t in recent years (Table 35.1). Though the reported catches of shortfin mako (*Isurus oxyrinchus*, Lamnidae) and unspecified sharks prior to 1996 were likely to have been mainly porbeagle, the effect on the overall catch trend is minimal. The International Observer Program has maintained 100% coverage of foreign catches in the Canadian zone since 1987, thus ensuring the accuracy of the foreign catches since that time. The recreational fishery for porbeagle sharks is minimal.

**Table 35.1** Landings (t) of porbeagles, sharks reported as makos, and unspecified sharks by fishery from Canadian waters; total allowable catch is for porbeagle only.

Year	Directed longline	Swordfish bycatch	Tuna bycatch	Other bycatch	Reported as mako	Reported as unspecified shark	Total shark	Total allowable catch
1991	329	0	0	0	0	185	514	—
1992	805	0	0	9	0	171	985	—
1993	912	0	0	8	4	174	1,098	—
1994	1,552	9	2	18	142	121	1,844	—
1995	1,313	21	0	15	111	40	1,500	1,500
1996	1,024	6	1	24	67	20	1,142	1,500
1997	1,295	6	0	40	86	43	1,470	1,000
1998	1,020	8	0	28	71	37	1,164	1,000
1999	930	2	1	23	64	16	1,036	1,000
2000	888	2	1	8	62	13	974	850



**Fig. 35.3** Long-term changes in the median size of porbeagles in the commercial catch by the offshore fleet during September–October on the southern Newfoundland mating grounds. A Loess curve has been fit to the data.

### *Trends in length and age composition*

A biological indicator of a high exploitation rate is a long-term decline in fork length in the catch. Because more than 142,000 porbeagle measurements were collated from a variety of sources for this study (Campana *et al.*, 2002b), analyses of trends in median size at age were possible. A plot of median fork length (measured over the curve of the body) against year of collection showed a long-term decline on the NF-Gulf mating ground in early fall (Fig. 35.3). The median lengths for the years prior to 1980 are most representative of the length composition of a lightly fished population. In contrast, 1999 and 2000 were characterized by very low median sizes, indicating the loss of many sharks of mature

size. There were no consistent long-term trends in size composition on the Scotian Shelf, an area dominated by smaller, primarily immature porbeagles.

Age determinations are an important component of a population analysis because ages form the basis for both growth and mortality rates. Natanson *et al.* (2002) presented a validated growth model for Northwest Atlantic porbeagles based on counts of growth bands in vertebral cross sections. The accuracy of the age interpretations was validated to an age of 11 years using known-age and tetracycline-injected recaptures (Natanson *et al.*, 2002), and subsequently to an age of 26 years using bomb radiocarbon dating (Campana *et al.*, 2002a). Although there was evidence of sexually dimorphic growth after the onset of sexual maturity, the difference in size at age was small. Therefore, a sex-combined growth curve was used to convert catch at length to catch at age using the approach described in Campana *et al.* (2002b).

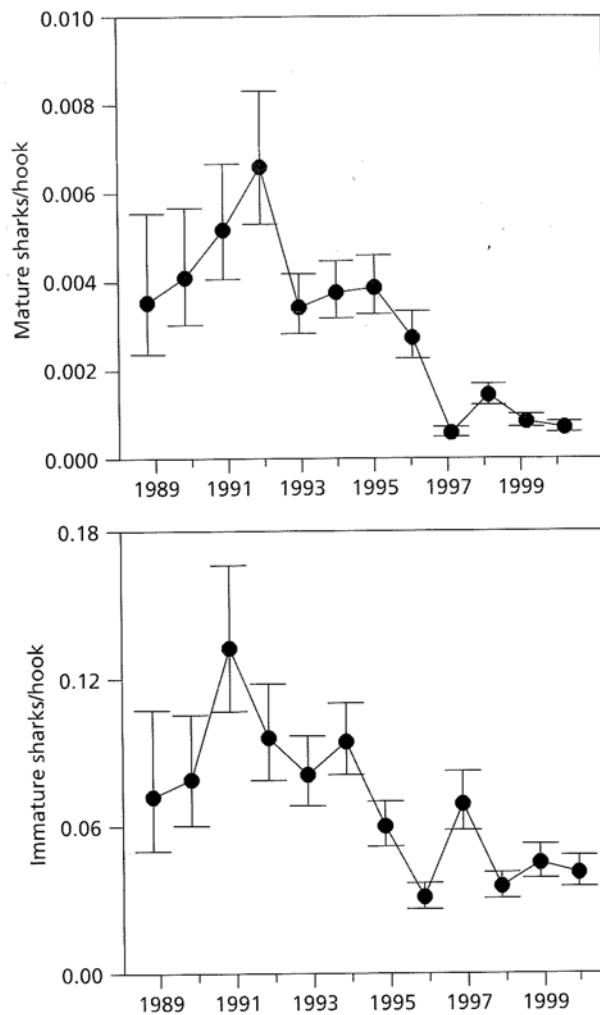
The age composition of past and present landings shows evidence of increased exploitation. In recent years, the age of full recruitment to the fishery has dropped to only 2–3 years in all areas. Prior to 1993, full recruitment occurred at 6–7 years. Prior to 1991, the most abundant age class off southern Newfoundland in the fall was 10–15 years, consistent with the use of this area as a mating ground by a lightly fished population. In contrast, porbeagle less than 3 years were the most abundant age classes in the NF-Gulf catch of 1998–2000.

### ***Commercial catch rates***

The overall trend in catch rate was analyzed using a linear model with subarea, month, fishing vessel, and year as factors (Campana *et al.*, 2002b). Calculations were based on directed longline catches, which account for virtually all historical catches. The standardized catch rate of mature porbeagles increased significantly between 1989 and 1992, but declined sharply afterward as effort increased and the abundance of the large sharks declined (Fig. 35.4). The 2000 point is the second lowest in the time-series, and is 10% of the 1992 value. The standardized catch-rate model for immature porbeagles was also highly significant, and also showed a significant decline since the early 1990s (Fig. 35.4). The 2000 point is about 30% of the 1991 point. However, the catch rate has remained roughly stable since 1996 (ignoring the 1997 value, which is also anomalous in the mature catch-rate series), consistent with the fleet-specific catch rates (Campana *et al.*, 2001). Overall, these catch rates suggest a monotonic and disturbing decline in the abundance of mature sharks, with a low but stable rate for immature sharks.

### ***Estimation of rates of natural and total mortality***

Trends in ln-transformed catch at age (catch curves) are shown in Fig. 35.5. The upper three panels show the catch curves of the 1961 (virgin) population, while the remainder show the catch curves for each of 3 recent years. Total instantaneous mortality rates ( $Z$ ) based on the slope of the descending limb of the catch curve indicate that recent mortality rates have usually been higher than those of 1961. However, the exact mortality rate in recent years may be underestimated by the reduced abundance of young sharks. This effect is shown by a much-reduced ascending limb to the catch curve, indicating an

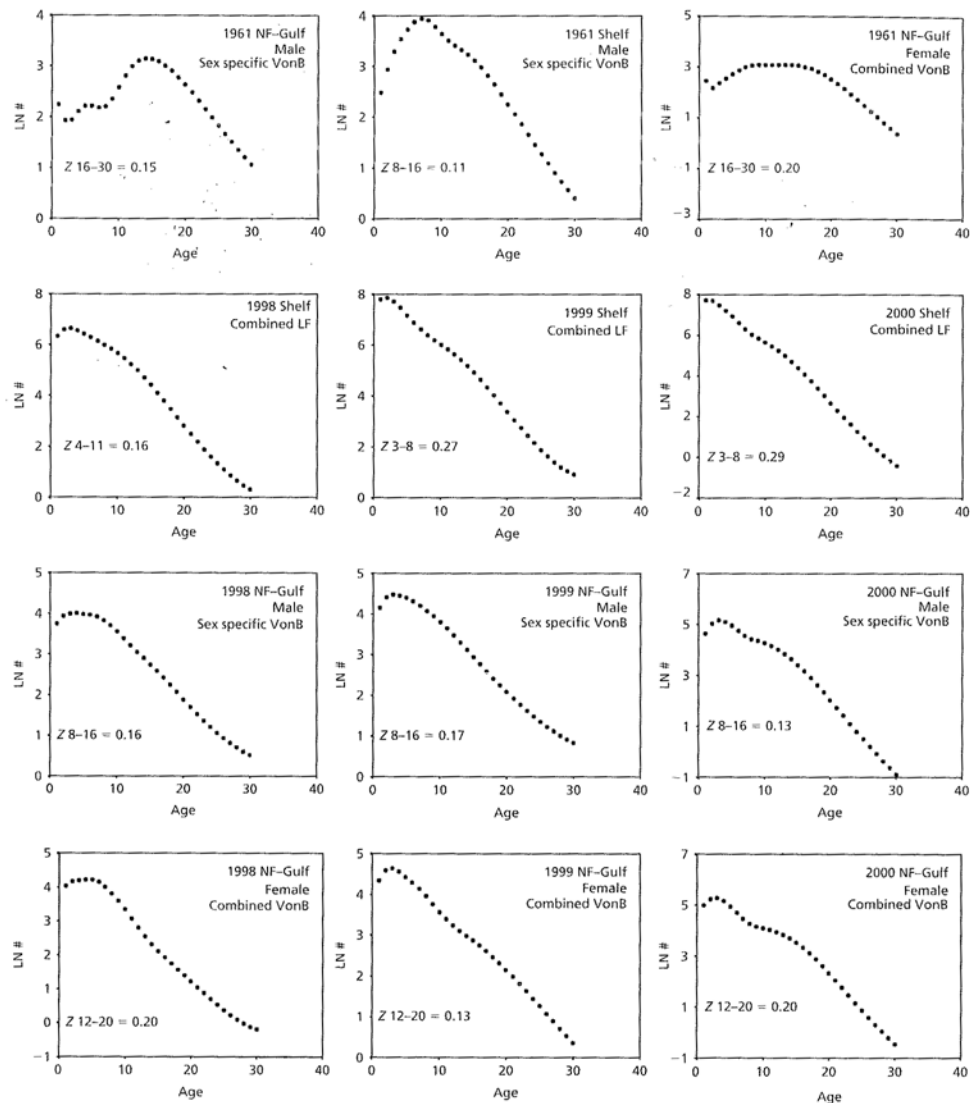


**Fig. 35.4** Standardized catch rate (number per hook) of sexually mature ( $>200$  cm fork length) and immature ( $<200$  cm) porbeagles. Factors in the analysis included year, month, area, and vessel. Error bars are 95% confidence intervals.

increasingly young age at recruitment to the fishery, which probably explains the apparently low total mortality rate of mature females in the recent NF-Gulf fishery.

The estimates of  $Z$  from the catch curves for the virgin 1961 population are also estimates of the instantaneous rate of natural mortality ( $M$ ). Campana *et al.* (1999) estimated  $M$  as 0.1 based on preliminary catch curves. Based on the refined catch curves presented here,  $M$  for maturing males on the Shelf indeed appears to be around 0.1 (Fig. 35.5). However, it appeared to be slightly higher (0.15) for fully mature males on the NF mating grounds.  $M$  could not be estimated for immature females in 1961, but  $M$  for mature females on the mating grounds was estimated as 0.20.

There is no reason to expect sex-specific differences in  $M$  prior to sexual maturity. Therefore,  $M$  was estimated for the combined length frequencies on the Shelf between



**Fig. 35.5** Catch curves (ln-transformed numbers at age) by subarea used to calculate instantaneous mortality rate ( $Z$ ) over specified age ranges. The 1961 samples are from a virgin population, and thus  $Z$  equals the instantaneous natural mortality rate ( $M$ ). Decomposition of lengths to ages was based on the combined (across sexes) von Bertalanffy growth model except where indicated.

1998 and 2000 for ages before maturity (3–8 years). The mean  $Z$  was 0.21. On the basis of exploitation rate estimated from tag returns (see Petersen analysis below, where recent  $F \sim 0.09$ ), recent  $M$  for immature porbeagles would be 0.12.

More precise estimates of  $M$  could be calculated given direct aging of samples collected in the 1961 fishery. At this point, however, an  $M$  of 0.1 for immature porbeagles of both sexes is consistent with the samples from the virgin population and with recent catch curves.  $M$  for mature males was also well estimated at 0.15.  $M$  for mature females appears to be higher than that of males and, based on the combined growth curve, would



be around 0.20. An increased natural mortality in mature animals, particularly females, is consistent with both the observed age composition and life-history theory (Roff, 1984), since mortality would be expected to increase in females carrying large embryos over an extended gestation period. Nevertheless, it appears that this is the first demonstration of this effect in sharks, probably because of the scarcity of reliable age determinations.

#### ***Recent mortality rates based on Paloheimo Z's***

Total instantaneous mortality rate ( $Z$ ) in the most recent years was estimated through use of Paloheimo  $Z$ 's, based on the reduction in catch at age along a cohort between adjacent years (Ricker, 1975). Details of the porbeagle calculation are presented in Campana *et al.* (2002b). All five of the mortality estimates ranged between 0.27 and 0.37, with a mean of 0.32. The  $Z$  estimates for mature porbeagle on the NF mating grounds were not significantly different from those for immature porbeagle on the Shelf.

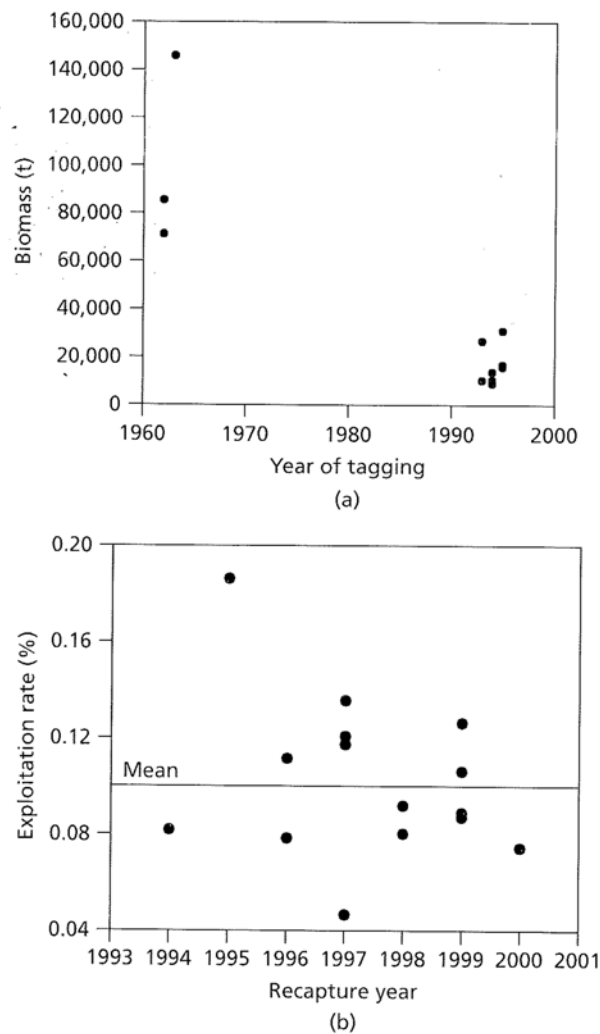
With a mean  $Z = 0.32$  for ages 3–9 on the Shelf, and given an immature  $M = 0.10$  (as calculated earlier), recent fishing mortality on immature Shelf porbeagles would be 0.22. This estimate would be slightly inflated if older but immature females were less available on the Shelf in the spring. In the NF-Gulf area in fall, mean  $Z$  for ages 9–13 was estimated as 0.33. Assuming an  $M = 0.15$  intermediate to that of immature and mature sharks, fishing mortality ( $F$ ) would be estimated at 0.18.

#### ***Petersen calculations of abundance and exploitation rate***

The biomass of both the virgin porbeagle population of the 1960s and that of the fished population in the 1990s was estimated through Petersen analysis of tag recaptures. Three independent and unpublished tag-recapture studies carried out by the Norwegians (1960s), the United States (1990s), and Canadians (1990s) were used. To optimize estimation rigor, the exploitation rate calculations were restricted to the Canadian and US tagging of age 0 and age 1 sharks (<125 cm fork length) between 1993 and 1997. The number of tags applied to these young sharks since 1993 was 1,177, of which 86 were subsequently recaptured. Full details of the biomass calculations (which are calculated for the year of tagging) are shown in Campana *et al.* (1999), while the exploitation rate calculations (calculated for the year of recapture) are shown in Campana *et al.* (2002b).

The independent US and Canadian tagging studies provided similar estimates of population biomass between 1994 and 1997. These population estimates were about 15–20% of the size of the virgin population tagged by the Norwegians (Fig. 35.6). However, the fact that many large sharks were tagged in the 1960s, but not in the 1990s, makes the population biomass comparison between recent and historic times somewhat tenuous.

The recent exploitation rate of the fished population in the 1990s was also estimated through Petersen analysis of tag recaptures, and because these rates are relatively insensitive to the assumptions required of biomass calculations, they are reasonably robust. The unadjusted exploitation rate ranged between 4% and 12%, with a mean of 8%. No trend was apparent across recent years, and the independent US and Canadian tagging studies yielded similar estimates of exploitation rate since 1994. When adjusted for age-specific selectivity (Campana *et al.*, 2002b), the exploitation rate was estimated to lie between 5% and 20%, with a mean of about 11% (Fig. 35.6).



**Fig. 35.6** Estimates of population biomass (a) and fishing mortality ( $F$ ) (b) based on Petersen analysis of tag recaptures from Canadian, American, and Norwegian tagging studies. Only years with more than four recaptures from a given tagging year are shown in the biomass plot, and years with more than three recaptures for the exploitation plot. The calculations of exploitation rate were restricted to sharks tagged at fork lengths <125 cm in the Canadian and American studies, and thus are most applicable to the spring fishery on the Scotian Shelf. Exploitation rates have been divided by age-specific selectivity to calculate the fully recruited exploitation rate.

### *Yield per recruit*

Yield per recruit was calculated on the basis of a fitted growth model (Natanson *et al.*, 2002), an empirical length–weight relationship (Campana *et al.*, 1999), the estimates of immature and mature female natural mortality determined from the catch curve analysis (Fig. 35.5), and an area-specific selectivity curve (Campana *et al.*, 2002b). The estimated  $F_{0.1}$  and yield values were not unduly affected by the selection of natural mortality schedules, although the choice of selectivity vectors was quite influential. Yield in the NF-Gulf

fishery was estimated to be higher (18.1 kg per recruit), but at a lower  $F_{0.1}$  (0.14), than that on the Shelf (15.4 kg per recruit at  $F_{0.1} = 0.20$ ). Using a combined selectivity vector (effort-weighted 2:1 for Shelf:NF-Gulf),  $F_{0.1}$  was estimated at 0.18 with a yield of 16.7 kg per recruit. Because the age of first capture occurs well before the age of sexual maturity, spawning stock numbers and population biomass would both be expected to be susceptible to even modest fishing mortalities. For example, fishing at  $F_{0.1}$  would be expected to reduce the number of mature females to 18% of their original numbers, and to reduce population biomass to 40% of its original value. Such a sharp decline in the predicted size of the spawning population resembles the decline in the observed catch rate of sexually mature porbeagle (Fig. 35.4).

Campana *et al.* (1999) suggested that an  $F_{0.1}$  yield would not be sustainable unless the  $F$  on the mature population was considerably less than  $F_{0.1}$ . As documented in the life table analysis in Campana *et al.* (2002b), it is now clear that  $F_{0.1}$  is not sustainable for porbeagle sharks.

### *Age- and sex-structured population model*

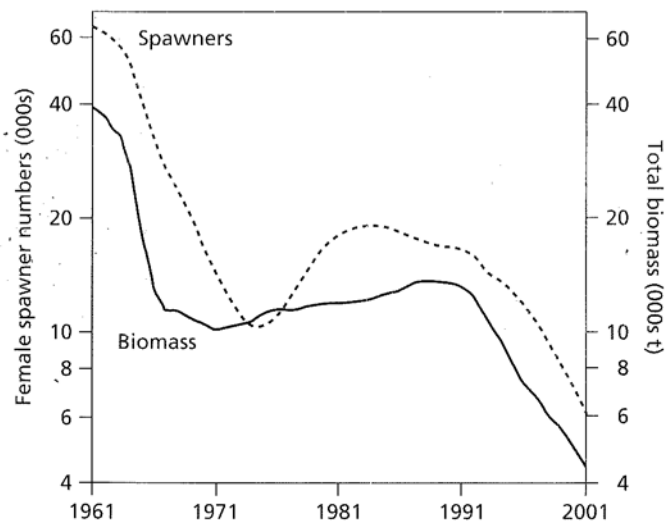
A forward-projecting, age- and sex-structured population dynamics model was developed for the Northwest Atlantic porbeagle to estimate current population status relative to that of earlier years. The model was fit to available catch at length and catch per unit effort data between 1961 and 2000, using the growth model, natural mortality rates, maturity ogives, fecundity, and area-season stratification described earlier. The steepness of the Beverton–Holt spawner-recruit model was defined a priori as 0.37 on the basis of the well-defined reproductive parameters of porbeagle (Jensen *et al.*, 2002). The base model assumed a combined-sex growth curve, a higher  $M$  in the first year of life, an increased  $M$  at the onset of sexual maturity, and a fixed selectivity. Model output included time-trends in biomass, female spawner numbers, and area-specific selectivity curves. AD Model Builder (Otter Research Ltd., Sidney, British Columbia, Canada) was used to prepare the model and fit the likelihood functions.

Estimates of both total biomass and spawning stock numbers declined sharply after the onset of the 1961 fishery, increasing slightly through the 1970s and 1980s, then declining once more to a record-low level (Fig. 35.7). Biomass in 2001 was estimated as 11% of the virgin biomass, and fully recruited fishing mortality in 2000 was estimated as 0.26 (Table 35.2). The time-series of fishing mortality indicates that  $F$  has been very high since the mid-1990s (Fig. 35.8). Of the four alternative runs considered, none resulted in more optimistic views of recent population status than the base run.

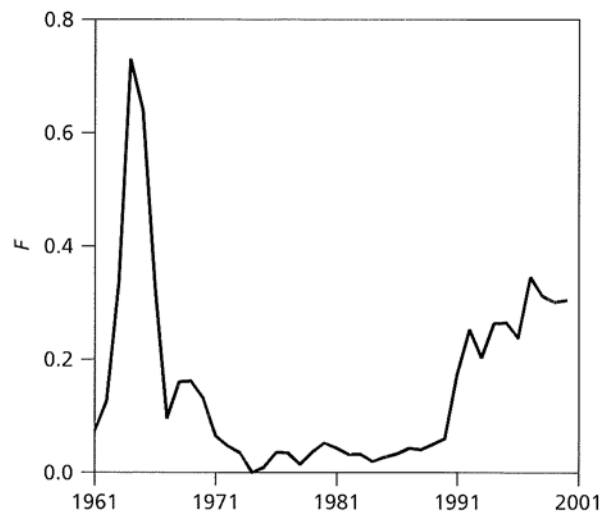
The biological reference points predicted by the model were similar in all runs: Maximum sustainable yield (MSY) was estimated to be about 1,000 t at an  $F_{MSY}$  of 0.04–0.05 (Table 35.2).

## **Discussion**

All of the indicators examined in the population dynamics analysis of the Northwest Atlantic porbeagle suggest that the population has collapsed for a second time in its



**Fig. 35.7** Time trends in porbeagle biomass and female spawner abundance from the base run of the age- and sex-structured population model.



**Fig. 35.8** Time trends in porbeagle fishing mortality ( $F$ ) from the base run of the age- and sex-structured population model.

43-year fishing history. Average catches of about 4,500 t/year in the early 1960s resulted in a fishery that collapsed after only 6 years and that did not fully recover over the next 25 years. Nevertheless, the fishery appeared sustainable during the 1970s and 1980s, when landings averaged 350 t annually. However, annual catches of 1,000–2,000 t throughout the 1990s appear to have once again impacted the population, driving it to record-low population numbers. Both the size and the age composition of the catch have declined, and

**Table 35.2** Output of five realizations of an age- and sex-structured population model for Northwest Atlantic porbeagle.\*

Run	Female spawners			Total biomass (t)			Exploitation rates in 2000				$B_0$ (t)	$F_{\text{MSY}}$	MSY (t)	$\text{MSY}/B_0$	$B_{\text{MSY}}$ (t)	$B_{2001}/B_{\text{MSY}}$
	1961	2001	2001/1961	1961	2001	2001/1961	Age 2	Age 5	Age 8							
Base	63,694	6,075	0.10	38,967	4,409	0.11	0.16	0.25	0.26	38,967	0.046	1,069	0.027	24,402	0.18	
Run 2	64,710	7,500	0.12	39,589	4,991	0.13	0.14	0.22	0.23	39,589	0.046	1,086	0.027	24,791	0.20	
Run 3	69,186	2,612	0.04	42,327	1,572	0.04	0.41	0.64	0.80	42,327	0.047	1,138	0.027	26,362	0.06	
Run 4	69,664	2,934	0.04	42,619	1,928	0.05	0.35	0.52	0.65	42,619	0.047	1,143	0.027	26,519	0.07	
Run 5	100,979	13,847	0.14	44,317	7,695	0.17	0.14	0.21	0.26	44,317	0.063	1,079	0.024	21,275	0.36	

Base:  $M$  increases at maturity, fixed selectivity, combined growth curve.

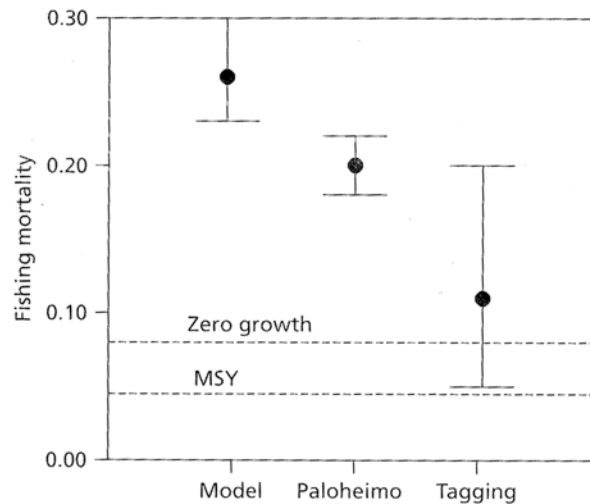
Run 2: As above but with no recruitment deviates.

Run 3: Estimating selectivity and recruitment deviates.

Run 4: Estimating selectivity without recruitment deviates.

Run 5: Estimating selectivity and recruitment deviates with no increased mortality.

\* $B$ : biomass;  $B_0$ : virgin biomass;  $F$ : fishing mortality;  $MSY$ : maximum sustainable yield.



**Fig. 35.9** Summary of recent fishing mortality ( $F$ ) estimates derived from independent analyses. Estimates are drawn from analysis of the years 1994–2000 (tagging), 1998–2000 (Paloheimo  $Z$ 's), and 2000 (population model). Error bars indicate the approximate range of uncertainty based on multiple estimates. All estimates of recent  $F$  are above a level that would allow population recovery (MSY) or maintain current population size (zero growth).

relatively few large sharks are left in the population. Catch rates are now 10–30% of those in the early 1990s. Petersen calculations based on tag recaptures and an age- and sex-structured population model show that recent biomass is only 10–20% of that present in the virgin population. With such a coherent picture of population decline in the face of modest catches, it is clear that the porbeagle population is very susceptible to overexploitation.

Life table analysis has indicated that the intrinsic rate of population growth ( $r$ ) in the unfished porbeagle population varies between 0.05 and 0.07 (Campana *et al.*, 2002b). Such values are very low compared to those of most fishes (Myers *et al.*, 1999), and indicate that the porbeagle population is intrinsically unproductive and slow to recover from stock depletion. Presumably this is because porbeagle produce few offspring and mature at a late age compared with the age of first capture. The current analysis confirms the unsustainability of fishing at  $F_{0.1} = 0.18$  for porbeagle, and indicates that a fishing mortality above 0.08 will cause the population to decline. A fishing mortality of 0.04 corresponds to the MSY, and fishing at or below this rate is required if the population is to be allowed to recover. Several independent estimates of recent fishing mortality suggest that recent catches averaging 1,000 t/year have resulted in an unsustainable  $F$  of about 0.20 (Fig. 35.9). An annual catch of 200–250 t would correspond to fishing at MSY and would allow population recovery.

Many shark species are unproductive compared to teleosts (Musick, 1999). However, with the production of only four pups per year, porbeagle are among the least fecund of the shark species (Aasen, 1963; Francis and Stevens, 2000; Jensen *et al.*, 2002). It is more difficult to compare published natural mortality rates among shark species, since most published estimates have used the predictive models of Hoenig (1983), Pauly (1980),

and Peterson and Wroblewski (1984) to estimate  $M$ , rather than direct measurements as are reported here, owing to lack of data. Nevertheless, porbeagle appear to have a somewhat lower  $M$  ( $=0.1$ ) than other shark species, which have been reported to have an  $M$  of 0.1–0.6 (Cortés, 1998, 1999; Stevens, 1999). Low values of  $M$  are normally associated with low productivity.

Fishing quotas based on “conservative” strategies such as  $F_{0.1}$  are commonly used to minimize the probability of either recruitment or growth overfishing in teleost fishes (Mace, 1994). Reporting results that would be viewed with skepticism in a teleost fishery, Rago *et al.* (1998) calculated that  $F_{\max}$  exceeded the fishing mortality at which population replacement of spiny dogfish (*Squalus acanthias*, Squalidae) could occur. The implications of our calculations extend beyond those of Rago *et al.* (1998), demonstrating that even the more conservative  $F_{0.1}$  fishing target is anything but conservative for porbeagle shark, and will eventually lead to stock collapse. Similar conclusions have been reached qualitatively for a wide range of low-productivity shark species, many of which appear incapable of supporting more than a nominal fishing mortality (Cortés, 1998, 1999; Walker, 1998; Musick, 1999; Simpfendorfer, 1999; Stevens, 1999). The inherent vulnerability of sharks and other elasmobranchs to overfishing and stock collapse was recently highlighted in an American Fisheries Society policy statement, which noted that most elasmobranch populations decline more rapidly and recover less quickly than do other fish populations (Musick *et al.*, 2000).

Despite obvious indicators of overexploitation, there are some key differences between the current porbeagle fishery and the fishery that was present prior to the 1967 collapse, which suggest that sustainability may yet be possible. More than 80% of the recent annual catch has been taken on the Scotian Shelf in the spring, at a time when availability is largely limited to immature sharks. A fishery that preferentially targets immature sharks is very different than that in the 1960s prior to the fishery collapse, when the fishery focused on aggregations of mature (and possibly mating) sharks in the fall off southern Newfoundland. Fishing mortality is now low and strictly regulated, with minimal bycatch in other fisheries. In addition, the fishing industry provides accurate catch and effort data, and measures each shark individually, thus facilitating population monitoring. Management measures to restrict or eliminate the catch of mature females through closed areas are recent innovations. Finally, and perhaps most importantly, the current porbeagle fishing industry in the Northwest Atlantic is highly motivated to conserve the population, and has assisted in its scientific study. While it remains to be seen if the porbeagle population can be fished sustainably, the necessary elements for a sustainable fishery appear to be in place.

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