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The biological limits of overexploitation of Greenland halibut, *Reinhardtius hippoglossoides*.

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Abstract

We examined the fundamental limitations imposed by the reproductive biology of Greenland halibut, *Reinhardtius hippoglossoides* to withstand overexploitation. Three stocks were examined; North East Arctic, ICES V & XIV, and Northwest Atlantic. We estimated the maximum sustainable fishing mortality using simple mathematical models. We estimated that the maximum fishing mortality for the three slowly maturing stocks ranges from 0.3 to 0.4.

Introduction

For many of the world's major fish stocks, exploitation rates have climbed well above the limits of economically optimal harvesting and are approaching or exceeding the biological limits (e.g., Ludwig et al. 1993, Rosenberg et al. 1993, Hutchings and Myers 1994). Surpassing the biological limit for exploitation implies that the population growth rate is negative until fishing pressure is relaxed (Hutchings and Myers 1994).

In this paper we will formulate, explicitly, the fundamental limitations of fish populations to withstand overexploitation. We will also demonstrate that much more stringent limits on fishing are necessary when juveniles of slowly maturing fish, such as Greenland halibut (turbot), are harvested.

Methods

For fish populations, reproduction is generally expressed as recruitment, the number of juvenile fish reaching, in a given year, the age of vulnerability to fishing gear. Thus, the reproduction curve (Royama 1992) for fish is displayed as a spawner-recruitment curve (Ricker 1954). From the reproduction curve, we will estimate the slope of this curve near the origin (low population).

Juvenile fish become vulnerable to fishing gear; that is, they recruit, at an age designated as a_{rec}. We consider the Ricker spawner-recruitment models which describe the number of recruits at age j in year $t + a_{rec}$, $N_{t+a_{rec},a_{rec}}$, resulting from a spawning stock biomass (SSB) of S_t. We follow the usual convention in fisheries of assuming the number of eggs produced is proportional to the biomass of spawners. The Ricker model has the form

$$E(N_{t+a_{rec},a_{rec}}) = \alpha S_t e^{-\beta S_t}, \qquad (1)$$

where α is the slope at the origin (measured, perhaps, in recruits per kilogram of spawners). Density-dependent mortality is assumed to be the product of β times the recruitment. The parameters were fit using maximum likelihood estimation assuming lognormal variability (Hilborn and Walters 1992; Myers et al. 1995).

The *standardized* initial slope, $\tilde{\alpha}$, is obtained by scaling the initial slope α by $\mathrm{SPR}_{F=0}$, i.e.

$$\tilde{\alpha} = \alpha \cdot \mathrm{SPR}_{F=0} \tag{2}$$

where $\mathrm{SPR}_{F=0}$ is the spawning biomass resulting from each recruit in the limit of no fishing mortality ($F = 0$). This quantity $\tilde{\alpha}$ may be interpreted as follows: at low population density each spawner will produce $\tilde{\alpha}$ spawners a_{mat} years later, where a_{mat} is the age at maturity.

We now consider a simple model that incorporates age-structure with overlapping generations introduced by Clark (1976), and extended by Botsford (1992) and Mertz and Myers (1995). The model makes the assumption that the proportion of spawners that survive each year in the absence of fishing is e^{-m} and it is reasonable to ignore somatic growth once maturity has been achieved. In this case the Clark model, under the assumption of Ricker recruitment in the absence of fishing, becomes

$$S_t = e^{-m} S_{t-1} + \tilde{\alpha} S_{t-a_{mat}} e^{-\beta S_{t-a_{mat}}}. \tag{3}$$

For low population sizes we can approximate the dynamics of a fish population with no exploitation as

$$S_t = e^{-m} S_{t-1} + \tilde{\alpha} S_{t-a_{mat}}. \tag{4}$$

The disadvantage of using the Ricker model, or any other stock recruitment model, is that the slope at the origin is influenced by observations far from the origin (Fig. 1). We investigated an alternative approach: we regressed recruitment versus spawner biomass using only the 6 observations with the lowest spawner biomass, forcing the regression line through the origin. This simple procedure should be reasonable because almost all the stocks have been reduced to very low levels.

Fig. 1 near here

A fishery on the juvenile component of a fishery is assumed to begin at the age of recruitment to the fishery (a_{rec}) and the fishing mortality is assumed to apply to adults as well. The dynamics would be

$$S_t = e^{-F} (e^{-m} S_{t-1} + e^{-(a_{mat}-a_{rec})F_j} \tilde{\alpha} S_{t-a_{mat}}, \tag{5}$$

where F_j is the fishing mortality on juveniles. With these stipulations, we find that F_j is given by

$$e^{-F-(a_{mat}-a_{rec})F_j} = \frac{1}{e^{-m} e^{F} + \tilde{\alpha}} \ . \tag{6}$$

If $e^{-m} e^{F} \ll \tilde{\alpha}$, then

$$e^{-(1+a_{mat}-a_{rec})F_{lim}} \approx \frac{1}{\tilde{\alpha}} \ , \tag{7}$$

where we have now written F_j as F_{lim} to emphasize that equation (7) defines the maximum possible fishing mortality on a stock which is subject to harvesting of juvenile fish.

Data

The data used are estimates obtained mostly from ICES assessments (Anon. 1994*a*, 1994*b*; Bowering and Chumakov 1987; Serebryakov et al. 1992).

The Ricker model was fit using a transformation recommended by Hilborn and Walters (1992): $\log(N_{t+j,j}/S_t) = \log \tilde{\alpha} - \beta S_t + \epsilon$, where ϵ is a normally distributed with mean zero and variance σ^2 (Fig. 1). The estimate of $\tilde{\alpha}$ from the above equation is $\exp(\widehat{\log\tilde{\alpha}} + \frac{1}{2}\widehat{\sigma^2})$, $\frac{1}{2}\widehat{\sigma^2}$ is a bias correction term that occurs because the nonlinear transformation that was used after estimation (Cox and Hinkley 1974).

Results

The Ricker model and the robust median estimate of the slope at the origin was estimated for the three spawner recruit time series (Table 1). We first compare the results for the Ricker model with the robust procedure. The slope at the origin for the Ricker model is higher than that calculated for the median slope from the 6 observations with the lowest SSB (Table 1).

Table 1 near here

The ability of a population to withstand fishing is determined by both the number of years that a cohort can be exploited before reproduction ($a_{mat} - a_{rec}$) and the slope at the origin (Fig. 2 and 3).

Fig. 2 and 3 near here

With the exception of the ICES V & XIV stock for the Ricker model the estimated maximum sustainable fishing mortality ranges from 0.3 to 0.4 for the Ricker model and the median model (Table 1, Fig. 2 and 3).

Discussion

We have demonstrated that the biological limits of exploitation can be calculated from data that is readily available.

The biological limits for exploitation for Greenland halibut range from a fishing mortality around 0.3 to 0.4. It has been shown that the smaller the number of years that a cohort can be exploited before reproduction ($a_{mat} - a_{rec}$) the higher the ability of a population to withstand fishing (F_{lim} will be large). In other words, if age of maturity is much greater than age of recruitment, then the juvenile fish has a very high probability of being caught before it has spawned even once. Also, the larger the number of replacements each spawner can produce at low population densities ($\tilde{\alpha}$), the higher F_{lim} will be.

Preventing overexploitation

There is a very simple strategy that will prevent overexploitation of Greenland halibut stocks, as well as any other marine fish: allow them to spawn at least once. This method works for marine fish because of the high ability they have to reproduce themselves at low spawner abundance; $\tilde{\alpha}$ is large for two of the stocks (Table 1, Fig. 2). There are clear advantages to maintaining more year classes in the fishery; catches would be more constant and more year classes spawning may reduce interannual variability in recruitment (Hutchings and Myers 1994).

Predictions of susceptibility to overexploitation

Our model predicts that the most vulnerable species to overexploitation are slow growing species which can be exploited for many years before reaching sexual maturity. The deep water species such as Greenland halibut, *Reinhardtius hippoglossoides*, which may not mature to age 12, as well as the late maturing rock fish of the genus *Sebastes*, which may not mature until age 15 are possibly two of the species which have the lowest limit to overexploitation. Such species should be managed with great care, and fishing mortality on juveniles eliminated.

Recommendations

We have shown that age of maturity, age of recruitment, and the number of replacements each spawner can produce at low population densities are very important biological factors in influencing the sustainability of the Greenland halibut stocks. In order to protect our Greenland halibut stocks and aid in their recovery from overexploitation, everyone must become aware of the biological limits of each stock in question. Quotas have be set with full awareness of these limitations and extensive research should be carried out on each stock as well as any other potentially exploitable stocks so that quota estimates will be as reliable as possible.

Acknowledgements

Literature Cited

Anon. 1994*a*. Report of the Arctic Fisheries Working Group. ICES Doc. C.M. 1994/Assess: 2.

Anon. 1994*b*. Report of the North-Western Working Group. ICES Doc. C.M. 1994/Assess: 19.

Botsford, L. W. 1992. Further analysis of Clark's delayed recruitment model, Bull. Math. Biol. 54:275-293.

Bowering, W. R., and A. K. Chumakov. MS 1987. The distribution and relative abundance of Greenland halibut (*Reinhardtius hippoglossoides*) in the Canadian Northwest Atlantic from Davis Strait to the Northern Grand Bank. NAFO SCR Doc. 86.

Clark, C. W. 1976. A delayed-recruitment model of population dynamics, with an application to baleen whale populations, J. Math. Biol. 3:381-391.

Cox, D. R., and D. V. Hinkley. 1974. Theoretical Statistics. Chapman and Hall, London.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Hutchings, J. A., and R. A. Myers. 1994. What can be learned from the collapse of a renewable resource? Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. Can. J. Fish. Aquat. Sci. 51: 2126-2146

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science 260: 17-36.

Mertz, G. and R. A. Myers. 1995. An augmented Clark model for stability of populations. Mathematical Biosciences in press.

Myers, R. A., J. Bridson, and N. J Barrowman. 1995. Summary of worldwide stock and recruitment data. Can. Tech. Rep. Fish. Aquat. Sci. 2024: iv + 327p.

Ricker, W. E. 1954. Stock and recruitment. J. Fish. Res. Bd. Can. 11: 559-623.

Rosenberg, A. A., M. J. Fogarty, M. P. Sissenwine, J. R. Beddington, and J. G. Shepherd. 1993. Achieving sustainable use of renewable resources. Science 262: 828-829.

Royama, T. 1992. Analytical population dynamics. Chapman and Hall, London.

Serebryakov, V. P., A. K. Chumakov, and I. I. Tevs. 1992. Spawning stock, population fecundity and year-class strength of Greenland halibut (*Reinhardtius hippoglossoides*) in the Northwest Atlantic, 1969-88. J. Northw. Atl. Fish. Sci. 14: 107-113.

TABLE 1. Summary statistics for each stock. a_{mat} gives the age of maturity. a_{rec} gives the age of recruitment. m gives the natural mortality. α(R) gives the slope at the origin for the Ricker Stock-Recruitment (SR) function. F_{lim}(R) gives the maximum rate of fishing mortality for the Ricker SR function. α(M) gives the slope at the origin for the Median Stock-Recruitment (SR) function. F_{lim}(M) gives the maximum rate of fishing mortality for the Median SR function.

Stock	a_{mat}	a_{rec}	m	α(R)	F_{lim}(R)	α(M)	F_{lim}(M)
North East Arctic	9.0	3.0	0.15	7.1	0.30	5.0	0.26
Northwest Atlantic	14.0	5.0	0.10	30.7	0.35	11.2	0.25
ICES V and XIV	10.5	5.0	0.15	42.8	0.58	7.2	0.33

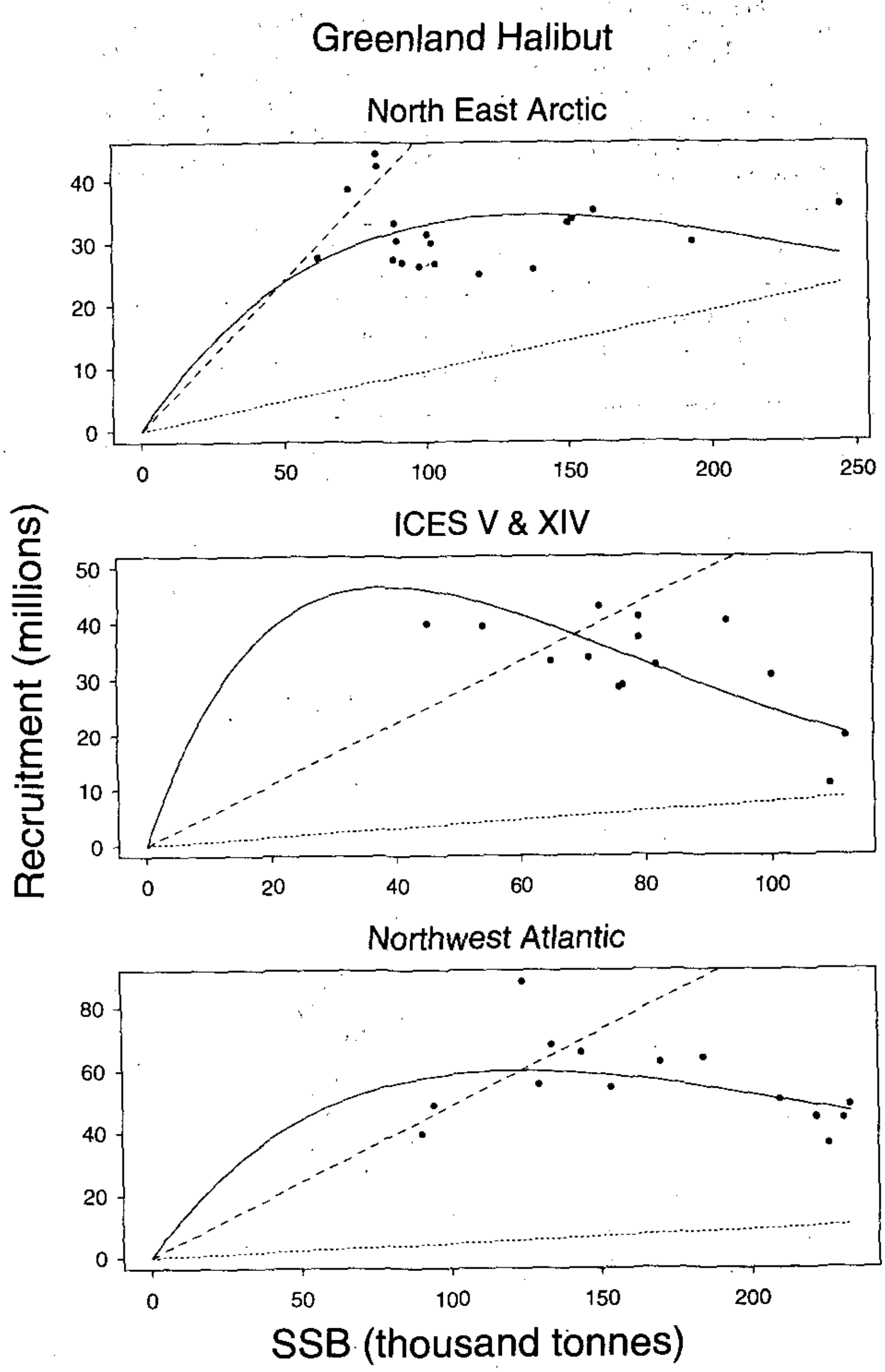

Fig. 1. Recruitment versus Spawning Stock Biomass (SSB) for the three representative Greenland halibut populations. The solid line is the maximum likelihood estimate of the mean for Ricker spawner-recruitment functions under the assumption that the probability distribution for any SSB is given by a lognormal distribution. The dashed line is the median slope at the origin estimated from the 6 points with the lowest SSB. The straight dotted line is the replacement line.

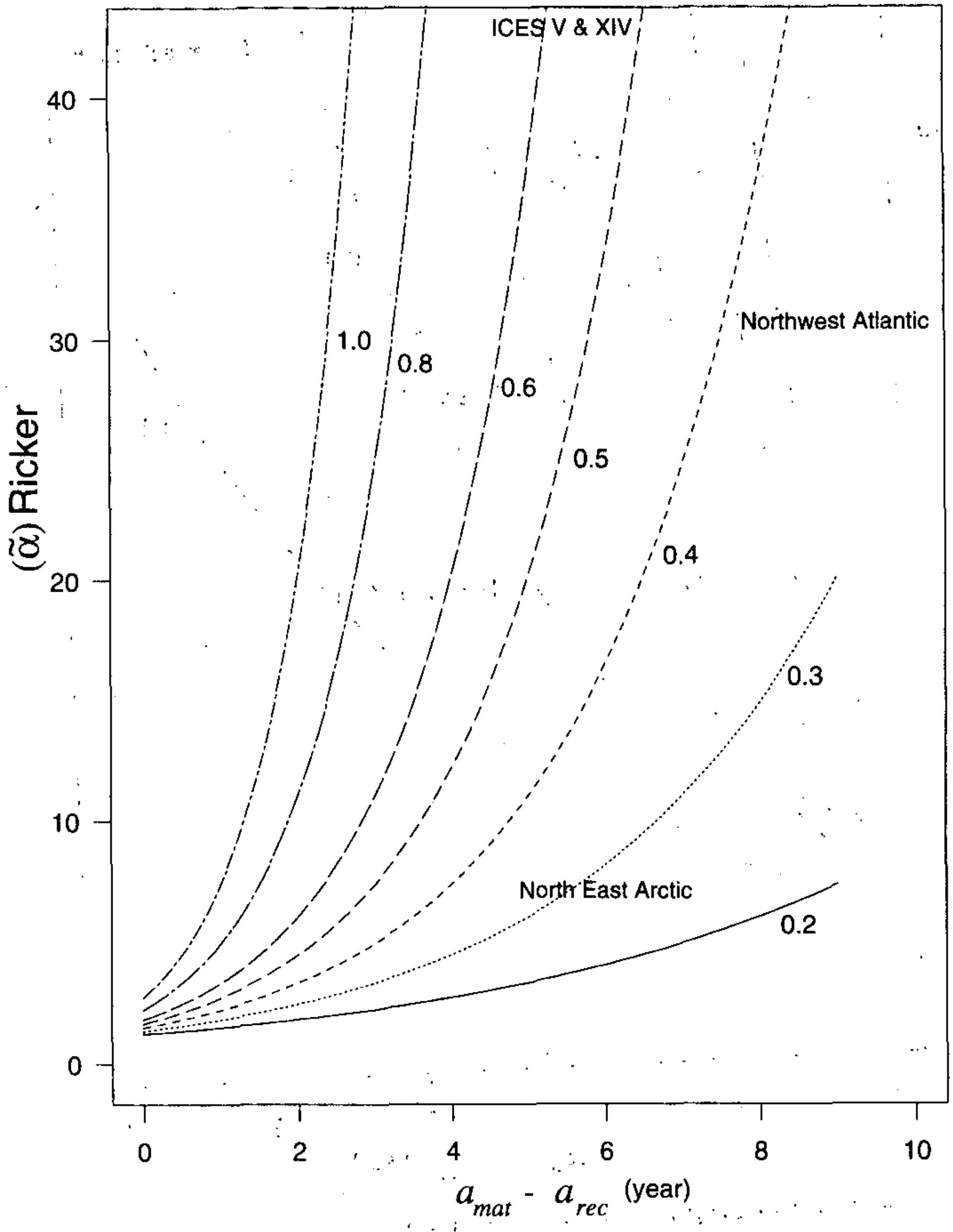

Fig. 2. Estimates of slope at the origin ($\tilde{\alpha}$) using the Ricker model at minimum population size and the approximate number of years before maturity ($a_{mat} - a_{rec}$) for Greenland halibut. The lines of equal levels of F_{lim}, the biological limit of fishing is given by Eq. 7. The levels of F_{lim} are: 0.2 (solid line), 0.3 (dotted line), 0.4 (short dashed line), 0.5 (medium dashed line), 0.6 (long dashed line), 0.8 (short & long dashed line) and 1.0 (short & medium dashed line).

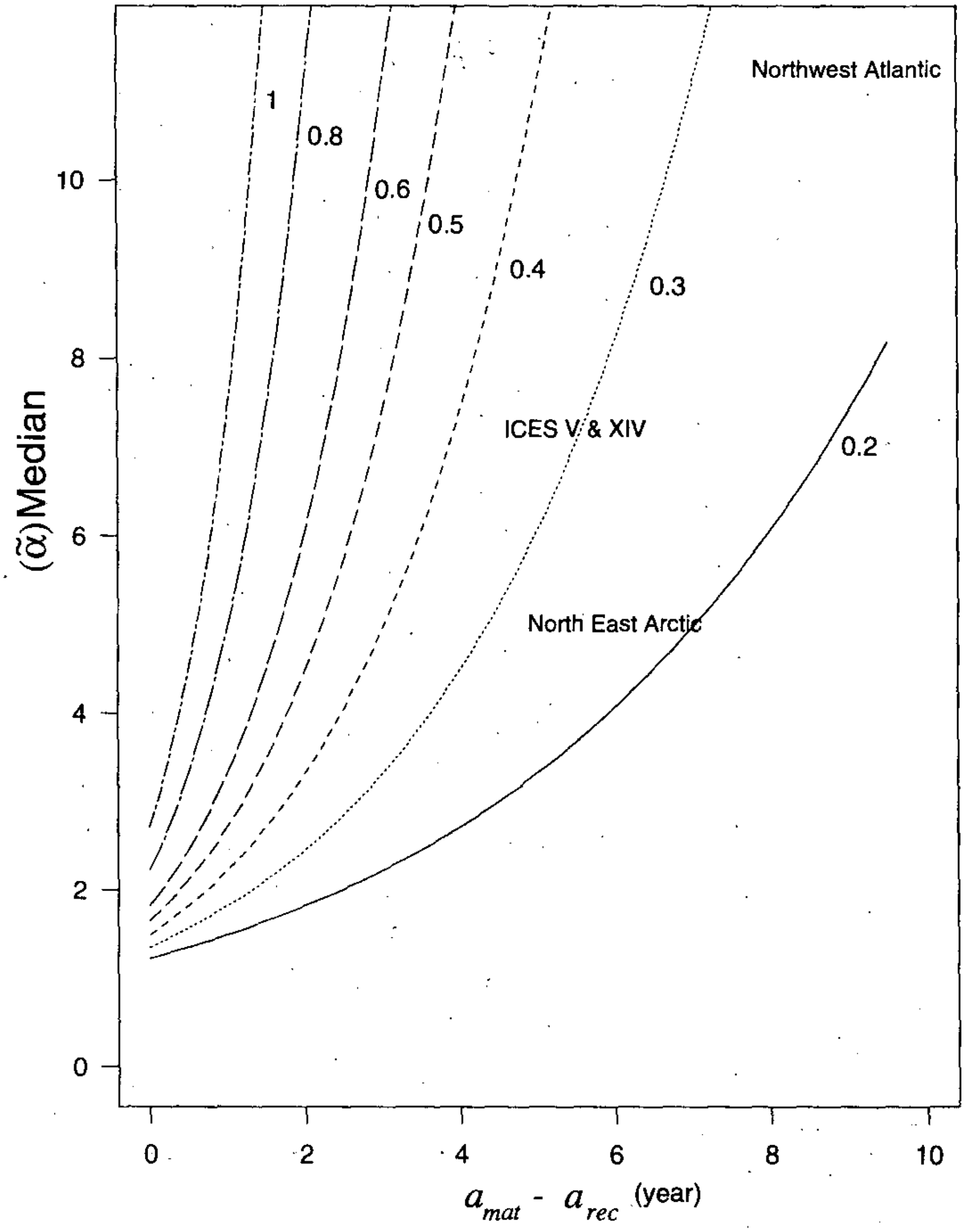

Fig. 3. Estimates of slope at the origin ($\tilde{\alpha}$) using the median method at minimum population size and the approximate number of years before maturity ($a_{mat} - a_{rec}$) for Greenland halibut. The lines of equal levels of F_{lim}, the biological limit of fishing is given by Eq. 7. The levels of F_{lim} are 0.2 (solid line), 0.3 (dotted line), 0.4 (short dashed line), 0.5 (medium dashed line), 0.6 (long dashed line), 0.8 (short & long dashed line) and 1.0 (short & medium dashed line).