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Production Functions of the Norwegian bottom trawl fisheries of cod in the Barents Sea

by
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Bioeconomic theory often expresses the production of catch as a function of two input factors: *fishing effort* and *stock biomass*. This paper applies a Cobb-Douglas production function to the Norwegian bottom trawl fisheries of cod in the Barents Sea. Catch and effort data from 1971-1985 for 18 vessels have been obtained. Statistical analyses have been carried out, using the per vessel trawl hours a day and the biomass of the cod stock (3+), as input factors. The biomass-on-day-data of each cohort are calculated from ICES-estimates by polynomial interpolation.

A model with an autocorrelated error term and season dependent fluctuating catchability term, has been used. The parameter estimation has been carried out by maximizing the log-likelihood function by numerical methods.

According to the statistical analyses the stock-output elasticity is 0.424, the effort-output elasticity is 1.232 and the annual technological growth is about 2%. The lowest catchability during a year is less than 30 percent of the maximum.

Key words: Bioeconomics, Production theory, Statistics

Introduction

The fishing mortality rate has been the main focus in modern management of the North European fisheries. A number of applied studies have been carried out, analysing the short term and long term effects on stock, of different values of the fishing mortality rate. However, surprisingly few studies have been carried out on the production of fishing mortality or the relationship between fishing mortality and the input of fishing effort.

In bioeconomic studies the Schaefer production equation (Schaefer, 1957) often is used, assuming a bi-linear relationship between the two production factors *fishing effort* (E) (capital and labour) and *stock biomass* (W) and the produced *catch* (h),

$$h(E,B) = q \cdot E \cdot W\,. \tag{1}$$

Similarly a linear relationship between *fishing effort* (number of boats, fishing days, trawl hauls, etc.) and the produced *fishing mortality rate* (F),

$$F(E) = q \cdot E\,, \tag{2}$$

where q is a constant, referred to as the catchability coefficient.

It seems to be a strong restriction on the model to assume the catchability coefficient to be a constant. The Schaefer production equation implies that an increase in stock biomass leads to an increase in the catch at the same rate, when keeping the fishing effort unchanged. The underlying assumption is that the fish stock is homogeneously distributed in the ocean, and the abundance of fish changes linearly. A similar assumption is related to the fishing gear, assuming it to fish with a predefined probability function of fish abundance.

A Cobb-Douglas production function has been suggested by several authors and some empirical work have been carried out on the North-East Arctic cod (Hannesson, 1983; Flaaten, 1987).

$$h(E, B) = q \cdot E^{\alpha} \cdot W^{\beta}, \tag{3}$$

where the parameters α and β are the effort-output and stock-output elasticities which gives the increase of *catch (h)* with an increase of one unit of respectively *fishing effort (E)* or *stock biomass (W)*. A priori one expect the elasticities to be within the range

$$\begin{aligned} &\alpha > 0 \\ &0 \leq \beta \leq 1 \end{aligned} . \tag{4}$$

The studies of Hannesson (1983) (covering the period 1971-1978) and Flaaten (1987) (covering the period 1971-1985, as in this study) confirm this. The α-values of both this varies substantially, with low levels of significance, while the β-values indicate some gear specific differences. *Active* gears, like bottom trawls which moves on the bottom while fishing, and long line, which attract fish by bait, tend to have a lower value of β than more *passive* gears have. Gill nets seems to have β-values closer to 1, which means that the probability of catch is almost proportional to the density of fish.

In this paper an empirical study of the production function of the bottom trawl cod fisheries of the Barents Sea, is presented. A disaggregated data base of day catches of trawlers, have made it possible to study the catch production more detailed than in earlier studies. A variety of model formulations within the family of Cobb-Douglas production functions have been tried out. The one presented in this paper is chosen not only because it statistically has the best performance, but it is also a model adjusted to the uncertainty in the data material.

Data

The catch data have been provided by the Norwegian Fisheries Directorate and include day catches of 18 trawlers during a period of 15 years (1971-1985), 37 748 observations altogether. The data base also contains information on vessel size, engine size, age of vessels, catch area, etc. A graphical presentation of the data base, plus some key numbers are shown in Table A1 and Figure A1 and A2, in the Appendix.

The 18 trawlers are not chosen randomly, but selected from a larger group using the criteria that they should have at least one catch registration each year during period 1971-1985.

With a data base of this size, a thorough quality control of the data is difficult and time consuming. Some obvious faults and mistakes have been found and data of the following kind has been removed from the material: Catches on not existent dates. Catches lacking registration of trawling hours, Catches of less than 10 kg and more than 100 tonnes a day of one vessel.

Biomass estimates of the North-East Arctic cod stock, from the ICES Arctic Fisheries Working Group (Anon., 1994), have been used as data input in this study. The biomass estimates are separated on cohorts (year classes from the age of 3 years up to 15 years and older) and refers to the date of January 1 of each year. To obtain biomass estimates of each day during the period, an interpolation method of interpolating polynomials of order 3, has been used. The results of the interpolations are presented graphically in Figure A3 and A4, in the Appendix. In this study the sum of the biomass of all cohorts has been used.

The seasonal fluctuations during a year is basically expected to be repeated each year. To take these fluctuations into consideration, a variable (index) s has been used in the data analyses,

$$s = \frac{\text{day number within a year}}{\text{total number of days of the year}}, \qquad 0 < s \leq 1 .$$

Two other indexes have been used. t, which gives the year (1971-1985) and i, which gives the data registration number as they are stored in the catch data base.

Model

The Cobb-Douglas production function applied in this study, involves both a catchability equation (q_s) and a technology term, γ representing the marginal change of efficiency due to technological improvement. The statistical analyses are carried out by maximizing the log-likelihood function of the production equation,

$$h_{i,s,t}(E_i, W_i) = q_s \cdot e^{\gamma \cdot t} \cdot E_i^{\alpha} \cdot W_i^{\beta} \cdot u_i . \tag{5}$$

Catch quantity (h) and stock biomass (W) are measured in tonnes, while the fishing effort (E) is measured in number of trawl hours a day of each vessel. The indexes i, s and t represent running data sorted on vessel and date (i), day number in the year divided by total number of days within the year (s) and year (t), as explained above. The error term u_t is expected to follow an autoregressive process of first order and is defined by

$$\begin{aligned} \log(u_i) &= \phi \cdot \log(u_{i-1}) + v_i \\ v_i &\sim N(0, \sigma) \end{aligned} , \tag{6}$$

with a constant ϕ, while the catchability function is a general sine function

$$q_s = k_1 \cdot e^{(k_2 \cdot \sin(k_3 \cdot s) + k_4 \cdot \cos(k_5 \cdot s))} , \tag{7}$$

including five parameters (k). This allow the model to correct for changes in catchability which can not be explained by the two independent variables E and W, because it is pure seasonal fluctuations. These fluctuations also include the changes of cod density in different areas caused by a normal migration pattern. One interpretation of the catchability function could therefore be the overlap between the cod stock and the fishing fleet (trawlers).

Results

The results of maximizing the log-likelihood function are presented in Table 1. The model explain about 38% of the observed variation in the data (r^2). The Durbin-Watson observator is close to 2, which confirm that the error term, u_t, take care of most of the autocorrelation in the model. The AIC observator has been used basically in comparing the results from this model to the results of other models.

Table 1. Results of the statistical analysis done on equation (5).

Parameter estimators and observators		Values
Estimators of parameters	α	1.232
	β	0.424
	ϕ	0.291
	γ	0.021
	k_1	$6.08 \cdot 10^{-6}$
	k_2	-42.32
	k_3	-0.120
	k_4	2.408
	k_5	3.260
Statistical observators	Akaike's Information Criterion (AIC)	32395.5
	Durbin-Watson (DW)	2.141
	Correlation coefficient (r^2)	0.377

The importance of including seasonal changes in the model is demonstrated in Figure 1, where the catchability factor of the low season is less than 30% of the catchability maximum the same year. This phenomena also seems to be reflected in the box plot of the raw data in Figure A2 in the Appendix.

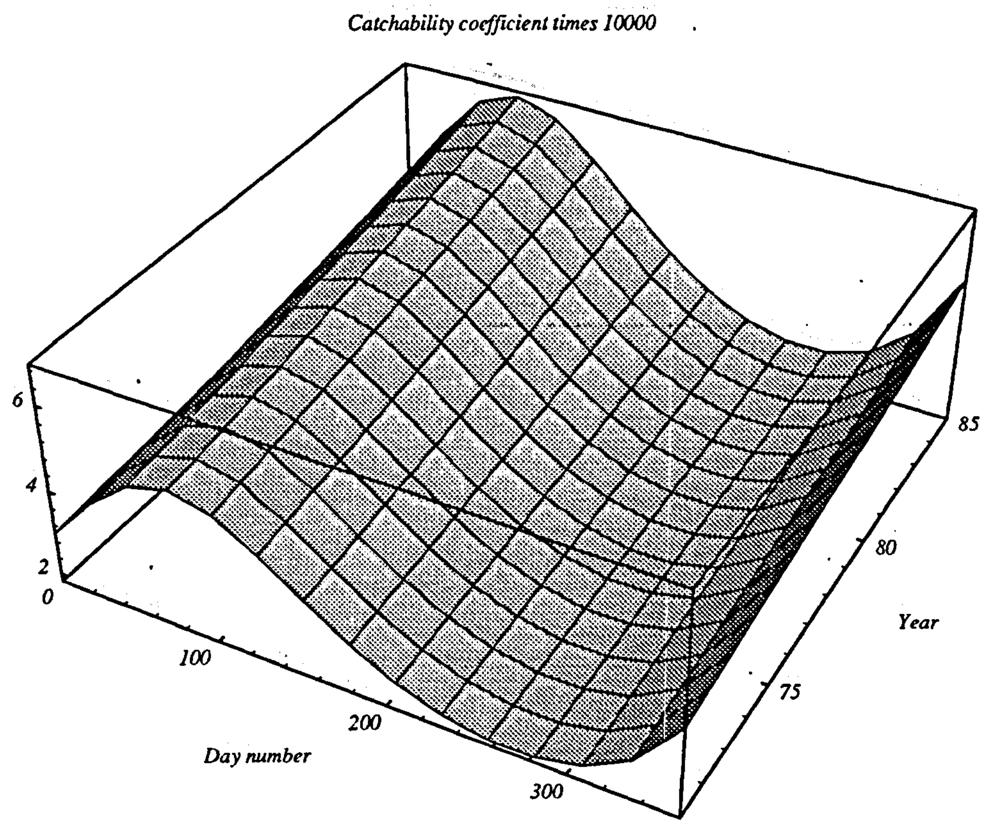

FIGURE 1. Graph showing the value of the catchability coefficient, Equation (7) multiplied by the technology term $e^{\gamma t}$, as a function of day number within a year and year, in the period 1971-1985. All the q-values each day in the period are presented as a surface. January 1 is day number 1.

Discussion

Less than 40% of the total variation in the data set is explained by the proposed model. This seems to be a low explanation rate, especially with 8 parameters and a large data base of close to 40 000 observations. Other models may explain a larger fraction of the variation in this specific data set, but the statistical performance is only one dimension of a production model. An other dimension is how the model fits the theoretical basis of catch production. The Cobb-Douglas production function is a formal representation of what we a priori would expect production of catch to look like. It satisfies the basic constrains of no effort gives no catch, etc.

In this analysis we have random variables with unknown probability distributions which has been assumed to be normal. The biomass data which have been used are estimates. The catch information involves all kind of measurement errors, from incorrect reporting to punching errors.

According to the α estimator (Table 1) short term per vessel catches will increase when the total number of vessels increases. This can be due to better information on the fish availability, either by observations of the positions of other vessels or by shearing information directly. There may also be other explanations, for instance a systematic trend in the data material towards increased activity as the fish abundance increase beyond the modelled increase. This could be due to random fluctuations.

The β estimator predict a harvest increase of 0.424 percent when the stock biomass increases one percent increased by one unit. One interpretation of this is that the density of cod at the trawling grounds may be less affected by changes in the total stock biomass, or the trawlers adjust trawling hours per haul, speed or other factors. Probably there exist a combinations of several of these factors. By separating between cohorts in the statistical analyses, the β-values could show to be age dependent as well as stock and gear dependent. Schooling habits of younger year classes would probably results in β-values closer to zero. Preliminary studies have confirmed this to a certain extent (Skjold, 1995), but this results is more speculative because of the difficulties in separating the catch quantities on cohorts. Nevertheless this could show to be an important factor, trying to increase the explained percentage of the observed variation in day catches. To fully include this age specific production functions, information on differences in age composition in areas of harvest, also is needed.

The k estimators of Equation (7) reflects the expected larger catchability of cod in the first part of each year. The maximum catchability correspond to the spawning season and the increased density along the coast related to the spawning migration.

The technological improvement increase the efficiency of the trawl fishery with about 2% on an annual basis (γ), which is consistent with the findings of Hannesson (1983) and Flaaten (1987). Hannesson (1983) found a technological progress of 2-7% per year while Flaaten (1987) found it to be 1-4% per year.

The results show that an assumption of linearity between fishing mortality and fishing effort has to be modified, at least regarding the bottom trawl fisheries for cod. The analyses of the impact this will have on long term fisheries management, has not been a part of this study, but it certainly has to be a part of a long term strategy of how to exploit the fish resources. Differences in stock output elasticities between gears, could have important economic consequences, as the relative profitability of gear types changes, when the stock biomass rise or fall. This certainly complicate the question of what gear and vessel is the most efficient one, but increased information in this area hopefully will give more adequate and useful input to fisheries management.

Acknowledgement

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Appendix

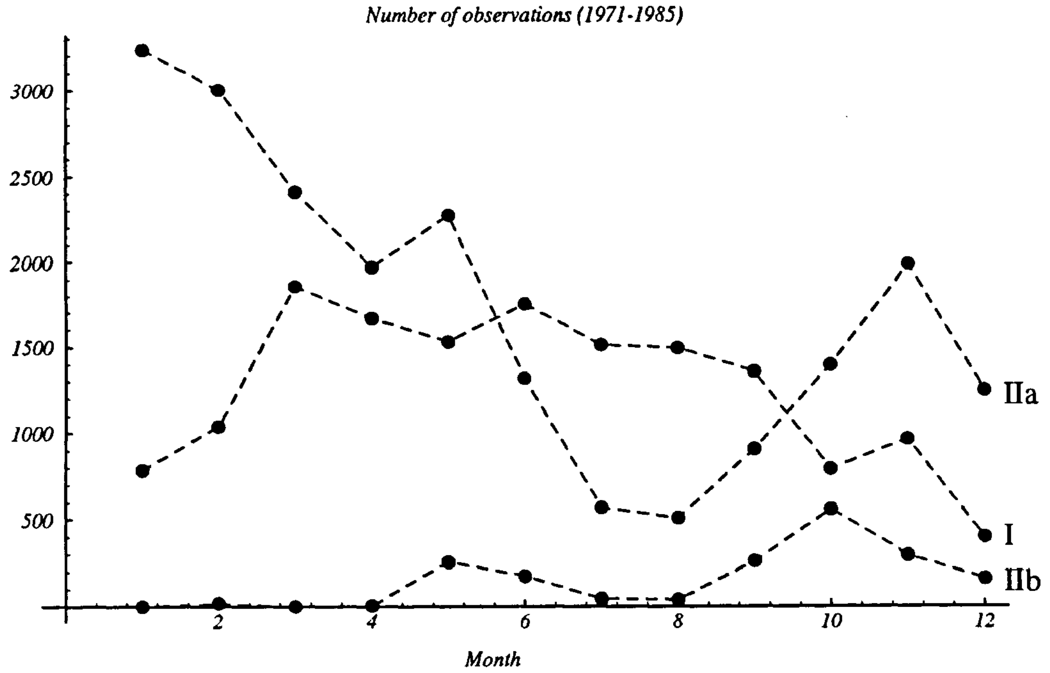

FIGURE A1. Number of trawl hauls in the data base of the 18 vessels, during the period 1971-1985, distributed on ICES areas I, IIa and IIb, and month (1=January, 2=February, etc.).

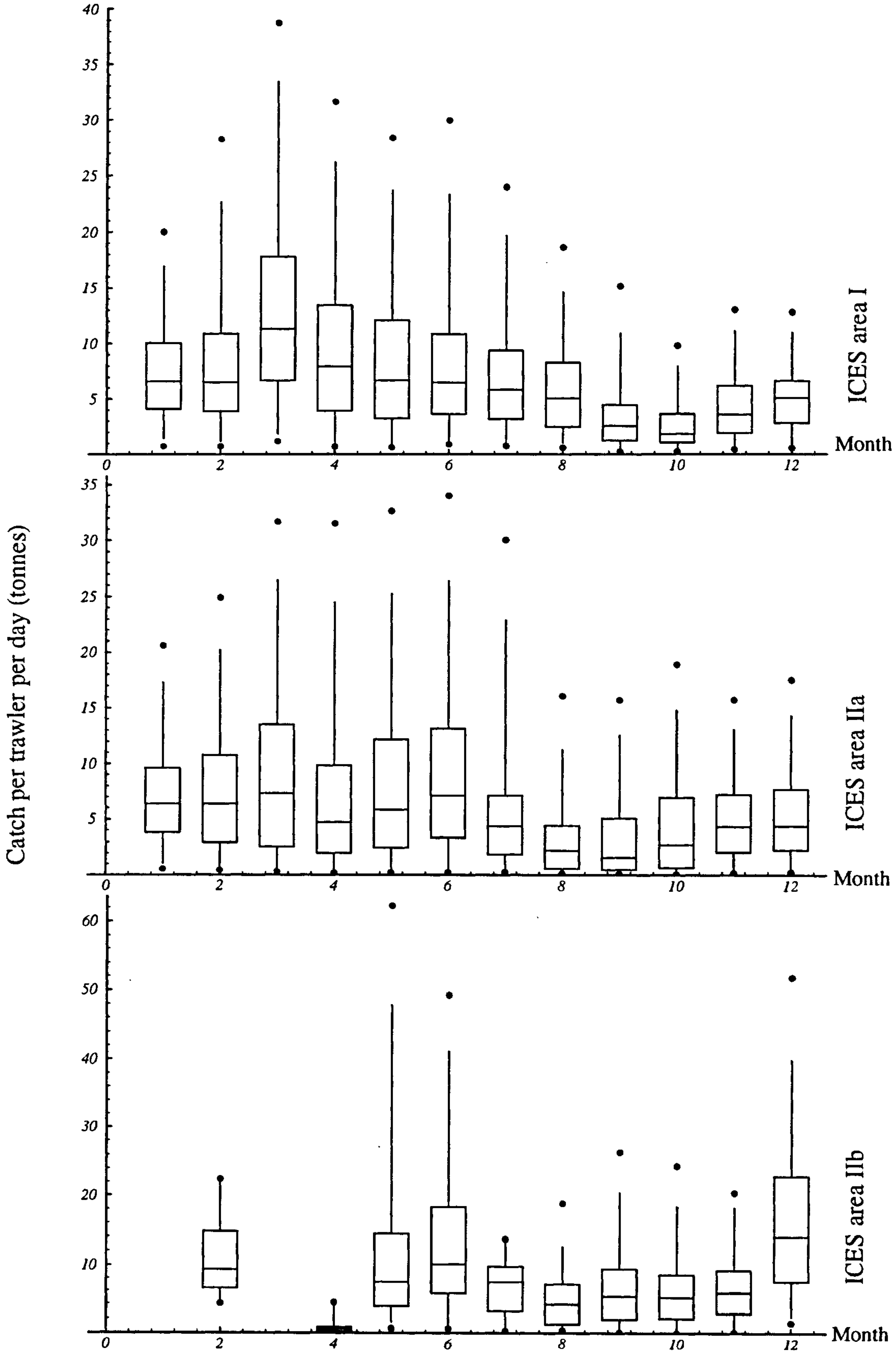

FIGURE A2. Box Plots of the trawl catches of the 18 vessels during 1971-1985.

TABLE A1. Trawlers included in the analysis. Average value and standard deviation of day catches of each trawler, distributed on quarters of a year, vessel size and horse powers of each vessel in 1971 and modifications during the investigated period, 1971-1985.

Vessel no.	Average day catch in tonnes (standard deviation in parenthesis)				Initial vessel size HP / length in m	Vessel modifications (HP or length in m)
	1 quarter	2. quarter	3. quarter	4. quarter		
1	9.65 (7.45)	9.24 (8.80)	6.28 (5.52)	5.02 (4.35)	1500 / 46.5	-
2	8.39 (6.55)	7.16 (6.86)	4.60 (5.24)	4.71 (3.90)	1500 / 46.5	1977 (1800)
3	8.38 (6.42)	7.65 (7.34)	4.02 (3.25)	4.44 (4.09)	1200 / 46.5	-
4	8.20 (6.27)	6.53 (5.99)	4.81 (3.89)	4.33 (3.09)	1050 / 38.7	-
5	8.42 (6.53)	7.67 (6.71)	4.74 (4.82)	5.62 (4.42)	1200 / 46.7	-
6	7.78 (6.32)	5.77 (5.55)	4.15 (4.74)	3.77 (3.91)	1200 / 41.8	1978 (1500) and 1978 (45.7)
7	8.91 (7.12)	8.78 (8.12)	5.18 (4.78)	5.58 (5.32)	1200 / 46.7	-
8	7.90 (6.56)	6.73 (6.00)	4.00 (4.49)	3.52 (3.44)	1200 / 41.8	1977 (45.7) and 1978 (1500)
9	9.19 (6.01)	7.12 (6.45)	4.94 (3.88)	5.20 (3.76)	1200 / 46.7	-
10	0.93 (0.64)	3.22 (2.08)	1.32 (1.59)	0.58 (0.66)	300 / 20.4	1981 (365)
11	13.07 (10.13)	13.39 (10.72)	7.85 (7.31)	10.10 (12.07)	1530 / 56.1	1974 (2700) and 1974 (67.6)
12	8.16 (6.67)	8.36 (7.29)	3.80 (3.86)	4.10 (3.72)	1200 / 42.1	1972 (1500)
13	9.68 (6.69)	8.89 (6.71)	7.77 (7.52)	6.20 (4.85)	1100 / 51.9	1979 (2350)
14	7.85 (6.65)	7.06 (7.71)	4.19 (4.98)	3.30 (4.10)	1500 / 45.4	-
15	13.10 (9.39)	12.72 (10.07)	8.44 (7.15)	8.24 (6.02)	1650 / 61.2	1982 (3000)
16	12.44 (10.79)	13.10 (14.26)	7.00 (7.34)	8.31 (7.44)	2300 / 75.5	-
17	13.22 (11.15)	15.33 (12.26)	9.31 (8.87)	9.25 (8.34)	2160 / 60.1	1984 (3000)
18	-	4.22 (3.08)	3.32 (2.57)	-	490 / 24.1	-

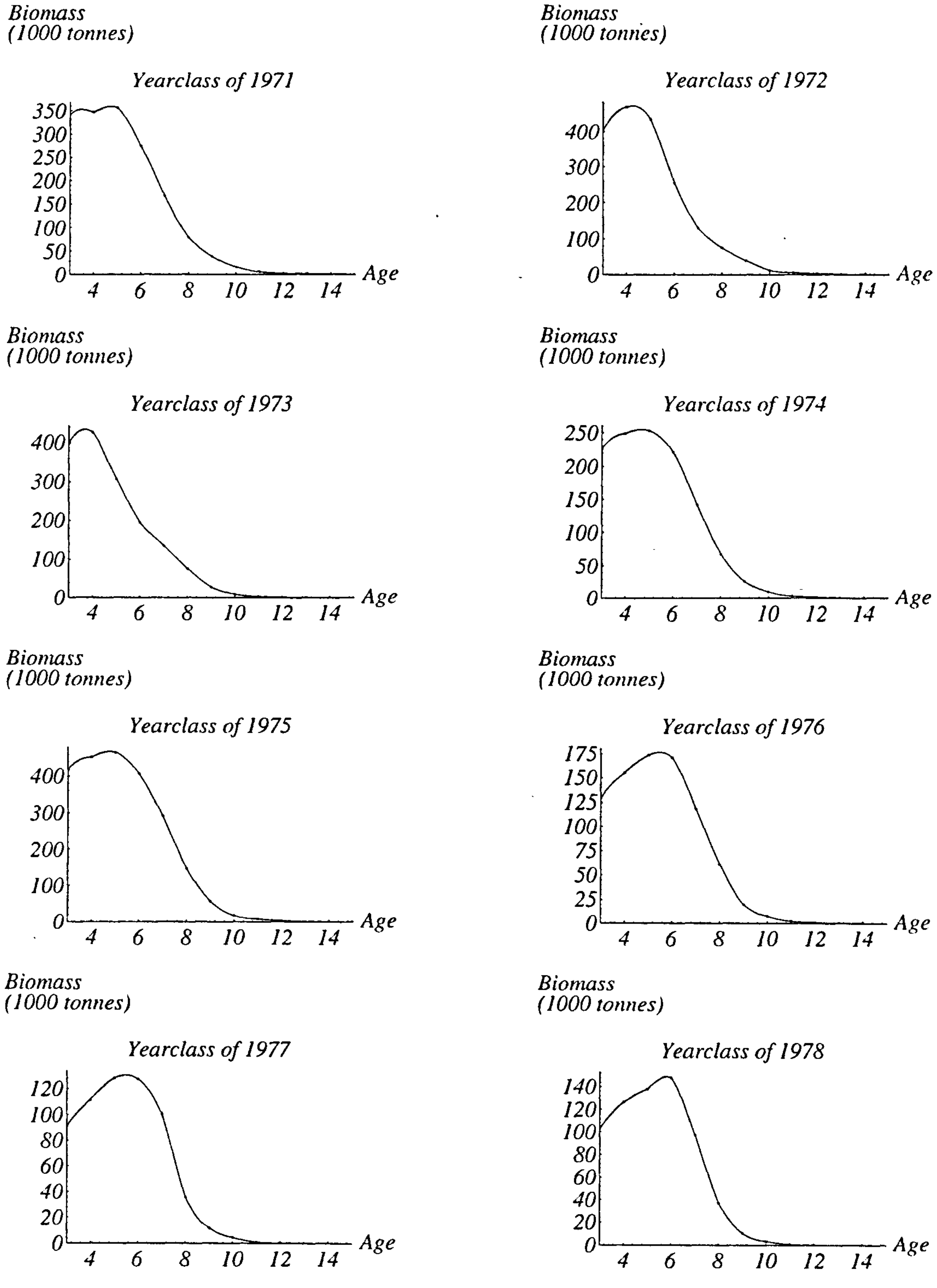

FIGURE A3. Graphical picture of the results of a polynomial interpolation of order 3, done on the estimated stock biomass of the cod year classes born in 1971-1978, on January 1. The estimates are from Anon. (1994).

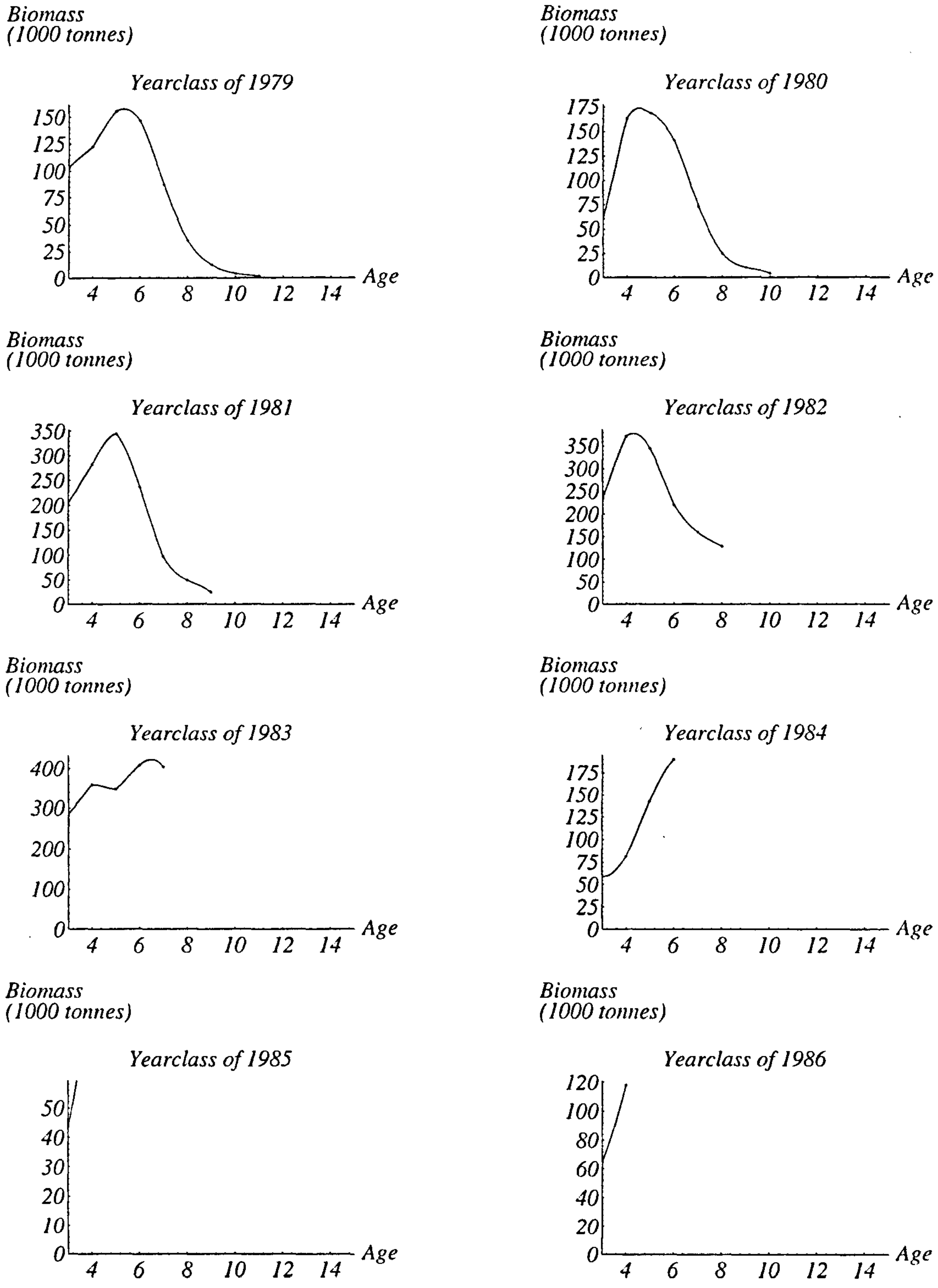

FIGURE A4. Graphical picture of the results of a polynomial interpolation of order 3, done on the estimated stock biomass of the cod year classes born in 1979-1986, on January 1. The estimates are from Anon. (1994).