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Trends of anchovy (*Engraulis encrasicolus*, L.) biomass in the northern and central Adriatic Sea*

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SUMMARY: Anchovy (*Engraulis encrasicolus*, L.) is one of the most important commercial species of the northern and central Adriatic Sea. The mean annual catch of anchovy estimated by IRPEM for these areas, in the time interval 1975-1996, is equal to 25,000 tonnes. Estimates of anchovy stock biomass at sea in the time interval 1975-1996 were obtained using two population dynamics methods based on different data inputs: Virtual Population Analysis (VPA) and the DeLury model with recruitment index. VPA was carried out tuning the estimated fishing mortality rate at age by fitting on corresponding Catch Per Unit of fishing Effort (CPUE). Both VPA and the DeLury model yielded sensible results. The effect on the assessments due to the use of a different birth date and thus of split-year data was investigated. Biomass values as well as patterns over time so estimated were similar on the basis of both assessment methods and calendar year versus split-year data. In particular, the biomass in more recent years (around 100,000 tonnes) was lower than in the second half of the 1970s and first half of the 1980s (over 200,000 tonnes). The minimum value (lower than 50,000 tonnes) was always estimated in 1987, when a strong drop in the catch and crisis of the anchovy fishery took place. Though high values of both fishing effort and fishing mortality/exploitation rate were obtained for some years before 1987, very low levels of recruitment in 1986 and 1987 seem to be mainly responsible for the collapse of the stock.

Key words: anchovy, Adriatic Sea, Virtual Population Analysis, Laurec-Shepherd tuning, DeLury model with recruitment index.

RESUMEN: TENDENCIAS EN LA BIOMASA DE ANCHOA (*ENGRAULIS ENCRASICOLUS*, L.) EN EL NORTE Y CENTRO DEL MAR ADRIÁTICO. – La anchoa (*Engraulis encrasicolus*, L.) es una de las especies comerciales más importantes en el norte y central Adriático. La captura media anual estimada de anchoas por el IRPEM para estas áreas en el intervalo 1975-1996, es de 25000 toneladas. Se obtuvieron estimas de la biomasa del stock de anchoa en el mar entre 1975-1996 mediante dos modelos de dinámica de poblaciones basados en diferentes entradas de datos: Análisis de Población Virtual (VPA) y el modelo de De Lury con índice de reclutamiento. El VPA se llevó a cabo sintonizando la tasa de mortalidad pesquera por edad ajustando a la correspondiente Captura por Unidad de Esfuerzo (CPUE). Tanto el VPA como el modelo de De Lury dan resultados sensibles. Se investigó el efecto sobre las evaluaciones del uso de una fecha de nacimiento diferente y en consecuencia de los datos por año. Los valores de biomasa, así como las pautas en el tiempo así estimadas fueron similares en base tanto a los métodos de evaluación como al calendario anual *versus* datos por año. En particular, la biomasa de los años más recientes (alrededor de 100000 toneladas) fue más baja que en la segunda mitad de los 70 y primera mitad de los 80 (unas 200000 toneladas). El valor mínimo (menor de 50000 toneladas) fue siempre estimado en 1987, cuando tuvo lugar un fuerte descenso en las capturas y una crisis en la pesquería de anchoa. Incluso si se obtuvieron valores altos de esfuerzo pesquero y tasas de mortalidad/explotación para algunos años antes de 1987, muy bajos valores de reclutamiento en 1986 y 1987 parecen ser los principales responsables del colapso de los stocks.

Palabras clave: anchoa, Adriático, análisis de poblaciones virtuales, Laurec-Shepherd tuning, modelo De Lury con reclutamiento.

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INTRODUCTION

Anchovy (*Engraulis encrasicolus*, L.) is one of the most important commercial species of the Adriatic Sea, and in 1991 the catch of Adriatic anchovies formed 19% of the Mediterranean anchovy catches (Stamatopoulos, 1993). The small pelagic fishery is particularly diffuse in the northern and central Adriatic Sea and anchovy is mainly fished by the Italian fleet, with catches from Slovenia and Croatia and the former Yugoslavian fleet accounting for approximately less than 1,000 tonnes per year. The Italian fleet in the northern and central Adriatic is composed of about 140 (70 couples) pelagic trawlers (*volante*), mainly operating from Trieste to Ancona and about 40 *lampara* vessels (purse seiners) which operate mainly in the central Adriatic Sea, i.e. south of Ancona (Cingolani *et al*., 1996a).

Stock assessments of anchovy in the Adriatic Sea were also performed by other researchers using different methods, such as echo surveys (Azzali *et al*., 1990), egg and larvae surveys (Piccinetti and Specchi, 1984; Regner, 1996) and population dynamics (Sinovcic, 2000).

Since 1975, IRPEM (Istituto di Ricerche sulla Pesca Marittima, Consiglio Nazionale delle Ricerche, Italy) has been conducting research on the biology and stock assessment of anchovy and sardine by population dynamics methods in the northern and central Adriatic Sea (Levi *et al*., 1984; 1985; Cingolani *et al*., 1993; Arneri, 1996; Cingolani *et al*., 1996a,b; 1998a,b,c; 2000; Santojanni *et al*., 1999; 2001a,b). This has involved the regular collection of catch, fishing effort and biological data pertaining to these stocks at a number of ports along the Italian Adriatic coast. Since the early 1990s, assessments of these stocks have been carried out jointly by IRPEM and MRAG Ltd. (London, UK).

On the basis of the IRPEM database, the mean annual catch of anchovy is 25,000 tonnes in the time interval 1975-1996, the maximum value of the catch being higher than 50,000 tonnes in 1978-1980. The minimum value was recorded in 1987 with around 4,000 tonnes, and corresponds to a strong crisis of the anchovy fishery. Though recovery of catches was observed, the mean annual catch is estimated at around 16,000 tonnes after 1987, in contrast with the 33,000 tonnes estimated before.

This paper deals with the values and patterns over time of estimated anchovy stock biomass at sea in the period 1975-1996. These estimates were obtained using two dynamic methods based on different data inputs: Virtual Population Analysis (VPA), based on the age frequency distribution of the catch, and a modified DeLury stock depletion model with an index of annual recruitment. The VPA was carried out using two types of Laurec-Shepherd tuning, which is employed to obtain reliable estimates of the individuals at sea belonging to the cohorts still being fished, i.e. in more recent years. The effect on the assessments due to the use of a different birth date of anchovy and thus of split-year data was investigated by both VPA and the DeLury model with recruitment index.

MATERIAL AND METHODS

Data

Monthly landings have been collected in the major fishing ports for pelagic fish along Italian coast (major ports in the text) such as Trieste, Chioggia, Porto Garibaldi, Cesenatico, Cattolica, Ancona, San Benedetto del Tronto and Vieste, and also in other fishing ports such as Grado, Marano Lagunare, Caorle, Goro, Rimini, Fano and Giulianova (Fig. 1), where landings were not so high as in the major ports. Landing data for Croatia and Slovenia were derived from published sources up to 1994 (Morsko Ribarstvo, 1975-1994), whereas data relative to 1995 and 1996 were given by the Institute of Oceanography and Fisheries of Split (G. Sinovcic, pers. comm.).

Landings can be considered a reliable estimate of catches because the Adriatic anchovy is always required by the market, so discarding is thought to be negligible (Cingolani *et al*., 2000). In addition, from the late 1970s up to the early 1980s, AIMA (Azienda di Stato per gli Interventi sul Mercato Agricolo), a governmental agency responsible for interventions in the agricultural market, regulated the price paid for excess catches of anchovies (and sardines) by buying surplus catch, thus effectively encouraging fishermen to catch and land as much as possible.

Annual series of standardised fishing effort data were calculated taking into account the number of vessels, fishing days spent and potential fishing capability of single vessels, such as gear and engine power (Cingolani *et al*., 1993, 1996a). Standardisation of effort was performed following a procedure defined by Levi *et al*. (1985) and using the FPOW computer program (Abramson, 1971).

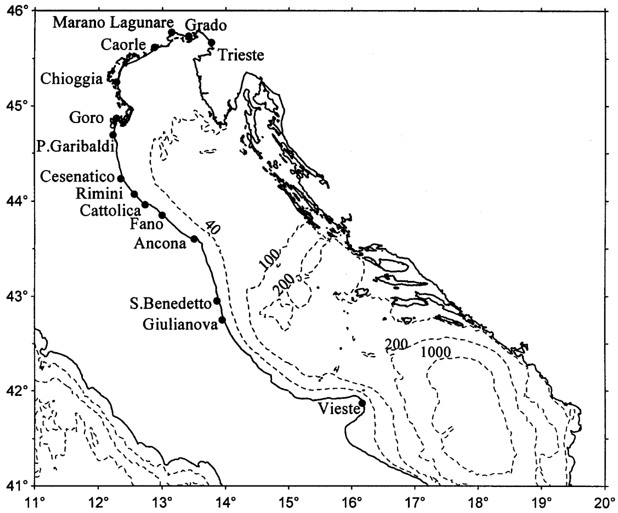

FIG. 1. – Geographic extent of the survey: the port of Vieste represents the southern limit.

Catch and effort data were utilised to calculate the time series of standardised Catch Per Unit of Effort (CPUE). Gaps in the data set made impossible to obtain a standardised CPUE series for all ports and all years. Therefore, the time series of CPUE calculated for the fleet (trawlers) of Porto Garibaldi was used in the assessments because, this was the port at which the best series of effort and greatest amount of caught anchovy were recorded. In the period 1975-1996, the average catch of Porto Garibaldi is 25% of the total Adriatic catch of anchovy. The annual values of Porto Garibaldi fishing effort are shown in Figure 2 along with corresponding catches; total catches are also reported. The series of effort shows fluctuations, the most pronounced being in the first half of the 1980s and probably related to the AIMA phenomenon. It should also be noted that the two series of catches have quite similar trends, with the highest values in the second half of the 1970s and subsequently decline, crash and partial recovery.

Monthly biological samples have been collected in the major ports. Annual catch-weighted length frequency distributions of the catch were obtained by measuring fishes on the basis of 0.5 cm length classes (1 cm before 1988). Age was estimated by reading 10,336 anchovy otoliths and annual age-length keys were calculated from age-length data pooled over months within the year and pooled across subsets of ports, i.e. northern and central (south of Ancona); these keys were then applied to the annual catch-weighted length frequencies for the two subsets of ports in order to obtain the estimated annual age frequency distributions of the total catch (Cingolani *et al.*, 1993). Age-length keys were thus obtained for the years 1977 (Table 1), 1978 (Table 2), 1986 (Table 3), 1989 (Table 4) and 1995 (Table 5), so that missing year data were replaced by available ones: the age-length key obtained for 1977 was also used for 1975 and 1976, the 1978 key for the period 1978-1983, the 1986 key for the period 1984-1987, the 1989 key for the period 1988-1991 and the 1995 key for the period 1992-1996. Trials of estimating missing age frequency distributions using the method of Kimura and Chikuni (1987) did not consistently give plausible estimates of catch-at-age. Possible reasons for this could be the limited number of age classes.

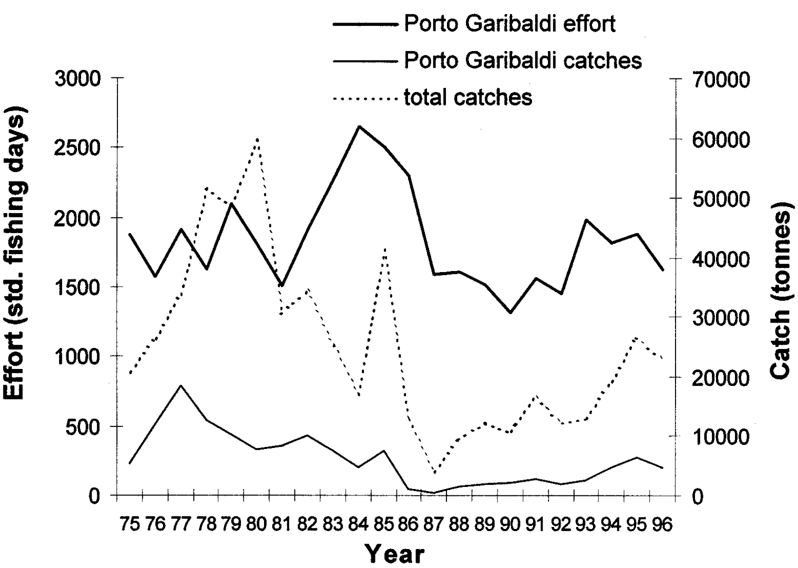

FIG. 2. – Anchovy standardised fishing effort for the fleet of Porto Garibaldi as a function of time. Total and Porto Garibaldi catches are also reported. Calendar year data were used.

TABLE 1. – Anchovy age (year) - length (cm) key calculated for 1977 and used for the period 1975-1977. Calendar year data were used.

Length	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
8.0	0	0	0	0	0	0	0
9.0	0.895	0.105	0	0	0	0	0
10.0	0.772	0.228	0	0	0	0	0
11.0	0.552	0.445	0.003	0	0	0	0
12.0	0.191	0.682	0.124	0.003	0	0	0
13.0	0.011	0.207	0.667	0.107	0.008	0	0
14.0	0	0.004	0.043	0.536	0.340	0.077	0
15.0	0	0	0	0.131	0.504	0.358	0.007
16.0	0	0	0	0	0.200	0.650	0.150
17.0	0	0	0	0	0	0	0
18.0	0	0	0	0	0	0	0
19.0	0	0	0	0	0	0	0

TABLE 2. – Anchovy age (year) - length (cm) key calculated for 1978 and used for the period 1978-1983. Calendar year data were used.

Length	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
8.0	0	0	0	0	0	0	0
9.0	0.867	0.133	0	0	0	0	0
10.0	0.764	0.236	0	0	0	0	0
11.0	0.275	0.696	0.029	0	0	0	0
12.0	0.005	0.427	0.554	0.014	0	0	0
13.0	0	0	0.400	0.580	0.020	0	0
14.0	0	0	0	0.364	0.525	0.111	0
15.0	0	0	0	0.009	0.303	0.615	0.073
16.0	0	0	0	0	0	0.286	0.714
17.0	0	0	0	0	0	0	0
18.0	0	0	0	0	0	0	0
19.0	0	0	0	0	0	0	0

TABLE 3. – Anchovy age (year) - length (cm) key calculated for 1986 and used for the period 1984-1987. Calendar year data were used.

Length	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
8.0	0	0	0	0	0	0	0
9.0	0	0	0	0	0	0	0
10.0	0.865	0.135	0	0	0	0	0
11.0	0.780	0.216	0.004	0	0	0	0
12.0	0.542	0.397	0.057	0	0.003	0	0
13.0	0.239	0.461	0.271	0.021	0.007	0	0
14.0	0.057	0.283	0.387	0.246	0.020	0.007	0
15.0	0	0.088	0.281	0.458	0.153	0.020	0
16.0	0	0	0.183	0.410	0.336	0.070	0
17.0	0	0	0	0.147	0.579	0.274	0
18.0	0	0	0	0	0.176	0.412	0.412
19.0	0	0	0	0	0	0	0

TABLE 4. – Anchovy age (year) - length (cm) key calculated for 1989 and used for the period 1988-1991. Calendar year data were used.

Length	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
8.0	0.897	0.103	0	0	0	0	0
8.5	0.875	0.125	0	0	0	0	0
9.0	0.915	0.085	0	0	0	0	0
9.5	0.884	0.116	0	0	0	0	0
10.0	0.864	0.136	0	0	0	0	0
10.5	0.774	0.226	0	0	0	0	0
11.0	0.773	0.227	0	0	0	0	0
11.5	0.762	0.238	0	0	0	0	0
12.0	0.717	0.283	0	0	0	0	0
12.5	0.602	0.398	0	0	0	0	0
13.0	0.304	0.670	0.026	0	0	0	0
13.5	0.138	0.751	0.110	0	0	0	0
14.0	0.021	0.441	0.524	0.014	0	0	0
14.5	0.008	0.348	0.553	0.091	0	0	0
15.0	0	0.220	0.364	0.364	0.053	0	0
15.5	0	0.090	0.513	0.282	0.115	0	0
16.0	0	0.019	0.615	0.250	0.115	0	0
16.5	0	0	0.500	0.429	0.071	0	0
17.0	0	0	0.043	0.696	0.261	0	0
17.5	0	0	0	1	0	0	0
18.0	0	0	0	0.500	0.500	0	0
18.5	0	0	0	0	0	0	0
19.0	0	0	0	0	0	0	0

TABLE 5. – Anchovy age (year) - length (cm) key calculated for 1995 and used for the period 1992-1996. Calendar year data were used.

Length	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
8.0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0
9.0	0	0	0	0	0	0	0
9.5	0.980	0.020	0	0	0	0	0
10.0	0.859	0.141	0	0	0	0	0
10.5	0.916	0.084	0	0	0	0	0
11.0	0.747	0.253	0	0	0	0	0
11.5	0.502	0.498	0	0	0	0	0
12.0	0.256	0.744	0	0	0	0	0
12.5	0.158	0.831	0.011	0	0	0	0
13.0	0.055	0.810	0.135	0	0	0	0
13.5	0.011	0.454	0.519	0.016	0	0	0
14.0	0	0.167	0.446	0.365	0.022	0	0
14.5	0	0.108	0.216	0.572	0.105	0	0
15.0	0	0.019	0.155	0.357	0.403	0.066	0
15.5	0	0.014	0.212	0.240	0.390	0.137	0.007
16.0	0	0	0.073	0.303	0.294	0.275	0.055
16.5	0	0	0.064	0.234	0.191	0.319	0.191
17.0	0	0	0	0.423	0.192	0.154	0.231
17.5	0	0	0	0.333	0.500	0.167	0
18.0	0	0	0	0.667	0.333	0	0
18.5	0	0	0	0	0	0	0
19.0	0	0	0	0	0	0	0

A raw recruitment index for a year was calculated as the weighted sum of proportions of 9-10.9 cm (9-10 cm before 1988) anchovies in the monthly catches for Porto Garibaldi, where the weights used were the estimated monthly Porto Garibaldi CPUEs in numbers. Individuals between 9 and 10.9 cm in length were considered to be recruits, taking into account the fact that the majority of fish in this length range fell into age class zero and possible effects of gear and sampling selectivity in sizes smaller then 9 cm, which occurred rarely in the Porto Garibaldi catches, i.e. around 2% (against 12% of the selected range) of the total distribution. In addition, this choice took into account the need to avoid double counting, as estimated growth rates suggest that anchovies are likely to grow through that length range in a month (Cingolani *et al.*, 1993). The general equation used to calculate the annual recruitment index is the following:

$$R_{year} = \sum_{month} P_{month} \frac{\dfrac{\sum_{port} catch_{port,\,month}}{\sum_{port} effort_{port,\,month}}}{Wt_{month}}$$

with R_{year} = annual recruitment index, P_{month} = monthly proportion of recruits in the monthly catch of the selected ports (Porto Garibaldi in the present analysis) and Wt_{month} = monthly mean weight of fish used to transform the corresponding CPUE in weight into CPUE in number of individuals. The annual R_{year} indices were then scaled so that their maximum across years was 1. The values thus obtained, on the basis of calendar year data, are plotted in Figure 3a and compared with corresponding annual CPUEs. Consistency (important for the success of DeLury fitting, see below) between recruitment index and CPUE is observed: higher values of stock abundance at sea are related to higher recruitment levels over time. This is not an obvious result for the procedure employed, as exemplified by the poor consistency observed when an analogous calculation was carried for sardine (Cingolani *et al.*, 2000).

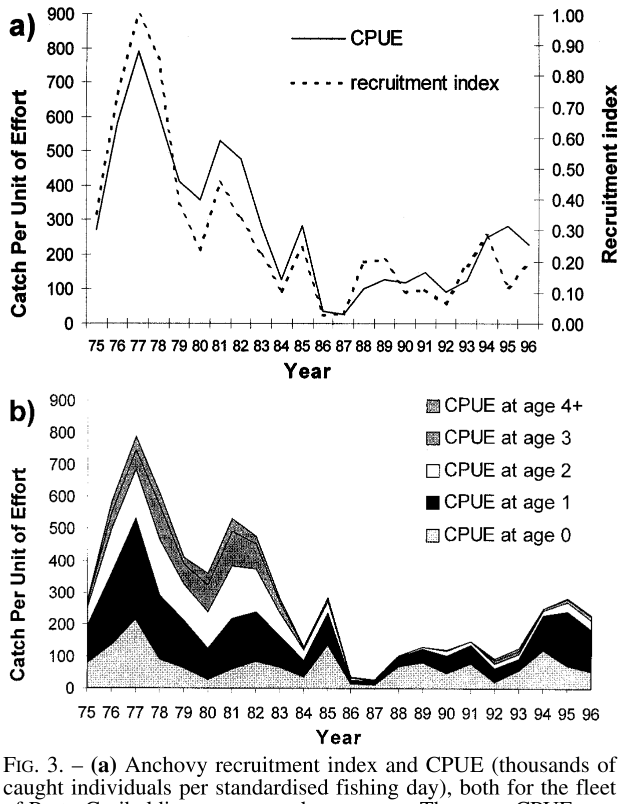

FIG. 3. – **(a)** Anchovy recruitment index and CPUE (thousands of caught individuals per standardised fishing day), both for the fleet of Porto Garibaldi, are compared over years. The same CPUEs are plotted **(b)** showing the weight of catches at different ages. These catch values, divided by the corresponding effort calculated for all the age classes, are the CPUEs at age 0, 1, 2, 3 and 4+ (including individuals older than 4 years) used in VPA calculations (tuning, see text). Calendar year data were used.

In the Figure 3b, CPUEs are plotted showing the importance of catches at different ages. These catch values, divided by the corresponding effort calculated for all the age classes, are the CPUE-at-age data used in VPA calculations (tuning, see below). The highest fractions of these catches are given by the age classes 0 and 1, which (mainly the class 0) correspond to the length range used to calculate the recruitment index. This holds on the whole so that consistency between CPUE at the youngest ages and length-based recruitment index in the same year is obtained, even if a high weight of older ages (2 and 3) is observed in the period 1978-1982, in contrast with a recruitment level in the same period that was still high as in the years before.

The use of calendar year data in fishery stock assessments implies that the conventional birth date (i.e. the day on which a cohort grows one year older) is on the first day of January. Since the reproduction of the Adriatic anchovy is particularly relevant in spring-summer (Regner, 1985), and a conventional birth date on the first of June is more coherent with the biology of the species, assessments were also made taking into account a different birth date. The birth date effect is expected to be not negligible more likely in the assessment based on catch-at-age data, i.e. Virtual Population Analysis. Consequently, all data (with the exception of age-length keys) originally recorded according to calendar year were then modified in order to calculate split-year ones, using the first day of June as the birth date, so that data relative to one year referred to the time interval ranging from the first of June of the year before up to the 31st May of that year.

Virtual Population Analysis (VPA)

Virtual Population Analysis (VPA) is based on analysis of the age frequency distributions of annual total catches (Gulland, 1983; Hilborn and Walters, 1992). VPA yields the estimate of the number of fish at sea for each age class and year. For this purpose, an estimate of the fishing mortality rate as a function of age and time is required ($F_{age,\ year}$). The natural mortality rate, M, is also required: this parameter is assumed as a constant function of age and time.

The fishing mortality rate for each age class in each year ($F_{age,\ year}$) is calculated by VPA on the basis of the corresponding annual age distribution of the catch. The annual age distributions of the Adriatic anchovy catches on the basis of calendar year data

TABLE 6. – Annual age frequency (millions of individuals) distribution of the anchovy total catch from 1975 to 1996. The last age class, 4+, includes individuals older than 4 years. Calendar year data were used.

Year	Age 0	Age 1	Age 2	Age 3	Age 4+	Total
1975	503	741	357	95	51	1,747
1976	479	778	485	177	116	2,035
1977	721	1,078	519	198	147	2,664
1978	632	1,376	1,232	727	271	4,239
1979	606	1,455	1,138	617	197	4,014
1980	343	1,189	1,439	1,062	447	4,480
1981	293	747	786	526	178	2,531
1982	475	874	778	448	145	2,721
1983	443	660	496	231	69	1,899
1984	345	435	279	100	25	1,184
1985	981	943	566	284	88	2,862
1986	203	163	129	121	86	701
1987	100	96	51	25	9	280
1988	495	290	55	11	2	854
1989	467	370	114	20	2	974
1990	281	310	121	23	6	741
1991	415	397	193	85	25	1,115
1992	105	257	135	125	96	718
1993	227	319	134	115	99	894
1994	399	607	209	137	69	1,422
1995	272	859	331	212	111	1,783
1996	209	560	272	238	149	1,428

are reported in Table 6: the age classes refer to years and range from 0 to 4+, with the last class including individuals older than 4.

VPAs were carried out using two types of Laurec-Shepherd tuning (Laurec and Shepherd, 1983; Pope and Shepherd, 1985). Both methods attempt to estimate the Fs at age in the final year by fitting to CPUE-at-age data in earlier years, under the assumption of constant annual selectivity at age. The two methods differ in the way they treat the annual Fs at the last true age (age 3 in our case). The first, and more commonly used method (method 1 in the text), makes the additional assumption that the annual F at the last true age is equal to the product of the constant k (fixed) and the average of the values of F obtained for a fixed number, n, of younger ages in the same year. The second method (method 2) requires the user to specify a vector of annual Fs (i.e. fixed) at the last true age. For both methods, tuning was carried out with respect to standardised Porto Garibaldi CPUE-at-age data.

For both methods, as already mentioned, a key assumption is that there are no trends over time in the annual selectivity at age, at least for the years over which tuning is carried out, e.g. technological improvement (not taken into account in the calculation of effort) leading to increased catchability. In order to examine how well the constant selectivity assumption has been met, plots of the annual differences between observed and predicted values of the natural logarithm of the age-specific catchability coefficient, q, were examined.

There is no fully reliable method for estimating $F_{3,\,1996}$, so it was estimated to be equal to the total fishing mortality rate in 1996. The estimates of this parameter ranged from 0.3 to 0.5 (yr^{-1}) and were obtained by subtracting M from Z, i.e. the total mortality rate, which was calculated by a catch curve analysis (Hilborn and Walters, 1992). In this paper, 0.5 as a precautionary value of $F_{3,\,1996}$ was used because it yielded the lowest biomass. Some shorter accounts of the estimates obtained by using 0.3 are also reported.

The values of $F_{3,\,year}$ in all the other years were calculated on the basis of a relationship between $F_{3,\,1996}$ and Porto Garibaldi effort, as follows:

$$F_{3,\,t} / E_t = F_{3,\,1996} / E_{1996}$$

where E_t is the effort in the year t. This relationship implies the assumption of the ratio between Porto Garibaldi and total effort constant over time. Since, for the Laurec-Shepherd tuning, it was assumed that the Porto Garibaldi CPUE is equal to the total CPUE, the ratio between the two effort series can be calculated as the ratio between the corresponding catches as well. Both the series of these catches are shown, on the basis of calendar year data, in Figure 2: their ratio (P.G. / total) fluctuates between 0.10 and 0.30 in most years, whereas it is equal to 0.45 and 0.55 in 1976 and 1977 respectively. Hence, the assumption mentioned above about effort roughly holds.

The natural mortality rate, M, was assumed to be equal to 0.6 (yr^{-1}) on the basis of the observed age distributions of the catches. The value used in these assessments, 0.6, is perhaps towards the low end of the range of estimates of M reported in the literature for anchovies, so VPA was also carried out using 0.7, 0.8 and 0.9 (with split-year data and $F_{3,\,1996} = 0.5$).

Finally, retrospective VPA was also performed. This application of VPA allows one to evaluate the stability of estimated biomass at sea as a function of length of the time series analysed, which is progressively reduced excluding recent years. In general, strong deviations from the results obtained using complete original time series could be due to biases in input data, such as trends in catchability and wrong natural mortality rate (Darby and Flatman, 1994). Thus, VPA calculations were repeated using data from 1975 to 1994, 1992, 1990, 1988, 1986, 1984 (with calendar year, $F_{3,\,1996} = 0.5$ and $M = 0.6$).

All VPA calculations were done using the MAFF-VPA software package (Ministry of Agriculture, Fishery and Food, UK), developed by Darby and Flatman (1994).

DeLury model with recruitment index

The DeLury model with recruitment index is a stock depletion model using total catch and CPUE data, which also takes into account interannual variability in recruitment (Hilborn and Walters, 1992; MRAG, 1992).

The relationship between the number of adults at sea in the year t+1, N_{t+1} and those in the previous year t is given by:

$$N_{t+1} = [(N_t + \lambda R_t) e^{-M/2} - C_t] e^{-M/2}$$

where N_{t+1} and N_t are the numbers of adults at the beginning of the year t+1 and t , respectively; C_t is the total number of individuals caught during the year t; R_t is the recruitment index during the year t; λ is the constant of proportionality between the recruitment index and the true annual recruitment number; M is the natural mortality rate.

In this formulation, annual recruitment is assumed to take place at the beginning of the year, with the main catches being taken in the middle of the year, and natural mortality occurring throughout the year. These relative timings were selected on the basis of analyses of monthly catches and length frequency (Cingolani *et al*., 1993).

The DeLury model with recruitment index specifies that the expected catch, $E(c_t)$, in the year t, is given by:

$$E(c_t) = q \; E_t \; [(N_t + \lambda R_t) e^{-M/2} - C_t / 2]$$

where q is the catchability coefficient, c_t is the catch in numbers taken with the fishing effort E_t applied in the year t; C_t in this case is total catch and c_t is Porto Garibaldi catch. The expected catch at the end of the year is thus directly proportional to catchability, effort and number of fish at sea in the middle of the year, this last feature being expressed by the term between square brackets.

The parameters q and λ are estimated by maximum likelihood methods along with N_1, the numbers of adults at the beginning of the first year (1975 in our case). In the estimation of the parameters, the catches c_t were assumed to have a gamma distribution. Confidence intervals were calculated for the three parameters at different precision levels (95, 90 and 75%) by means of bootstrap method (Hilborn and Walters, 1992; MRAG, 1992).

The natural mortality rate, M, was assumed to be equal to 0.6 as for VPA.

The model was fitted by the software package CEDA (Catch Effort Data Analysis), developed by MRAG (1992).

RESULTS

When the Laurec-Shepherd tuned VPA was based on method 1, plausible results were only obtained if the annual F at the last true age was equal to the product of the constant k and the average of the Fs obtained for n specified younger ages in the same year, with k being chosen around 1.3 or higher. This is rather unusual, as it is more common that fishing mortality rates at age either flatten out with increasing ages, or even diminish (i.e. flat-topped or dome-shaped fishing mortality curves), rather than increasing as they do using such high values of the constant k. In the Adriatic anchovy fishery, it is known that in the early 1990s part of the fleet (Ancona and San Benedetto fleets for instance) fished in deeper waters targeting large anchovies, which fetched higher prices. It is therefore plausible that the fishing mortality curves may consistently increase with age, at least in the most recent years. Prior to the 1990s, however, the degree of targeting on larger anchovy was known to be considerably lower. At any rate, on the basis of the log-catchability residuals (Fig. 4), the assumption that selectivity at age had remained constant is untenable. Therefore, no reliable results could be obtained from method 1.

When tuning method 2 was used, the resulting pattern of log-catchability residuals was considerably better than that obtained by method 1 (Fig. 4). The estimated fishing mortality at age pattern also showed a distinct shift from a flat-topped curve prior to 1990 to a steadily increasing pattern with age in the early 1990s. This coincides with what was believed to have happened in the fishery. Hence, the following VPA results always refer to this method of Laurec-Shepherd tuning.

The mid-year biomass values estimated by VPA (with $F_{3,\,1996} = 0.5$ and M = 0.6) and total catches, on the basis of calendar year data, are compared over years in Figure 5. The highest biomass is observed in 1977 (370,000 tonnes). Then there is a decline up

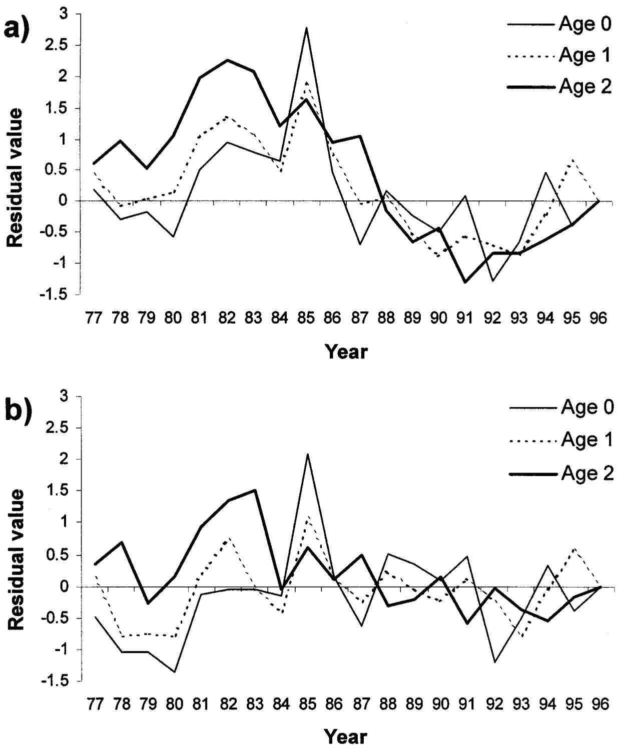

FIG. 4. – Differences (= residual values) between observed and predicted values of the natural logarithm of the age-specific catchability coefficient, q , as a function of time for two VPAs, based on different procedures of calculation of the fishing mortality rate, F, at the last true age for each year: these rates are **(a)** equal to the product between the constant k (fixed) and the average of the values of F obtained for a fixed number, n , of younger ages in the same year, or **(b)** fixed values. The VPA based on the latter method was carried out using the fishing mortality rate $F_{3,\ 1996} = 0.5$, while for both VPAs the natural mortality rate, M , was equal to 0.6. Calendar year data were used.

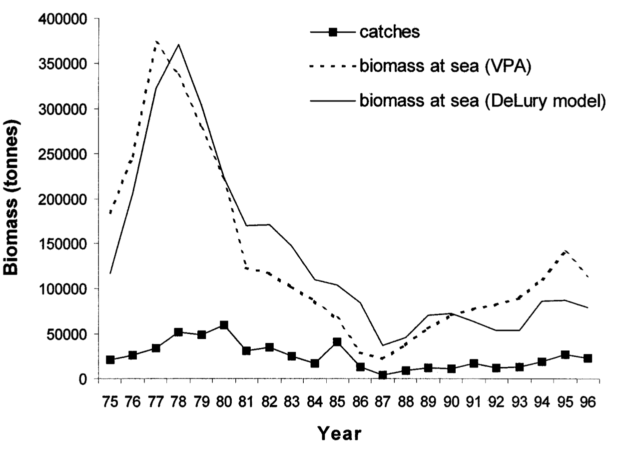

FIG. 5. – Mid-year anchovy biomass at sea estimated by VPA and DeLury model with recruitment index are compared over years; total catches are also reported. VPA was carried out using the fishing mortality rate $F_{3,\ 1996} = 0.5$. For both methods, the natural mortality rate, M , was equal to 0.6. Calendar year data were used.

to 1986 and 1987, with biomass being estimated to be around 25,000 tonnes. This is the minimum value and is associated with the lowest catch level, which represented a serious crisis for fishermen. In the subsequent years, biomass increases up to 110,000 tonnes in 1994 and 140,000 tonnes in 1995, associated with a partial recovery of the catch. In 1996, a decrease in biomass is observed, with an estimate of 110,000 tonnes. All the values estimated in the period 1993-1996 are higher than in 1986, i.e. before the collapse of the stock. However, they are lower than the estimates for the period 1975-1980.

A pattern of abundance at sea which is similar on the whole to that just described is also observed in the (calendar year) Porto Garibaldi CPUE (Fig. 2). This series of CPUE, as stated above, was used as tuning data in VPA calculations, i.e. not as input data. The effect yielded by CPUE was thus on the estimates for more recent years rather than earlier ones. What is more, this effect was weaker when method 2 was used, the values of fishing mortality rates at the oldest age being fixed. Hence, the observed consistency between CPUE and biomass patterns could support reliability of the VPA estimates.

The annual fishing mortality rates calculated by the above-mentioned VPA as a function of age and year are reported in Table 7 along with corresponding estimated numbers of individuals at sea. In the same table, the annual unweighted averages of Fs on the age interval 0-3 are also reported: the minimum value of these averages is observed in 1977 and 1992 (0.23) and the maximum one in 1985 (0.91). A high percentage (77%) of Fs is below 0.40 and the average calculated for the whole period 1975-1996 is equal to 0.35. Consequently, the exploitation rate, i.e. the ratio F / (F + M), is equal to 0.36 in the period 1975-1996, and in particular 0.60 in 1985.

The results yielded by retrospective VPA (with calendar year data, $F_{3,\ 1996} = 0.5$ and M = 0.6) are shown in Figure 6: quite high stability in the recent values of mid-year biomass at sea and strong stability in the oldest ones are observed. Again, this supports reliability of the assessments based on VPA.

The use of $F_{3,\ 1996} = 0.3$ in VPA calculations (with calendar year data and M = 0.6) involved higher biomasses for an average amount equal to 31% of the biomass estimated using $F_{3,\ 1996} = 0.5$. With $F_{3,\ 1996} = 0.3$ the mean annual fishing mortality rate and exploitation rate was 0.25 and 0.28 respectively, and was again relatively high in 1985 (0.72 and 0.55).

Changing M in the VPA (with split-year data and $F_{3,\ 1996} = 0.5$) did not yield great differences in biomass values, when M = 0.7 and 0.8 were used instead of 0.6 (Table 8). The VPA performed with M = 0.9 yielded very high and less realistic biomass

TABLE 7. – Values of the anchovy fishing mortality rate, F, and number (millions) of individuals at sea at the beginning of the year, as a function of age and year, derived from the VPA carried out using $F_{3,1996} = 0.5$ and the natural mortality rate M = 0.6. The last age class, 4+, includes individuals older than 4 years. The annual unweighted averages of Fs on the age interval 0-3 are also reported. Calendar year data were used.

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
	Fishing mortality rate																					
Age 0	0.04	0.03	0.03	0.04	0.06	0.05	0.07	0.09	0.10	0.13	0.92	0.26	0.07	0.19	0.13	0.10	0.14	0.03	0.04	0.07	0.04	0.06
Age 1	0.28	0.11	0.15	0.13	0.18	0.23	0.23	0.47	0.26	0.22	1.11	0.62	0.30	0.50	0.33	0.19	0.32	0.18	0.15	0.21	0.36	0.17
Age 2	0.35	0.47	0.15	0.42	0.23	0.44	0.36	0.66	0.92	0.26	0.83	0.74	0.66	0.45	0.63	0.26	0.27	0.26	0.21	0.22	0.26	0.28
Age 3	0.57	0.48	0.59	0.50	0.64	0.55	0.46	0.59	0.70	0.81	0.77	0.70	0.49	0.49	0.47	0.40	0.48	0.44	0.61	0.56	0.58	0.50
Age 4+	0.57	0.48	0.59	0.50	0.64	0.55	0.46	0.59	0.70	0.81	0.77	0.70	0.49	0.49	0.47	0.40	0.48	0.44	0.61	0.56	0.58	0.50
Mean	0.31	0.27	0.23	0.27	0.28	0.32	0.28	0.45	0.50	0.36	0.91	0.58	0.38	0.41	0.39	0.24	0.30	0.23	0.25	0.27	0.31	0.25
	Number (millions) of individuals at sea																					
	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Age 0	19,330	18,733	28,901	21,771	14,918	9,138	5,949	7,527	5,900	3,681	2,076	1,145	1,863	3,808	4,968	3,877	4,254	5,579	7,945	7,365	8,887	4,712
Age 1	4,029	10,242	9,932	15,336	11,488	7,746	4,765	3,051	3,786	2,916	1,770	455	483	950	1,731	2,388	1,923	2,034	2,986	4,195	3,751	4,680
Age 2	1,566	1,678	5,056	4,670	7,419	5,252	3,393	2,076	1,051	1,602	1,286	319	134	196	315	684	1,086	770	930	1,407	1,864	1,443
Age 3	284	603	575	2,399	1,682	3,250	1,855	1,299	590	231	678	309	84	38	68	92	289	457	325	414	621	785
Age 4+	151	394	427	895	536	1,369	627	420	175	57	209	218	29	7	7	22	86	352	279	208	326	492
Total	25,359	31,650	44,890	45,070	36,043	26,755	16,590	14,373	11,501	8,487	6,020	2,446	2,592	4,999	7,090	7,064	7,638	9,192	12,465	13,588	15,450	12,112

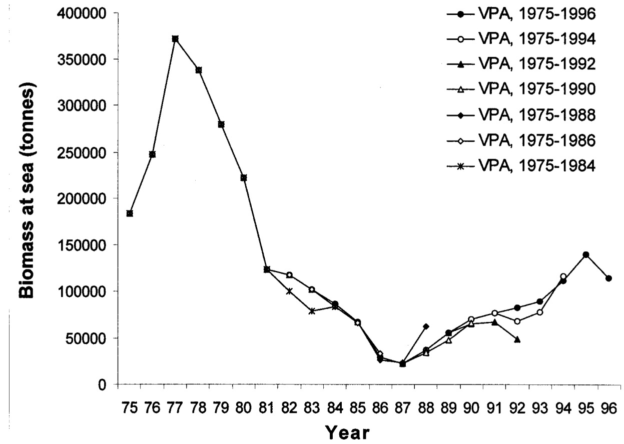

FIG. 6. – Mid-year anchovy biomass at sea estimated by retrospective VPA, using data for different time intervals, from 1975 to 1996/ 94/ 92/ 90/ 88/ 86/ 84. These VPAs were carried out using the fishing mortality rate $F_{3,1996} = 0.5$ and natural mortality rate M = 0.6. Calendar year data were used.

TABLE 8. – Mid-year anchovy biomass (tonnes) at sea estimated by the VPA carried out using $F_{3,1996} = 0.5$, as a function of year and natural mortality rate, M. Split-year data were used.

Year	M = 0.6	M = 0.7	M = 0.8	M = 0.9
1978	353,000	439,000	552,000	946,000
1982	125,000	143,000	165,000	260,000
1985	78,000	89,000	102,000	157,000
1987	25,000	30,000	35,000	57,000
1996	106,000	123,000	145,000	232,000

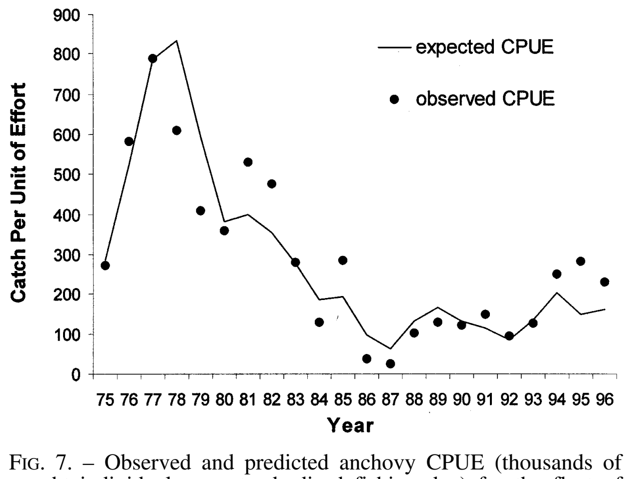

FIG. 7. – Observed and predicted anchovy CPUE (thousands of caught individuals per standardised fishing day) for the fleet of Porto Garibaldi, as a function of time. The series of predicted values was obtained by fitting the DeLury model with recruitment index. Calendar year data were used.

values in the second half of 1970s, ranging from around 700,000 to over 900,000 tonnes.

The DeLury model with recruitment index fitted well with the empirical data. The proportion of variability in the Porto Garibaldi catches, c_t, explained by the model was quite high, as indicated by the value of

TABLE 9. – Estimates of DeLury model parameters obtained from the anchovy stock assessment are reported along with lower and upper limit values of confidence intervals at 95, 90 and 75%, calculated by the bootstrap method. Calendar year data were used.

Parameter	Mean	Lower limit	Upper limit
q (95%)	2.17 x 10^{-5}	2.91 x 10^{-10}	4.38 x 10^{-5}
q (90%)	2.17 x 10^{-5}	8.03 x 10^{-10}	3.99 x 10^{-5}
q (75%)	2.17 x 10^{-5}	5.13 x 10^{-6}	3.54 x 10^{-5}
N_1 (95%)	7.13 x 10^{9}	1.19 x 10^{5}	5.48 x 10^{14}
N_1 (90%)	7.13 x 10^{9}	3.08 x 10^{5}	1.37 x 10^{14}
N_1 (75%)	7.13 x 10^{9}	1.33 x 10^{9}	4.48 x 10^{10}
λ (95%)	3.37 x 10^{10}	2.05 x 10^{10}	1.58 x 10^{15}
λ (90%)	3.37 x 10^{10}	2.18 x 10^{10}	4.87 x 10^{14}
λ (75%)	3.37 x 10^{10}	2.37 x 10^{10}	1.23 x 10^{11}

R^2 obtained, 0.84. The trends of empirical CPUE of Porto Garibaldi and that predicted by the model were similar (Fig. 7). The estimated values of parameters q, N_1 and λ are reported in Table 9 along with corresponding lower and upper limits of confidence intervals, calculated at different precision levels. The intervals are large at the levels of 95% and 90%, but they become very smaller when calculated at 75%.

The mid-year biomass values estimated by the DeLury model on the basis of calendar year data are compared in Figure 5, with the corresponding estimates obtained from VPA (with $F_{3,\,1996}$ = 0.5 and M = 0.6). The highest DeLury estimate is observed in 1978 (370,000 tonnes). Then there is a decline up to 1987 and 1988, with biomass being estimated to be 35,000 and 45,000 tonnes respectively, which represent the minimum values. Then, biomass increases

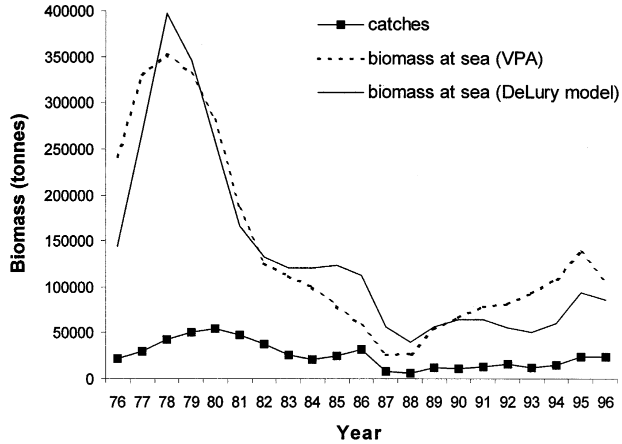

FIG. 8. – Mid-year anchovy biomass at sea estimated by VPA and DeLury model with recruitment index are compared over years; total catches are also reported. VPA was carried out using the fishing mortality rate $F_{3,\,1996}$ = 0.5. For both methods, the natural mortality rate, M , was equal to 0.6. Split-year data were used.

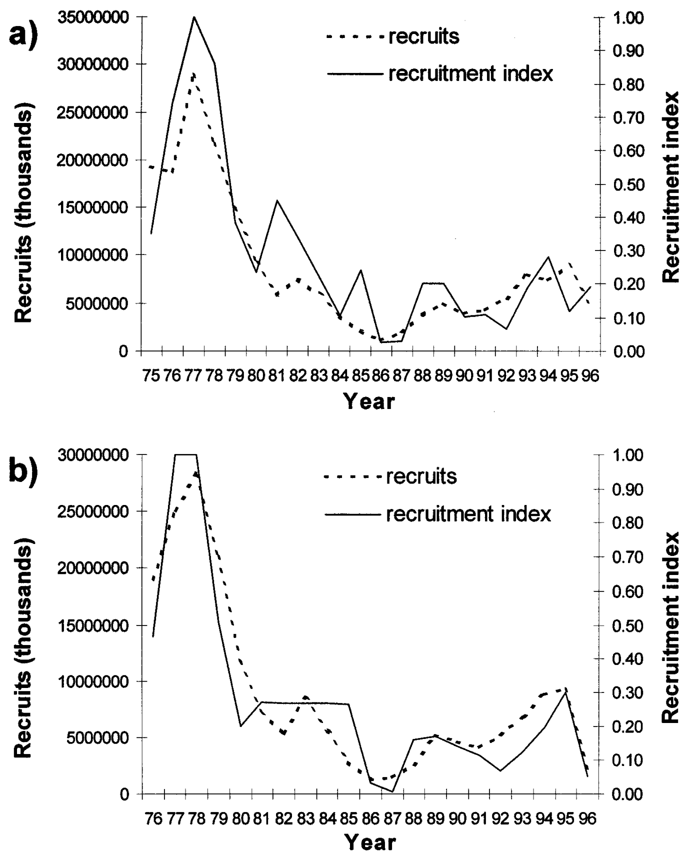

FIG. 9. – Anchovy recruit numbers estimated by VPA and recruitment indices used in the DeLury model assessment are compared over years. VPA was carried out using the fishing mortality rate $F_{3,\,1996}$ = 0.5. For both methods, the natural mortality rate, M, was equal to 0.6. Both calendar (**a**) and split-year (**b**) data were used.

again and is estimated to be 80,000 tonnes in 1996. On the whole, the values of DeLury estimated biomass as well as patterns over time are consistent with those derived from VPA. However, the recovery of the stock after the crisis is more pronounced on the basis of VPA estimates.

The mid-year biomass yielded by the DeLury model and VPA (again with $F_{3,\,1996} = 0.5$ and $M = 0.6$) and total catches, on the basis of split-year data, are compared over years in Figure 8. Biomass values as well as patterns over time are not strongly influenced by the split-year approach. When one is using split-year data the two methods give a more similar trend of biomass after 1987 and also the peak value of biomass is observed in the same year (i.e. 1978); on the other hand, in the period 1982-1986 (before the collapse) VPA estimates decrease constantly while DeLury estimates show a sudden drop only in 1987.

The recruit numbers (age class 0) estimated by VPA (with $F_{3,\,1996} = 0.5$ and $M = 0.6$) show a pattern over time consistent with the recruitment index (mainly age class 0) series required by the DeLury model, using both calendar and split-year data, as shown in Figure 9: the recruitment index is more fluctuating over time when calendar year data are used. Recruitment decrease up to 1986/87 and the subsequent recovery are always observed.

A tentative stock-recruitment relationship was derived from the DeLury model assessment on the basis of calendar year data, plotting mid-year spawning biomass in year t as a function of number of recruits at sea at the beginning of the year t+1. It was thus assumed that all mid-year recruits (as well as adults) are spawners. This is consistent with the range (9-10.9 or 9-10 cm) of length data used to calculate the recruitment index required by the DeLury model. In fact, the proportion of sexually mature individuals of Adriatic anchovy was estimated to be 50% at the length of 9 cm and over 90% at 10 cm (Sinovcic, 1999). As a consequence, many recruits are likely spawners in the middle of the year. The plot of the stock-relationship is shown in Figure 10: dispersion of data points is strong. This effect is particularly pronounced for higher values of spawning biomass. That means a spawning biomass value may be associated with very different recruitment levels in the following year.

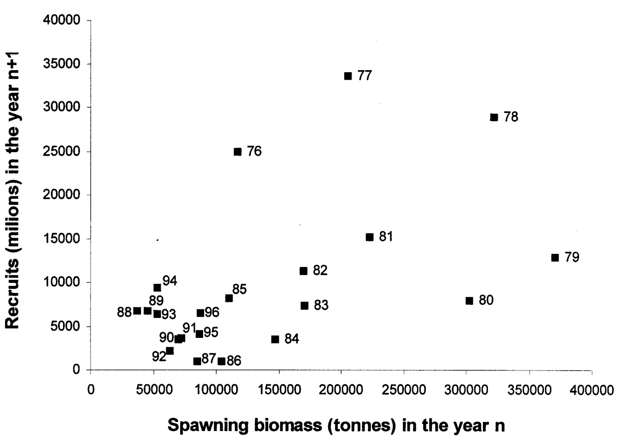

FIG. 10. – Anchovy stock-recruitment relationship derived from the DeLury model with recruitment index, with mid-year spawning biomass in the year n and number of recruits at the beginning of the year n+1. Calendar year data were used.

DISCUSSION

The estimated stock biomass of Adriatic anchovy showed a great fluctuation in the period 1975-1996. The decline after 1978 was very pronounced, with biomass decreasing from around 370,000 to over 170,000 tonnes in the subsequent three years (VPA with $F_{3,\,1996} = 0.5$ and both VPA and the DeLury model with $M = 0.6$). On the contrary, the recovery of the stock biomass after the collapse in 1987 showed a relatively constant trend. This general pattern of biomass over the whole period was similar using the two assessment methods as well as calendar and split-year data.

Assessments for the Adriatic Sea based on echo surveys (Azzali *et al.*, 1990) gave a similar pattern of abundance at sea over time, with a peak of instantaneous anchovy stock biomass in 1978, a subsequent decline with the lowest value in 1987 and a subsequent partial recovery. The values of mid-year

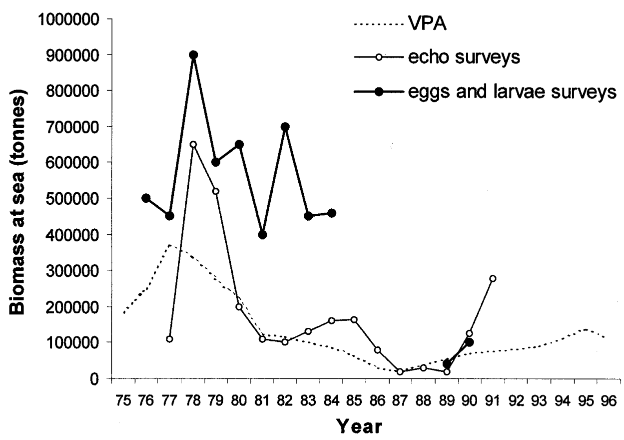

FIG. 11. – The trend of mid-year anchovy biomass at sea estimated by VPA is compared with the trends of instantaneous stock biomass at sea, obtained from the two assessments based on echo surveys and egg and larvae surveys. VPA was carried out using the fishing mortality rate $F_{3,\,1996} = 0.5$ and the natural mortality rate $M = 0.6$. Calendar year data were used.

stock biomass estimated by VPA (with calendar year data, $F_{3,\ 1996} = 0.5$ and $M = 0.6$) are compared with the estimates based on echo surveys in Figure 11: the agreement between values is relatively good, but the peak yielded by echo surveys is more pronounced, with a biomass similar to those given by VPA for higher values of M. In this picture, the echo survey series is upgraded to 1991, whereas the corresponding biomass densities (tonnes per square nautical mile) are available up to 1996 in Azzali *et al*. (2001). After an increase in 1992-1993, these densities show a drop to low values not far from that observed in 1987 in the same series. This feature is in contrast with the continuous increase in VPA estimates, but it is somewhat consistent with the slow rate of the recovery suggested by VPA. In fact, in the series of biomass density, the sharp increase in the series of echo survey biomass shown in Figure 11 disappears.

Assessments based on egg and larvae surveys (Regner, 1996) also yielded higher values in 1976-1984 than in 1989-1990, as well as higher instantaneous stock biomass in 1990 than in 1989 (Fig. 11).

Further circumstantial evidence of these changes in the level of biomass is given by the observed changes in the age-length keys under the hypothesis that anchovy growth is negatively influenced by density at sea. It appears that anchovies grew more slowly in 1978 than they did in 1986 and 1989, when biomass was estimated to be lower. The 1995 age-length data suggest that growth rates have again slowed as the stock recovered from the crash, but not to the extent seen in the late 1970s data (Cingolani *et al*., 1993; 1998c).

Finally, the observed increase in net-zooplankton biomass in the Adriatic during the last decade might be due to a decrease in consumers such as anchovy (Fonda-Umani, 1996).

The stock abundance of Adriatic anchovy could have been negatively influenced by fishery. In fact, VPA yielded high values of fishing mortality rate and exploitation rate in some years, and in particular before the collapse of the stock in 1987. In Figure 12, biomass estimated by the DeLury model with recruitment index is displayed together with Porto Garibaldi fishing effort, on the basis of calendar year data: from 1981 up to 1984, effort increases (76%) and reaches the highest value, while biomass decreases. On the other hand, the decline of biomass starts before 1981, when effort shows smaller fluctuations.

The stock dynamics of many fish species is thought to be highly influenced by environment, which determines food availability both in time and in space for larvae and juveniles (Shepherd *et al*., 1984; Heath, 1992; Mann, 1993; Cushing, 1996). The influence of environment on recruitment is suggested by the fact that a lower spawning biomass yielded a higher number of recruits in more recent years, as in 1994. Spawning biomass yielded a high number of recruits in 1976, as well as the lowest ones in 1986 and 1987. This suggests that the low recruitment just before the collapse in 1987 was mainly caused by environmental factors rather than low spawning biomass.

Regner (1996) suggested that anchovy abundance could have been negatively influenced by summer blooms of phytoplankton and benthic diatoms, par-

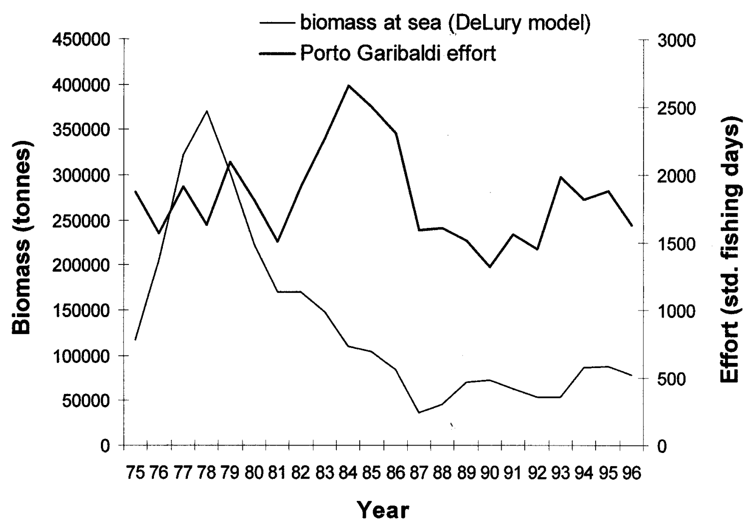

FIG. 12. – Anchovy standardised fishing effort for the fleet of Porto Garibaldi and mid-year anchovy biomass at sea estimated by the DeLury model with recruitment index (with the natural mortality rate M = 0.6) are compared over years. Calendar year data were used.

ticularly between 1986 and 1989, by increasing mortality rates of larvae and postlarvae.

The negative influence on the anchovy stock due to predation of eggs and larvae by the jellyfish *Pelagia noctiluca* was also discussed by Regner (1996). He argued that the blooms of this jellyfish occurred in the period 1977-1985, when the decrease in anchovy stock was not yet as sharp as in 1986, so subsequent collapse is not clearly correlated with the blooms. The results yielded by the present assessments are not in contrast with these conclusions.

In conclusion, although overfishing is thought not to be the primary cause of the anchovy collapse, it remains true that the subsequent levels of estimated recruitment after 1987 have not risen to former higher levels. As a consequence, the current levels of spawning biomass could have also not yet recovered to former levels. While this remains the case, it would be unwise for fishing effort to be allowed to rise.

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