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BIOLOGICAL REFERENCE POINTS AND NATURAL LONG-TERM FLUCTUATIONS: THE CASE OF THE EASTERN ATLANTIC BLUEFIN TUNA

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ABSTRACT

Defining biological key reference points is of importance within the precautionary approach. Most of the reference points, such as the F_{MSY}, $F_{0.1}$, *presuppose a steady state, i.e. the natural long-term fluctuations of the population are low or moderate. In this manuscript, we present historical data from Sicilian, Sardinian, Portuguese, and Tunisian traps of the Atlantic bluefin tuna during 200 to 400 years. Long-term fluctuations in trap data could be considered as a good proxy for long-term trend in true abundance because trap is a passive gear which was submitted to low modification until the XX century and because data from different areas display similar long-term variations. Trends in trap data appear bell shaped, with a maximum at the end of the* XIX^{th} *century and two comparable minima at the beginning of the* XIX^{th} *and* XX^{th}, *respectively. There is a factor of about 4 between periods of low and high abundance. A longer series of catches going back to the 16th century show consistent long-term fluctuations all along the 400 years. These results would indicate that the Eastern Atlantic bluefin tuna, as some populations of Atlantic cod and herring, as well as the North Atlantic albacore, display large natural long-term fluctuations. Further researches need to be done in order to improve our understanding of the causes of this long-term variability. Because of this dynamics, the* F_{MSY}, $F_{0.1}$ *or other steady state points do not appear appropriate for the Eastern Atlantic bluefin tuna. Empirical and relative reference points related to the instantaneous biomass and/or exploitation rate need to be defined.*

RÉSUMÉ

La définition des points biologiques de référence est l'un des éléments majeurs de l'approche de précaution. La plupart de ces points, tels que le FPME, F0.1, implique la stationnarité, i.e., les fluctuations naturelles à long terme des populations sont faibles ou modérées. Dans cet article, nous présentons des données historiques de captures de thon rouge provenant de madragues siciliennes, sardes, portugaises et tunisiennes sur 200 à 400 ans. Les fluctuations à long terme des captures des madragues peuvent être considérées comme un bon indice des fluctuations à long terme des populations parce que la madrague est un engin passif qui a subi peu de modifications jusqu'au XXème siècle et parce que les données des différentes zones géographiques montrent des fluctuations à long terme similaires. Les tendances dans les données de captures des madragues présentent un maximum à la fin du XIXème siècle et deux minima comparables au début du XIXème et XXème siècles. Les abondances de la période maximale sont environ 4 fois plus élevés qu'en périodes minimales. Une série de capture commençant au XVIème siècle montre d'importantes fluctuations à long terme tout au long des 400 ans de données. Ces résultats indiqueraient que le thon *rouge de l'Atlantique nord-est, tout comme certaines populations de morue, hareng et germon de l'Atlantique nord, présente des fluctuations d'abondance à long terme. Des recherches complémentaires sont nécessaires pour améliorer notre compréhension sur les origines de cette variabilité à long terme. Toutefois du fait de cette dynamique, les FPME, F0.1 ou autres points de référence stationnaires n'apparaissent pas appropriés pour le thon rouge de l'Atlantique nord-est. Des points de références relatifs et empiriques reliés à la biomasses instantanée et/ou au taux d'exploitation devraient être définis.*

RESUMEN

Dentro del enfoque precautorio, es importante definir los niveles de referencia biológicos. La mayor parte de los niveles de referencia, tales como Frms, F0.1, presuponen un estado estable, es decir, las fluctuaciones naturales a largo plazo de la población son bajas o moderadas. En este documento, presentamos datos históricos de las almadrabas de atún rojo atlántico de Sicilia, Cerdeña, Portugal y Túnez a lo largo de 200 a 400 años. Las fluctuaciones a largo plazo de los datos de almadrabas se deberían considerar como una buena aproximación para la tendencia a largo plazo de la abundancia real, ya que la almadraba es un arte pasivo que ha sufrido escasas modificaciones hasta el siglo XX, y porque los datos de distintas zonas muestran variaciones similares a largo plazo. Las tendencias en los datos de almadraba tienen forma de campana, con un máximo a finales del siglo XIX y dos mínimos comparables a comienzos de los siglos XIX y XX, respectivamente. Hay un factor de aproximadamente 4 entre períodos de abundancia escasa y alta. Una serie de capturas más amplia, retrocediendo hasta el siglo XVI, muestra fluctuaciones coherentes a largo plazo durante los 400 años. Estos resultados indicarían que el atún rojo del Atlántico este, igual que algunas poblaciones de bacalao y arenque, así como de atún blanco del Atlántico norte, muestran amplias fluctuaciones naturales a largo plazo. Es necesario llevar a cabo mayor investigación con el fin de mejorar nuestra comprensión de las causas de esta variabilidad a largo plazo. A causa de esta dinámica, el Frms, F0.1 u otros puntos estables no parecen adecuados para el atún rojo del Atlántico este. Es necesario definir los niveles de referencia relativos y empíricos relacionados con la biomasa instantánea y/o tasa de explotación.

INTRODUCTION

The choice of the biological reference points mainly depends on the management strategy (Caddy & Mahon 1995, Rosenberg & Restrepo 1995, Caddy 1998). Tunas are most often managed by quotas, so that the maintenance of a given proportion of the population is the main objective. In that case, reference points based on production model, such as F_{MSY}, or Yield/Recruit and SSB/Recruit analyses, such as $F_{0.1}$ or $F_{0.2}$, appear more relevant than reference points based on stock-recruitment approaches, which would emphasise the subsistence of the spawning biomass and potential recruitment.

However, all these underlying models, that allow to determine biological reference points, imply that the population is at an equilibrium or a steady state (Gulland 1977, Laurec & Le Guen 1981). In other words, the natural long-term fluctuations of the population are supposed to be low or moderate. This modelling constraint may be acceptable for tropical tunas populations which do show stable recruitment and stable productivity over long periods of time (e.g. Fonteneau et al. 1998). However, temperate tunas, such as albacore and bluefin tuna, could display non-equilibrium stock biomass because of variable environmental conditions (Longhurst 1998). We here present historical data from Mediterranean traps which indicate the presence large natural long-term fluctuations within the Eastern Atlantic bluefin tuna. At the light of these results, we further discuss the adequacy of more empirical biological reference points that could be preferentially used within a precautionary approach of this population.

GENERALITIES ON THE MEDITERRANEAN TRAPS

The first evidences of tuna fishing in the Mediterranean sea were found to be around 9000-8000 years old (Desse & Desse-Berset 1994, Doumenge 1998). The first Mediterranean traps appear later, probably around 3000-4000 years ago. The genetic migration patterns of bluefin tuna, which were already approximately described by the ancient Greek philosopher Aristote in 350 BC, were well understood since the middle-age. Since the XV century, the most propitious locations along the migration routes of bluefin tuna were also well known and exploited in all the Mediterranean sea and along the Southern Atlantic coasts of Spain and Portugal. From the middle-age to the middle of the XIX century, traps were submitted to minor changes (Fig. 1, the traditional trap is made of several rooms and one final room, the 'death room', as well as one queue, i.e. the net going offshore, which is in average around 3 km long). However, the replacement of sail boats by steam boats to manage the traps has probably increased the fishing efficiency during the second half XIX century. The main changes, however, took place during the XX century because of increasing coastal traffic, noise and coastal pollution which probably decreased the trap efficiency. More recently (since the 50-60's), the interference with modern and active fishing gears, such as purse seine and long lines, have also probably contributed to the decline of the traps (Farrugio 1981, Addis et al. 1997, Doumenge 1998).

In summary, trap is a passive gear which was submitted to low modification until the XX century. Furthermore, we know that the major spawning areas are located in small coastal locations (i.e. the Balearic islands and the Messine straits) and that bluefin tuna used to do, in May-June, the same genetic migration along the coasts to reach these points. Therefore, long-term fluctuations in trap catches could be considered as a good proxy for long-term trend in true abundance as soon as trap data from different areas display similar long-term variations. In order to test this hypothesis, we compared trap data (yearly catches) from Portugal, Tunisia, Sicily and Sardinia (we ignored Spanish traps from the present analysis because of a lack of data during the XIX century).

DATA

Most of the data used in the present manuscript have been already published in various books, articles or reports. All the series are expressed in number of fishes (Fig. 2). Tunas caught by traps were always large fishes, i.e. spawners doing their pre- or post-spawning migration (see e.g. Pavesi 1889, Sella 1929, Rodriguez-Roda 1964, Farrugio 1981). The literature sometimes distinguishes between spawners caught in May, *'atun de derecho'* as named by the Spanish trap fishermen, and spawners caught in July, *'atun de reves'*. The former females are usually 20% bigger than the later. As we here worked on numbers, we just summed together all the catches to obtain yearly values.

Sicilian traps. Favignana and Formica traps are situated on the Western Sicilian coast. These two traps, which were of great importance until recently, are among the oldest in the Mediterranean sea (probably active since at least the XI century, Doumenge pers. comm.). Because the data are aggregated during the XX century, we only consider the sum of both traps as one time series. Data from Favignana and Formica in 1599–1818 years have been published by Cancila (1972). The period 1840-1855 has been provided by Cancila (pers. comm.) and the 1978-1995 years by Picinetti and Omiccioli (1999) and Guarrasi (pers. comm.).

Sardinian traps. We here only consider the traps data from the Southwest coast of Sardinia published by Addis et al. (1997). These data correspond to the catches of three traps located in the same area, Portoscuso, Porto Paglia and Caloforte, which are summed into one time series. This series extends from 1825 to 1977.

Portuguese Traps. We here refer to the data published by Neuparth (1925), which present catches from all the Portuguese traps of the Algarve province (Southern coast of Portugal) from 1797 to 1816 and 1896 to 1923, as well as data from the Medo das Casas trap (one of the main trap of the Algarve) from 1797 to 1816 and 1837 to 1923.

Tunisian trap. We here only consider the major Tunisian trap Sidi-Daoud. Data were collected by Roule (1925) for the period 1863-1923. The series was updated by Picinetti and Omiccioli (1999) and Hattour (pers. comm.).

RESULTS

Long-term trends have been estimated using a Kernel smoother with a triangle window and a bandwidth of 4 to 8 depending on the length of the series. Computation have been made under S-Plus software (S-Plus 4 1997).

Because the series are not normally distributed, we performed Spearman correlation coefficient, which is the non-parametric equivalent to Pearson correlation coefficient, e.g. (Sokal & Rohlf 1995). To test for significance, we used a Monte Carlo simulation procedure. We first computed correlation on raw data (Table 1, normal type), then on detrended time series (Table 1, italic type). The comparison between both allowed to distinguish whether a significant correlation on raw data is only due to the presence of the trends or not, see e.g. (Fromentin et al. 1998).

	South-Sardinia	**Medo das Casas**	**Algarve**	**Sidi-Daoud**
Favignana-Formica	0.54*** _0.02_^{ns}	0.12^{ns} _0.05_^{ns}	0.33** _0.11_^{ns}	0.76*** _0.18*_
South-Sardinia	-	0.35*** _0.05_^{ns}	0.28* _0.07_^{ns}	0.71*** _0.27***_
Medo das Casas	-	-	0.70*** _0.67***_	0.56*** _0.01_^{ns}
Algarve	-	-	-	0.51*** _0.39**_

Table 1: Spearman correlation coefficients between original (normal type) and detrended time series (italic type). *** significant at 1% level, ** significant at 5% level, * significant at 10% level, ^{ns} non significant.

At the exception of the couple Favignana-Formica / Medo das Casas, all the series are significantly correlated between each others when considering the raw data (the absence of significant correlation between Favignana-Formica and Medo das Casas appear to be due to the lack of data during the 1856-1877 years at Favignana-Formica together with a quicker decrease in the catches at Medo das Casas and a shorter period of comparison). Correlation analysis on detrended time series shows that only 4 of the 10 correlation coefficients remain significant. Significant correlation between time series is thus mainly due to similar long-term trends, whereas year-to-year fluctuations appear in 60% of the cases different.

The similarity between long-term trend can also be noticed on Figs. 2 and 3. During the first part of the XIX century, catches are low to moderate. They increased during the second half century to reach a first peak in the period 1876-1884 (first vertical dotted line on Fig. 2). There was a slight decrease and a second peak at the beginning of the XX century, in 1904-1906 (second vertical dotted line on Fig. 2). From 1915 to 1960, the catches reached a plateau at low to moderate levels, which were however comparable to the values at the beginning of the XIX century. In the early 70's, there was a second important decline in Sardinia and Sicily traps and catches reached their lowest historical level (probably because of increasing traffic and pollution as well as interference with modern fishing techniques, see previous section).

These results tend thus to support our hypothesis: long-term trends in trap data can be seen as a good proxy for long-term trends in true abundance. The fact that traps data show similar long-term trends but different year-to-year fluctuations in 60% of the cases would indicate that some local and regional variability do occur. This year-to-year variability could be due to different factors such as:

- Local and regional variations in environmental factors, such as wind stress, currents and temperature
- Differences in fish behaviour from one area to another (tunas migrating more offshore in one area than in another in a given year)
- Local variations in human factors, such as the fishing efficiency due to the ability of the 'Reis' (fisherman leader), or in gears, such as accidental damages in the nets.

Long-term variations in abundance are of importance; there is a factor 3 to 10 between period of high (1876-1884) and moderate to low abundance (1825-1850 or 1915-1960, we here do not consider data after the 60's). Investigating the longest time series (Favignana-Formica), one can see that these large secular fluctuations regularly occurred. Between 1599 and 1818, the catches have displayed two main and clear peaks, around 1620-1635 and 1755-1775, and two main periods of very low to moderate catches around 1700-1715 and 1790-1810. In this series, the main periodicity appear thus to be around 100-120 years (as confirmed by spectral analysis, result not shown).

DISCUSSION

The above results indicate that the Eastern Atlantic bluefin tuna displays large natural long-term fluctuations. One may argue that traps only caught a non-representative proportion of the population, so that fluctuations in catch would not represent those in biomass. We do not believe in such a statement since there would have been no reasons that long-term fluctuations appear synchronous between locations being more than 3000 km apart. It would be, however, of great interest to investigate all the historical information on trap fishing in order to confirm these results.

It would also remain to understand the causes of such secular variation. This is not the task of the present article (and this would imply much more work) but we will however briefly give two main hypotheses:

- Impact of long-term environmental fluctuations. Such relationships have been already shown for several Atlantic fish populations, e.g. Cushing & Dickson 1976. Bluefin tuna is furthermore a widespread species which only reproduces in a small spatio-temporal window (small Mediterranean areas during one month per year), so that the success of recruitment could be more related to local environmental conditions than the size of the spawning stock (Bakun 1996).
- Resonant effects within the bluefin tuna population. Bjørnstad et al. (1999) have recently demonstrated that cannibalism between cohorts or asymetric competition could have played the role of a 'resonator' within the life cycle of the Norwegian Skagerrak cod, so that the high frequency variations in the recruitment have finally induced low frequency fluctuations (or trends) into the population.

Because of these long-term fluctuations, a suitable precautionary approach could be of great help for the conservation of this species. This need is furthermore reinforced because of: (i) a large amount of uncertainty in the Atlantic bluefin East stock assessment (Fonteneau 1997, Anonymous 1998, Fromentin 1998), and (ii) an intensifying effort (and important increase in yields) since 1994 during the seasonal aggregation of the spawners in May-June around the Balearic Islands (of which the consequences are still not fully evaluated by the scientific community).

However, a suitable precautionary approach implies to take into account the peculiar features of this fishery as well as peculiar aspects of the Atlantic bluefin tuna population dynamics, biology and main life history traits. During the last ICCAT Atlantic bluefin tuna working group, a list of possible bias in CPUE indices has been made for the East stock (SCRS/98 1999). It thus appeared that quantification of effective fishing effort was highly uncertain because of (i) changes in gear-technology and tactics, (ii) changes in vessels cooperation and competition, (iii) changes in ages targeted, (iv) expansion of the fishing area and (v) the fact that unsuccessful effort are not taken into account. All these biases lead to strong uncertainties when applying production and Y/R models.

Furthermore, classical production models imply an equilibrium population for a stable effort. The above results indicate that the Eastern Atlantic bluefin population do not show one natural equilibrium state. Such a result is not surprising and natural long-term fluctuations have been already described for several North Atlantic populations since more than a century (Ljungman 1882, Russell et al. 1971, Cushing & Dickson 1976, Southward et al. 1988, Dickson & Brander 1993, Cushing 1995).

For all these reasons, we think that biological reference points based on classical production or Y/R modelling, such as the F_{MSY}, $F_{0.1}$, $F_{0.2}$, are not appropriate for the East stock of Atlantic bluefin tuna.

It is however as much as difficult to fit a reasonable stock-recruitment model on SSB and recruitment data, as estimated by a tuned VPA conducted during the last ICCAT Atlantic bluefin tuna working group (SCRS/98 1999, see Fig. 4). The absence of stock-recruitment relationship may be due to biases in catch and effort data, ageing procedure, or cascading problems within the VPA procedure. Because of certain traits in the life history of the Atlantic bluefin tuna, such as the homing in small locations at temperate latitudes (i.e. the Balearic islands and the Messine straits) and a unique and short spawning season during the entire year (mid of May to mid of June), it is likely that the recruitment is highly variable from one year to another (Wooster & Bailey 1989, Longhurst 1998, Cury et al. 1998). Thus, the presence of natural long-term fluctuations in the SSB and the possibility of strong noise in recruitment can blurred systematically the S/R relationship. Therefore, biological reference points based on S/R modelling (e.g. F_{MED}) are probably inappropriate for the Eastern Atlantic bluefin tuna.

The previous conclusions could appear quite pessimistic and not very constructive. However, a suitable precautionary approach of the East stock of the Atlantic bluefin tuna is possible.

- The first approach would be to develop modelling which take into account natural long-term fluctuations in population, such as non-equilibrium production models or non linear S/R modelling (Solari et al. 1997). This solution has, however, the disadvantage to delay the application of the precautionary approach (FAO 1995).
- Therefore, empirical reference points could be, in the meantime, determined. Caddy (1998) gave examples of reference points based on past fishery yields or other empirical approaches, such as the Current Annual Yield (CAY), the ‘Magnusson-Stefansson feedback gain rule’, or the use of a spawning escapement (40% of the biomass for instance). These empirical points (and others) could be used as a basis to define adequate reference points for the East stock of the Atlantic bluefin tuna.

Natural long-term fluctuations imply that the management of the Eastern Atlantic bluefin tuna should be, in the long run, adaptable. In other words, a precautionary management of this "variable stock" should be based on variable fishing efforts: higher fishing effort (producing high catches) could be exerted during periods of high abundance, whereas periods of low SSB would involve lower effort and low catches. This policy of an adaptable management, which would assume a better understanding the population dynamics, might be difficult to implement with modern industrial fishing fleets, but would be of key importance to use and to maintain the biological productivity of this resource.

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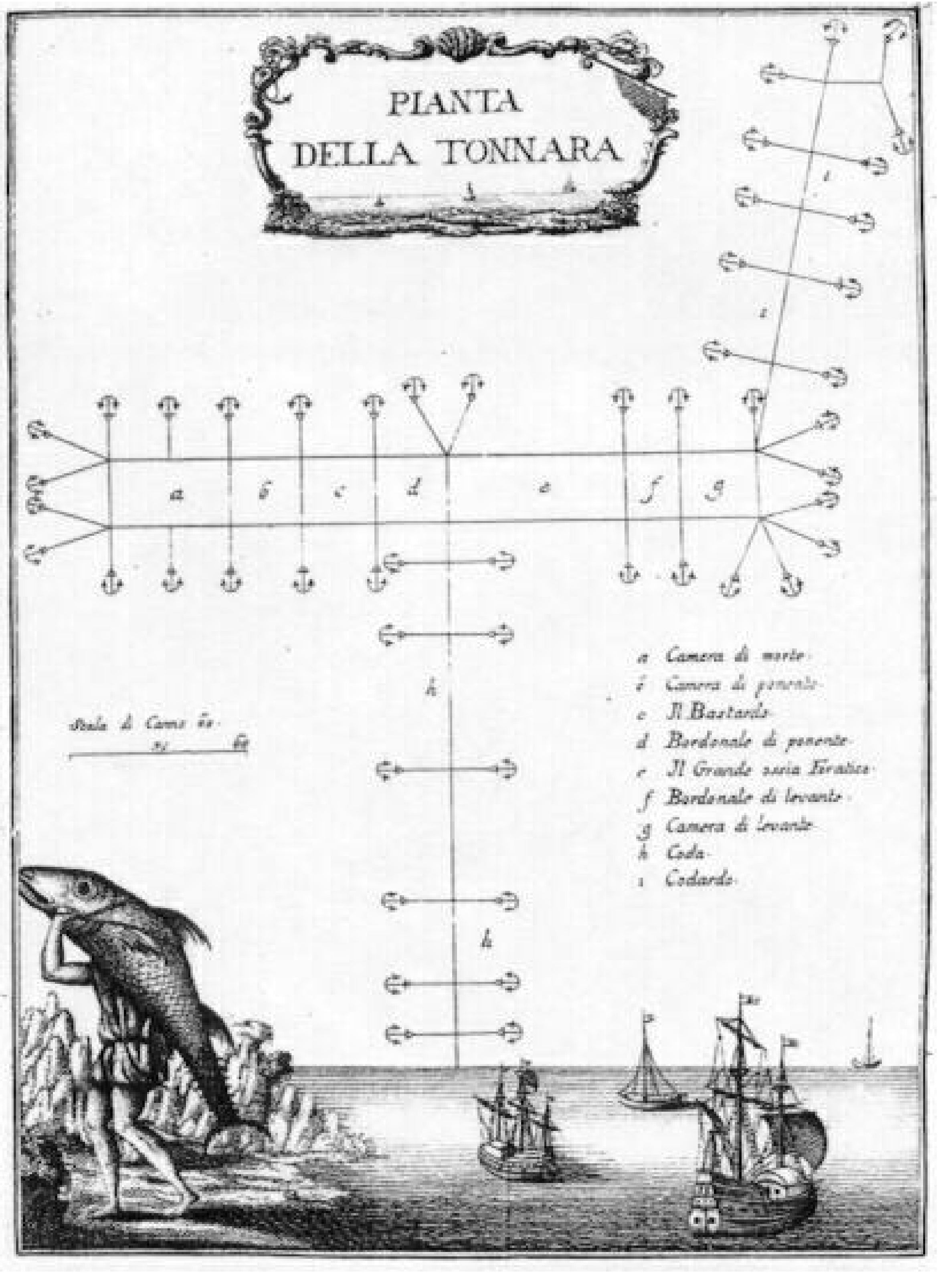

Figure 1

Map of a XVIIth century Sicilian trap

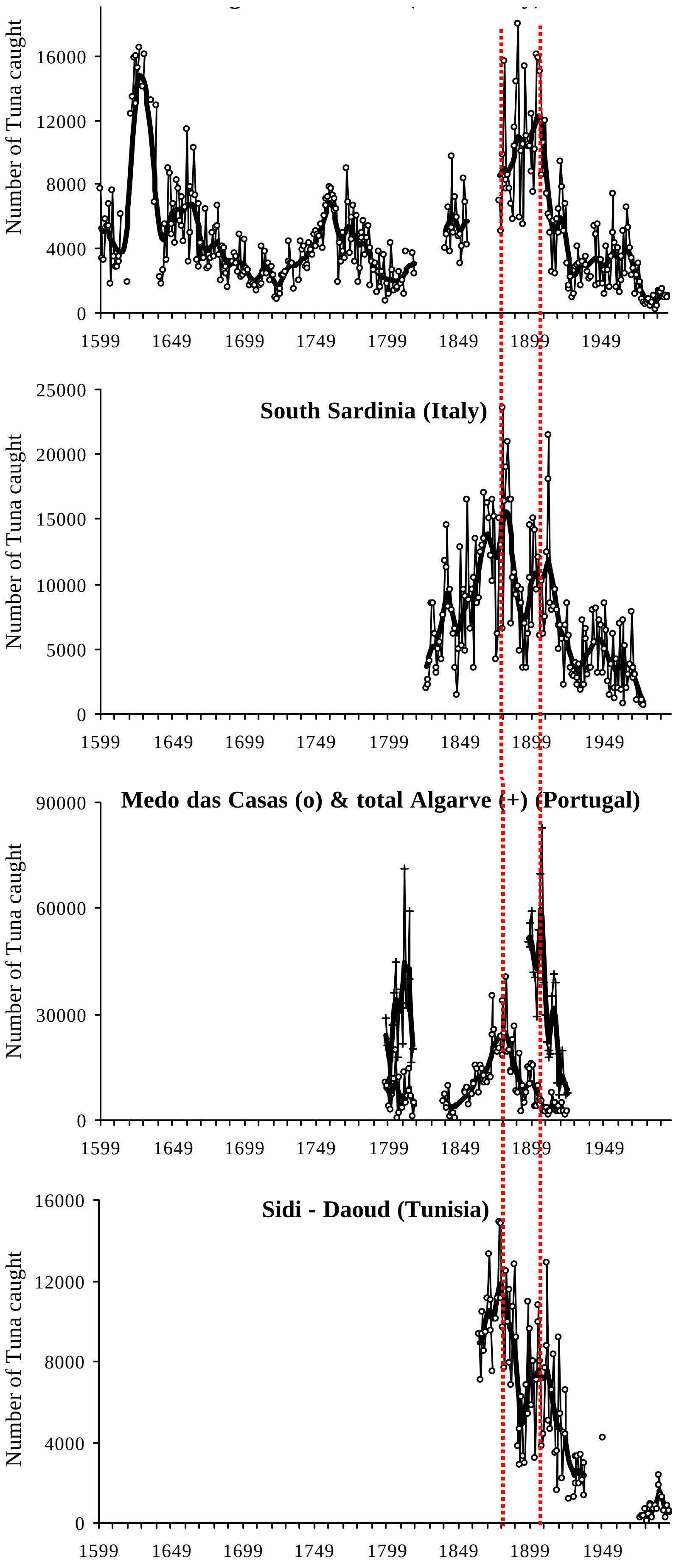

Figure 2

Catches, in number of fish, of Atlantic bluefin tuna in some Mediterranean and East Atlantic traps from 1599 til now.

Open circles: raw data, line: kernel smoothing.

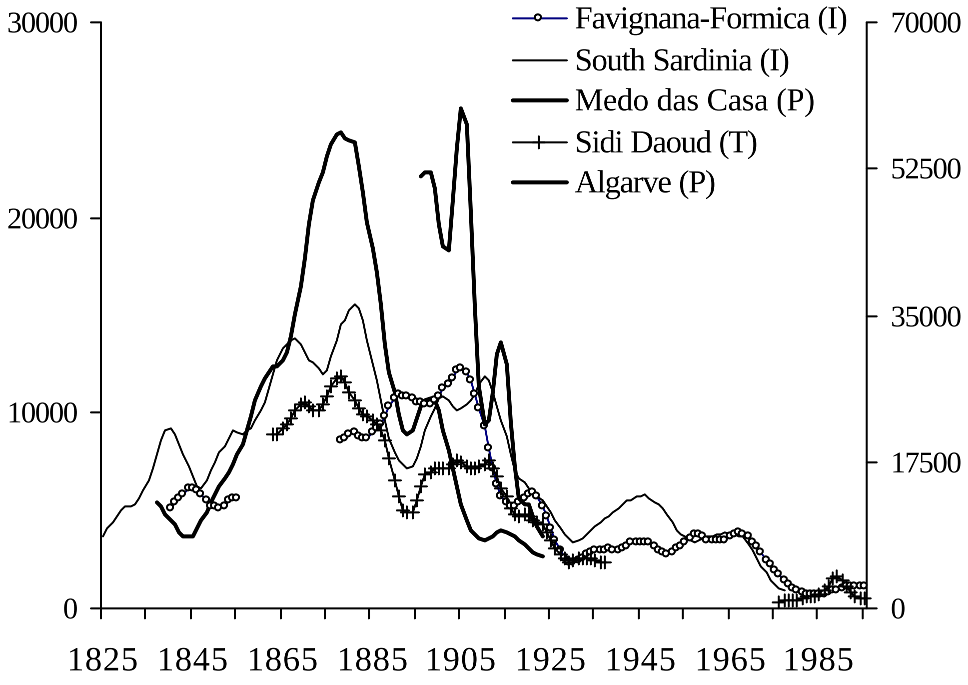

Figure 3

Catches of Atlantic bluefin tuna in some Mediterranean and East Atlantic traps from 1825 til now, smoothed by a Kernel filter and superimposed.

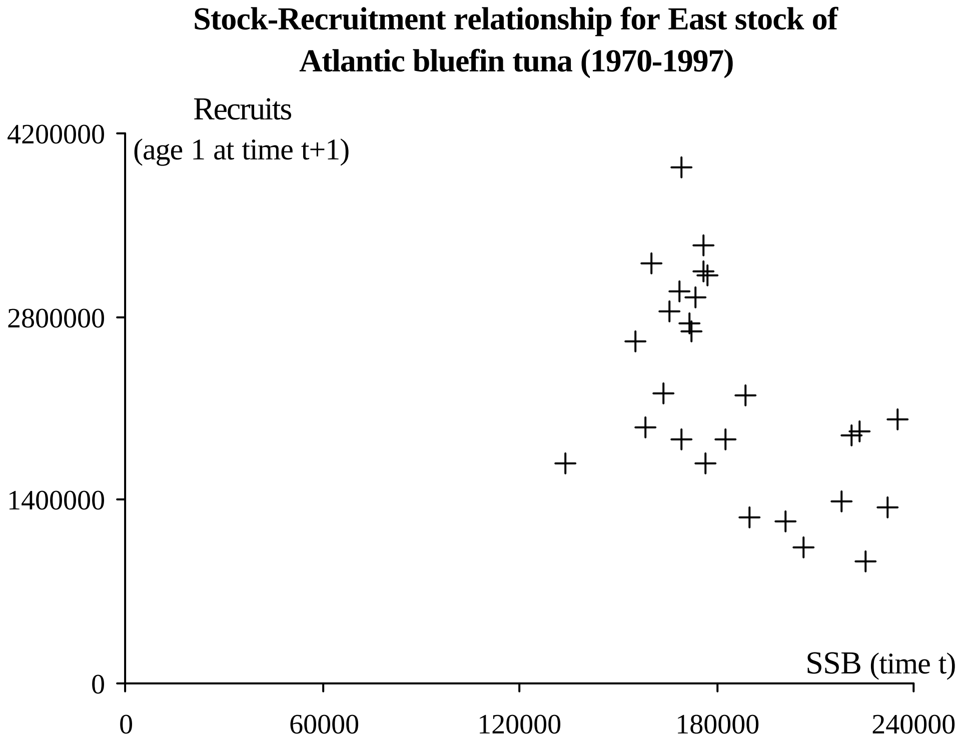

Figure 4

Scatterplot of the recruitment, as fish of 1 year old at time t+1, against the Spawning Stoch Biomass (SSB) at time t