Featured Article

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Application of a multi-annual generalized depletion model to the assessment of a data-limited coastal fishery in the western Mediterranean

Francesc Maynou

Institut de Ciències del Mar, CSIC, Psg. Marítim de la Barceloneta 37-49, 08003 Barcelona, Spain.
E-mail: maynouf@icm.csic.es

Summary: A multi-annual generalized depletion model was applied to a coastal fishery in Vilanova i la Geltrú (western Mediterranean) to assess the exploitation status of striped red mullet (*Mullus surmuletus*) and cuttlefish (*Sepia officinalis*), two of the main target species of Mediterranean small-scale fisheries. It is shown that in data-limited stocks, which is often the case in small-scale fisheries, catch and effort data at high temporal frequency (day, week, month) complemented with biological information and a priori knowledge (mean body weight, natural mortality and period of recruitment to the fishery) can be effectively exploited to produce assessment results applicable to fisheries management. For the two species analysed, the assessment results showed that exploitation rates are high and vulnerable biomass has been decreasing over the last 14 years.

Keywords: stock assessment; data-limited; depletion model; small-scale fisheries; *Mullus surmuletus*; *Sepia officinalis.*

Aplicación de un modelo multi-anual generalizado de depleción para la evaluación de una pesquería costera con limitación de datos en el Mediterráneo occidental

Resumen: Se utilizó un modelo multi-anual generalizado de depleción para evaluar el estado de explotación del salmonete de roca (*Mullus surmuletus*) y la sepia (*Sepia officinalis*) capturados por la flota costera de Vilanova i la Geltrú (Mediterráneo occidental). Estas especies representan dos de las principales especies objetivo de las pesquerías mediterráneas artesanales. El análisis muestra que para stocks pesqueros con información limitada, los datos de captura y esfuerzo a alta frecuencia temporal (diaria, semanal o mensual), junto a información biológica y conocimiento a priori (peso corporal medio, mortalidad natural, periodo de reclutamiento), pueden ser utilizados de manera efectiva para producir resultados de evaluación aplicables a la gestión de pesquerías. En las dos especies analizadas, los resultados de la evaluación muestran que las tasas de explotación son elevadas y que la biomasa vulnerable ha disminuido de manera continua en los últimos 14 años.

Palabras clave: evaluación de stocks; limitación de datos; modelo de depleción; pesquerías artesanales; *Mullus surmuletus*; *Sepia officinalis.*

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INTRODUCTION

The assessment of Mediterranean fisheries is often hampered by lack of complete data sets fulfilling the requirements of standard stock assessment models of the virtual population analysis (VPA) family (Lleonart and Maynou 2003, Caddy 2009). In the last ten years this situation has changed, at least for target species of major fishing fleets, thanks to the resources made available by the Data Collection Regulation (DCR) and the Data Collection Framework (DCF) programmes (EU reg. 1543/2000 and EU reg. 665/2008, respectively), and stock assessments carried out under the umbrella of the Scientific, Technical and Economic Committee for Fisheries (STECF; Colloca et al. 2013, Cardinale et al. 2010, 2011). However, data of sufficient quality is inevitably tied to important fisheries which produce large amounts of landings and fall within DCR/DCF obligations. In the Mediterranean, important fisheries routinely assessed since 2008 for the STECF are those based on demersal or semi-pelagic trawling (hake, red mullets, red shrimp and pink shrimp) and purse seining (sardine and anchovy). Small-scale fisheries produce a large variety of species using several fishing methods, but due to the small quantities produced they are usually not eligible for data collection in DCR/DCF programmes and biological samplings are not routinely carried out (except when they produce significant amounts of the trawl target species listed above). However, small-scale fishing in the Mediterranean sea, and in Europe in general, is important from the socio-economic point of view: for instance, vessels <12 m LOA comprise 84% (or 70000 units) of the EU25 fishing fleet and provide *ca*. 100000 direct jobs, corresponding to 53% of the employment in the fishing sector (Guyader et al. 2013).

In small-scale Mediterranean fisheries, data are often not suitable for standard stock assessment methods because of incomplete monitoring, related both to the high diversity of small-scale fisheries (in terms of fishing gears and target species, Guyader et al. 2013) and the low quantity of production. Small-scale fisheries have local socio-economic importance, however, and their impact on coastal resources must be evaluated to help diagnose the status of these fisheries and take management initiatives leading to their sustainable exploitation. In this data-limited situation (Johannes 1998, Prince 2003) fisheries assessment methods alternative to the standard VPA family must be considered, making best use of whatever type of data are available (Caddy 2009).

Despite the lack of routine biological samplings, landings by species and fleet type and fishing effort are reported in most areas at high frequency (for instance, daily in Catalonia) for statistical or taxing purposes. These high-frequency data, when collected over several years and combined with limited additional information on the biology of target species, can be used for stock assessment purposes using depletion models. In multi-annual generalized depletion (MAGD) models (Roa-Ureta 2012, 2014), the classical assumptions of depletion of a closed population subject to direct proportionality between catch per unit effort (CPUE) and abundance (Brodziak and Rosenberg 1993, McAllister et al. 2004) are relaxed. When running at a monthly scale, the regular annual pulses in abundance produced by the recruitment of a new cohort to the fishery can be used in MAGD models as prior information to the timing and magnitude of recurrent perturbations.

MAGD models were used to assess the status of two species which are typical targets of Mediterranean trammel net fisheries, the striped red mullet (*Mullus surmuletus*) and the cuttlefish (*Sepia officinalis*) (Martín et al. 1999, Belcari et al. 2002). Both species are, additionally, valuable by-catch of coastal bottom trawl vessels. Both species have clear recruitment periods (autumn in *M. surmuletus*; spring in *S. officinalis*) and other aspects of their biology are relatively well known (maturity, reproductive strategy, growth and natural mortality) (Martín et al. 1999, Belcari et al. 2002, Royer et al. 2006, Maravelias et al. 2014) but long time series of length frequency data are unavailable for both species and the fleets exploiting them.

The objective of the work is to evaluate the applicability of MAGD models to assess the exploitation status of these species in a coastal Mediterranean fishery.

MATERIALS AND METHODS

Data sources

The daily landings of the small-scale and the bottom trawl fleets of Vilanova i la Geltrú (henceforth, Vilanova for short) were obtained from the Fishers' Association for the period from 1 January 2000 to 31 December 2013 (14 complete years or 168 months). Vilanova is a representative fishing port of Catalonia (ranking 3rd out of 20 in terms of landings) with an active small-scale coastal fleet of 21 fishing vessels using set nets. The units range from 8 to 13 m LOA and 3 to 12 tons GRT, and have engines of 22-92 kW (Maynou et al. 2011). The bottom trawl fleet comprises 24 units using low vertical aperture bottom trawls and ranging from 15 to 24 m LOA and 32 to 60 tons GRT, with engines ranging from 186 to 375 kW (data provided by the Fishers' Association). The vessels undertake daily fishing trips of 6 to 12 h, with compulsory return to their homeport to sell the catch in the fish auction of the fishers' association, and they rest on Saturdays and Sundays.

All fishing trips made by the small-scale fishing fleet with landings of *M. surmuletus* (4847 records) and *S. officinalis* (36408 records) were selected, corresponding to trammel net metiers D and F in Maynou et al. (2011). The landings (kg) were aggregated at a monthly scale. Fishing effort was measured as number of vessels × number of days per month in each metier because these two species are the main species produced in the specific metiers Maynou et al. (2011). The two species considered are by-catch of the bottom trawl fishery and fishing effort is not directed at these species. As a measure of effort, the number of vessels x number of days per month of the 24 bottom trawlers was used, regardless of the metier practised. Analysis at finer time resolution scales (e.g. daily or weekly scales) is possible with MAGD models, but in the coastal fishery assessed here the frequency of fishing trips is relatively low (on average, 2-3 days per week for trammel netters, Maynou et al. 2011). The time series of landings and effort are shown in Figure 1.

Because no size frequency data is collected regularly for this fishery, the landings data set was complemented with frequency data obtained in the course of a biological sampling project ("Conflict" project, Ref. CGL2008-00047 of the Spanish National Research Plan) during the period 2009-2010. On-board sampling of the entire catch of one trammel netter and one bottom trawler which collaborated voluntarily with the project was carried out 2-3 times per month (N=29 samples in the 12-month period), including length (mm TL for striped red mullet and mm ML for cuttlefish) and body weight measurements (g BW). The size and body weight frequencies are shown in Figure 2.

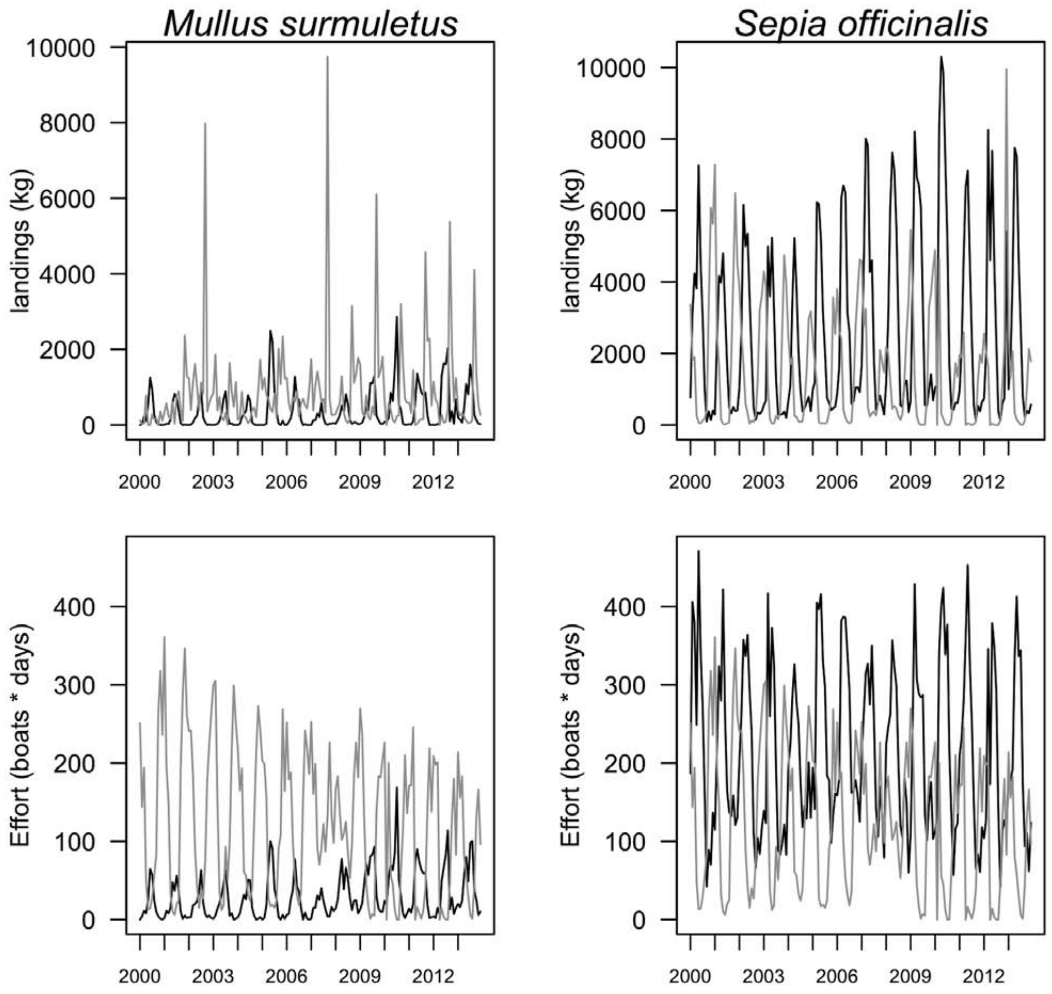

Fig. 1. – Landings (top) and effort (bottom) of striped red mullet (*Mullus surmuletus*, left) and cuttlefish (*Sepia officinalis*, right) in Vilanova i la Geltrú during the period 2000-2013. Grey lines, bottom trawl; black lines, trammel net.

In generalized depletion models, catches are used as a time series of catch in number, while the landings database provides catch in weight. Body weight frequency data (Fig. 2) were used to transform catch in weight to catch in number, following Roa-Ureta (2014): size frequencies were measured in only 12 consecutive months of the 14 years and a Monte Carlo resampling procedure was used to estimate the mean monthly body weight for each species with its standard error. For striped red mullet, two series of mean monthly body weight were estimated, one for trammel net and one for bottom trawl, because their selection patterns are significantly different (cf. Martín et al. 1999). The length frequencies of cuttlefish did not differ between the two sampling gears (cf. Belcari et al. 2002) and a common monthly body weight series was produced. A polynomial surface was fitted to the monthly body weight data in Figure 3 using the *loess* function in the statistical package R v3.1.0 with the function's default parameters. The smoothed time series of monthly body weight and its standard error (Fig. 3) were used to generate 14 different annual time series of body weight for each species. The resampling was carried out from a truncated normal distribution (within the 10-90 percentile interval) using the R package *Runuran* (Leydold and Hörmann 2012).

A starting value of monthly natural mortality (M) for *Mullus surmuletus* was obtained from FishBase (www.fishbase.org) by averaging the two values shown there and dividing by 12 (M=0.034 month^{-1}). For *Sepia officinalis* an estimate of natural mortality is more uncertain and, following Royer et al. (2006), a range of values from 0.05 month^{-1} to 0.15 month^{-1} was tried (model diagnostics, below). The best results were obtained for M=0.12 month^{-1}.

Model

Generalized depletion models keep track of all fishing removals to estimate vulnerable biomass. In addition to fishing, natural mortality (M) depletes the population of each species (Chapman 1974). For one species and one fleet, Chapman's depletion model is:

$$C_t = qE_t\left(N_0 e^{-Mt} - e^{-M/2}\left(\sum_{i=0}^{i=t-1} C_i e^{-M(t-i-1)}\right)\right)e^{-M/2} \qquad [1]$$

where C_t is catch in numbers at time t=1...T (T=168 in the present study), q is a coefficient of catchability,

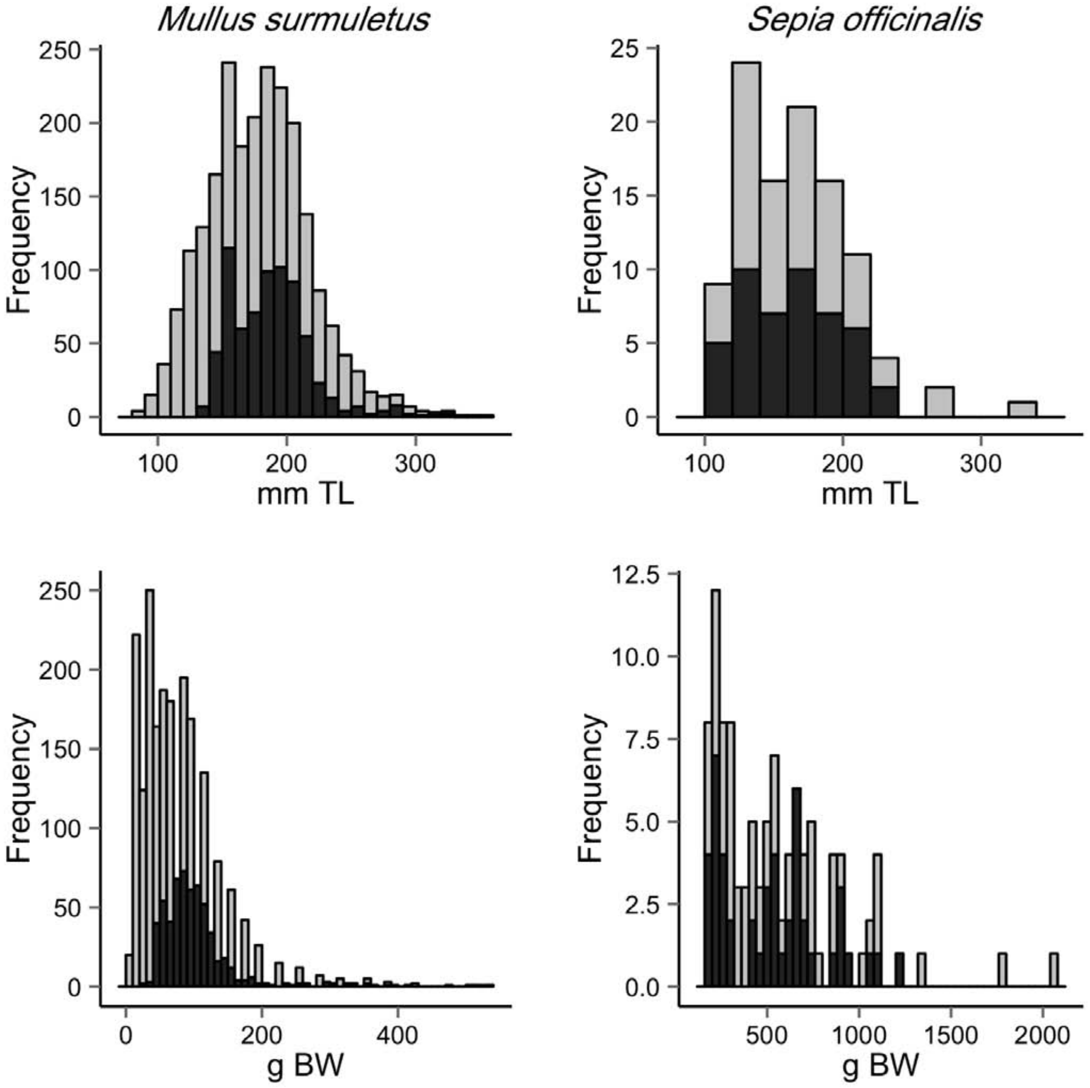

Fig. 2. – Size frequency (top) and body weight frequency (bottom) of striped red mullet (*Mullus surmuletus*, left) and cuttlefish (*Sepia officinalis*, right) in Vilanova i la Geltrú during the period 2000-2013, based on 12 month on-board sampling in 2009-2010. Grey bars: bottom trawl, black bars: trammel net.

E_t is fishing effort at time t, N_0 is the initial number of fish in the population, and M is the natural mortality. The sum over i cumulates the catches over the study period, assuming that C_0=0. The quantity between the outer brackets models the depletion of initial numbers (N_0) as a result of natural mortality and catch.

In the MAGD model (Roa-Ureta 2012, 2014), annual pulses of recruitment in an age-structured population are interpreted as perturbations that reset the depletion process. For a MAGD model running at monthly scale, the set of perturbations $\{R_j\}$ can happen in month p_j, where j is the number of perturbations (j=1, …, 14 in the present case). Additionally, the MAGD model assumes that catchability q is possibly non-linearly related to fish abundance N:

$$q(N) = kN^{1-\beta} \qquad [2]$$

where k is a catchability factor and β measures the response of CPUE to fish abundance: β is 1 when catchability is proportional to abundance, β<1 when catchability varies less than population numbers (hyperstability) and β>1 when catchability varies more than population numbers (hyperdepletion) (Hilborn and Walters 1992, Hatley et al. 2001). Furthermore, catches may be non-linearly related to fishing effort:

$$C_t(N,E) = q(N)E_t^{\alpha} N_t^{\beta} \qquad [3]$$

where α is a proportionality parameter between fishing effort and catches that can account for nonlinear effects (Roa-Ureta 2014). Finally, the complete formulation of the MAGD model for one species and two fleets, f, is (Roa-Ureta 2014)

$$C_t = \sum\nolimits_f k_f E_{f,t}^{\alpha_f} \left(N_0 e^{-Mt} - e^{-M/2} \left(\sum\nolimits_{i=0}^{i=t-1} C_{f,i} e^{-M(t-i-1)} \right) + \right.$$
$$\left. + \sum\nolimits_{j=1}^{j=J} R_{j,f} e^{-M(t-p_{j,f})} \right)^{\beta_f} e^{-M/2} \qquad [4]$$

For each species, the number of parameters to estimate is 64 from 168 pairs of catch and effort observations. From the 64, the 14×2 parameters,

$p_{j,f}$, corresponding to the timing of the perturbations are relatively easy to estimate because peaks of recruitment to the fishery are easily identified in the observed catch series as spikes not explained by concurrent spikes in effort. Roa-Ureta (2014) proposed a statistic for graphical display of the perturbations of catch spike S_t:

$$S_t = 10\left(\frac{X_t}{\max(X_t)} - \frac{E_t}{\max(E_t)}\right) \qquad [5]$$

where X_t is the observed catch in numbers for each species and fleet.

For each year and each species, the perturbations in the catch spike were selected visually a priori from the set April-May-June for the trammel net fleet for both species and the set November-December-January-February for the bottom trawl fleets. These values were entered in the estimation algorithm as starting values of perturbation timings.

The remaining model parameters (36 for each species) were estimated by minimizing the likelihood function of difference between the observed catch series and the predicted catch series $L(\theta, \{X_t, C_t\})$, assuming that catch in number at time step (month) is a random variable with random errors modelled as normal (top) or lognormal (bottom) distribution functions:

$$L\left(\theta;\{X_t,E_t\}\right)=\begin{cases}\left(\frac{1}{2\pi\sigma^2}\right)^T e^{\left(\frac{\sum_1^T (X_t-C_t)^2}{\sigma^2}\right)} \\ \left(\frac{1}{2\pi\sigma^2}\right)^T e^{\left(\frac{\sum_t^T (\log X_t-\log C_t)^2}{\sigma^2}\right)} \prod_1^T {}^{1}\!/_{C_t}\end{cases} \qquad [6]$$

where θ is a vector of parameters, and σ^2 is the variance of the distribution, assumed constant in time. The simplified likelihood function proposed by Roa-Ureta (2014) ignores the error derived from the transformation of catch in weight as well as the estimation variance, by adopting the modified profile approximation to the likelihood function (Pawitan 2001, Section 10.6), which is

$$l_p\left(\theta;\{X_t,E_t\}\right)=\begin{cases}\left(\frac{T-2}{2}\right)\log\left(\sum_1^T (X_t-C_t)^2\right) \\ \left(\frac{T-2}{2}\right)\log\left(\frac{\sum_t^T (\log X_t-\log C_t)^2}{\sigma^2}\right)\end{cases} \qquad [7]$$

The model estimation was performed with the R package CatDyn v. 1.0-5 (Roa-Ureta 2012, 2014), with the options CG (conjugate gradient optimization) and SPG (spectral projected gradient), as recommended in Roa-Ureta (2014). The function CatDynExp was used to graphically fine-tune the initial values of certain parameters (N_0, R, p). Different values of N_0 were tested sequentially, from N_0 equal to maximum observed catch in numbers (scenario 1×) to N_0 equal to 20× the maximum observed catch (scenarios 2×, 5×, 7.5×, 10×, 15×, 20×). Each scenario was run in 4 modalities: options CG and SPG and error distributions lognormal and normal. The model fit with lowest Akaike Information Criterion (AIC) was selected

In addition to the model parameters, the CatDyn package also provides an estimate of population number and biomass vulnerable to the fishing gears. Vulnerable biomass was integrated at annual scale to assess the evolution of this statistic over time in the studied fisheries. Likewise, fishing mortality is a key quantity to assess the evolution over time of the exploitation rate and was calculated with the following relationship (based on Eqs 2 and 3 above), and integrated to annual scale:

$$F_j = k_j N^{1-\beta} E^{\alpha} \qquad (8)$$

RESULTS

Figure 1 (top, left) shows that landings of striped red mullet *Mullus surmuletus* are highly seasonal, with higher production in spring and summer by trammel netters and higher production by bottom trawlers in autumn. The landings of both fishing gears show considerable year-to-year variability. Fishing effort (Fig. 1, bottom, left) shows seasonal variability, with higher activity of the trammel netters in summer and a decrease in activity of bottom trawlers corresponding to a partial 1-2 month close season in summer. Note, incidentally, that the overall trend of bottom trawl fishing effort is decreasing (grey line in Fig. 1, bottom panels). The landings of cuttlefish *Sepia officinalis* are also highly seasonal, with higher production in spring and summer by trammel netters and higher production

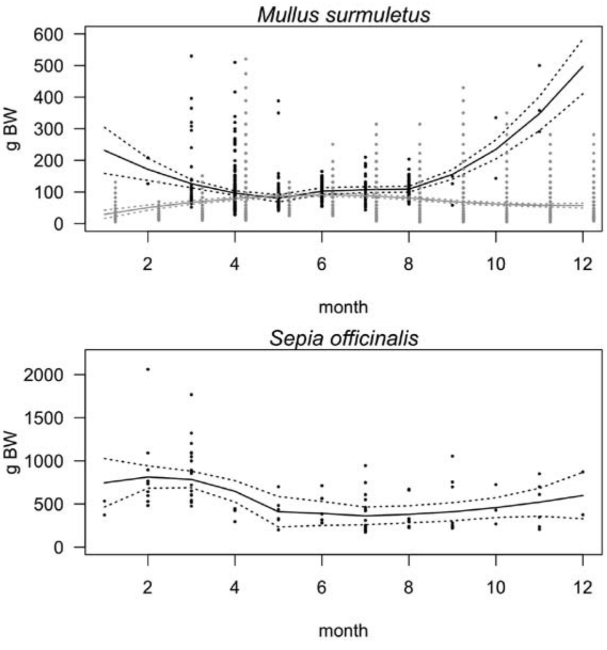

Fig. 3. – Top: Body weight of individual striped red mullet (*Mullus surmuletus*) measured on board along a 12-month sampling period (grey circles, bottom trawl; black circles, trammel net). Smooth *loess* predictor of monthly mean body weight with 95% confidence interval (grey lines, bottom trawl; black lines, trammel net). Bottom: Body weight of individual cuttlefish (*Sepia officinalis*) with smooth *loess* predictor and confidence intervals for both fishing gears combined.

Table 1. – Akaike Information Criterion values under different conditions of starting values for N_0 (5 to 20 times the maximum observed catch value in numbers) corresponding to different algorithms (CG and spg) and error distributions (lognormal and normal) used in the fit of the multi-annual general depletion model.

	Mullus surmuletus				*Sepia officinalis*			
	lognormal		normal		lognormal		normal	
Scenario	CG	spg	CG	spg	CG	spg	CG	spg
5×	-1249.64	-1213.89	-694.03	-677.50	-1238.64	-1224.89	-698.03	-684.50
7.5×	-1239.36	-1217.10	-706.67	-704.93	-1241.36	-1225.10	-698.67	-691.93
10×	-1268.10	-1247.29	-769.00	-773.00	-1243.10	-1234.29	-700.40	-695.10
15×	-1230.96	-1231.00	-747.23	-716.49	-1239.96	-1226.00	-699.23	-693.49
20×	-1260.67	-1238.20	-728.75	-667.46	-1240.67	-1240.20	-698.75	-691.46

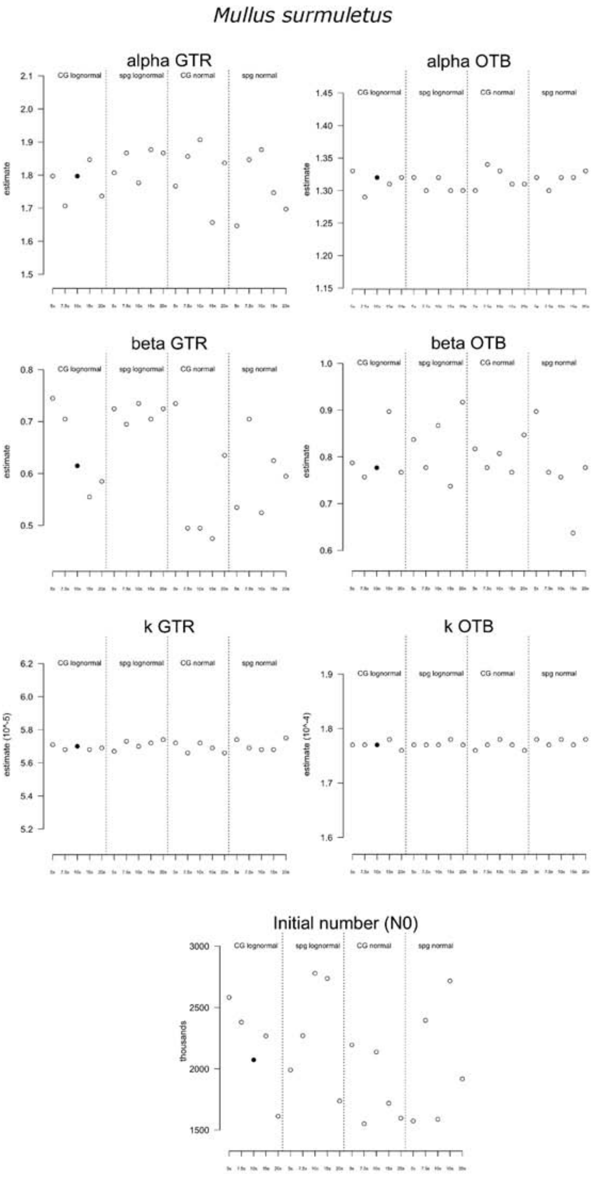

Fig. 4. – Estimates of parameters α_f, β_f, k_f and N_0 for *Mullus surmuletus* of the Vilanova i la Geltrú fishery, under different scenarios and optimization algorithms (refer to Table 1). The parameters estimated for the model with the lowest Akaike Information Criterion are shown with filled circles.

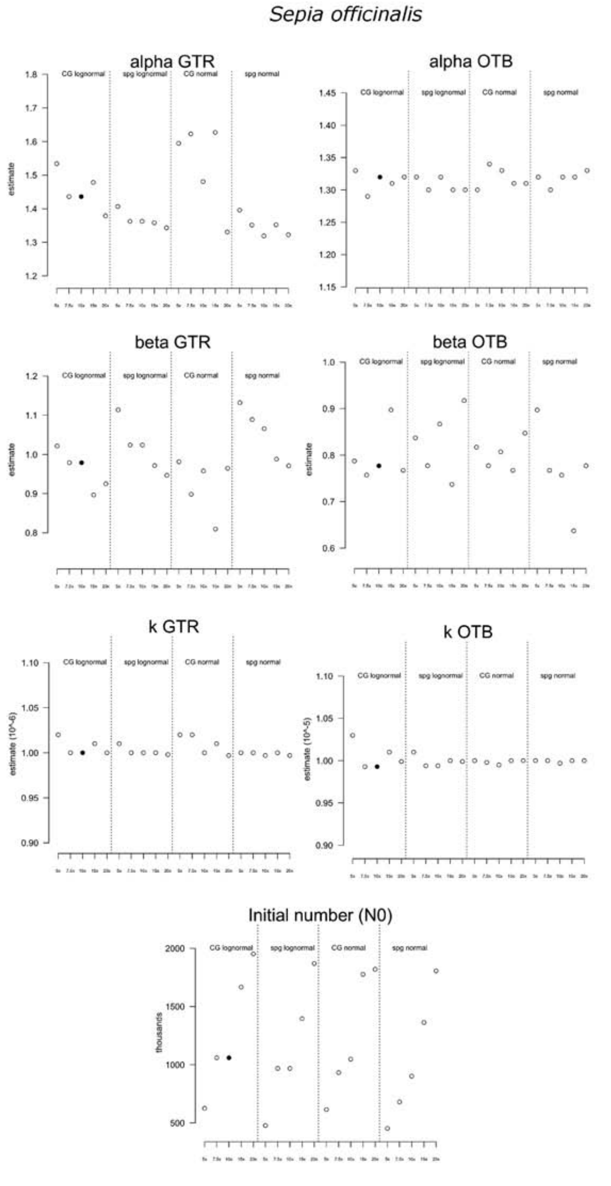

Fig. 5. – Estimates of parameters α_f, β_f, k_f and N_0 for *Sepia officinalis* of the Vilanova i la Geltrú fishery, under different scenarios and optimization algorithms (refer to Table 1). The parameters estimated for the model with the lowest AIC are shown with filled circles.

in late winter by bottom trawlers (Fig. 1, top right). Note that contrary to striped red mullet, the cuttlefish landings and effort of trammel netters is higher than those of trawlers.

The size and body weight frequencies obtained in the biological samplings are shown in Figure 2. The left panel (corresponding to striped red mullet) shows that the smallest individuals caught by trammel net are larger than the smallest individuals of bottom trawl, while the right panel shows that the size and body weight frequencies of cuttlefish do not differ significantly between the two fishing gears.

Table 2. – Results of the multi-annual generalized depletion model applied to the Vilanova trammelnet (GTR) and bottom trawl (OTB) fisheries for striped red mullet (*Mullus surmuletus*) and cuttlefish (*Sepia officinalis*) in the period 2000-2013. Results (MLE, maximum likelihood estimate; CV, coefficient of variation) shown are for the selected model, assuming lognormal distribution in the errors under CG (Conjugate Gradient optimization, cf. Table 1). N_0, number of individuals at the start of the period; p1 to p14, timing; R_1 to R_{14}, magnitude of perturbation (recruits); *k*: catchability parameter; α, catchability-effort parameter; β, abundance-CPUE parameter. Note that the CV could not be estimated for some parameters.

				Striped red mullet				Cuttlefish	
	Parameter	month	Year	MLE estimate	CV of estimate	month	Year	MLE estimate	CV of estimate
	M (month^{-1})			0.0181	-			0.0149	83.1
	N_0 (000s)			2072.58	25.5			1281.53	-
GTR	R_1 (000s)	p_1: 6	2000	217.83	361.7	p_1: 5	2000	363.69	-
	R_2 (000s)	p_2: 6	2001	178.75	230.6	p_2: 5	2001	234.22	363.8
	R_3 (000s)	p_3: 6	2002	225.65	819.7	p_3: 5	2002	218.61	293.3
	R_4 (000s)	p_4: 6	2003	246.27	-	p_4: 5	2003	205.77	126.2
	R_5 (000s)	p_5: 5	2004	212.01	-	p_5: 5	2004	220.38	111.7
	R_6 (000s)	p_6: 5	2005	243.42	-	p_6: 5	2005	273.60	279.7
	R_7 (000s)	p_7: 5	2006	172.42	154.9	p_7: 5	2006	340.67	217.6
	R_8 (000s)	p_8: 5	2007	135.46	114.4	p_8: 5	2007	356.04	293.6
	R_9 (000s)	p_9: 4	2008	104.66	110.3	p_9: 5	2008	405.30	-
	R_{10} (000s)	p_{10}: 4	2009	169.28	129.4	p_{10}: 5	2009	361.62	13.2
	R_{11} (000s)	p_{11}: 5	2010	251.67	158.5	p_{11}: 5	2010	277.28	84.9
	R_{12} (000s)	p_{12}: 5	2011	352.95	-	p_{12}: 5	2011	287.25	155.8
	R_{13} (000s)	p_{13}: 6	2012	313.29	115.4	p_{13}: 5	2012	299.74	350.1
	R_{14} (000s)	p_{14}: 5	2013	137.78	134.6	p_{14}: 5	2013	282.33	148.0
	k			5.70E-05	303.4			9.65E-07	73.3
	α			1.7970	3.0			1.3547	8.4
	β			0.6148	68.0			0.644	7.9
OTB	P1 (000s)	12	2000	194.69	300.8	2	2000	469.14	-
	P2 (000s)	12	2001	171.69	294.2	1	2001	280.98	187.2
	P3 (000s)	12	2002	197.44	331.2	12	2001	236.48	142.1
	P4 (000s)	12	2003	244.81	86.0	12	2002	232.03	94.3
	P5 (000s)	12	2004	203.49	-	12	2003	208.22	55.0
	P6 (000s)	12	2005	219.71	-	12	2004	265.69	86.4
	P7 (000s)	12	2006	168.52	157.8	12	2005	362.31	-
	P8 (000s)	12	2007	107.28	105.4	12	2006	542.50	-
	P9 (000s)	12	2008	139.26	139.0	12	2007	578.05	105.2
	P10 (000s)	12	2009	216.23	166.0	12	2008	393.21	329.2
	P11 (000s)	12	2010	255.18	175.8	12	2009	370.49	102.8
	P12 (000s)	12	2011	333.65	-	12	2010	280.75	59.7
	P13 (000s)	12	2012	227.30	172.1	11	2011	386.45	261.9
	P14 (000s)	11	2013	198.95	171.7	1	2013	399.83	-
	k			1.77E-04	226.6			1.13E-04	104.4
	α			1.3200	6.7			1.3104	3.5
	β			0.7767	52.0			0.4365	25.4

The body weight of each sampled individual and its monthly smooth function are shown in Figure 3. The mean body weight of striped red mullet caught by bottom trawlers was lower in late autumn and winter, corresponding to the recruitment of the species to the bottom. Conversely, trammel netters caught few but large specimens in autumn and winter, with the smallest sizes caught appearing in May. Figure 3 (bottom) shows a common mean body weight smooth function for cuttlefish for the two fishing gears, because the selection pattern is not significantly different, with minimum sizes observed in late spring and summer.

A sensitivity analysis to select starting values for N_0 showed that N_0 corresponding to 10× the maximum observed catch in numbers yielded the lowest value AIC in both species, with the CG algorithm and lognormal distribution producing the best estimates (Table 1). The algorithms converged only for initial values of N_0 corresponding to 5× the observed value or higher. The estimates of α_f, β_f, k_f and N_0 parameters with the different configurations are shown in Figures 4 (striped red mullet) and 5 (cuttlefish). These figures show that the parameter estimates are robust to different specifications of initial N_0 values.

Stock assessments of both species with the CG and SPG configurations under normal and lognormal error models yielded similar results, although the combination CG and lognormal error model had consistently lower AIC. The SPG algorithm failed to converge for striped red mullet under lognormal error and the CV of some parameters could not be computed in all cases (Table 2). Figures 6 and 7 show the results of the model fit for striped red mullet and cuttlefish, respectively (catch in numbers observed and predicted in the top left panel and diagnostics based on the model residuals in the remaining three panels). The diagnostics of the selected models (Figs 6 and 7) show that the catches (in number) can be reasonably predicted by the model and that predictions are unbiased. However, high catches are not successfully predicted by the model in the case of red mullet produced by bottom trawl and cuttlefish in both fishing gears.

The values of the model parameters estimated are shown in Table 2. The initial population estimate (N_0) of striped red mullet was *ca.* 2 million individuals, with regular peaks of recruits to the trammel net in April, May or June (depending on the year) varying from 138 to 252 000 individuals, with no clear annual trend. The time of recruitment to the bottom trawl was estimated as December in all years except the last one (2013, in November). The quantity of recruits to the gear varied from 107 to 334 000 individuals, with no

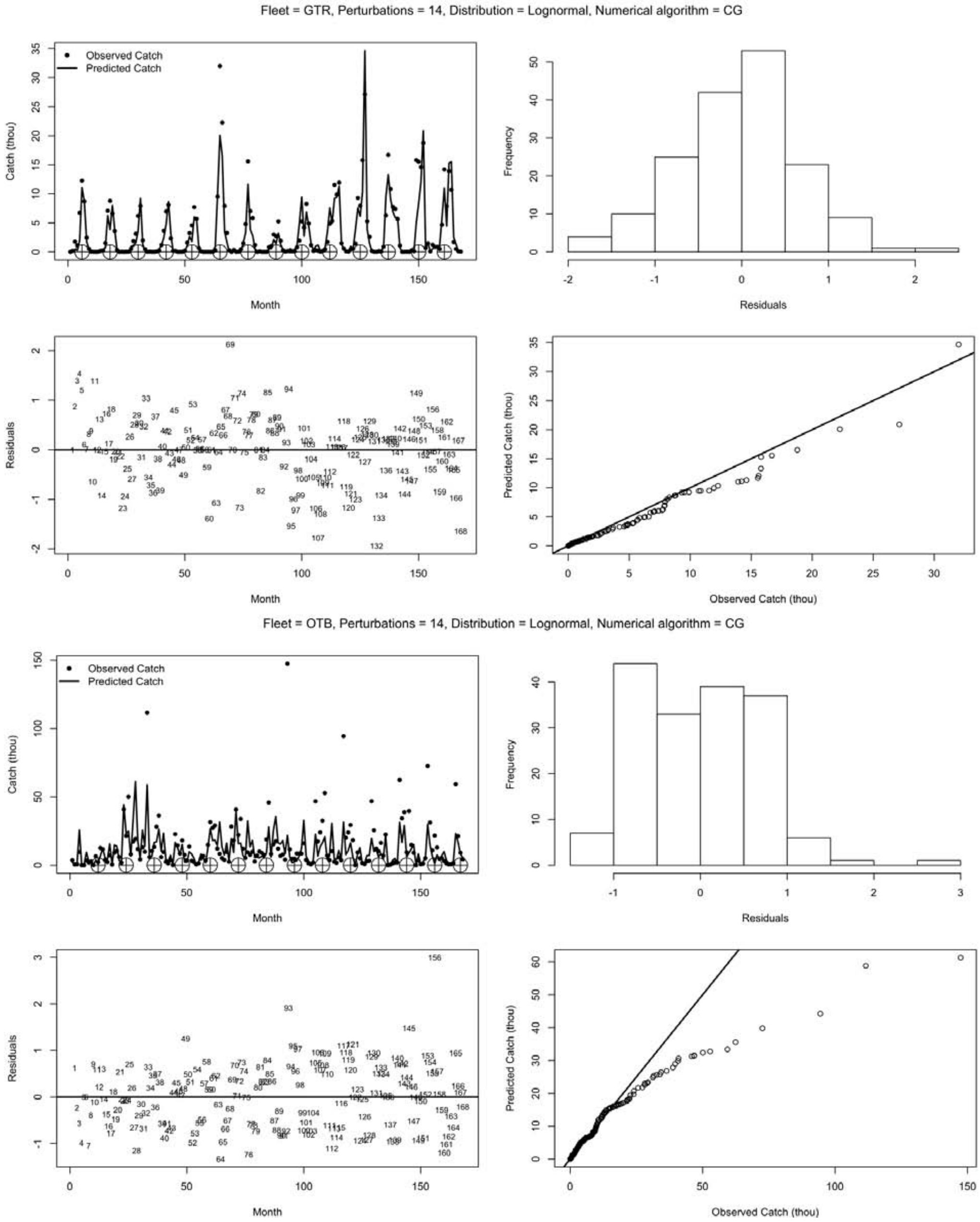

Fig. 6. – (Upper panel, trammel net (GTR); lower panel, bottom trawl (OTB)) Stock assessment prediction results for striped red mullet (*Mullus surmuletus*). Top left: predicted (continuous line) and observed catches in number. Target symbol shows the timing of the perturbations. Top right: empirical distribution of the residuals. Bottom left: scatter plot of the residuals. Bottom right: quantile-quantile plot of the generalized depletion model.

clear trend. The values of the α parameter were larger than 1 in both fishing gears, suggesting that catches grow synergistically with population abundance. The values of the β parameter were lower than 1 in both fishing gears, suggesting hyperstability in the populations (non-declining CPUE despite decreasing abundance).

In the case of cuttlefish, the model parameters in Table 2 show an initial population of 1.282 million individuals, with regular annual recruitment pulses to the trammel net fishery in May of between 206 and 405000 individuals, with no clear temporal trend. The recruits to the bottom trawl ranged between 208 and 578 000 individuals, from year to year without trend. The timing of recruitment was in December for most years, although in some years the peak was detected in January, February or November. The parameter α was also positive, as for striped red mullet, while β was lower than 1 for trammel net and bottom trawl.

The evolution of vulnerable biomass showed a clear decreasing trend in both species (Fig. 8, top), with the amount of vulnerable biomass having halved over the 14-year period. Fishing mortality of striped red mullet increased over time in both fishing gears, and the increase was of similar magnitude. Conversely, the fishing mortality of cuttlefish produced by trammel nets was stable and much lower than the mortality produced by bottom trawl.

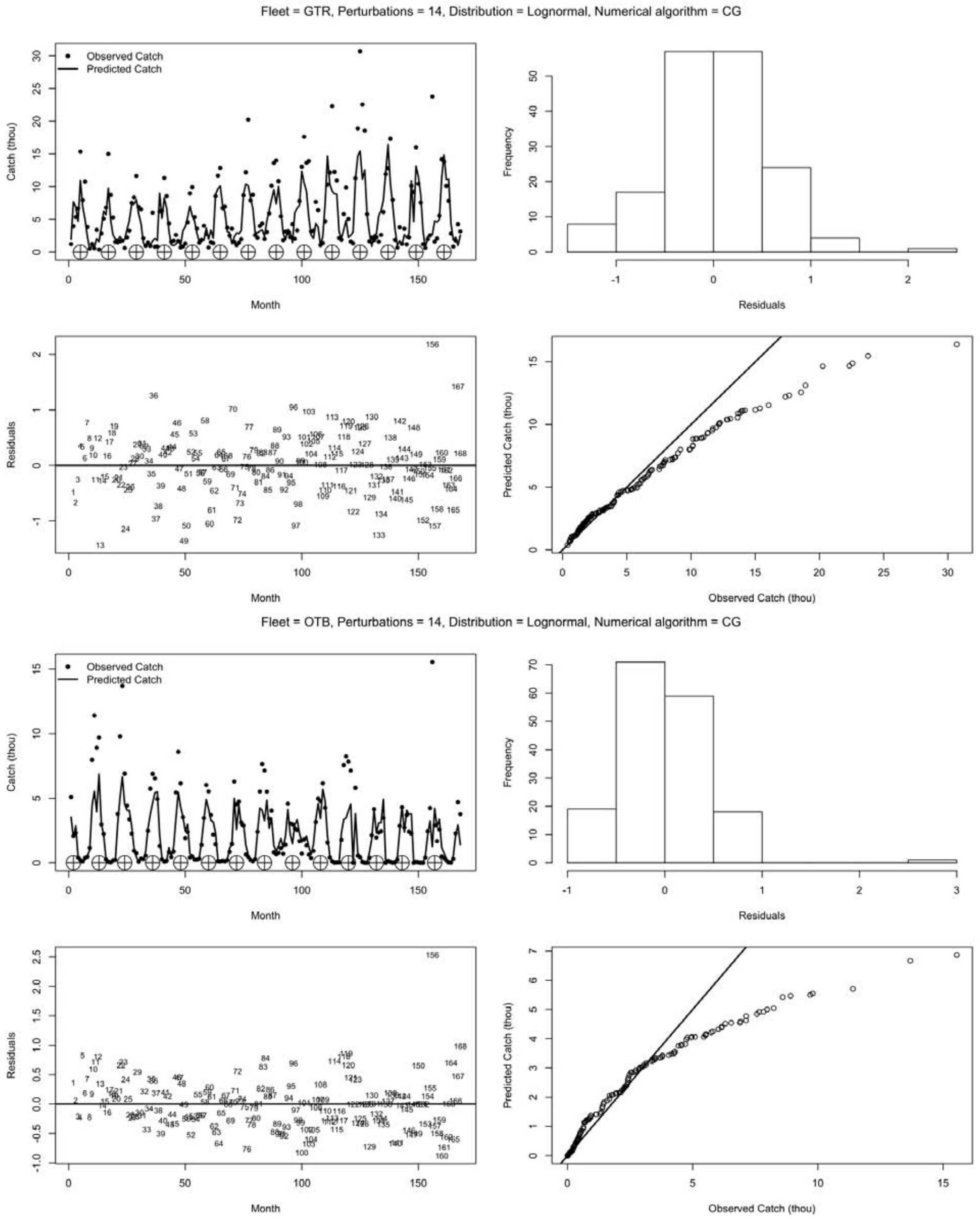

Fig. 7. – (Upper panel: trammel net (GTR); lower panel: bottom trawl (OTB)) Stock assessment prediction results for cuttlefish (*Sepia officinalis*). Top left: predicted (continuous line) and observed catches in number. Target symbol shows the timing of the perturbations. Top right: empirical distribution of the residuals. Bottom left: scatter plot of the residuals. Bottom right: quantile-quantile plot of the generalized depletion model.

DISCUSSION

This application of the MAGD model (Roa-Ureta 2012, 2014) shows that it is possible to produce some indicators (vulnerable biomass, fishing mortality) and fisheries parameters (M, k, α, β) relevant to the management of fish populations in the case of coastal stocks with high frequency catch and effort data, even if biological data are relatively poor, leading to a “minimal stock assessment” (Roa-Ureta 2014). The minimal stock assessment of striped red mullet (*Mullus surmuletus*) shows that the exploitation by the combination of trammel net and bottom trawl exerts significant levels of fishing mortality (varying from 0.5 to 1.5 yr^{-1} approximately, and increasing over time) and that trammel nets are capable of producing similar levels of fishing mortality to bottom trawl. Although no previous assessments exist for the striped red mullet stock in Geographical SubArea 6 (GSA6: Northern Spain), stock assessments in nearby areas (GSA5: Balearic islands, GSA9: North Tyrrhenian and Ligurian seas) show that the values obtained here are comparable to the fishing mortalities produced in other striped red mullet Mediterranean stocks or even higher. Fishing mortality calculated for GSA5 in 2009 for two similar fleets (trammel nets and trawl) was 0.759 yr^{-1}, lower than the values reported here but higher than the fishing mortality that would ensure a

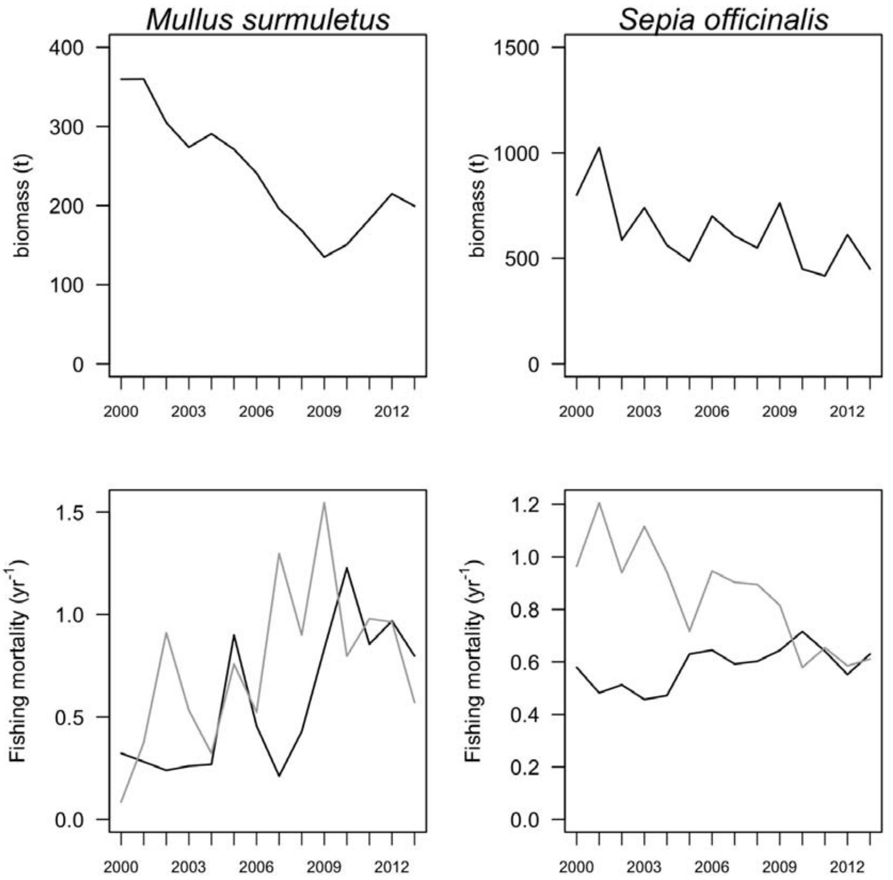

Fig. 8. – Vulnerable biomass (top) and fishing mortality by fishing gear (black, trammelnet; grey, bottom trawl) estimated for striped red mullet (left) and cuttlefish (right) based on the multi-annual generalized depletion model.

sustainable exploitation, estimated at F_{MSY}=0.288 yr^{-1} (Cardinale et al. 2010). Striped red mullet is exploited by three fishing gears in GSA9 (gillnets, in addition to trammel nets and bottom trawl), which produce a combined fishing mortality of F=0.71 yr^{-1}, more than double F_{MSY}=0.31 (Cardinale et al. 2011). Maravelias et al. (2014) report fishing mortalities of 1.36 and 1.22 yr^{-1} for striped red mullet exploited by static nets and bottom trawl, respectively, in Greece, similar to the values obtained here for the Vilanova fleet in recent years. The high fishing mortality estimated for striped red mullet, together with the decreasing trend in the vulnerable biomass (also reported for GSA5 and GSA9 in the first decade of the 21st century, Cardinale et al. 2010, 2011), suggests that the exploitation rate of the species is excessive. The values of the β parameter calculated (0.615 for trammel net and 0.777 for bottom trawl) indicate hyperstability of striped red mullet, i.e. the catches per unit effort are stable over time while the abundance of the stock is actually decreasing (Harley et al. 2001), indicating that perceived trends in the CPUE series are not indicative of the real stock status.

The application of MAGD to red mullet and cuttlefish showed that the model could not capture the existence of months with high catches that appear as outliers in the models (qq-plots in the lower right panels of Figs 6 and 7). This is due to skewness in the data that is not sufficiently captured by the lognormal error distribution. Its impact on the estimated parameter values is expected to result in underestimation of population abundance and overestimation of fishing mortality, but these biases are likely to be small because the distribution of residuals overall is symmetrical (top right panels in Figs 6 and 7) and the residual scatterplot shows a random scatter with homogeneous variance (lower left panel in Figs 6 and 7).

Cuttlefish has not been assessed recently in the Mediterranean, but the minimal stock assessment obtained here shows that vulnerable biomass decreased over the study period, despite relatively low and constant fishing mortality by trammel net and decreasing fishing mortality by bottom trawl. The catches produced by trammel net are at present similar to those produced by bottom trawl, while in the past they were much lower (Belcari et al. 2002), suggesting increased effort on this valuable resource by trammel netters. An important limitation of this, as well as other depletion models, in the application to cephalopods in particular is the assumption of constant natural mortality over the period of study because cephalopods are short-lived semelparous species that sustain very high natural mortalities after spawning. The effect of this fact on the model results is not known but might warrant future studies of depletion models with time varying natural mortality.

Even if small-scale fishing are perceived as relatively low impact, compared with semi-industrial fishing in the Mediterranean (Lleonart and Maynou 2003, Maynou 2011), increased effort on certain target species, such as *Mullus surmuletus* in recent years, may result in a non-sustainable activity. The reasons for the increasing exploitation rates of coastal, high-value species is difficult to know without proper assessment of the dozens of other species caught by the coastal fleets of Vilanova, but increasing unit prices or low yields of other species should be evaluated.

The abundance response coefficient (α) was higher than 1 for both species and fishing gears, and it was particularly high for red mullet caught by trammel netters (α=1.8). This is indicative of disproportionately large effects of increasing fishing effort on these two species. Coupled with the observed effort response (β) lower than 1 in both fishing gears and species, suggesting hyperstability of landings per unit effort, the results show that the efficiency of small-scale fishing can be as high as that of coastal trawl vessels.

A limitation of depletion methods when applied at small geographical scales (such as the area fished by the fleet of a single harbour, here) is that the analysis may not include the entire geographical stock distribution. The results for recruitment strength, for instance, cannot discriminate individuals recruited to the local population from individuals immigrated from neighbouring areas, because catchability varies with changes in the spatial distribution of stocks and CPUE becomes an index of the apparent abundance of stock only (Hilborn and Walters 1992). Because definition of natural stocks units is highly deficient in the Mediterranean (Caddy 2009) and the spatial dynamics of the species studied here are not well-known (cf. Royer et al. 2006 for *Sepia officinalis* in the English Channel), this issue cannot be solved for the moment and the MAGD method must be applied bearing in mind this limitation. However, "minor" (sic) immigration and emigration events are accounted for in the random variability of catch in the MAGD method (Roa-Ureta 2012, p. 1410).

Using methodologies amenable to exploiting data-limited situations, such as the MAGD model developed by Roa-Ureta (2012, 2014), may help produce a more complete picture of the exploitation of marine resources in the Mediterranean, moving beyond the picture derived from standard VPA-type assessments applied recurrently to a handful of important commercial species (e.g. those given in Cardinale et al. 2010, 2011 and similar reposts). The application of the MAGD model is relatively straightforward with the CatDyn library of the R statistical environment, but it requires good starting estimates for the model parameters, particularly natural mortality (M) and the magnitude and timing of the perturbation events (corresponding to annual recruitment pulses). Information on individual fish weight is also necessary in order to convert the landings in weight to numbers. Starting estimates of other parameters (such as α, β or k) can be obtained relatively quickly iteratively with the CatDynExp function of the package CatDyn, even in the absence of prior knowledge on these parameters, by examining the residual diagnostics of plausible sets of parameters.

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