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Rebuilding Mediterranean fisheries: a new paradigm for ecological sustainability

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Abstract

In Mediterranean European countries, 85% of the assessed stocks are currently overfished compared to a maximum sustainable yield reference value (MSY) while populations of many commercial species are characterized by truncated size- and age-structures. Rebuilding the size- and age-structure of exploited populations is a management objective that combines single species targets such as MSY with specific goals of the ecosystem approach to fisheries management (EAF), preserving community size-structure and the ecological role of different species. Here, we show that under the current fishing regime, stock productivity and fleet profitability are generally impaired by a combination of high fishing mortality and inadequate selectivity patterns. For most of the stocks analysed, a simple reduction in the current fishing mortality (F_{cur}) towards an MSY reference value (F_{MSY}), without any change in the fishing selectivity, will allow neither stock biomass nor fisheries yield and revenue to be maximized. On the contrary, management targets can be achieved only through a radical change in fisheries selectivity. Shifting the size of first capture towards the size at which fish cohorts achieve their maximum biomass, the so-called optimal length, would produce on average between two and three times higher economic yields and much higher biomass at sea for the exploited stocks. Moreover, it would contribute to restore marine ecosystem structure and resilience to enhance ecosystem services such as reservoirs of biodiversity and functioning food webs.

Keywords Mediterranean fisheries, MSY, optimal length, over-exploitation.

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Introduction

The World Summit on Sustainable Development (WSSD; United Nations, 2002), held in Johannesburg in August 2002, laid the foundation for a radical shift about how marine ecosystems and fisheries are to be managed in the future. The Plan of Implementation adopted during WSSD encouraged the application by 2010 of the ecosystem approach to fisheries management (EAF, Garcia and Cochrane 2005), the elimination of destructive fishing practices and the establishment of marine protected areas consistent with international laws and based on scientific information. WSSD also agreed to restore the world's depleted fish stocks to levels that can produce the maximum sustainable yield (MSY) on an urgent basis where possible no later than 2015. After 8 years from the adoption of WSSD, Europe is still far from achieving these objectives (Froese and Proelß 2010). The Common Fisheries Policy (CFP) was inefficient in terms of reducing fishing capacity (Villasante and Sumaila 2010) as well as in rebuilding marine ecosystems (Worm *et al.* 2006). The fishery sector is still suffering from overfishing, fleet over-capacity, heavy subsidies, low economic resilience and decline in the volume and size of fish caught (European Commission 2009a). Most of the stocks in European waters (88%) are estimated as being overfished and 30% of them are outside safe biological limits, which mean that they may not be able to replenish (European Commission 2009b).

In the Mediterranean, the achievements of WSSD targets risks to be further delayed by the assessment and management systems currently enforced at the national and EU level. The first attempts to assess stocks, through the application of equilibrium production models, were made in the 1970s by the scientific Working Groups of the General Fisheries Council for the Mediterranean (GFCM) of the FAO (GFCM 1972; Pereiro and Fernández 1974; Caddy and Garcia 1982). However, analytical assessment (i.e. incorporating the effect of fishing on the structure of the population) of commercial stocks in the Mediterranean started about 15 years later (i.e. in the early 1990s: Aldebert *et al.* 1993; Abella *et al.* 2002; Oliver 2002) compared to other European marine areas, such as the North Atlantic. The lack of a more systematic data collection hindered the assessment and management of many fisheries resources in several Mediterranean areas until the early 2000s when the EU Data Collection Regulation (DCR, EU reg. 1543/2000) was enforced in all EU Member States. Also, the standardized collection of fisheries-independent data started relatively late with the MEDITS bottom trawl survey in the beginning of 1990s (Bertrand *et al.* 2002) and the more recent MEDIAS pelagic acoustic survey in 2008 (MEDIAS 2010). The number of consistently assessed stocks by GFCM and European Scientific, Technical and Economic Committee for Fisheries (STECF-SGMED: Sub-group for the Mediterranean Sea, STECF 2009a,b) increased significantly in the last 5 years as a result of the enhanced data collection system and commitment of Mediterranean scientists, elucidating the status of fisheries resources in the Mediterranean. A general condition of overfishing emerged for most of the stocks, confirming results of assessments carried out in the past (Lleonart and Maynou 2003; Lleonart 2005). According to STECF (2010), 32 of 38 stocks assessed in Mediterranean European countries are overfished (about 84%), while only 4 stocks are considered sustainably exploited compared to the fishing mortality (*F*) level able to provide MSY. MSY is defined as the largest catch or yield that can be taken on a continuous basis (i.e. with low risks of stock collapse) from a stock under normal environmental conditions. In this context, F_{MSY} is the fishing mortality that allows exploiting the stock at MSY. In particular, all assessed demersal fish stocks (100% of 18 stocks) were found over-exploited, while among the nine crustacean stocks assessed, seven were over-exploited while the status of two stocks was unknown. The highest rate of sustainable exploited stocks (27%) was found among the small pelagics as anchovy and sardine (i.e. three of 11 stocks).

Although over-exploitation was already identified in the past, a higher resilience of Mediterranean stocks compared to Atlantic stocks has often been advocated (Caddy 1993; Lleonart 2005). Such resilience was argued to be linked to high exploitation rates on juveniles but low mortality on adults, because of the occurrence of offshore spawning refuges, which have the capability of reducing risks of stock depletion and collapse (Caddy 1993, 1999). However, the effects of such exploitation regime on fisheries yield and size-structure of exploited populations were poorly investigated, and the impact on the economy of fisheries not fully understood. Nevertheless, it is clear that improving the selection pattern of the fishing gear, especially for trawl, would result in improved economic yields from demersal resources (Lleonart *et al.* 2003; Merino *et al.* 2008).

Almost all management strategies currently adopted by the Mediterranean countries are limited to the control of fishing capacity and fishing effort and/or to the application of technical measures, such as mesh size regulation, establishment of a minimum landing size and closures of areas and seasons for fishing. However, scientific advice has rarely been used to implement technical measures (Lleonart and Maynou 2003). For instance, the adopted legal minimum landing sizes for the major commercial species do not show any consistent relationships with biologically meaningful target sizes, such as the size at first maturity (L_m) or size at which a cohort attains its maximum biomass (L_{opt}; Beverton and Holt 1957; Froese *et al.* 2008). Furthermore, sensitive areas such as nurseries or spawning grounds of commercial species are still exploited by fishing fleets even though a large amount of scientific knowledge is available on their spatial distribution (Fiorentino *et al.* 2003; Tsagarakis *et al.* 2008; Colloca *et al.* 2009; Fortibuoni *et al.* 2010a; Giannoulaki *et al.* 2010) and specific protection measures are defined by a recent regulation of the European Council (EC reg. n. 1967/2006). In addition, control and surveillance at sea, a crucial step of any management process, has not been efficient in enforcing the adopted measures. This is also because fishermen are not usually included in decision processes, as recommended during the review process of the CFP (European Commission 2009a), and the new regulations enforced are often not fully implemented. In general, there is a lack of communication among the three main groups of stakeholders for an adaptive management: managers, fishermen and scientists (Lleonart and Maynou 2003).

Exploitation at or below F_{MSY} has been a commonly accepted fisheries objective, and most management regimes have been built around this framework (Worm *et al.* 2009) as well as the maximization of fishery yields (Dichmont *et al.* 2010). Nevertheless, rebuilding the size- or age-structure of exploited populations is a management objective that combines single species targets as MSY with specific EAF goals, such as maintaining a healthy trophic configuration through the preservation of the community size-structure (Froese *et al.* 2008) and the ecological role of the different species. To this aim, Froese *et al.* (2008) have proposed L_{opt}, in the classical formulation of Beverton and Holt (1957) and Beverton (1992), as a target reference point to catch fish avoiding risks of growth and recruitment overfishing. In this context, rebuilding population structure is an important target for the Mediterranean stocks as many commercial species show truncated size- and age-structures resulting from historical overfishing. Owing to the combined effect of high fishing pressure and low size selectivity, the catch composition of most of the Mediterranean commercial stocks is dominated by age 1 and 2 specimens, with a low occurrence of large individuals (see STECF 2009a,b). Because of the general lacking of long time series, only in few cases a decreasing trend in the mean size related to fishing exploitation was directly observed for certain commercial species such as sardine in the Aegean Sea (Voulgaridou and Stergiou 2003 further supported by recent estimates of Antonakakis *et al.* 2011) and in the Adriatic Sea (STECF 2009a,b), red mullet in Castellamare Gulf – Sicily (Fiorentino *et al.* 2008), hake in the Balearic area (Hidalgo *et al.* 2009) as well as swordfish in southern Ionian Sea (De Metrio *et al.* 1999) and the wider Mediterranean Sea (Anonymous 2010). A demographic erosion because of fishing is clearly evident when the size- or age-structure of populations under different exploitation levels are compared, as in the case of coastal species in marine protected areas (e.g. Macpherson 2000; Stobart *et al.* 2009) and for commercial crustaceans (D'Onghia *et al.* 2005). There is a growing support that age truncation can make the abundance of exploited fish stocks more variable because of their reduced ability to successfully cope with the environmental fluctuations (Anderson *et al.* 2008; Stenseth and Rouyer 2008). This process has been suggested for hake in the Balearic area (Hidalgo *et al.* 2011), where the long-term exploitation pattern is likely to have eroded the age-structure of the stock.

In an attempt to improve our understanding of the status of Mediterranean fisheries, we compiled and analysed available data on commercially exploited stocks, namely size of recruitment, fishing mortality at age and further relevant biological parameters. We used published data, obtained from GFCM, ICCAT and STECF-SGMED assessment reports, to explore whether the current exploitation pattern (F_{cur}) supports the agreed management targets of WSSD and EAF, namely (i) exploitation of stocks at F_{MSY}; (ii) maximization of fisheries yields; and (iii) rebuilding population structure of the exploited stocks. We measured the performance against these objectives for the main commercial stocks in ecological and economic terms under three different fishing regimes: the current fishing exploitation regime (F_{cur}) as obtained from stock assessment carried out in 2008–2009; an MSY exploitation pattern (F_{MSY}) without any change in the current fishery selectivity; and an alternative fishing regime (F_{Lopt}) that exploits the stock at MSY but with a radical shift of the fishing selectivity towards the optimal length (L_{opt}) and a maximization of fisheries yield. Notably, fishing at F_{MSY} implies a reduction in the effort but without any major change in fishing selectivity (European Commission 2006), while harvesting at F_{Lopt} includes a modification of the fishing selectivity to exploit the stock at the optimal length. Here, we used F_{01} (i.e. fishing mortality that produces a marginal 10% increase in yield per recruit compared to that at $F = 0$) as proxy for F_{MSY} (European Commission 2006, STECF 2009a,b). Kell and Fromentin (2007) also suggested using F_{01} derived from yield-per-recruit analysis as an appropriate proxy of F_{MSY} in case of limited data or high uncertainty as is the case for most Mediterranean stocks.

An additional objective of our work was to assess the effect of such alternative management scenarios, F_{MSY} and F_{Lopt}, on the economic yield of Mediterranean fisheries, particularly how increased catches and improved size-structure would affect average prices and revenue. In fisheries, prices are formed by the interaction between supply and demand, disregarding any government interference on price formation (Clark 1990). On the other hand, different qualities of fish (such as freshness or size) may fetch different prices in local markets. The influence of quantities and fish quality on prices have often been overlooked in bioeconomic models, because these models usually work with constant prices for simplicity (Nøstbakken and Bjørndal 2003). However, knowledge about the demand functions is important in the analysis of fisheries under optimal management (Nøstbakken and Bjørndal 2003) and may help understand historical developments of important marine fisheries, such as the North Sea herring fishery (Nøstbakken 2008).

Materials and methods

We collected data on 36 stocks assessed in recent years within FAO-GFCM, STECF-SGMED and International Commission for the Conservation of Atlantic Tunas (ICCAT) working groups in different Mediterranean GSAs (geographical sub-areas, Fig. 1, Table 1). These stocks belong to the most important commercial species of fish, namely Atlantic bluefin tuna (*Thunnus thynnus*, Scombridae), swordfish (*Xiphias gladius*, Xiphiidae), European hake (*Merluccius merluccius,* Merlucciidae), red mullet (*Mullus barbatus*, Mullidae), striped red mullet (*Mullus surmuletus*, Mullidae), blackspot seabream (*Pagellus bogaraveo*, Sparidae), common sole (*Solea solea*, Soleidae), sardine (*Sardina pilchardus*, Clupeidae), anchovy (*Engraulis encrasicolus*, Engraulidae) and crustaceans such as Norway lobster (*Nephrops norvegicus*, Nephropidae), deep-water rose shrimp (*Parapenaeus longirostris*, Penaeidae), blue and red shrimp (*Aristeus antennatus*, Aristeidae) and giant red shrimp (*Aristaeomorpha foliacea*, Aristeidae) exploited by the most relevant pelagic and demersal fisheries in the Mediterranean Sea (Bas 2006).

Biological and fisheries parameters

For each stock, we followed one cohort instead of the entire population under the current (F_{cur}) and

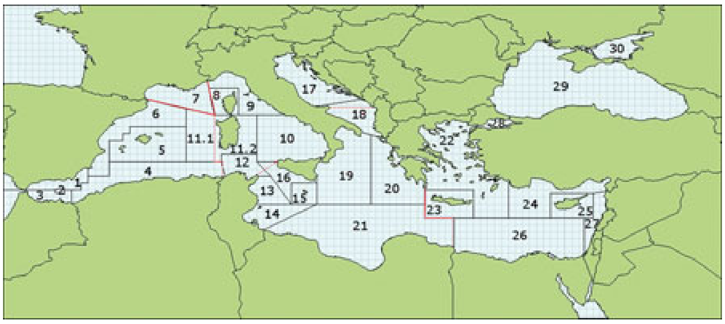

Figure 1 Map showing the different Mediterranean FAO – GFCM GSAs (geographical sub-areas). 1 Northern Alboran Sea, 2 Alboran Island, 3 Southern Alboran Sea, 4 Algeria, 5 Balearic Islands, 6 Northern Spain, 7 Gulf of Lions, 8 Corsica Island, 9 Ligurian and North Tyrrhenian Sea, 10 South Tyrrhenian Sea, 11.1 Sardinia (west), 11.2 Sardinia (east), 12 Northern Tunisia, 13 Gulf of Hammamet, 14 Gulf of Gabes, 15 Malta Island, 16 South of Sicily, 17 Northern Adriatic, 18 Southern Adriatic Sea, 19 Western Ionian Sea, 20 Eastern Ionian Sea, 21 Southern Ionian Sea, 22 Aegean Sea, 23 Crete Island, 24 North Levant, 25 Cyprus Island, 26 South Levant, 27 Levant, 28 Marmara Sea, 29 Black Sea, 30 Azov Sea. Retrieved from http://www.gfcm.org/gfcm/en (accessed September 2011).

two alternative fishing regimes (F_{MSY} and F_{Lopt}) to avoid assumptions about stock recruitment relationships that are unknown for most Mediterranean exploited stocks (STECF 2009a,b). We collected recruitment data, biological parameters and fishing mortality for each stock (Table 1). The mean initial number of recruits (*R*) was calculated for each stock averaging the last three annual available recruitment estimates (in general 2007–2009). The biological parameters used were the von Bertalanffy growth parameters (*VBGP*), the length–weight relationship, age at maturity and natural mortality at age (*M*). A fishing mortality at age vector (*F*) was used to incorporate the selection pattern in cohort modelling. F_{MSY} corresponds to the F_{01} in the case of demersal fish, crustaceans and large pelagic fish, whereas for the small pelagic species like anchovy and sardine stocks, it refers to the value that corresponds to the empirical exploitation rate $E_{0.4}$ suggested by Patterson (1992) and currently used by SGMED (STECF 2009b). In the F_{MSY} scenario, we used the same selectivity pattern as for F_{cur}, to simulate the assumed reduction in *F* without changes in gear selectivity.

Computation of cohort biomass and yield at age

We used the following equations to calculate cohort biomass and yield at age for each stock under the three different fishing scenarios. Firstly, for each age class, we calculated the respective length (*L*) using the von Bertalanffy growth function (VBGF):

$$L_t = L_\infty\left(1 - \exp^{-k(t-to)}\right) \tag{1}$$

where L_∞ is the asymptotic length, k is a curvature parameter that determines how fast individuals approach L_∞, and t_o determines the point in time when the fish has conceptually zero length. In a next step, we calculated the number of individuals at age (N_{t+1}) using the exponential decay equation:

$$N_{t+1} = N_t e^{-(F_t+M_t)^{\Delta t}} \tag{2}$$

where N_t is the number of individuals at age *t*; F_t is the fishing mortality at age *t*; and M_t is natural mortality at age *t*. N_t at age 0 is the estimated number of recruits. Biomass at age was then obtained as the product of N_{t+1} and mean weight at age as determined from the length–weight relationship. To obtain yield at age, we first calculated the annual catch at age C_t using Baranov's catch equation:

$$C_t = \frac{F_t}{Z_t} N_t (1 - e^{-(Z_t)}) \tag{3}$$

where Z_t is the total mortality at age *t* obtained summing fishing F_t and natural M_t mortality at age *t*. Catch-at-age estimates where then multiplied by the mean weight at age to obtain yield at age. We estimated the critical length of each stock (i.e. the length of the age group at which the cohort reaches its maximum biomass) under the F_{cur} and F_{MSY} scenarios, thus L_{cur} and L_{F01}, respectively, and the optimal length (L_{opt}) as the mean length of the age group in which the biomass of an unexploited

Table 1. Population parameters of Mediterranean commercial stocks in different geographical sub-areas (GSA)

Species	GSA	L_∞ (cm)	$k_{(year^{-1})}$	t_o	a	b	t_r	R (millions)	M	F_{cur}	F_{MSY}	F_{Lopt}	References
European hake	5	85.0	0.17	−0.18	0.0048	3.12	0.5	1.6	0.47 (0–14)	0.91 (0–14)	0.25	0.54	STECF (2009a, 2009b)
	6	106.7	0.20	0.00	0.0048	3.12	0.5	231.7	0.48 (0–11)	1.30 (0–11)	0.16	0.32	STECF (2009a, 2009b)
	7	100.7	0.23	−0.35	0.0070	3.03	0.5	65.2	0.26 (0–10)	0.41 (0–10)	0.26	0.19	Jadaud *et al.* (2009)
	9	104.0	0.20	0.03	0.0070	3.03	0.5	117.0	0.39 (0–11)	0.46 (0–11)	0.22	0.38	STECF (2009b)
	10	97.9	0.13	−0.02	0.0035	3.22	0.5	59.3	0.27 (0–17)	0.54 (0–17)	0.24	0.48	STECF (2009b)
	15–16	81.5	0.15	−0.08	0.0043	3.15	0.5	59.0	0.29 (0–15)	0.30 (0–15)	0.16	0.24	STECF (2008)
	19	107.0	0.20	0.00	0.0048	3.13	1.0	13.5	0.27 (1–12)	0.59 (0–12)	0.15	0.23	STECF (2009b)
Red mullet	1	26.0	0.41	−0.40	0.0062	3.16	0.2	11.6	0.29 (0–12)	1.11 (0–12)	0.26	0.45	Quetglas and García (2008)
	5	26.0	0.41	−0.40	0.0062	3.16	0.2	1.3	0.29 (0–12)	1.11 (0–12)	0.40	0.69	Quetglas *et al.* (2008)
	6	34.5	0.34	−0.14	0.0062	3.16	0.2	140.3	0.29 (0–12)	1.00 (0–12)	0.16	0.25	Fernández *et al.* (2008)
	7	26.0	0.41	−0.40	0.0081	3.11	0.2	8.4	0.20 (0–12)	0.38 (0–12)	0.53	0.71	STECF (2009b)
	9	29.0	0.60	−0.10	0.0005	3.12	0.2	164.0	0.53 (0–12)	0.79 (0–12)	0.49	1.04	STECF (2009b)
	11	29.1	0.41	−0.39	0.0010	3.02	0.2	220.0	0.33 (0–12)	0.49 (0–12)	0.22	0.38	STECF (2009b)
	25	26.6	0.18	−2.49	0.0080	3.12	0.2	1.5	0.10 (0–12)	0.46 (0–12)	0.22	0.17	STECF (2009b)
Striped red mullet	5	40.1	0.16	−1.88	0.0084	3.12	0.5	8.2	0.31 (0–12)	0.46 (0–12)	0.73	1.35	Quetglas *et al.* (2009)
Common sole	17	39.6	0.44	−0.46	0.0070	3.06	0.5	5.2	0.31 (0–7)	1.29 (0–7)	0.26	0.39	Scarcella (2010)
Blackspot seabream	3	53.9	0.13	−1.02	0.0124	3.14	1.0	0.5	0.20 (0–17)	0.12 (0–17)	0.20	0.29	Belcaid (2009)
Atlantic bluefin tuna	All GSA	319.0	0.09	−0.09	0.0246	2.95	1.0	2.6	0.15 (0–26)	0.60 (0–26)	0.09	0.12	International Commission for the Conservation of Atlantic Tunas (ICCAT) (2009a)
Swordfish	All GSA	238.6	0.18	−1.40	0.0009	3.55	1.0	1.2	0.20 (0–26)	0.37 (0–26)	0.33	0.65	ICCAT (2009b)
Anchovy	1	19.0	0.34	−2.32	0.0040	3.19	0.5	45.1	0.46 (0–5)	1.48 (0–5)	0.36	0.91	Giráldez *et al.* (2009)
	6	19.0	0.34	−2.32	0.0040	3.19	0.5	577.9	0.33 (0–5)	1.04 (0–5)	0.22	0.44	Torres *et al.* (2009)
	7	19.1	0.35	−1.45	0.0056	3.03	0.5	4477.1	0.93 (0–5)	0.13 (0–5)	0.62	1.29	Bigot and Roos (2010)
	17	16.2	0.40	−2.04	0.0025	3.37	0.5	31440.1	0.68 (0–5)	0.17 (0–5)	0.44	1.14	STECF(2009a, 2009b)
	22	19.1	0.38	−1.56	0.0030	3.31	0.5	43694.4	0.85 (0–6)	0.29 (0–6)	0.53	1.32	STECF(2009b)
Sardine	1	24.1	0.25	−2.66	0.0086	3.00	0.5	381.8	0.33 (0–7)	0.38 (0–7)	0.22	0.41	Quintanilla *et al.* (2009)
	6	24.1	0.25	−2.66	0.0086	3.00	0.5	2222.1	0.33 (0–7)	0.73 (0–7)	0.22	0.41	Bellido *et al.* (2009)
	17	18.8	0.38	−2.30	0.0095	2.94	0.5	14431.2	0.52 (0–9)	0.62 (0–9)	0.35	0.88	STECF (2009a, 2009b)
	22	19.5	0.39	−0.48	0.0045	3.22	0.5	7639.9	0.78 (0–6)	0.43 (0–6)	0.49	0.41	STECF(2009b)
Norway lobster	9	74.0	0.17	0.00	0.0005	3.04	0.2	31.0	0.40 (0–13)	0.32 (0–13)	0.21	0.34	STECF(2009b)
	17	59.5	0.34	−0.130	0.0004	3.18	0.2	73.3	0.33 (0–16)	0.46 (0–16)	0.15	0.35	Santojanni *et al.* (2009)

Table 1. (Continued)

Species	GSA	L_∞ (cm)	$k_{(year^{-1})}$	t_o	a	b	t_r	R (millions)	M	F_{cur}	F_{MSY}	F_{Lopt}	References
Deep-water rose shrimp	3	49.9	0.50	−0.33	0.0051	2.26	0.4	16.8	0.90 (0–5)	0.55 (0–5)	0.58	1.09	El Ouamari (2009)
	6	45.0	0.39	0.10	0.0019	2.61	0.4	202.2	1.25 (0–9)	0.42 (0–9)	0.58	1.16	STECF(2009b)
	9	43.5	0.60	0.00	0.0069	2.24	0.4	165.0	0.78 (0–4)	0.18 (0–4)	0.70	1.05	STECF(2009b)
	15–16	43	0.63	−0.20	0.0036	2.44	0.4	1200	0.71 (0–3)	1.59 (0–3)	0.35	0.48	STECF (2008)
Giant red shrimp	15–16	68.9	0.61	−0.20	0.0013	2.64	0.4	159	0.65 (0–5)	0.76 (0–5)	0.34	0.32	STECF(2009b)
Blue and red shrimp	6	77.0	0.38	−0.06	0.0024	2.47	0.4	91.0	0.45 (0–9)	1.36 (0–9)	0.30	0.53	STECF(2009b)

L_∞, K, t_o: growth parameters; a, b: parameters of the length–weight relationship, t_r: estimated age at recruitment (years); R: annual recruitment, M: mean natural mortality for the age classes indicated in brackets; F_{cur} mean fishing mortality for the age classes indicated in brackets; F_{MSY}: fishing mortality corresponding to F_{01}; F_{Lopt}: fishing mortality at optimal length. F_{cur} is estimated as the average of all age classes considered in the analysis, thus it is not directly comparable with F_{cur} reported by FAO-GFCM, STECF-SGMED and ICCAT working groups.

cohort (with $F = 0$) reaches its maximum. For this calculation, we estimated numbers at age using the equation 2 on the same initial number of recruits and M at age of a cohort exploited at F_{cur}. F_{cur} is estimated as the average of all age classes considered in the analysis, thus it is not directly comparable with F_{cur} reported by FAO-GFCM, STECF-SGMED and ICCAT working groups. VBGP parameters and length–weight relationships were then used to estimate length at age and the corresponding biomass. We did not use the classical equation of Beverton and Holt (1957) to estimate L_{opt} because, assuming fixed M, it does not allow considering the effect of change in natural mortality with growth.

Maximization of annual yield

In the F_{Lopt} scenario, the optimal F-at-age vector that is required to maximize annual fisheries yield was estimated iteratively imposing the following constraints: (i) fishing mortality starting from $L = L_{opt}$; (ii) the ratio between yield at F_{Lopt} and yield at F_{MSY} is maximized; (iii) F at age ranging between 0 and 2.5 times of the estimated F_{MSY}. The extent of the variation of F_{MSY} was found to be more than a factor of two in a study aimed at investigating the sensitivity of MSY-based reference points to changes in selectivity (Scott and Sampson 2011). Therefore, we assumed that F_{Lopt} can achieve the goal of exploiting the stock at MSY if the F value does not exceed 2.5 times the F_{MSY} value estimated with the current selectivity pattern.

Computation of economic yield

The data sources used to compute economic value were two data sets of fisheries catches and prices for all species, the first corresponding to Catalonia (north of GSA6: Northern Spain, 2000–2009; fisheries production data base of the Catalonian Fisheries Directorate) and the second corresponding to Italy (ISMEA, 2002–2010, http://www.ismea.it, accessed September 2011). While the second data set has information on catches and prices by fleet segment and fish category ('small,' 'medium' and 'large'), the first data set does not provide information on sizes. The first data set was applied to GSAs in Spain and France (GSA 1: Northern Alboran Sea, GSA5: Balearic Islands, GSA 6 and GSA 7: Gulf of Lions), while the ISMEA data set was used to estimate economic yield in Italian and Greek GSAs.

Economic yields for the combination of each species and GSA were computed using the catch at age predicted under the three management options (F_{cur}, F_{MSY} and F_{Lopt}) multiplied by the price. Prices were computed under three different assumptions for each species and GSA combination (Table S1):

1. Assuming constant ex-vessel prices, that is, prices are independent of fish size and local offer, the average annual price in the data set was used.
2. Assuming quantity-dependent prices by computing the flexibilities *b* between mean annual price and annual catch at the local level (GSA), usually higher offer results in lower price (negative flexibility), linearizing the equation, price = *a* Catch^b, based on the time series 2000–2009 for Spanish and French GSAs and the series 2002–2010 for Italian and Greek GSAs. This equation was used only when coefficient *b* was significant at the 5% level.
3. Assuming size-dependent prices by computing the average annual price for each size category of catch, usually larger fish fetches higher prices (positive flexibility). The length distribution of each species was divided into the categories 'small,' 'medium' and 'large' according to our expert judgment.

Although the third scenario is likely to be the most reasonable one, applying the three scenarios aims to cover different aspects of the behaviour of the market that can be highly variable.

In all cases, prices were corrected for inflation using the annual average rates for each country available from EUROSTAT (http://epp.eurostat.ec.europa.eu, accessed September 2011) and expressed as 2010 real prices. Owing to data limitations, not all three scenarios could be computed for each species and GSA combination. Specifically, size-dependent prices (assumption 3) could only be calculated for some species in Italian and Greek GSAs (i.e. hake in GSAs 9: Ligurian and Northern Tyrrhenian Sea, GSA 10: South and Central Tyrrhenian Sea, GSA 15–16: Malta and South of Sicily and GSA 19: Western Ionian Sea, Table S1) and the resulting size-dependent prices were assumed valid for all Spanish and Greek GSAs. Moreover, for Atlantic bluefin tuna and swordfish, assumption 2 could not be applied because the regressions were not significant.

Results

Exploitation status of Mediterranean stocks

Based on the most recent assessments, 26 of the 36 stocks analysed (72%) are exploited above target F_{MSY} levels (Table 1). Overfishing is the general condition concerning teleostean stocks targeted by trawl fisheries except for the case of red mullet in the GSA 7, striped red mullet in the GSA 5 and blackspot seabream in the Southern Alboran Sea (GSA 3). Hake stocks are exploited at a fishing mortality rate around 1.8–8.1 times higher (F_{cur} = 0.30–1.30) than the assumed reference level (F_{MSY} = 0.15–0.26). A similar pattern was observed for most red mullet stocks, sole, Norway lobster and the two species of red shrimps: *Aristeus antennatus* and *Aristeomorpha foliacea*. Deep-sea rose shrimp stocks are considered fished at or below F_{MSY} except in the South of Sicily (GSA 15–16, Table 1). Bluefin tuna and swordfish, two species of large pelagic fishes that are routinely assessed within the ICCAT stock assessment working group, were overfished (6.6 and 1.1 times F_{MSY} for bluefin tuna and swordfish, respectively).

Among small pelagics, anchovy stocks were found over-exploited in Spain (GSAs 1 and 6) and fished in a sustainable way in the GSA 7, Aegean Sea (GSA 22) and Adriatic Sea (GSA 17). Sardine stocks were generally overfished in the Western Mediterranean and sustainably exploited in GSA 22.

For all those stocks, the current age at first capture corresponds to the first or second year of life (age classes 0 and 1) and often occurs before the achievement of first maturity and spawning (Table S2). In general, the current critical length (L_{cur}) is well below L_{opt}. For instance, in the case of hake, the L_{cur} values ranged between 20 and 36 cm, whereas the estimated L_{opt} is between 50 and 81 cm. Similarly, bluefin tuna showed an L_{cur} that is about half of L_{opt}. Fishing at F_{MSY} will only achieve L_{opt} for four stocks of small pelagic fish like anchovy in GSAs 1, 7 and 17, sardine in GSA 17 and for deep water rose shrimp in GSA 6 (Table S2). As showed in Fig. 2, when the difference between F_{Lopt} and the current fishing mortality (F_{cur}) increases (i.e. smaller F_{Lopt}/F_{cur} ratio), the deviation of the L_{cur} from L_{opt} also increases (i.e. higher L_{opt}/L_{cur} ratio).

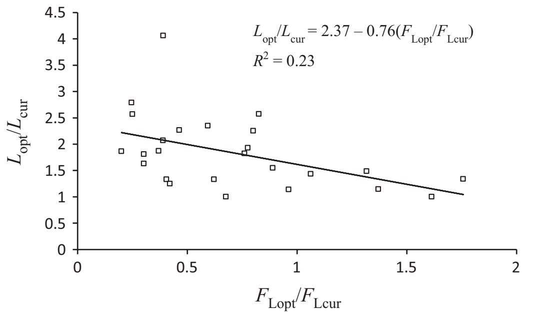

Figure 2 Effect of the fishing exploitation level, measured by the ratio between the estimated fishing mortality at optimal length (F_{Lopt}) and current fishing mortality (F_{cur}) on the achievement of the optimal length (L_{opt}/L_{cur}). L_{cur} is the critical length under the current fishing regime for Mediterranean commercial stocks and L_{opt} is the mean length of the age group in which the biomass of an unexploited cohort (with $F = 0$) reaches its maximum (only over-exploited stocks were considered).

Effect of the different fishing mortality regimes on the Mediterranean fish stocks

Currently, high exploitation coupled with very poorly selective gears determines a low production level for most of the examined stocks and fisheries. Under the current fishing regime, calculated biomass at sea and predicted fishery yield remain at generally lower levels compared to those expected under the F_{MSY} or the F_{Lopt} scenarios. Table S2 summarizes the results of the simulations carried out for the examined stocks. The cohort biomass of demersal fish stocks (i.e. hake, red mullet, striped mullet, sole) and large pelagics (bluefin tuna and swordfish) under the F_{Lopt} fishing regime is estimated on average 9.3 times higher (range between 1.9 and 40) than the current biomass, except for the blackspot seabream that is currently sustainably exploited by the trawl fleet in GSA 3 (Fig. 3a). The two small pelagic species reacted dissimilarly to the adoption of the F_{Lopt} regime, presenting an increase in cohort biomass for sardine and a decrease for anchovy stocks. In the case of sardine, the F_{cur} leads to a lower critical length (L_{cur}) compared to the F_{Lopt} (L_{opt}), whereas in the case of anchovy, with the exception of one stock, the F_{Lopt} produces L_{opt} that is equal or even lower than L_{cur}. This could be attributed to the combined effect of fast growth, short life span and exploitation pattern that begins at the size at which the anchovy cohorts achieve their maximum biomass (Table S2 and Fig. 4a). For crustaceans, the biomass at F_{Lopt} would be 3.1 times

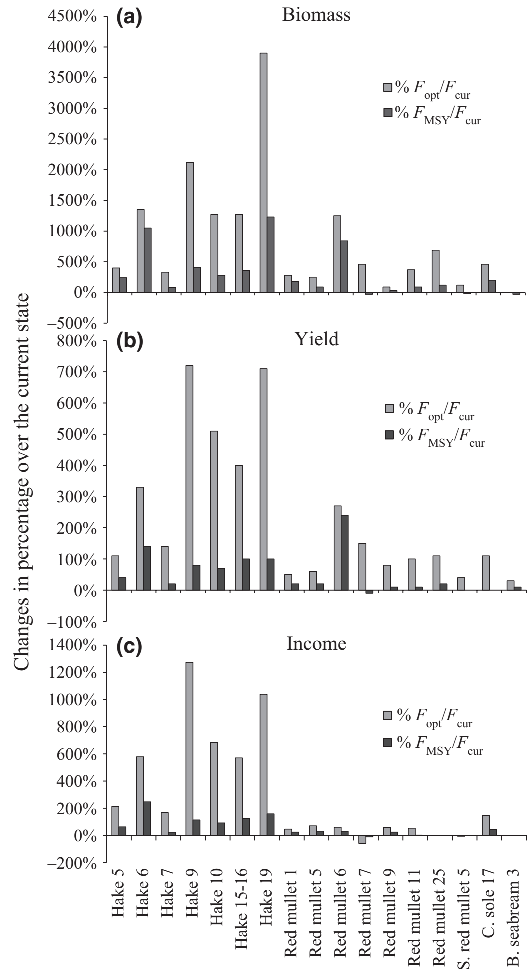

Figure 3 Estimated percentage change over the current state of the biomass at sea (a), yield (b) and income (c) of Mediterranean demersal fish stocks under the fishing at maximum sustainable yield (MSY) (F_{MSY}, black) and fishing mortality at optimal length (F_{Lopt}, grey) fishing regimes. Yield, biomass and income values obtained under the F_{MSY} and F_{Lopt} fishing regimes were compared with values obtained under the current fishing regime (F_{cur}).

higher on average than the current biomass (range 0.9–5.1, Fig. 5a).

Similarly, based on our estimations, the F_{Lopt} scenario would result in higher or much higher yields for all demersal stocks (except giant red shrimp in GSA 15–16) and large pelagics (average, 2.8; range, 1.2–8.2), (Table S2 and Figs 3b, 4b and 5b). In the case of small pelagics, F_{Lopt} produces an increase in yield of underexploited stocks, such as anchovy in GSA 7, 17 and 22 and sardine in GSA 17 along with decreases in biomass. The opposite is generally observed for over-exploited small pelagics

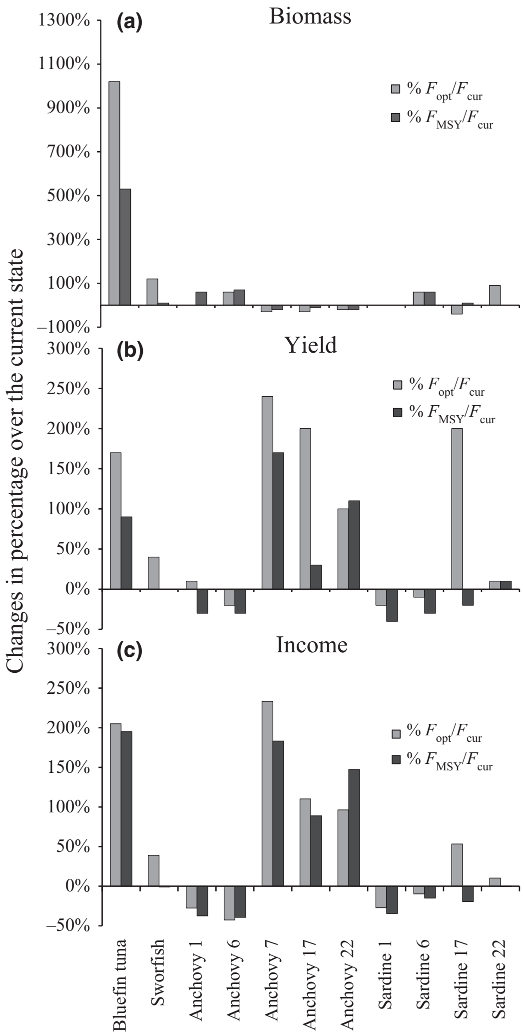

Figure 4 Estimated percentage change over the current state of the biomass at sea (a), yield (b) and income (c) of Mediterranean pelagic fish stocks under the fishing at maximum sustainable yield (MSY) (F_{MSY}, black) and fishing mortality at optimal length (F_{Lopt}, grey) fishing regimes. Yield, biomass and income values obtained under the F_{MSY} and F_{Lopt} fishing regimes were compared with values obtained under the current fishing regime (F_{cur}).

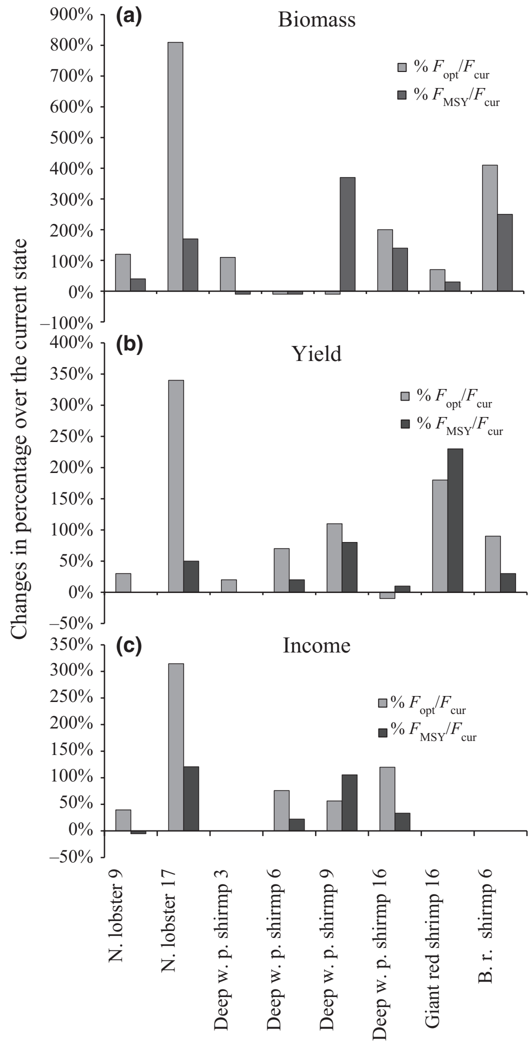

Figure 5 Estimated percentage change over the current state of the biomass at sea (a), yield (b) and income (c) of Mediterranean crustacean stocks under the fishing at maximum sustainable yield (MSY) (F_{MSY}, black) and fishing mortality at optimal length (F_{Lopt}, grey) fishing regimes. Yield, biomass and income values obtained under the F_{MSY} and F_{Lopt} fishing regimes were compared with values obtained under the current fishing regime (F_{cur}).

stocks (Table 1 Fig. 5b). As the two alternative fishing regimes (F_{Lopt} and F_{MSY}) do not produce any significant change in the critical length, the effects on the stock yield and biomass are just related to the fishing mortality (Table 1).

The F_{Lopt} strategy would return larger biomass at sea and yield than the F_{MSY} fishing regime for all the stocks of demersal and large pelagic fish, as well as for most of the crustacean stocks. For small pelagics, the effect of F_{Lopt} is similar to F_{MSY} depending on the status of the stock (Table S2 and Fig. 4a). Size-structure of the populations under the different fishing regimes analysed here was also compared against the no-fishing situation. Figure 6 shows the predicted biomass as a function of the length at age. The combination of high fishing mortality and poor selectivity produced stock structures dominated by small individuals. It is evident that for all demersal species and large pelagics, F_{Lopt} fishing regime is effective in achieving a size-struc-

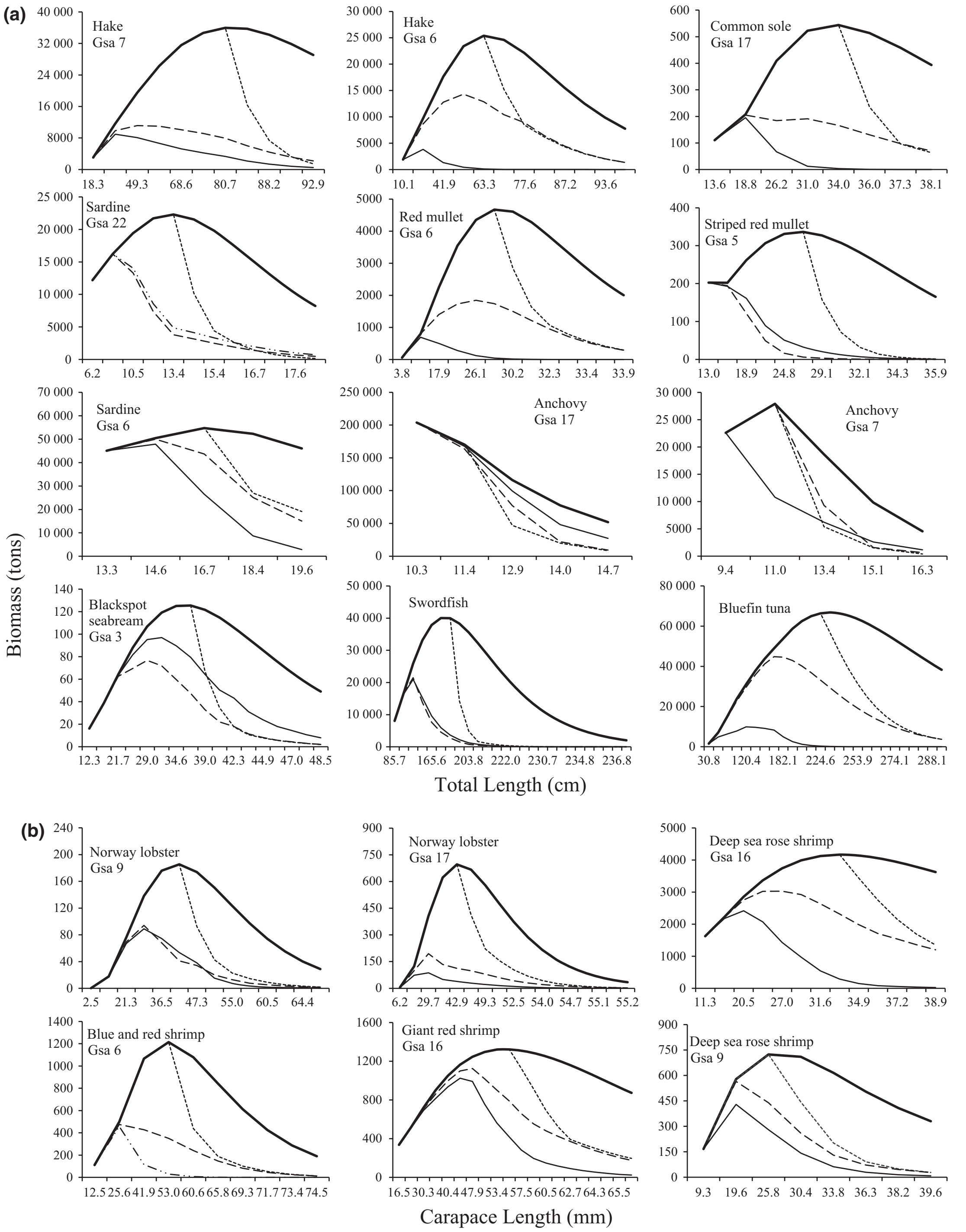

Figure 6 Cohort biomass against mean length at age, with no-exploitation (bold line), exploitation at maximum sustainable yield (MSY) (F_{MSY}, dashed line), exploitation at optimal length (F_{Lopt}, dotted line) and current exploitation pattern (F_{cur}, thin line) for a selection of Mediterranean exploited stocks. (a) Fish; (b) crustaceans.

ture that more closely resembles the un-fished situation. The only exception is given by anchovy where the current fishing exploitation does not seem to significantly impact the structure of the population (Fig. 6). For the same stocks, the predicted size composition of the fisheries catches

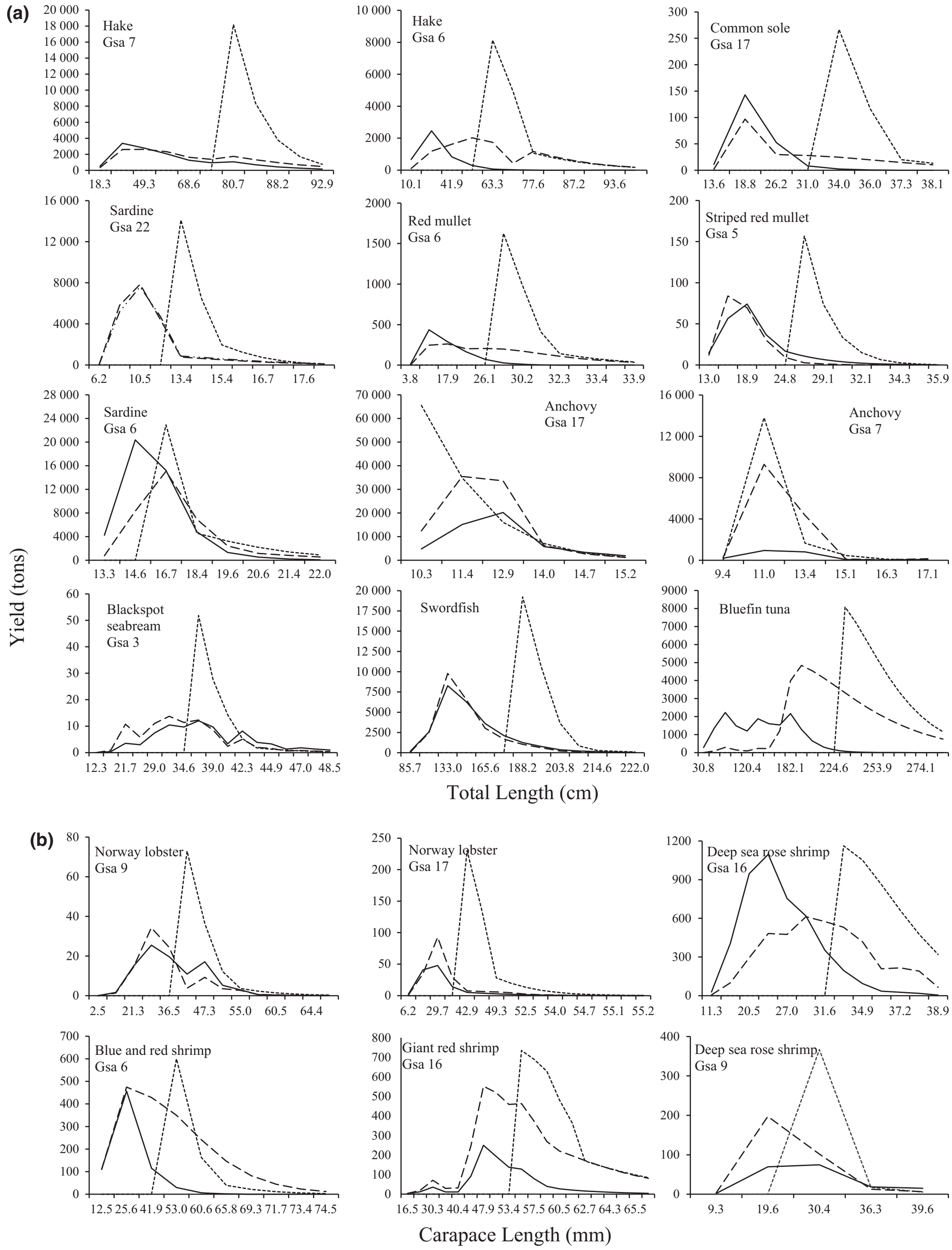

Figure 7 Cohort yield against length at age, with no-exploitation (bold line), exploitation at maximum sustainable yield (MSY) (F_{MSY}, dashed line), exploitation at optimal length (F_{Lopt}, dotted line) and current exploitation pattern (F_{cur}, thin line) for a selection of Mediterranean exploited stocks. (a) Fish; (b) crustaceans.

corresponding to the different fishing regime scenarios is shown in Fig. 7. Except for small pelagic species, fishing at F_{Lopt} produced a larger shift of the catch towards large individuals compared to the current or F_{MSY} fishing regimes.

Effect of the different fishing mortality regimes on the Mediterranean fleet profitability

In economic terms, both F_{MSY} and F_{Lopt} management scenarios would provide higher economic revenue for most combinations of species and GSAs. Under the three different price-formation assumptions (constant, offer-dependent and size-dependent prices), applying F_{MSY} would provide relative incomes near 1 or higher for most demersal species, suggesting that the application of this management measure will not be economically detrimental to the fisheries in the mid to long term (Table S3). Only in three demersal stocks (red mullet in GSA 7; striped red mullet in GSA 5 and Norway lobster in GSA 9) the relative income is lower than 1 (but still higher than 0.9) under the F_{MSY} management scenario (Table S3, Figs 3c and 5c). Conversely, under F_{Lopt}, all demersal stocks would provide substantially higher income, as much as 9 to 10 times for hake in GSAs 9 and 19, 2.7 times for red mullet in GSA 6, or 3.9 times for Norway lobster in GSA 9 (Table S3, Figs 3c and 5c). In the case of small pelagic stocks, the performance of alternative management scenario is less clear and depends greatly on each stock/GSA combination (Fig. 4c). Management under F_{MSY} or F_{Lopt} would be clearly beneficial in economic terms for anchovy in GSA 7, 17 and 22, whereas for sardine, it was only clearly shown in GSA 17 and 22 (Table S3, Fig. 4c). For large pelagics, F_{MSY} and F_{Lopt} would produce a three times increase in the income for bluefin tuna, whereas it is only the F_{Lopt} strategy that seems beneficial for swordfish (Fig 4c).

Discussion

Mediterranean fisheries resources have a long history of human exploitation conducted with a variety of fishing gear, such as traps, nets, lines and beach seines, some of which are still in use (Horden and Purcell 2000). The number and power of fishing vessels as well as their efficiency increased after the second world war, rising up abruptly at the end of the 1960s in some areas, to peak at the end of the 1980s (Colloca *et al.* 2004; Franquesa *et al.* 2008). The effects of these long-term changes in fishing exploitation of Mediterranean populations, communities and ecosystems have just begun to be understood. For example, decline and extinction of sensitive species such as elasmobranchs, because of high fishing pressure (Ferretti *et al.* 2008; Fortibuoni *et al.* 2010b), have been recently described, as well as biodiversity threats, habitat loss and degradation of food web, all related to fishing exploitation (Coll *et al.* 2010). At the same time, a decreasing trend in the abundance of commercial species has been detected in those areas where longer time series are available (e.g. Adriatic Sea, Coll *et al.* 2009) as well as the over-exploitation status of several commercial stocks (Lleonart and Maynou 2003; STECF 2009a,b). Nonetheless, fisheries management is still ineffective in the Mediterranean, and few actions have been undertaken so far to mitigate the fishing impact on the ecosystem and rebuild exploited populations (Mora *et al.* 2009).

Here, we demonstrated that under the current fishing regime, stock productivity and fleet profitability are generally impaired by a combination of high fishing mortality and poor selectivity featuring the main fisheries. For most of the stocks analysed, a simple reduction in the current fishing mortality (F_{cur}) towards a MSY reference value (F_{MSY}) without any change in the fishing selectivity will not allow neither to maximize the stock biomass nor the fisheries yield and revenue. On the contrary, we showed that these two management targets can be achieved only through a radical change in fisheries selectivity, shifting the size of first capture towards the size at which unexploited fish cohorts achieve their maximum biomass, the so-called optimal length (Beverton and Holt 1957), and exploiting the stock at the corresponding F_{MSY} value. For instance, at the F_{Lopt} fishing regime, hake stocks would produce up to four times more biomass and yield than at F_{cur} and F_{MSY}. Fishing at F_{Lopt} would also increase the catching efficiency of the fleets because it produces higher yield per unit of fishing mortality than the F_{01} exploitation pattern for most of the stocks examined. Furthermore, F_{Lopt} regime would generally produce 2 or 3 times higher economic yields (with the exception of some small pelagic stocks). Even taking into account the negative effect on prices of increased catch (i.e. offer–price relationship, economic assumption 2), overall income would increase because of enhanced population structure, with higher abundance of large size individuals in the catches, which fetch usually higher prices. Only for 27% of the stocks analysed, the economic yield will be lower for F_{MSY} than F_{cur}. The stocks for which fishing at MSY would result in diminished economic yields compared to current yields are all small pelagics, which does not preclude that urgent action is taken on fleets exploiting demersal resources and large pelagics, because the fleets targeting the latter groups of species are completely different than the fleets targeting small pelagics and thus can be managed independently.

The mechanisms of price formation in European fisheries have received little attention from the economic literature (Nøstbakken and Bjørndal 2003). In our case also, the shortness of the data series (9–10 years) impeded an in-depth analysis of the sea food market in the Mediterranean. But regardless of the actual price-formation mechanism (constant prices, prices as a function of quantities or prices as a function of fish size), we showed that both alternative management strategies (F_{MSY} and F_{Lopt}) would enhance revenues for the Mediterranean fleets and that the effect is particularly clear in heavily fished demersal stocks and large pelagics.

In a similar study, Froese *et al.* (2008) estimated the effect of exploiting some of the North Atlantic fish stocks at L_{opt}. They, however, did not account for the likely change in F_{MSY} because of the shift in selectivity towards the optimal length. In our simulations, we showed that exploiting the stock at L_{opt} can be accompanied by a substantial increase in F_{MSY} (up to 2.5 times the estimated F_{01}) and yield without negative impacts on the estimated biomass at the sea or the economy of the fisheries.

Our results indicated also another important aspect related to the long-term sustainability of Mediterranean fisheries. In fact, setting F_{MSY} as a general management objective will generally be insufficient for developing advice, because their values change widely according to the variability in fishing mortality at age, increasing with directional changes in selectivity. This has been demonstrated in the classical Beverton and Holt's yield-per-recruit model (1957). This means that a given stock, even under constant biological and environmental conditions, does not have a unique F_{MSY} value because it will depend on the selectivity pattern of the fisheries. This is in turn contingent to many factors including gear selectivity of the fishing methods used to exploit the stock and the allocation of effort among these methods (Goodyear 1996; Scott and Sampson 2011). When, as in the Mediterranean mixed-species fisheries, different fleets and gears compete for a resource, fishing selectivity and therefore F_{MSY} can change very quickly relative to the management timescales (Maunder 2002). In these situations, as stated by Goodyear (1996), setting MSY as a management objective will therefore be insufficient for developing management advice unless the desired long-term age composition of the catch or some other qualifying factor is also specified.

It is also surprising that current fishery management agencies do not attempt to manipulate selectivity more effectively to enhance yield (Jennings and Revill 2007; Scott and Sampson 2011). Maintaining or restoring stocks to levels that can produce MSY is the goal of the EU Common Fisheries Policy in line with the Implementation Plan adopted at the WSSD (United Nations 2002; European Commission 2006). However, this management target does not include any objective for improving fishing selectivity even though the European fisheries currently depend on young and small fish that mostly get caught before they can reproduce. For instance, about 90% of the cod in the North Sea are fished before they can spawn (International Council for the Exploration of the Sea 2007), and a similar pattern occurs also for important Mediterranean species, such as hake (STECF 2009a,b).

Exploiting the stocks at smaller length implies also very low F_{MSY} values given the relationships between size at first capture and F_{MSY} as demonstrated in the classical Y/R models and showed clearly in our estimates of F_{Lopt} (see Table 1). This means that for some highly exploited stocks, such as hake in several GSAs, moving towards F_{MSY} without any change in the current fisheries selectivity pattern implies the necessity to an abrupt decrease in the fishing effort that can be hardly achieved in the short or medium term. In the Mediterranean, the current regulation for mesh and minimum landing sizes is not focused on the protection of significant phases of the life cycle of the species, but rather on market aspects (there is a certain tradition of eating small, whole fish rather than fish fillets as elsewhere in Europe). In particular, the selectivity of demersal trawl fleet is poor and a high proportion of undersized fish are captured (Lleonart and Maynou 2003). Also, recent EU regulation (reg. EC 1967/2006) aimed at improving trawl mesh selectivity (from 40 mm diamond, to 40 mm square or 50 mm diamond) does not really modify the catch composition of the trawl for the most important commercial species, even if fisheries yield would likely benefit in the long term (Guijarro and Massutí 2006). In the case of hake for instance, current minimum landing size of 20 cm, well before its size of maturity, results in a size-structure with very few large fish left in the population. Nevertheless, the legal mesh size recently enforced by the regulation EU 1967/2006 allows a minor increase in the size of first capture (Bethke 2004; Guijarro and Massutí 2006; Hidalgo *et al.* 2009).

To have more 'natural' population in which the size-structure resembles as closely as possible that of an unexploited stock is increasingly understood as one of the requirements for sustainable fisheries (Froese *et al.* 2008). Here, we show that another crucial benefit of fishing at F_{Lopt} is that such fishing regime determines significant rebuilding of the population structure towards a more 'natural' size composition because of an increase in the proportion of large fish. On the contrary, the current fishing regime largely reduces the abundance of large fish in the population as only a small proportion of the cohort biomass survives and fish are harvested at an average size that is smaller than the size that would produce the maximum yield. Populations with a reduced abundance of large fish, as a consequence of high fishing mortality on juveniles, have been demonstrated to suffer of increased variability because of unstable population dynamics and reduced ability to contrast environmental fluctuations (Anderson *et al.* 2008). On the other hand, populations with a healthy age-structure are composed by individuals of different age classes. These populations are generally spawning in different locations and times and therefore contributing to a bet-hedging capacity of the stock that is important in smoothing out short-term environmental variability (Hsieh *et al.* 2010). In addition, there is growing evidence that big spawners are able to produce higher quality and quantity of eggs ('maternal effect'; e.g. Longhurst 2002). A positive effect on recruitment of rebuilding the population age-structure was demonstrated in Mediterranean for red mullet along the Sicilian coasts (Fiorentino *et al.* 2008). As the result of a trawling ban, the abundance of large spawners increased, likely determining higher annual recruitments also via the extension of the recruitment period. Furthermore, size-selective fishing can determine adaptive changes in the populations that can be inheritable and difficult to be reversed with implications for recruitment and recovery of the stock (Law 2007). High harvesting rate on juveniles and decreasing vulnerability of large-sized individuals as observed for several stocks in the Mediterranean (e.g. hake) should benefit early maturing and fast-growing individuals that have the advantage to grow more quickly through the window of lengths vulnerable to the fishery (Ernande *et al.* 2003). Even though experimental evidence of evolutionary processes induced by fishing for Mediterranean stocks is lacking, the theoretical consequence of the current exploitation pattern might be a loss of reproductive potential owing to the shift towards maturation at smaller sizes.

Rebuilding of the size-structure of exploited populations allows also to mitigate the impact of fishing on ecosystems and fish communities, achieving MSY for an increasing number of stocks and thus complying with the EAF. When fishing reduces the proportion of large fishes, which are usually located at the higher levels of the trophic chain, the dynamics of the lower trophic levels can be modified and the entire ecosystem is transformed (Daskalov *et al.* 2007; Casini *et al.* 2008). Typically, in such situations, as the proportion of large fish decreases, their prey and/or competitors increase owing to decreased predation and competitive release (Worm and Myers 2003; Bascompte *et al.* 2005). Such fishing-induced trophic modifications result in changes in the composition and abundance of species, often exacerbated by large-scale oceanographic change (Frank *et al.* 2005, 2006; Casini *et al.* 2009).

In the Mediterranean, the increased exploitation has altered and simplified the food web structure over time, especially by reducing the proportions of top predators and large-sized fish and increasing the abundance of non-commercial species at lower trophic levels (e.g. benthic invertebrates) and species with higher turnover rates (e.g. cephalopods and small benthopelagic fish) as observed in the Catalan (Coll *et al.* 2008) and Adriatic Sea (Coll *et al.* 2010; Lotze *et al.* 2011). A general reduction in the mean trophic level of the community was observed in the Aegean Sea since 1960s (Stergiou and Koulouris 2000) as well as a long-term decline in large-sized and late-maturing fish species in the Adriatic Sea (Fortibuoni *et al.* 2010b). Because all these studies on Mediterranean food web are based on presence/absence and/or biomass data on species abundance without accounting for ontogenic effects owing to changes in trophic level with age/size, their results are likely to be conservative. The trophic level of fish and invertebrate predators generally increases with size, and therefore a reduction in the mean size of the individuals within a population will decrease the mean trophic level of the population and in turn of the entire community.

The preservation of healthy size-structure of communities is therefore one of the objectives of the ecosystem approach, and precautionary single species management can substantially contribute to its achievement (Cook 2003; Jennings and Revill 2007; Froese *et al.* 2008). Accordingly, the MSY management regime would greatly benefit by setting or putting incentive for L_{opt} as the target size, and this will have the benefit to reconcile single species management objective with the holistic targets of the EAF. Fishing at L_{opt} also allows maintaining high fisheries yield and therefore the level of profitability of the fishers, another target of both CFP and EAF. Using instruments that align fishers' objectives with those of management has been found to be a significant factor underlying stock recovery in most fisheries where recovery has indeed occurred (Worm *et al.* 2009; Dichmont *et al.* 2010). In addition to the ecological consequences of the over-capacity of the Mediterranean fleets, excess effort and inadequate selectivity, there are important economic consequences of mismanagement in terms of lost rent, as elsewhere in the world (FAO 2008). Owing to over-capacity of the fleets along with low levels of fish abundance, the costs of fishing have increased in recent decades, while fish prices have not undergone parallel increases (Delgado *et al.* 2003), resulting in net economic losses in most Mediterranean fleet segments (Franquesa *et al.* 2008). Because the same quantity of fish may reach different prices according to its size or overall fish offer in the market, the effect of the different fishing regimes (i.e. F_{cur}, F_{MSY} and F_{Lopt}) will not be the same in conservation terms (biomass at sea), catches or economic yield, but it is important to note that moving towards F_{MSY} or F_{Lopt} would not be detrimental in terms of economic revenues. Here, we showed that a substantial economic benefit can be obtained adopting a F_{MSY} fishing regime. However, and most importantly, a further economic gain can be obtained increasing substantially the size of exploited individuals for species as bluefin tuna, red mullet, hake, Norway lobster and deep-sea shrimps. Also, the increased amount of large fish in the population will be in line with policies of other important stakeholders, such as non-governmental environmental protection agencies and society in general, and will produce socio-economic benefit for sport and tourist fishermen, divers and nature lovers. It is important to notice that the improved selectivity does not seem to significantly increase the economic performance of fisheries for small and some large pelagic fish (e.g. anchovy, sardine, swordfish), whose price is mostly independent of the size of fish.

It is clear that the improvement of the selectivity in Mediterranean fisheries is challenging because of their mixed species composition. Although for some stocks, such as red mullet in GSA 1 and 5, swordfish, small pelagics and the giant red shrimp, the current critical length (L_{cur}) is not so far from the L_{opt}, for hake, bluefin tuna, blue and red shrimp or striped red mullet stocks, the achievement of L_{opt} implies a strong increase in length at first capture, which is estimated between 1.5 and 4 times of L_{cur}. In the case of hake, the adoption of the mesh size required to move towards L_{opt} will determine the loss of many commercially important small-sized species, such as red mullet, crustaceans and cephalopods. This is particularly relevant for the economic sustainability of the L_{opt} scenario for the trawl fisheries, which exploits a large pool of demersal species often from the outer continental shelf up to 700 m depth in the middle slope. In such mixed trawl fisheries, it is not realistic to think about a 'compromise' mesh size as a solution to achieve MSY in the medium or long term for commercial stocks (Jennings and Revill 2007). A set of technical improvements can be adopted to reduce the impact of the trawl on vulnerable species or juveniles, such as grid, escape panel, modified separator trawl and modified codends and minimize the impact on the seabed (Sacchi 2008). In any case, more selective and less impacting gears, such as gillnets, longlines, pots and others, should be promoted, mainly over the continental shelf, to move into a full application of the EAF. In addition, the ban of trawling activity in the permanent offshore nursery areas of those species that would still be caught as juveniles by the new legal mesh size should be ensured to protect juveniles that are particularly exposed to trawl fisheries after the bottom settlement stage (Caddy 1999). In the case of the purse seine fishery, which is characterized by the exploitation of few different species and practically null mesh selectivity, modern echo-acoustic techniques allow to know *in situ* the size of individuals forming the school and then to protect juveniles or spawners applying a pseudo-selectivity prior to catch, searching for schools made up of fish over a given size. Finally, more restrictive regulations and larger mesh sizes have already been proved to determine benefits to some mixed-species Mediterranean artisanal fisheries, showing that larger sizes of commercial species are accompanied by an increase in their CPUE (Fiorentino *et al.* 2008; Guidetti *et al.* 2010; Matić-Skoko *et al.* 2011). Results of these management experiences showed also that improved gear selectivity and effort reduction can be beneficial for local fisheries resources even at a small geographical scale where co-management can play an important role (Guidetti *et al.* 2010).

Lack of selectivity in Mediterranean trawling has implied that less-productive species (e.g. elasmobranchs) experienced a too high fishing mortality that has strongly reduced their stocks until local collapse and regional extinctions (Ferretti *et al.* 2008). Also, many commercial fish stocks have suffered high mortality on juveniles affecting their productivity and population structure (Hidalgo *et al.* 2009). We showed that a fundamental management target in the implementation of EAF and MSY framework can be obtained modifying substantially the current fishing selectivity pattern of the Mediterranean fisheries, increasing the size at which commercial species are captured by fishing fleets. This will have the effect of producing both higher economic yield for the fleets and high biomass at sea of the exploited stocks. But most importantly, it will contribute to restore ecosystem structure and resilience.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Economic parameters used to estimate the market value of landing of Mediterranean species in different GSAs (FAO-GFCM Geographical Sub-Areas) under different management regimes.

Table S2. Estimated critical lengths and fisheries yields for Mediterranean species in different FAO Geographical Sub-areas (GSAs).

Table S3. Simulated economic yield (million euro) of Mediterranean species in different FAO Geographical Sub-Areas (GSAs) under the current fishing regimes (F_{cur}), exploiting the stock at F_{01} (F_{MSY}) and fishing at optimal length with a radical shift in fisheries selectivity (F_{Lopt}).

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