Status and rebuilding of European fisheries

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Status and rebuilding of European fisheries

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ABSTRACT

Since January 2014, the reformed Common Fisheries Policy (CFP) of the European Union is legally binding for all Member States. It prescribes the end of overfishing and the rebuilding of all stocks above levels that can produce maximum sustainable yields (MSY). This study examines the current status, exploitation pattern, required time for rebuilding, future catch, and future profitability for 397 European stocks. Fishing pressure and biomass were estimated from 2000 to the last year with available data in 10 European ecoregions and 2 wide ranging regions. In the last year with available data, 69% of the 397 stocks were subject to ongoing overfishing and 51% of the stocks were outside of safe biological limits. Only 12% of the stocks fulfilled the prescriptions of the CFP. Fishing pressure has decreased since 2000 in some ecoregions but not in others. Barents Sea and Norwegian Sea have the highest percentage (> 60%) of sustainably exploited stocks that are capable of producing MSY. In contrast, in the Mediterranean Sea, fewer than 20% of the stocks are exploited sustainably. Overfishing is still widespread in European waters and current management, which aims at maximum sustainable exploitation, is unable to rebuild the depleted stocks and results in poor profitability. This study examines four future exploitation scenarios that are compatible with the CFP. It finds that exploitation levels of 50–80% of the maximum will rebuild stocks and lead to higher catches than currently obtained, with substantially higher profits for the fishers.

1. Introduction

Overexploitation of fish stocks occurs at global scale [1], and some stock depletions have received prominent media coverage (e.g. cod *Gadus morhua* in Canada: [2]). Despite this overall overexploitation pattern, current exploitation and biomass trends differ between few well-managed regions where stocks are recovering, and many badly managed regions where stocks continue to decline [3]. For example, the majority of fish stocks in North American and Australian waters are currently stable with the prospect that reduced exploitation will lead to rebuilding of their biomass [3]. In the rest of the world, fish biomass is, on average, declining due to overexploitation [4] or low fisheries management capacity [3,5].

The Common Fisheries Policy (CFP) of the European Union (EU) [6] calls for rebuilding all commercially used fish stocks above levels that are capable of producing the maximum sustainable yield (MSY) as its explicit objective in Art. 2, §2 of the legally binding Basic Regulation of 11 December 2013. As a first step to achieve this goal, fishing pressure (F) shall be reduced to the maximum sustainable level (F_{msy}) by 2015, latest by 2020. Rebuilding the biomass (B) of stocks above the MSY-level (B_{msy}) requires further reduction of fishing pressure, i.e., F must be smaller than F_{msy}, but the extent of this reduction is left unspecified in the CFP and is thus a matter of controversy among fisheries scientists and managers [7]. Three possible indicators for helping in the selection of adequate fishing pressure are the time required for rebuilding, the expected catches, and the profitability of the fisheries during and after the rebuilding phase. These indicators are functions of the current status of the stocks (B/B_{msy}), the remaining level of exploitation (F/

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F_{msy}), and the net productivity or intrinsic rate of population increase (r) of the stock [8]. The monitoring of the CFP implementation is of great importance for the European Union (EU), European Commission (EC) and its Directorate-General for Maritime Affairs and Fisheries (DG MARE). The Scientific, Technical and Economic Committee for Fisheries (STECF) is the main scientific advisory body on fisheries policy to the EC and has the task of reporting on the CFP implementation through the estimation and publication of a series of indicators [9].

Within EU waters, the proportion of stocks that are routinely and regularly assessed is higher in the northeast Atlantic [10] compared to the Mediterranean and Black Seas [11,12] partly due to the multi-specific nature of fisheries in the southern areas [13] and partly due to the higher fisheries management capacity in the wealthy countries of northern Europe. With respect to the Atlantic fisheries, Cardinale et al. [10] evaluated the status and exploitation of 41 demersal, pelagic and benthic fish stocks of the Northeast Atlantic, Gascuel et al. [14] examined the catches of major stocks in the European waters of the Atlantic Ocean, and Fernandes and Cook [15] reviewed recent stock assessments in the Northeast Atlantic. Recent evaluations of Mediterranean and Black Sea fisheries have been based on data from landings [16], scientific surveys [17], or stock assessments [18–22] and ecosystem models [23]. However, these studies did not use a coherent MSY framework as required by the CFP and covered only a fraction of the exploited stocks.

The purpose of this study was to examine all European stocks for which at least catch data were available and to determine stock status (B/B_{msy}) and exploitation (F/F_{msy}) in the context of the legal CFP requirements. This was done with an advanced implementation of a surplus production model [24] to assess how rebuilding time, catch and profitability depend on the rebuilding strategy, as determined by the chosen level of future exploitation. In summary, this study is meant to help European fisheries managers in the selection of future exploitation levels that are sustainable, profitable, ecologically sound, and compatible with the CFP.

2. Methods

2.1. Dataset

Fish and invertebrate stocks from ten ecoregions of the European Seas were assessed. Six of the ecoregions were located in the northeast Atlantic Ocean (Barents Sea and Norwegian Sea; Iceland, Faroes and Greenland; Greater North Sea; Baltic Sea; Celtic Seas and Rockall; Bay of Biscay, Iberian Coast and Azores), three in the Mediterranean Sea (western Mediterranean: includes Gulf of Lions, Balearic Sea and Sardinia; central Mediterranean: includes Adriatic and Ionian Seas; eastern Mediterranean: includes Aegean Sea and Cyprus waters), while Black Sea was assessed as a single ecoregion (Fig. 1). Overall, 397 fish and invertebrate stocks were assessed, of which 357 (90%) were being exploited within their respective ecoregions, whereas 40 of them were wide-ranging stocks.

For the northeast Atlantic, catch and biomass trajectories or relative abundance indices from formal stock assessment were extracted from the advice documents published by the International Council for the Exploration of the Seas (ICES) and the International Commission for the Conservation of Atlantic Tunas (ICCAT). For the Mediterranean, the landings were acquired from the Food and Agriculture Organization-General Fisheries Commission for the Mediterranean (FAO-GFCM) database (1970–2014) for each ecoregion [25] and the biomass or relative abundance data from the Data Collection Framework (DCF) programme. The reports from the regular assessments of STECF were used in some cases [20,26–30]. For the Black Sea, latest available stock assessment reports were used [31]. The aforementioned reports were also used as officially accepted independent stock assessments for comparison with the findings of the present work.

2.2. Estimation of reference points

The open-source CMSY stock assessment tool [24] was used to estimate the stock status for European stocks. The CMSY catch-only

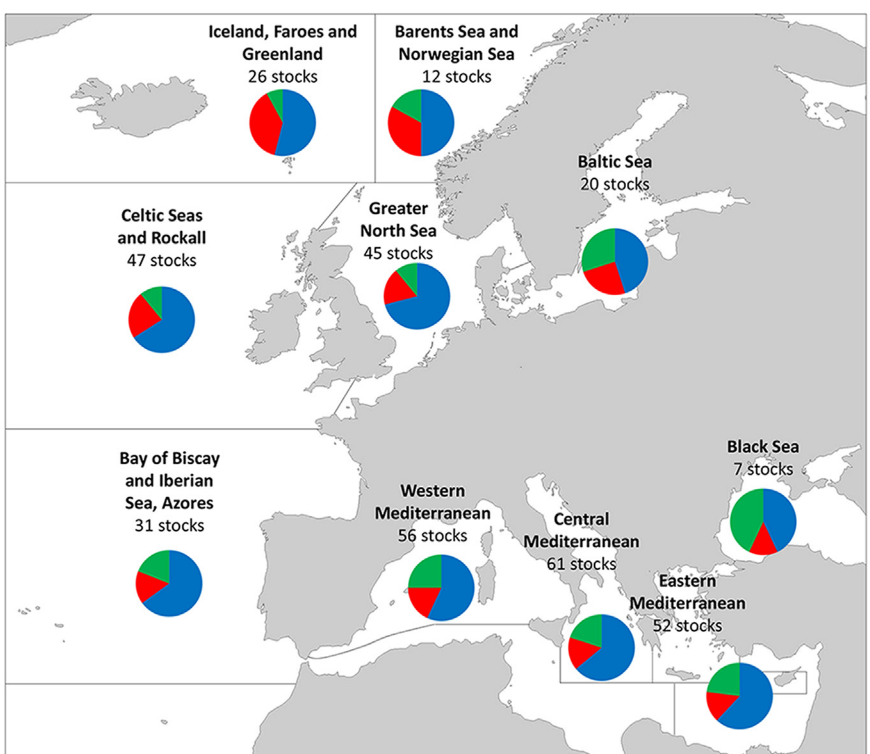

Fig. 1. Map with the ten ecoregions and the percentage of stocks per functional group (large predators: red; pelagic plankton feeders: green; benthic organisms: blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

approach applies advanced Monte-Carlo filtering to produce proxies for maximum sustainable yield (MSY), fishing pressure that can produce MSY (F_{msy}), biomass that can produce MSY (B_{msy}), and indicators such as relative stock size (B/B_{msy}) and exploitation (F/F_{msy}) based on catch data and resilience information within a Bayesian framework. In addition, a Bayesian state-space Schaefer surplus production model (BSM) is included within the CMSY software and produces refined stock status estimates if biomass or abundance indices are available.

CMSY aims to combine information on the stock's productivity and exploitation history with data from surveys and official catch reports and can also account for gaps (or absence) in abundance information, which is its main advantage with respect to other models. Priors for productivity can be specified using qualitative indications (e.g. medium, high, low resilience) that are automatically transformed into lognormal prior distributions. CMSY requires "expert" prior information to be specified for biomass depletion at the beginning and the end of the time series. Further details on the CMSY estimation framework and concepts are given in the detailed CMSY documentation in Froese et al. [24].

2.3. Estimation of rebuilding time

The time needed to reach B_{msy} is a function of biomass depletion and remaining fishing pressure [32] and can be calculated from Eq. (1).

$$\Delta t = \frac{1}{2F_{msy} - F} ln \left(\frac{\frac{B_{msy}}{B} 2\left(1 - \frac{F}{2F_{msy}}\right) - 1}{2\left(1 - \frac{F}{2F_{msy}}\right) - 1} \right) \tag{1}$$

where Δt is the time in years to reach B_{msy}, B is the biomass in the last year with available data, and other parameters are as defined above.

This estimate of rebuilding time corresponds well with the results obtained from projecting biomass forward in cases where the initial biomass is larger than half of B_{msy}. However, Eq. (1) assumes full productivity independent of stock size and is therefore too optimistic in severely depleted stocks where recruitment may be impaired and depensation may play a role [32,33]. For the purpose of this study we therefore estimated rebuilding time by projecting biomass forward with extended surplus production equations [24], which assume reduced recruitment at low stock sizes ($B/B_{msy} < 0.5$) and average recruitment otherwise (Eqs. 2 and 3) [34].

For the purpose of this study, the Schaefer model [35] was expressed as a function of B/B_{msy} and F_{msy} in Eq. (2), which was used to predict next year's status if current biomass was equal to or higher than half of B_{msy}.

$$\frac{B_{t+1}}{B_{msy}} = \frac{B_t}{B_{msy}} + 2F_{msy}\frac{B_t}{B_{msy}}\left(1 - \frac{B_t}{2B_{msy}}\right) - \frac{B_t}{B_{msy}}F_t \qquad | \frac{B_t}{B_{msy}} \geq 0.5 \tag{2}$$

Eq. (3) was used to predict next year's status if current biomass was lower than half of B_{msy}.

$$\frac{B_{t+1}}{B_{msy}} = \frac{B_t}{B_{msy}} + 2\frac{B_t}{B_{msy}}2F_{msy}\frac{B_t}{B_{msy}}\left(1 - \frac{B_t}{2B_{msy}}\right) - \frac{B_t}{B_{msy}}F_t \qquad | \frac{B_t}{B_{msy}} < 0.5 \tag{3}$$

where ($2\,B_t/B_{msy}$) is a multiplier that decreases linearly from 1 to zero as B_t/B_{msy} decreases from 0.5 to zero. Eqs. 2 and 3 were not simplified further to maintain readability.

Uncertainty estimates associated with the key input parameters B/B_{msy}, B_{msy}, and F_{msy} (Supplementary Table S1) were incorporated by means of Monte-Carlo simulations based on 1000 samples. The data used in this study and the source code in R are available for download as part of the online material.

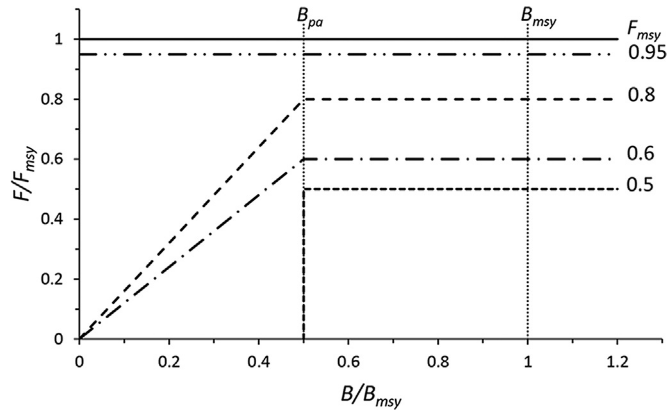

Fig. 2. Schematic representation of the different harvest control rules used as scenarios in this study. The vertical dotted line marked as B_{pa} indicates the biomass below which recruitment may be impaired. The vertical dotted line marked as B_{msy} indicates the lowest biomass at which stocks are capable of producing the maximum sustainable yield. The broken lines indicate the relative fishing pressure (F/F_{msy}) applied at a certain relative stock size (B/B_{msy}) under the different scenarios.

2.4. Exploitation scenarios in detail

The stock status projected for 2018, the first year for which managers had not yet set catch levels at the time of this study, was used to apply four different exploitation scenarios until the year 2030:

1. **The 0.5 scenario**: no fishing takes place in stocks where biomass is less than half of B_{msy} and which are therefore endangered by impaired recruitment and considered outside of safe biological limits [6]. If stock size is equal to or larger than half of B_{msy}, fishing occurs with 0.5 F_{msy}.
2. **The 0.6 scenario**: Fishing mortality of 0.6 F_{msy} is applied if stock size is at or above half of B_{msy}. Below that level fishing mortality is linearly reduced to zero with decrease in biomass ($F_{reduced}$), similar to the harvest control rule of ICES [36] (Eq. (4)).

$$F_{reduced} = 2\frac{B_t}{B_{msy}}F \qquad | \frac{B_t}{B_{msy}} < 0.5 \tag{4}$$

3. **The 0.8 scenario:** Fishing mortality of 0.8 F_{msy} is applied if stock size is at or above half of B_{msy}. Below that level fishing mortality is linearly reduced to zero with decrease in biomass (Eq. (4)).
4. **The 0.95 scenario:** Fishing mortality of 0.95 F_{msy} is applied throughout, independently of stock size.

The different scenarios or harvest control rules applied in this study are shown in Fig. 2. Trajectories resulting from the four exploitation scenarios for rebuilding time, catch and profitability are presented separately for the Northeast Atlantic, the Mediterranean and Black Sea, and all stocks combined. Trajectories for rebuilding and catch start in 2013, the last year for which actual catch data and exploitation rates were available for all stocks. Biomass was then modelled using the last exploitation rates until 2018. From 2018 to 2030 the exploitation rates of the four scenarios were applied. Trajectories for profitability start in 2014, the last year for which estimates of net profit margins were available [37]. For consistency, all projections in the main text are shown from 2014 to 2030.

2.5. Addressing the underestimation of fishing mortality

In order to address the problem of surplus production models of underestimating fishing mortality in fully selected versus partly selected age classes in stocks with severely truncated age structure, the

Table 1
Stock numbers, stocks subject to sustainable exploitation ($F \leq F_{MSY}$), stock size above the level capable of producing MSY ($B > B_{MSY}$), stocks outside of safe biological limits ($B < 0.5\ B_{MSY}$), severely depleted stocks ($B < 0.2\ B_{MSY}$), sustainably exploited stocks, total biomass, total biomass level capable of producing MSY, total catch, total MSY level, and compliance with CFP targets, for 397 stocks in 10 European ecoregions and two wide-ranging regions. The unit (Mt) refers to million tonnes.

Ecoregion	Stocks n	$F \leq F_{MSY}$ n (%)	$B > B_{MSY}$ n (%)	$B < 0.5B_{MSY}$ n (%)	$B < 0.2B_{MSY}$ n (%)	Sustainable n (%)	Biomass (Mt)	B_{MSY} (Mt)	Catch (Mt)	MSY (Mt)	CFP conform n (%)
Barents Sea and Norwegian Sea	12	10 (83)	8 (67)	2 (17)	1 (8)	8 (67)	19	21	1.9	4.6	6 (50)
Iceland, Faroes and Greenland	26	15 (58)	5 (23)	11 (42)	5 (19)	12 (50)	3.7	6.8	0.6	1.6	4 (15)
Greater North Sea	45	25 (56)	9 (20)	21 (47)	6 (13)	23 (51)	9.9	11	1.6	3.4	9 (20)
Baltic Sea	20	12 (60)	6 (30)	9 (45)	1 (5)	12 (60)	3.1	4.0	0.69	0.96	5 (25)
Celtic Seas and Rockall	47	24 (51)	11 (23)	19 (40)	7 (15)	22 (47)	1.3	2.1	0.23	0.48	10 (21)
Bay of Biscay, Iberian Coast and Azores	31	13 (42)	5 (16)	7 (23)	3 (10)	12 (39)	0.86	1.3	0.20	0.34	4 (13)
Western Mediterranean	56	4 (7)	0 (0)	40 (71)	4 (7)	3 (5)	0.48	1.00	0.15	0.30	0 (0)
Central Mediterranean	61	16 (26)	4 (7)	39 (64)	8 (13)	12 (20)	0.55	1.13	0.19	0.29	1 (2)
Eastern Mediterranean	52	5 (10)	0 (0)	32 (62)	4 (8)	5 (10)	0.19	0.38	0.07	0.11	0 (0)
Black Sea	7	1 (14)	1 (14)	3 (43)	2 (29)	1 (14)	0.68	1.3	0.24	0.40	1 (14)
Wide-ranging ICCAT	10	5 (50)	5 (50)	1 (10)	1 (10)	5 (50)	1.0	0.96	0.13	0.19	4 (40)
Wide-ranging ICES	30	13 (43)	5 (17)	18 (60)	10 (33)	9 (30)	10.6	11.9	2.8	2.7	2 (7)
TOTAL	**397**	**143 (36)**	**59 (15)**	**202 (51)**	**52 (13)**	**124 (31)**	**51.36**	**62.87**	**8.8**	**15.37**	**46 (12)**

estimate of F_{msy} was reduced as a linear function of biomass below 0.5 B_{msy} (Eq. (5)).

$$F_{msy\_red} = 2\frac{B_t}{B_{msy}}F_{msy} \qquad | \frac{B_t}{B_{msy}} < 0.5 \tag{5}$$

where F_{msy_red} is a reduced value of F_{msy} to account for reduced productivity in stocks with reduced recruitment.

2.6. Calculation of profitability

A simple comparison between the profitability of the four scenarios can be obtained from the equilibrium curve of yield over effort when average effort and average profitability of the current fisheries are known. We define profitability according to the official definition used in the EU, where net profit is income from landings plus other income minus crew costs minus unpaid labor minus energy costs minus repair costs minus other variable costs minus non variable costs minus depreciation cost minus opportunity cost of capital [37, section 6.4]. For European fisheries in 2014 the mean net profit margin, which is net profit as a percentage of fishing income, was $\mu_{mean} = 7.7\%$ (SD = 1.2%) for the whole region (excluding distant water fleets because they fish on other stocks and excluding Greece because of incomplete data), $\mu_{mean} = 8.5\%$ (SD = 1.6%) for the Northeast Atlantic (assuming that profit margins for Spain and France referred mostly to Northeast Atlantic stocks), and $\mu_{mean} = 3.8\%$ (SD = 3.5%) for the Mediterranean and Black Sea [37]. Based on data for stocks with more than 10,000 t of catch in 2013, $(C/MSY)_{mean}$ and $(F/F_{msy})_{mean}$ were 0.68 and 1.43 for the whole area, 0.67 and 1.36 for the Northeast Atlantic, and 0.72 and 1.79 for the Mediterranean and Black Sea, respectively. No data on other income were available and thus revenues from fishing were taken as the main income, assuming a constant fish price over time, as is common in the literature [38]. All variable cost were assumed as proportional to effort, i.e. marginal cost of effort are constant, and fishing mortality was used as a proxy for effort. This means that resource rents are not dissipated in European fisheries, as could be the case for example under conditions of regulated open access [39]. This is consistent with the 2016 STEFC report of overall positive profit margins in European fisheries [37]. Based on the above assumptions, an index of profitability is derived as annual net profit in percent of fishing revenues at MSY. Using the above data, this index was calculated as shown in Eq. (6).

$$\pi_t = \frac{F_t}{F_{msy}}\left(\frac{B_t}{B_{msy}} - \frac{\left(1-\frac{\mu_{mean}}{100}\right)\left(\frac{C}{MSY}\right)_{mean}}{\left(\frac{F}{F_{msy}}\right)_{mean}}\right) \tag{6}$$

where π_t is the profitability index for year t, μ_{mean} is the observed mean net profit margin (in percent), $(C/MSY)_{mean}$ is the observed mean catch relative to MSY and $(F/F_{msy})_{mean}$ is the observed mean fishing mortality relative to F_{msy} as a proxy for mean effort. F_t and B_t are fishing mortality and biomass in the four considered scenarios.

For the purpose of simplicity, discount rates were assumed zero for the projected period.

3. Results

3.1. Stock status and exploitation pattern

Out of the 397 considered stocks, the ecoregions of the Northeast Atlantic were represented by 181 stocks, those of the Mediterranean by 169 stocks and the Black Sea by 7 stocks (Fig. 1). The majority of the stocks were benthic organisms (60%), followed by large predators (22%) and plankton feeders (18%), with the variation per ecoregion shown in Figure.

Of the 397 stocks, 254 (64%) were subject to ongoing overfishing ($F > F_{msy}$) and 202 stocks (51%) had stock sizes outside of safe biological limits ($B < 0.5\ B_{msy}$) (Table 1). In 45 stocks (11%) catches exceeded the maximum sustainable yield ($C/MSY > 1$). Two hundred eight stocks (52%) were in critical condition, defined by being outside of safe biological limits and subject to overfishing or being severely depleted ($B < 0.2\ B_{msy}$) and still subject to exploitation. Altogether, 274 stocks (69%) were subject to unsustainable exploitation ($C/MSY > 1$ or $F > F_{msy}$ or $B < 0.2\ B_{msy}$). In contrast, only 46 stocks (12%) could be considered as being well managed and in good condition according to the CFP, defined by not being subject to overfishing and having a biomass above the one that can produce MSY

Barents Sea and Norwegian Sea have the highest percentage (50%) of stocks that comply with the goals of the Common Fisheries Policy (CFP 2013) by having a biomass above the level that can produce MSY and not being subject to overfishing (Table 1). Biomass and catches are also highest in this ecoregion, followed by wide-ranging ICES stocks and by the Greater North Sea (Table 1). The Mediterranean and Black Sea are still far away from the goals of the CFP, with only 2 out of 176 stocks in compliance. Average stock biomass in the ecoregions of the Mediterranean and Black Sea was about 50% of the level that can produce MSY, whereas in the northern ecoregions (Barents Sea to Iberian Sea) average biomass was about 80% of that level (Table 1).

The fishing pressure (F/F_{msy}) – stock state (B/B_{msy}) plot clearly shows that, across ecoregions, most species are overexploited and/or outside of safe biological limits in the last years with available data (2013–2015) (Fig. 3). Some of the stocks (n = 27) are not shown in the plot because they are located beyond the F/F_{msy} axis limits, i.e. their F/

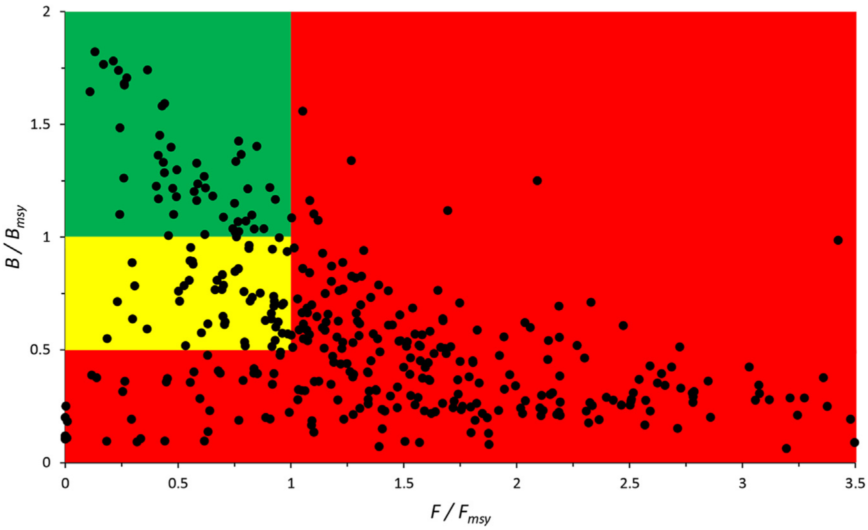

Fig. 3. Presentation of 397 stocks in European Seas in a pressure (F/F_{msy}) – status (B/B_{msy}) plot, for the last years with available data (2013–2015). Red area: stocks that are being overfished or are outside of safe biological limits; yellow area: recovering stocks; green area: stocks subject to sustainable fishing pressure and of a healthy stock biomass that can produce high yields close to MSY. Several stocks are not shown because their fishing pressure was beyond the upper end of the X-axis. Note that several depleted stocks are not recovering despite zero commercial catches (lower left corner). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

F_{msy} exceeds 3.5. Several depleted stocks located at the lower left corner of the graph are not recovering despite zero commercial catches (Fig. 3).

The percentage of stocks that fulfill the requirements of the CFP varied among ecoregions (Fig. 4, Table 1). There is a remarkable north-south gradient, with over 60% of the stocks exploited sustainably with a biomass above the one that can produce MSY in the Barents Sea and Norwegian Sea, compared to less than 20% of stocks with these properties in the Mediterranean Sea ecoregions and the Black Sea (Fig. 4).

Independent stock assessment estimates of F_{msy} and F in the final year with available data were available for 93 (23%) out of the 397 stocks examined in this study (Fig. 5). A comparison of independent stock assessment estimates with those derived from this work shows that 62 stocks (67%) were less than 50% different from the independent stock assessment estimates. More importantly, in 76 stocks (82%) the F/F_{msy} estimates derived from this work came to the same classification of overfishing ($F > F_{msy}$) as the independent estimates. In 14 of the 17 diverging cases (82%), the independent stock assessments diagnosed overfishing, while this work proposed sustainable exploitation levels (Fig. 5).

3.2. Rebuilding of stock biomass

With the exploitation rates of 2013 carried forward to 2017 (Fig. 6), there was an overall increase of the percentage of stocks at or above B_{msy} from 17% to 28%. The fastest and highest rebuilding from 2018 onward was predicted under the 0.5 scenario, with overall 86% of the stocks recovered in 2030. The slowest rebuilding was predicted for the 0.95 scenario, with 54% of the stocks recovered in 2030. The 0.6 and the 0.8 scenarios were intermediate.

Looking at the regions, the fastest and highest rebuilding for the Northeast Atlantic was predicted under the 0.5 scenario, with overall 84% of the stocks recovered in 2030 (Fig. 6). The slowest rebuilding was predicted for the 0.95 scenario, with 63% of the stocks recovered in 2030. The 0.6 and the 0.8 scenarios were intermediate. In the Mediterranean and Black Sea, the fastest and highest rebuilding was predicted under the 0.5 scenario, with overall 87% of the stocks recovered in 2030. The slowest rebuilding was predicted for the 0.95 scenario, with 43% of the stocks recovered in 2030. The 0.6 and the 0.8 scenarios were intermediate.

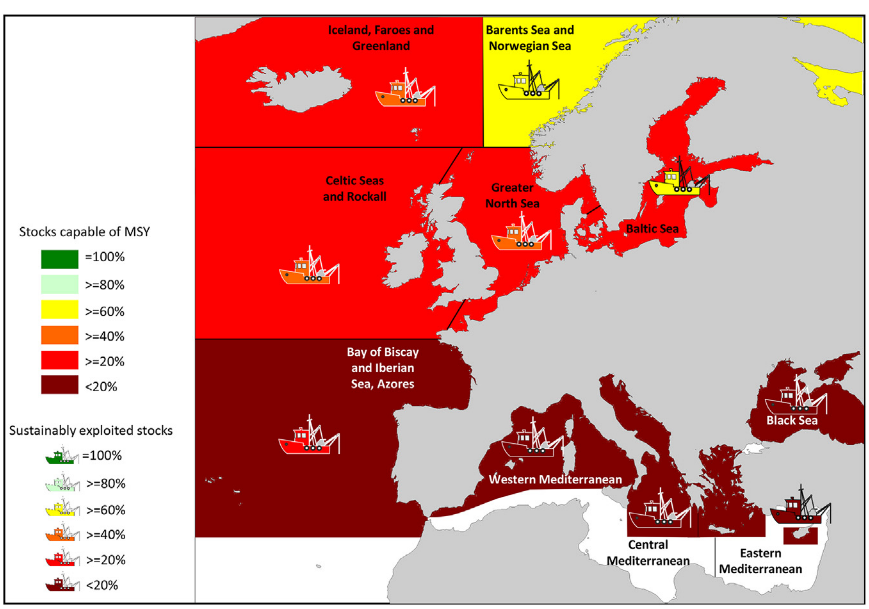

Fig. 4. Map of the European seas showing the compliance with the Common Fisheries Policy of the EU, for 357 stocks in 10 ecoregions, for the last years (2013–2015) with available data. The color of the areas indicates the percentage of stocks with sizes that are above the level that can produce maximum sustainable yields and the color of the fishing boats indicates the percentage of stocks that are exploited sustainably.

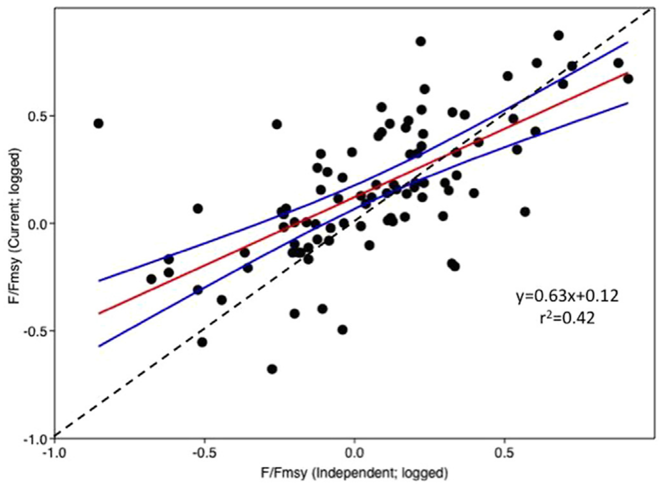

Fig. 5. Comparison of the F/F_{msy} (log-scale) by the present study with the corresponding independent estimates from official sources. The dashed line indicates the 1:1 relationship, suggesting that overexploitation may be even more severe than found by the methods used in this study.

3.3. Catch

Despite exploitation rates assumed constant from 2013 to 2017, overall catches were predicted to increase slightly from 8.5 million tonnes (Mt) in 2013 to 9.4 Mt in 2017 (Fig. 7), due to ongoing recovery of biomass in the Northeast Atlantic (stocks in the yellow and green areas of Fig. 3). Overall catches increase steeply in 2018 under the 0.8 and 0.95 scenarios, due to stronger exploitation of large stocks that were previously exploited at lower levels. In contrast, catches decrease from 9.4 in 2017 to 7.8 Mt in 2018 under the 0.5 scenario, mostly because under this scenario no fishing occurs on stocks outside of safe biological limits and less fishing occurs on stocks that were previously exploited above 0.5 F_{msy}. After 2018, overall catches decline under the 0.95 scenario to 13.7 Mt in 2030. Under the 0.8 scenario, catches increase to 14.2 Mt in 2030, an increase of more than 5 Mt. Under the 0.5 and 0.6 scenarios, catches are predicted to increase gradually to about 11.3 and 12.5 Mt in 2030, respectively.

Looking at the regions, catches in the Northeast Atlantic start at a high level of about 8 Mt in 2013. The predicted trends thereafter are very much identical to the overall catch trends described above (Fig. 7). In the Mediterranean and Black Sea, catches start at a much lower level of about 0.7 Mt in 2013, remain about stable until 2017, and then drop steeply in 2018 under all but the 0.95 scenario. The decline in catch is strongest under the 0.5 scenario, because under this scenario no fishing occurs in the many depleted stocks and because most Mediterranean stocks were previously exploited well above 0.5 F_{msy}. Despite strong differences in catches in 2018, the 0.95 and 0.5 scenarios lead to similar catches of about 0.8 Mt in 2030. The 0.6 scenario results in 0.9 Mt and the 0.8 scenario results in about 1 Mt. Note that uncertainty of catch predictions is considerably higher in the Mediterranean compared to the Northeast Atlantic, because of shorter or missing time series of abundance in the Mediterranean stock assessments.

3.4. Fisheries profitability

Profitability in fisheries is a function of the market value of the catch and of the cost of fishing [37]. Contrasting cost with the expected equilibrium yield (= expected catches after the same level of effort has been applied for sufficiently long time) was used for a first simple comparison of the long-term profitability of the different exploitation scenarios examined in this study (Fig. 8). Highest profitability was predicted for the 0.8 scenario, with 5% less for the 0.6 and 13% less for the 0.5 scenario. Long-term profitability of the 0.95 scenario cannot be predicted, because equilibrium yield assumes rebuilding of all stocks, an assumption that is strongly violated by the 0.95 scenario (see above).

Because of the uncertainties associated with the assumption of equilibrium catch, predicted profitability of fisheries from 2014 to 2030 was also estimated dynamically from the annual interplay of predicted biomass, catch and fishing mortality (Eq. (6)) for the respective aggregated values of the regions (Table 2).

Changes in mean profitability of European fisheries are reported relative to the year 2014 (Fig. 9). Under the 0.8 and 0.95 scenarios overall profitability increases steeply in 2018, because of increased fishing intensity in several large stocks that were previously exploited at lower rates. In 2019, profitability decreases in the 0.95 scenario and is thereafter more or less flat, at about 50% above the 2014 value. The other scenarios reach about 220% above the 2014 value in 2030 (Fig. 9). The profitability trends in the Northeast Atlantic are very similar to the overall trends described above, because catches in the

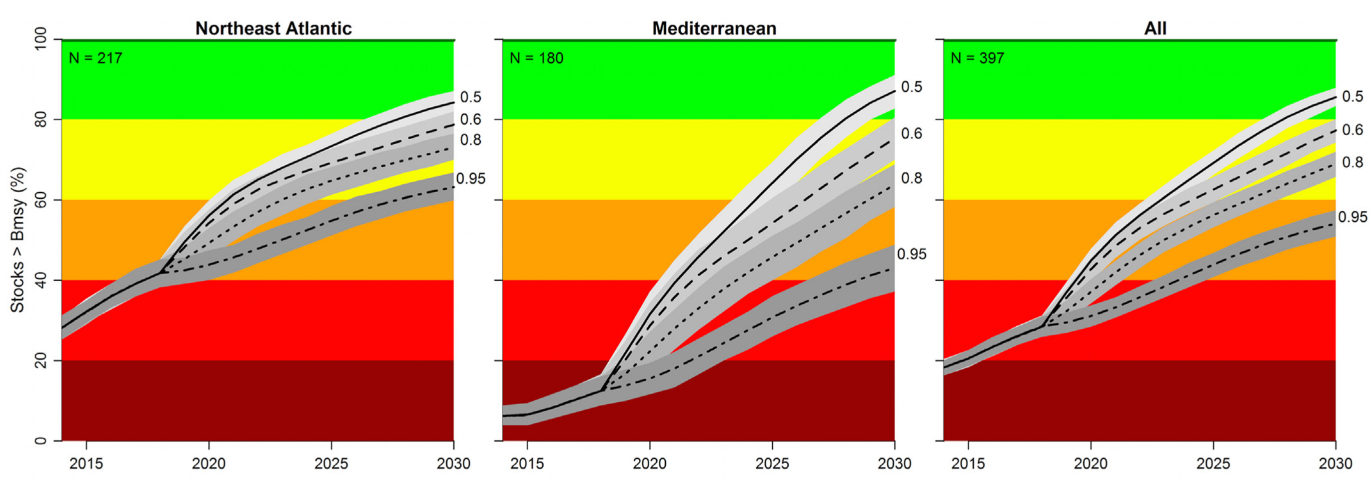

Fig. 6. Predicted percentage of stocks capable of producing MSY for the Northeast Atlantic, the Mediterranean and Black Sea and both areas combined under four different exploitation scenarios of F ranging from 0.5 to 0.95 F_{msy}. For the years 2014 to 2017, the same exploitation rates as in 2013 were assumed to project stock biomasses. The shaded areas indicate approximate 95% confidence limits.

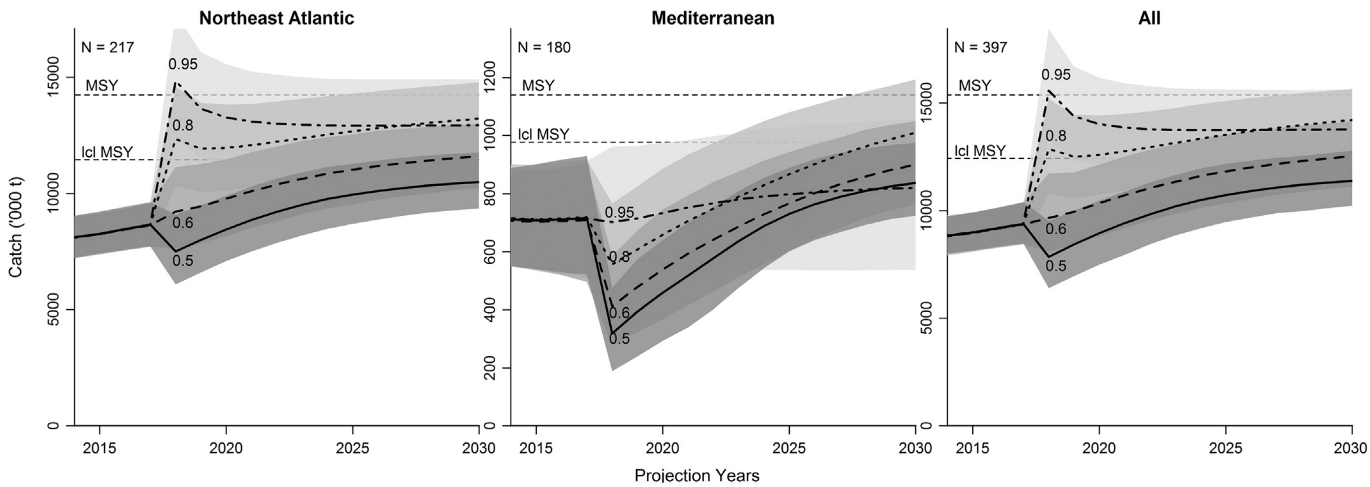

Fig. 7. Predicted cumulative catch for the Northeast Atlantic, the Mediterranean and Black Sea and both areas combined under four different exploitation scenarios of F ranging from 0.5 to 0.95 F_{msy}. The shaded areas indicate the range of uncertainty. Note different scales on the vertical axes, where catches are aligned relative to MSY; lcl MSY indicates the lower 95% confidence limit of MSY.

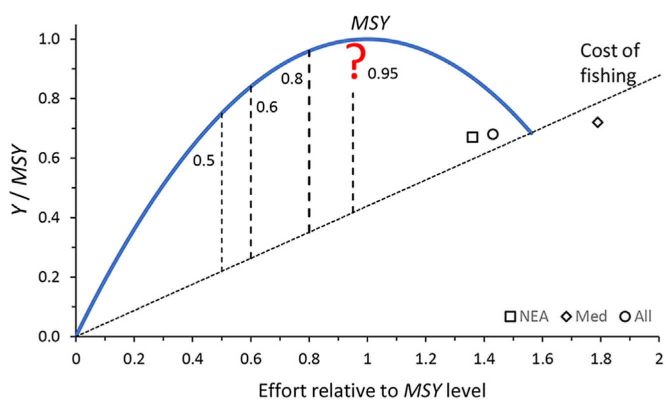

Fig. 8. Schematic exploration of the profitability of fishing, with cost of fishing assumed directly proportional to fishing mortality and expected catches indicated as equilibrium yields of a surplus production model. The three points indicate relative yield over relative effort for stocks with over 10,000 t of catch in 2013–2015. The vertical dashed lines indicate the potential maximum profits achievable under the scenarios explored in the study, highest at $F/F_{msy} = 0.8$ (100%), followed by 0.6 (95%) and 0.5 (87%), respectively. The profitability of the 0.95 scenario is questionable "?" because the equilibrium yield assumes that all depleted stocks have been rebuilt, an assumption that is strongly violated under this scenario.

Northeast Atlantic constitute about 90% of the total European catch. Predicted profitability in the Mediterranean and Black Sea increases steeply to about 3-fold in 2030 compared to 2014 in the 0.5, 0.6 and 0.8 scenarios. Under the 0.95 scenario, profitability first stagnates and then increases slowly to about 40% above the 2014 level in 2030 (Fig. 9).

3.5. Rebuilding of depleted stocks

In the context of this study, stocks are considered as depleted if stock size falls below half of B_{msy}. The percentage of depleted stocks is predicted to decrease until 2030 under all scenarios, albeit with large differences. Across all stocks, 37% remain depleted under the 0.95 scenario. The 0.5 scenario leads to the most substantial reduction in depleted stocks, with 8% remaining in 2030. Under the 0.6 and 0.8 scenarios, the percentage of depleted stocks decreases about linearly to 12% and 14% in 2030, respectively (Fig. 10).

The recovery of depleted stocks in the Northeast Atlantic starts from a level of 35% in 2018 and reaches 29% in 2030 under the 0.95 scenario (Fig. 10). The 0.5 scenario leads to the fastest reduction in depleted stocks, with 9% remaining in 2030. Under the 0.6 and 0.8 scenarios, the percentage of depleted stocks decreases about linearly to about 13% and 15% in 2030, respectively. In the Mediterranean and Black Sea, recovery of depleted stocks starts from a high level of 56% in 2018 and reaches 46% in 2030 under the 0.95 scenario. The 0.5 scenario leads to the fastest reduction in depleted stocks, with 6% remaining in 2030. Under the 0.6 and 0.8 scenarios, the percentage of depleted stocks decreases about linearly to about 10% and 14% in 2030, respectively (Fig. 10).

4. Discussion

4.1. General considerations

For the purpose of comparing the impact of different future fishing scenarios on the rebuilding of 397 stocks and profitability of the respective fisheries, a number of simplifying assumptions were made: (1)

Table 2
Mean predicted profitability index of fisheries and approximate 95% confidence intervals (C.I.) were estimated from the interplay of predicted biomass, catch and fishing mortality (Eq. (6)) for the respective aggregated values of the Mediterranean and Black Sea (MED); the Northeast Atlantic (NEA); and the regions combined (All). Estimates are shown for the year 2014 and for 2030 under four exploitation scenarios ranging from 0.5 to 0.95 Fmsy.

		NEA				MED				ALL			
		Mean	C.I.			Mean	C.I.			Mean	C.I.		
	2014	3.74	3.29	–	4.19	2.11	1.59	–	2.66	5.22	4.55	–	5.90
2030 scenario	**0.5**	9.32	9.08	–	9.54	8.30	8.02	–	8.58	17.38	17.00	–	17.78
	0.6	9.51	9.19	–	9.83	8.20	7.79	–	8.61	17.45	16.91	–	17.94
	0.8	9.68	9.34	–	10.05	8.23	7.76	–	8.72	17.50	16.91	–	18.07
	0.95	6.06	5.47	–	6.70	3.03	2.11	–	3.99	8.53	7.36	–	9.58

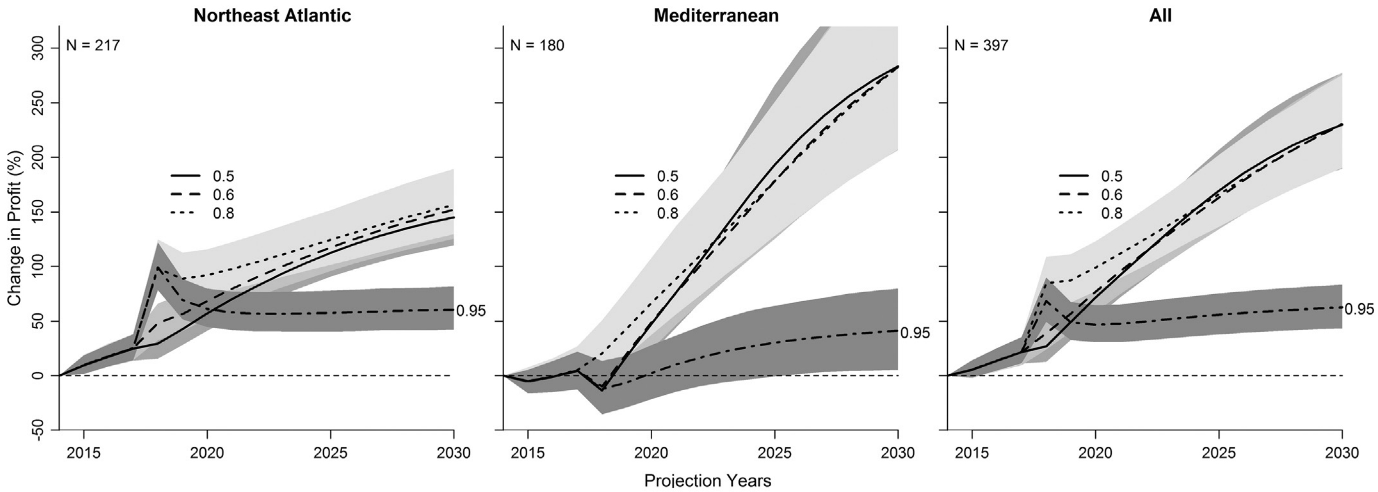

Fig. 9. Predicted profitability relative to the one in 2014 for the Northeast Atlantic, the Mediterranean and Black Sea and both areas combined under four different exploitation scenarios. The shaded areas indicate the range of uncertainty.

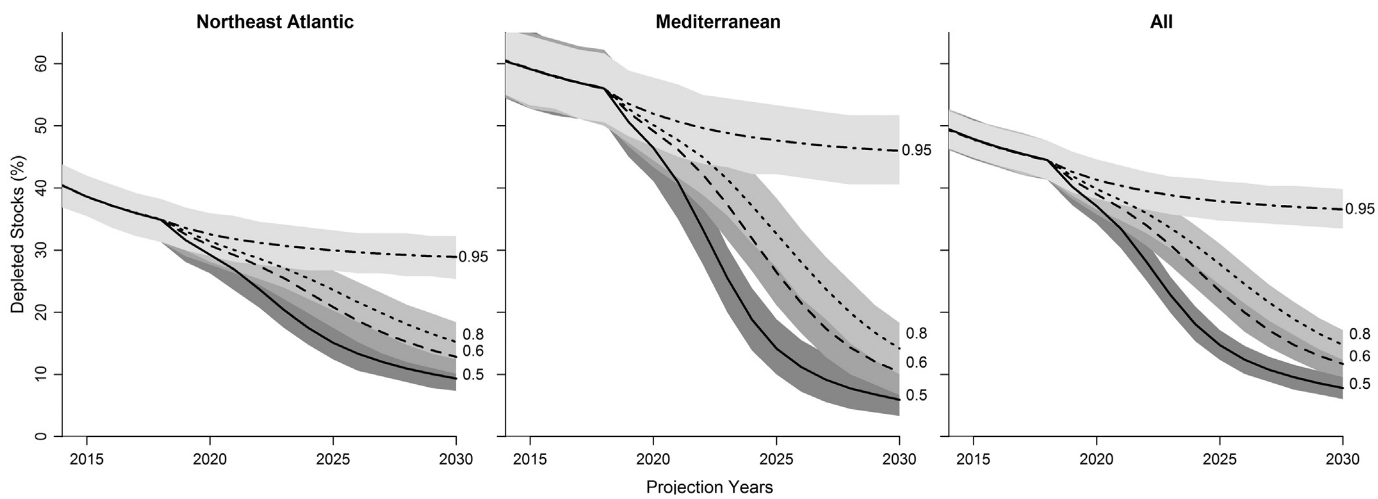

Fig. 10. Predicted percentage of depleted stocks in European waters for the Northeast Atlantic, the Mediterranean and Black Sea and both areas combined under four different exploitation scenarios. The shaded areas indicate the range of uncertainty.

environmental conditions and biological properties of the examined stocks were assumed to remain the same as they were in the last years with available data (2013–2015); (2) cost of fishing relative to effort were assumed to remain the same as they were in the year 2014; (3) the price of fish was assumed to remain constant and independent from supply; and (4) all fisheries were assumed to be profitable under all scenarios.

These assumptions are highly unlikely to be met by all considered stocks and fisheries over the projected period until 2030. However, the purpose of this study was not to provide the most realistic biomass, catch and profit estimates for all individual fisheries, but rather to get an overall impression of the performance of different future exploitation scenarios relative to each other. Cases where some of the assumptions are likely to be violated in a given scenario are pointed out below.

4.2. Stock status and exploitation

This is the first extensive assessment-based meta-analysis of all European stocks and an important step towards the implementation of the CFP requirements. The 181 assessed stocks of the northeast Atlantic and the 7 stocks of the Black Sea represent over 60% of total landings in these areas, while the 169 assessed stocks of the Mediterranean Sea represent around 50% of the total Mediterranean landings [25]. The missing landings consist mostly of catches not identified to the species level [25]. Previous assessments in the NE Atlantic were available only for 50 stocks [7], whereas previous assessments in the Mediterranean Sea represent around 25% of total landings and involved 24 species and 125 stocks that were assessed at a very narrow geographical range [11].

The stock status estimates of the present work were comparable with the results from corresponding age structured stock assessments such as provided as advice to the European Commission by ICES in the Northeast Atlantic and STECF in the Mediterranean. Looking at the discrepancies, the results of this study tended to be more optimistic in suggesting lower exploitation levels than the official stock assessments (Fig. 5).

Several independent studies agree with the present work on the general pattern that up to 2015, most European stocks were subject to high fishing pressure with a resulting overall decline in biomass, but with declining degree of overfishing and some improvements in stock size in northern Europe. For example, in their evaluation of the status and exploitation of 41 fish stocks of the NE Atlantic, Cardinale et al. [10] report improved exploitation status for the most important stocks within a decade following the 2002 CFP reform. Gascuel et al. [14] examined the catches of major stocks in the European waters of the Atlantic Ocean and report a decline in catches since the mid 1970s as a result of overexploitation. In recent years, the stock indicators these authors used show declining fishing mortality and stable spawning stock biomass in most areas [10,14]. In the cases of the Mediterranean and the Black Seas, a decline in catches and stock biomass has been recently shown to occur for the entire area [16,18,19,40]. Colloca et al. [18] collected the output of all stock assessments in the Mediterranean and concluded that over 90% of the assessed stocks are overexploited. Out of the seven stocks that have been recently assessed in the Black Sea, one (European sprat *Sprattus spattus*) is sustainably exploited, one is depleted (piked dogfish *Squalus acanthias*) and the remaining ones are overexploited [21].

The remarkable north-south gradient in fishing pressure and stock size (Fig. 4) is confirmed by Fernandes et al. [41] who examined 95 assessments in European waters and report 19 sustainable stocks in the Northeast Atlantic and none in the Mediterranean.

The better condition of the Atlantic stocks may partly be due to the improved fisheries management in the wealthy countries of northern Europe, the long time series of available data, and the early establishment of research and academic institutions focused on fisheries science [42,43]. For example, ICES stock assessments in the North Sea are available since the 1950s [14]. In contrast, the Mediterranean, which has been exploited for millennia, suffers from fleet overcapacity, illegal and unreported catches, unselective harvesting and lack of coordination among Mediterranean countries [11,12]. Furthermore, Cardinale and Scarcella [22] argue that the major reasons for the bad status of Mediterranean Sea stocks include the ineffectiveness of the current effort system to control fishing mortality, the continuous non-adherence to the scientific advice and inadequacies of existing national management plans as a key management measure. Stock assessments in the Mediterranean have a history of less than 20 years but are increasing in numbers and geographical coverage since 2010 [23].

In their evaluation of the world's unassessed fisheries, Costello et al. [44] analyzed hypothetical stocks that were defined as country/area combinations, instead of using real stocks based on working group decisions on stock delineations and the best available data, as in the present work. Their median B/B_{msy} ratio was calculated as 0.58 for the Northeast Atlantic, the Mediterranean and Black Sea. Thus, despite methodological differences, the work by Costello et al. [44] confirms that a large proportion of European stocks are outside of safe biological limits.

In a global meta-analysis of overexploited marine populations, Neubauer et al. [45] report reduced resilience of stocks that collapsed or suffered from prolonged and intense overexploitation, thus confirming the results obtained in this study.

4.3. Evaluating the different exploitation scenarios

The four future fishing scenarios explored in this study assume that the respective harvest control rules are enforced and followed and that catches include illegal, unreported and unregulated (IUU) removals. While inclusion of IUU removals in total allowed catches is common practice in ICES advice [46], this may be a challenge in the Mediterranean and Black Sea [47].

The 0.5 scenario was the only one to include a stop of fishing for stocks outside of safe biological limits, assumed here for biomass less than half of the biomass that can produce MSY, because at such low stock sizes recruitment may be impaired [6,48–51]. The 0.5 scenario was the fastest and best in reducing the number of depleted stocks and in rebuilding the biomass of stocks above MSY-levels. Thus, if fast rebuilding and best recovery of depleted stocks with high profitability of the fisheries are the main objectives of management and lower catches (about 80% of highest catch) are acceptable, then the 0.5 scenario should be considered. In that case special measures should be implemented to help the fishers through the initial year with reduced catch [52], especially in the Mediterranean.

The 0.6 scenario provides fast rebuilding in the first years, but then slows down and results in 10–20% fewer rebuilt stocks in 2030 than under the 0.5 scenario. Reduction of depleted stocks is also slower in this scenario, but still good with only 10–12% depleted stocks remaining in 2030. Profitability under this scenario increases fast and to a high level. Thus, if reasonably fast rebuilding and high profitability of the fisheries are the main objectives of management but a temporary drop in catches such as in the 0.5 scenario is unwanted, then the 0.6 scenario should be considered.

Under the 0.8 scenario, only 73% of the stocks in the Northeast Atlantic and only 64% of the stocks in the Mediterranean are predicted to rebuild by 2030. There is a strong increase in catches in 2018 in the Northeast Atlantic. In the Mediterranean, this scenario predicts the highest catches and profitability. About 15% of the stocks remain depleted in 2030. Biomass increases in the Mediterranean but remains about unchanged after 2018 in the Northeast Atlantic and overall. Thus, if high catch and high profitability are the main objective of management and slow rebuilding is deemed tolerable, then the 0.8 scenario should be considered.

An $F = F_{msy}$ scenario was not applied because, by definition, such scenario is not capable of rebuilding stock size above the *MSY*-level as required by the CFP, and the *MSY*-level itself is approached asymptotically and reached in infinite time. Instead, the 0.95 scenario was explored as a possible but least ambitious attempt to rebuild stocks above the *MSY*-level. Under this scenario, rebuilding of stocks is slowest with about 90% of the depleted stocks being unable to recover. Profitability is far below that of the other scenarios in the medium and long-term. Given the slow rebuilding, the inability to recover the most depleted stocks, long-term catches below those of other scenarios, and lowest profitability, the 0.95 scenario is not seen as viable option for management. Moreover, because of this list of problems it is questionable whether this scenario would comply with the CFP [6]. Note also that catches under this scenario may be too optimistic, because the assumption may be wrong that stocks that were exploited at much lower levels in 2013–2015 can be legally and profitably exploited at 0.95 Fmsy from 2018 onward.

Although the degree of required reduction of fishing pressure is unclear due to the inconsistency in Art. 2 § 2 of the Basic Regulation [6,53], the rebuilding of stocks above *MSY* must be viewed from the perspective of long-term environmental and social sustainability as emphasized throughout the CFP. The preamble to the Basic Regulation, which clearly emphasizes sustainability, serves as a guidance for interpretation of the CFP. Additionally, Art. 3 lit. d) of the Basic Regulation fosters “a long term perspective” as a principle of good governance applicable in the context of the CFP. Hence, in the 0.95 scenario that only marginally achieves a rebuilding of stocks above MSY and in the light of its low profitability one can argue that the CFP's objectives would not be met. Note that the CFP implicitly recognizes the need for rebuilding age and size structure by calling for the establishment of minimum conservation reference body sizes to be derived under consideration of the size at maturity (Article 4 of CFP) and for the establishment of fish stock recovery areas (Article 8 of CFP).

4.4. Suitability of surplus production models for stock assessment

The conclusions of this study are based on 397 stock assessments that used an advanced implementation of a surplus production model [24]. Species interactions and environmental impact are implicitly considered in such models by the rate of net productivity or intrinsic rate of population increase (r), which summarizes natural mortality such as caused by predation by other species, somatic growth such as modulated by available food sources, and recruitment such as impacted by environmental conditions and by parental egg production [32,54]. In addition, the applied model accounted explicitly for reduced recruitment at small stock sizes [24,55].

Note, however, that surplus production models do not account for size and age structure and tend to overestimate sustainable productivity in stocks where excessive fishing pressure has truncated the age structure [56], decreased age at maturity and generation time [57], and increased somatic growth due to reduced competition for food [58]. Compared with age-structured models where exploitation is typically reported for a narrow range of fully selected age classes, surplus production models estimate exploitation as total catch to total biomass ratio. This is similar to using the mean exploitation rate across all age classes weighted by their respective contribution to the catch. If the catch consists to a large part of juveniles that are only partly selected by the gear, then the overall rate of fishing mortality strongly underestimates the fishing mortality of the fully selected older year classes. Here, this problem was addressed by accounting for reduced recruitment and reduced productivity in depleted stocks (Eqs. 3 and 4).

The danger of uncritical use of surplus production models is visible in the assessment of 166 stocks by Worm et al. [59], where several constraints in the model biased the results and no correction for reduced recruitment and thus reduced productivity in depleted stocks was made. The constraints and uncritical application of the model contributed to the result that "[i]n 5 of 10 well-studied ecosystems, the average exploitation rate has recently declined and is now at or below the rate predicted to achieve maximum sustainable yield for seven systems" [59]. This surprisingly positive result is in stark contrast to other studies that found global fisheries in overall decline, despite some local improvements [4,5,40,60–63]. Looking at the 12 ecoregions supporting the 397 stocks analyzed in this study (Table 1), including nine large marine ecosystems also analyzed in Worm et al. [59], no region had an average exploitation rate at or below the rate predicted to achieve maximum sustainable yields (Table 1). Similarly, Rosenberg et al. [64] apply a combination of four data-limited methods with strong known biases [24,65] and no corrections for reduced recruitment to global catch data and conclude that, e.g., half of the stocks in the Northeast Atlantic and the Mediterranean and Black Sea have a biomass near or above B_{msy} in 2013, whereas our more detailed study shows that this applies to only 28% and 5% of these stocks, respectively.

4.5. Relation among catch, biomass and profitability

The profitability of a fishery is determined by the discounted difference between the revenues – the market value of the catch, with prices assumed here constant – and the cost of fishing, assumed here directly proportional to fishing mortality [66]. Note that there may be cases where increased catches lead to lower and reduced catches lead to higher market prices [67]. In such case, our assumption of constant prices tends to underestimate profitability at lower catches (thus overestimating the economic costs of rebuilding the stocks) and tends to overestimate the profitability at higher catches (thus underestimating the economic benefit of rebuilding). However, given the growing seafood consumption and thus demand in Europe [68], the decline of market price with increased regional catches may be compensated by the overall trend of increasing seafood prices. In order to focus on the comparison of future exploitation scenarios, this study ignored this and other economic sources of uncertainty. Therefore, under the assumptions of constant prices and constant cost per unit of fishing effort, the low profitability of the 0.95 scenario stems from higher cost associated with higher effort and slow and incomplete rebuilding of biomass, which leads to lower catches and thus low fishing revenues.

4.6. The fallacy of 'High F is good for the fishery'

In a 2011 World View article on the European fisheries reform [43], the prescriptions of the reformed CFP were praised, but its chances of success were questioned, given that implementation depended on the same people and institutions who had, for decades, justified and administered overfishing. Despite the well-established negative effects of overfishing on exploited populations [61,69], there is a widespread misconception among fisheries managers and fishing lobbyists that a high fishing mortality F is good for the fishery. This is visible in the request of the European Commission to its advisory body to provide "ranges of F_{msy}" including values larger than F_{msy} [7]. The CFP gives another example for this misconception in the preamble to the Basic Regulation where it is stated that exploitation rates above the level that can produce the *MSY* can be postponed "if achieving them by 2015 would seriously jeopardize the social and economic sustainability of the fishing fleets involved". Indeed, in the short term, catch equals F multiplied by the mean biomass [32], and thus the higher F, the higher the immediate catch. However, a high catch in the short term reduces future fish abundance [32] and thus reduces fishing revenues in the long term. Moreover, there are socio-economic trade-offs in fisheries: Employment in the fishery scales positively with F, but profitability scales negatively with F [70,71]. Increasing employment when profits are declining is not an economically viable option. Instead, economic sustainability of fisheries requires a reduction of fishing mortality. The EU policy of keeping fishing effort high undermines the long-term economic viability of fisheries, such as currently experienced in most European fisheries [37]. Sustainable fisheries management should not strive for the highest possible *F* and the associated short-term gain, but rather for fishing mortalities well below the maximum, thus sustaining fish populations and economic viability of fisheries in the medium and long term [72].

5. Conclusions

The concept of "pretty good yield" (PGY) was introduced by Alec MacCall (National Marine Fisheries Service, Santa Cruz, CA, USA, retired) at the Mote Symposium in Florida in 2000, proposing catches of about 80% or more of *MSY* as a meaningful and realistic target. The concept has been embraced by fisheries scientists because it deals with the fact that *MSY* itself is an often unknown, unobtainable or undesirable target [54,73,74]. In this study, rebuilding time, catch and profitability were examined for 397 stocks in the Northeast Atlantic, the Mediterranean and the Black Sea under four exploitation scenarios, all resulting in pretty good yields for most stocks. Implementation of one of the described scenarios would be straightforward for the stocks in the Northeast Atlantic which are already managed with total allowable catches (TACs) based on exploitation rates and harvest control rules for depleted stocks. The next meeting of the responsible EU ministers could set the respective TACs for the next years according to the selected scenario. For the Mediterranean and Black Sea implementation is a much larger and complicated problem as no TACs exist (except for Bluefin tuna *Thunnus thynnus* and swordfish *Xiphias gladius* starting in 2017) and management is mainly based on effort control and technical measures, with problematic enforcement and confounding effects [22]. In addition, numerous third countries are involved in the fisheries of wide-ranging species, with different objectives from the CFP and often no control or enforcement [75]. Such obstacles must be addressed and solved through better cooperation in the framework of the regional fisheries management organizations, so that all countries contribute to and benefit from the rebuilding of the stocks. Within this context, the CFP correctly foresees regionalization for a number of instruments and measures: multiannual plans, discard plans, establishment of fish stock recovery areas and conservation measures necessary for compliance with obligations under EU environmental legislation.

In summary, rebuilding of fish stocks in European waters is not only required by the CFP but also possible and, depending on the chosen management regime, would likely lead within a few years to pretty good catches and substantially higher profits for the fishers, with significant positive economic consequences for the fishing sector [76].

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2018.04.018.

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