AUTHOR QUERY FORM

ELSEVIER	**Journal:** FISH **Article Number:** 4057	**Please e-mail your responses and any corrections to:** **E-mail:** corrections.esch@elsevier.thomsondigital.com

Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list. Note: if you opt to annotate the file with software other than Adobe Reader then please also highlight the appropriate place in the PDF file. To ensure fast publication of your paper please return your corrections within 48 hours.

For correction or revision of any artwork, please consult http://www.elsevier.com/artworkinstructions.

Any queries or remarks that have arisen during the processing of your manuscript are listed below and highlighted by flags in the proof. Click on the 'Q' link to go to the location in the proof.

Location in article	**Query / Remark: click on the Q link to go** **Please insert your reply or correction at the corresponding line in the proof**
Q1	Please confirm that given names and surnames have been identified correctly.
Q2	Please check all author names and affiliations.
Q3	"Your article is registered as belonging to the Special Issue/Collection entitled ". . ..". If this is NOT correct and your article is a regular item or belongs to a different Special Issue please contact i.gopinath@elsevier.com immediately prior to returning your corrections.".
Q4	Rosenberg et al. (2007, 2014), Watling et al. (2011), Raetz et al. (2013) and Punt et al. (2011) are cited in the text but not provided in the references list. Please provide them in the references list or delete these citations from the text.
Q5	The citations Patrick et al. (2010), Hobday et al. (2004), Cordue et al. (2012) and Ferretti (2005 and 2013) have been changed to Patrick (2010), Hobday and Smith (2004), Cordue (2012) and Ferretti et al. (2005 and 2013), respectively, to match the author name/date in the reference list. Please check here and in subsequent occurrences, and correct if necessary.
Q6	The spelling of the author name in the text has been changed to Scheipl to match the reference list. Please check the spelling, and correct if necessary.
Q7	Please note that Table 3 was not cited in the text. Please check that the citation as suggested by the copyeditor is in the appropriate place, and correct if necessary.
Q8	This section comprises references that occur in the reference list but not in the body of the text. Please cite each reference in the text or, alternatively, delete it.
Q9	Please provide the page range for the bibliography in Cope et al. (2011) and Ferretti et al. (2013).
Q10	Please provide complete bibliographic details in European Commission and Thorson et al. (in press).
Q11	Please confirm whether the first name and surname have been identified correctly for all the authors.
Q12	Please provide the volume number and page range for the bibliography in Ricard et al. (2012) and Thorson and Cope (2015).
Q13	Please supply the name of the city of publication for Wood (2006) and Zuur et al. (2008).

Location in article	Query / Remark: click on the Q link to go Please insert your reply or correction at the corresponding line in the proof
	Please check this box or indicate your approval if you have no corrections to make to the PDF file ☐

Thank you for your assistance.

Fisheries Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks

Giacomo Chato Osio[a,*], Alessandro Orio[a,b], Colin P. Millar[a,c]

[a] European Commission Joint Research Centre, Institute for the Protection and Security of the Citizen (IPSC), Via Enrico Fermi 2749, 21027 Ispra, VA, Italy
[b] Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Marine Research, Turistgatan 5, S-453 30 Lysekil, Sweden
[c] Marine Scotland Science, Freshwater Laboratory, Faskally, Pitlochry PH16 5LB, Perthshire, UK

A R T I C L E I N F O

Article history:
Received 23 April 2014
Received in revised form 3 February 2015
Accepted 9 February 2015
Available online xxx

Keywords:
Productivity susceptibility analysis
Data poor stocks
Mediterranean
Fisheries
Stock status

A B S T R A C T

According to the Common Fisheries Policy, all commercial fish stocks in the Mediterranean and Black Sea should be managed at MSY by 2015–2020. However, currently 95% of assessed stocks are overexploited and 73% of demersal species are not assessed. To explore the risk of overexploitation to un-assessed stocks, vulnerability scores were constructed using Productivity Susceptibility Analysis (PSA) for 151 Mediterranean demersal fish species. Out of 151 species, 58 displayed low vulnerability, 20 medium vulnerability, 25 high vulnerability and 48 were considered of major concern. More than half of stocks showed a risk of being overfished (termed "vulnerability"), greater than that of the stocks currently assessed in the Mediterranean Sea. Most of the cartilagineous fish fell into the high and major concern areas. The quality of data used for the PSA was scored and these scores could be used to improve future collection of data. Vulnerability scores are well correlated with IUCN red list classification. To rank the priority of commercial stocks still to be assessed, vulnerability scores were scaled with landings and mean price per stock. Eight of the top fifteen ranking stocks are currently not assessed. When the vulnerability of cartilaginous fish was tested against rate of decline estimated from trawl survey time-series, no strong correlation was found. The exploitation ratio (F/F_{msy}) of assessed stocks was regressed, using generalized mixed models, against PSA scores and area and a significant relationship was found. Using this result, assessed stocks were used as a training set to predict the exploitation of un-assessed stocks. F/F_{msy} was predicted for 151 species in 14 management areas (GSAs). The results over all areas is that 39 species-area combinations are exploited sustainably, all occurring in area 20 (Greece), while the remaining 2075 are exploited unsustainably with respect to F_{msy} ($F/F_{msy} > 1$). This prediction model, albeit after further refinement with more data and testing, could be used to predict exploitation ratio when no information on stock status is available. We predict that ≈98% of the unassessed demersal fish species are potentially overexploited in the evaluated areas. This makes it clear that strong management action will be required to achieve the targets of the Common Fisheries Policy in the next 1–5 years.

1. Introduction

There has been an increase in effort world-wide to assess the status of living marine resources. Management bodies and Regional Fisheries Management Organizations (RFMOs) focus on determining the exploitation status of important commercial stocks. While progress has been made, still only a fraction of stocks under directed commercial fishing or caught as bycatch are currently assessed. According to Costello et al. (2012), fisheries lacking formal assessment comprise >80% of global catch. Many regional policies mandate that all fish stocks, or fish stocks with economic value, should be managed in a sustainable way (US Magnusson-Stevenson Act; European Community Common Fisheries Policy (CFP) and Maritime Strategy Framework Directive (MSFD); Australia's Fisheries Administration Act 1991), but many countries are far from reaching this target. To address the lack of knowledge on stock status, several efforts aiming at developing new methods for assessing the status of data poor stocks are under development (Rosenberg et al., 2014, this issue).

In the Mediterranean and Black Sea the situation is the same. According to the revised CFP, European stocks subject to commercial fishing should be managed at their long term maximum sustainable yield (MSY) by 2015, or at the latest 2020 (EU Regulation No. 1380/2013). In the Mediterranean, a fish stock is

* Corresponding author. Tel.: +39 0332785948.
E-mail address: giacomo-chato.osio@jrc.ec.europa.eu (G.C. Osio).

http://dx.doi.org/10.1016/j.fishres.2015.02.005
0165-7836/© 2015 Published by Elsevier B.V.

traditionally defined as one species in one GFCM statistical area, under the strong assumption that stock unit and statistical area coincide. In the last five years, out of the 98 stock assessments with analytical results, less than 25 species have been assessed at least once in one of the 27 Mediterranean sub areas (GFCM GSA), while more than 100 species are subject to fishing. Therefore the stock status, at species level, is known for around a fourth of the species subject to commercial fishing. However, at the stock level this fraction is much smaller. Additionally the status of the 25 assessed species is not known uniformly across GSAs.

The Mediterranean demersal stocks have been subject to trawling at least since 1700 (Osio, 2012), one of the longest trawl fishery exploitation in the Western world. A consequence of this is that around 95% of assessed stocks are classed as overexploited based on assessments performed between 2008 and 2012. The few stocks considered to be exploited sustainably are either short-lived small pelagics or crustaceans.

Given that approximately 75% of Mediterranean species are not assessed, there are two main problems: (1) the lack of knowledge on exploitation status of unassessed stocks is of particular concern given the generally high exploitation rate in assessed stocks; (2) in policy terms, it will be impossible to show MSY and fulfill the CFP and MSFD targets in compliance with the timelines set in the CFP. While there are stocks that have landing time series and could be assessed with methods for intermediate data situations as those tested in Rosenberg et al. (2014), many of the un-assessed stocks are effectively data poor, meaning that not even landings time series are available. Understanding which species should be assessed is a clear need, as well as gaining a realistic picture of the vulnerability of the data poor stocks. Hobday et al. (2011) developed in Australia the Ecological Risk Assessment for the Effects of Fishing (ERAEF) where different levels of risk assessment are implemented based on data availability and risk. The novelty of this framework is a hierarchical structure, a precautionary approach to uncertainty and tracking of uncertainty across levels (Hobday et al., 2011).

There are different methodologies for assessing stock vulnerability. Typical approaches are semi-quantitative risk assessments Q5 (Patrick, 2010) such as evaluating fishery impact on target and bycatch species (Stobutzki et al., 2001a), evaluating the impacts on ecosystem viability (Astles et al., 2006) or the extinction risk of a determinate species (Mace et al., 2008). Among these is a widely used method known as Productivity and Susceptibility Analysis (PSA), originally devised in Australia (Milton, 2001; Stobutzki et al., 2001b). PSA is based on scoring an array of productivity and susceptibility attributes for each stock, which are then summed to provide a productivity and susceptibility value by stock, often presented graphically. The approach has since been modified to include habitat and community components (Hobday and Smith, 2004) and further revisions have been suggested by Rosenberg et al. (2007).

The PSA methodology has benefits and limitations (Watling et al., 2011).

Benefits:

- It is suitable in data-poor situations where data for traditional stock assessments are lacking (it is based on qualitative data).
- The outputs provide a visual tool for examining the relative vulnerability of a suite of species to a particular fishery.
- The method can be tailored to the data availability and state of knowledge of species and fisheries by carefully selecting productivity and susceptibility attributes.
- The method is rapid and is based on previously developed, tested and published protocols, and has a history of application as a risk assessment method in fishing.
- It is easy to add new information as soon as better data become available.

Limitations:

- The PSA analysis essentially measures potential for risk. A measure of absolute risk requires some direct measure of abundance or mortality rate for the stock in question, and this information is generally lacking (Hobday et al., 2007). In this assessment, species are ranked relative to each other. However, comparing with assessed stocks can give more absolute results.
- The analysis is only what it appears, a vulnerability analysis, and it should be used as a tool to highlight potential management strategies, vulnerable species, and areas where particular attention should be paid.
- This assessment is fishery-specific, as susceptibility rankings are specific to a species' interaction with the fishery in question.
- The results are only as strong as the attributes included. There are many more attributes that increase or decrease a species' susceptibility or recovery potential. Attributes should be added or removed based on the fishery and as more information becomes available.
- The method lacks ecosystem context. It primarily focuses on the individual fish species and not the broader ecosystem.

The goals of this paper are the following:

(1) Calculate vulnerability via scoring susceptibility and productivity for commercially exploited demersal fish in the Mediterranean Sea using the outputs from a PSA analysis.
(2) Produce a ranking of species with high vulnerability, as well as high vulnerability and economic importance, to identify those deserving more attention in terms of stock assessment and management.
(3) Investigate the relationship between PSA scores and (1) exploitation level of assessed stocks, (2) IUCN red list classification and (3) estimated annual rate of change from trawl survey catch per unit of effort for cartilagineous fish.
(4) Predict the potential exploitation status of unassessed stocks from the relationship between vulnerability and exploitation status in assessed stocks.

2. Material and methods

We evaluated 151 demersal and bathydemersal fish species including 40 chondrichthyans (Supplementary materials, file "psa_scores_Med.xlsx") in the Mediterranean Sea. Only species caught (or likely to be caught) by otter-trawl were considered. Species were selected based on their listing in the European Data Collection Framework (DCF) landings database and their presence in the international Mediterranean bottom trawl survey (MEDITS) over the past 19 years—see Bertrand et al. (2000) for a description of the MEDITS database. Discard data is generally poor from commercial landings, thus the use of a comprehensive list of demersal fish caught in the MEDITS survey helped detect species that are captured by trawlers and that might go undetected in discard sampling. Extremely rare species, like sturgeons and angel sharks, were added to the PSA analysis to assess if the PSA could identify a high potential risk, explaining current disappearance and rare sightings. Therefore, the analysis included un-assessed species as well as all the assessed demersal and bathydemersal species (99 stock assessments performed in 16 sub-areas over 5 years (http://www.europarl.europa.eu/document/activities/cont/201312/20131217ATT76355/20131217ATT76355EN.pdf).

Please cite this article in press as: Osio, G.C., et al., Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. Fish. Res. (2015), http://dx.doi.org/10.1016/j.fishres.2015.02.005

2.1. PSA methods

The vulnerability of a stock is directly related to overfishing and is defined as a function of its productivity and susceptibility. The productivity of a stock is a combination of its capacity to produce MSY and its resilience, while the susceptibility is the potential for the stock to be impacted by the fishery (Patrick et al., 2009). The PSA was conducted using the software PSA 1.4, developed in 2010 by NOAA and included in the Stock Assessment toolbox (NOAA, 2010).

The values for the two factors, productivity and susceptibility, are determined by providing a score ranging from 1 to 3 for a standardized set of attributes. A common problem is how to deal with lack of information for some attributes. Different approaches are available: scores can borrow information from similar taxa or be determined on a "best guess" derived from expert knowledge (Cope et al., 2011), or be given the value that produces the highest vulnerability score as a precautionary approach (Hobday et al., 2011). Choosing between the latter two options can create substantial differences in the results of a PSA. The precautionary approach will result in more false positives (stocks identified at higher risk than would occur when assessed at a higher level with more data) than false negatives (stocks scored at a lower risk than would occur when assessed at a higher level with more data). This bias is important to consider. To perform a sensitivity analysis of the difference in scoring data deficient attributes, we performed both types of scoring, i.e., we produced both a more conservative (following Hobday et al., 2011) and a less conservative (following Cope et al., 2011) PSA.

Once assigned, the scores are averaged for each factor and graphically displayed on an x–y scatter plot. There are two commonly used approaches to calculate overall susceptibility and productivity, the weighted average method and the multiplicative approach. In the latter, if one attribute has a low rank, then the species is considered not at risk; thus the multiplicative approach has a tendency to underestimate susceptibility (ICES WKLIFE3 report). Consequently we decided to use the average method since it is used more often than the multiplicative approach and avoids the tendency to underestimate vulnerability. The overall vulnerability score of a stock is calculated as

$$\text{vulnerability} = \sqrt{(\text{susceptibility} - 1)^2 + (3 - \text{productivity})^2}$$

which is the distance from the origin of the PSA plot to the data point (Fig. 1). Stocks that received a low productivity score and a high susceptibility score are considered to be the most vulnerable to overfishing, while stocks with a high productivity score and low susceptibility score are considered to be the least vulnerable (Patrick et al., 2009).

The PSA plot is divided into areas by three contour lines representing vulnerability (V) reference points based on the approach used by Cope et al. (2011). The three contour lines are considered the limits between vulnerability classes (low concern $V < 1.6$ medium concern $V < 1.8$, $1.8 \leq$ high concern $1.8 \leq V < 2.0$ and major concern $V \geq 2.0$), see Fig. 1. The reference point of 2.0 was chosen based on the fact that the two Mediterranean stocks, according to the assessments, present a mean exploitation rate higher than 4.0 have a V score close to 2.0 (2.09 for *Merluccius merluccius*, 2.02 for *Lophius budegassa*). The contour line of $V = 1.8$ was chosen because the stocks with mean exploitation ratio between 2.0 and 4.0 have a mean vulnerability score around that value (1.84) while the contour line of 1.6 was chosen because none of the stocks with a mean exploitation ratio higher than 1.0 have a vulnerability score lower than 1.63.

Each productivity and susceptibility score is also evaluated for the quality of the data used to determine the score. Data quality scores range from 1 to 5 as follows:

- (Best data): Information is based on established and substantial data.
- (Adequate data): Information has limited coverage and corroboration.
- (Limited data): Information deserves limited confidence and may be based on similar taxa.
- (Very limited data): Information is based on expert opinion or the general literature review.
- (No data): There is no information on which to base score.

Seven productivity and seven susceptibility attributes were assessed for each stock and are described in Table 1 in Appendix A.

Every attribute is given a weight ranging from 1 to 4 that will multiply by the attribute score. Multiplying attributes by the weights gives the user the opportunity to give more importance to one or more attributes in the calculation of the overall Susceptibility and Productivity score. Most studies have given the attributes equal weight (so no difference in deciding to use the weighting system or not). In our case the majority of susceptibility attribute scores occupied a narrow range between 1 and 3. The exception was the "Desirability" score, which had a wider range. We gave desirability a higher weight in the analysis and this resulted in a wider overall range for the Susceptibility score.

All the data used to score the productivity and susceptibility attributes come from stock assessments, EU annual economic reports (http://stecf.jrc.ec.europa.eu/documents/43805/581354/2013-09_STECF+13-15+-+AER+EU+Fleet+2013_JRC84745.pdf) IUCN (www.iucn.org), FAO (www.fao.org), FishBase (www.fishbase.org), literature reviews (Broadhurst et al., 2006) or the best available data. The scoring thresholds of all the attributes except for "Areal overlap" were based on the ones applied to the PSA of the fish stocks considered to be representative of U.S. fisheries (Patrick et al., 2009; Patrick, 2010).

2.2. Stock prioritization

One of the objectives of this analysis, other than estimating the risk of overfishing, is to produce a ranking of species with high vulnerability, which could identify those stocks deserving more attention in terms of stock assessment and/or data collection. We expect that the elasmobranchs would rank highly, but since these species have a relatively small contribution to total landings in the Mediterranean, rankings based on landings would give elasmobranchs low priority. We propose an additional ranking where total landings (L_k) by species (k) are multiplied by the mean economic price (MP_k) and then scaled by the vulnerability scores from the PSA (V_k) ($\text{Rank} = L_k \times MP_k \times V_k$). This ranking aims at balancing the three factors, e.g. we want to rank the highest the stocks that are more important in landing volume, that have high value but are also vulnerable.

To build a priority list, we used the 2011 landings of each species in the Mediterranean Sea obtained by the FAO-GFCM Capture Production 1970–2011 (as of March 2014) (www.fao.org/fishery/statistics/gfcm-capture-production/en). The mean price (euro/kg) was calculated for each species across years 2008–2011 and data is based on the EC Annual Economic Report (http://stecf.jrc.ec.europa.eu/documents/43805/581354/2013-09_STECF+13-15+-+AER+EU+Fleet+2013_JRC84745.pdf). Only 52 species assessed in the PSA were reported in the FAO-GFCM database.

Please cite this article in press as: Osio, G.C., et al., Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. Fish. Res. (2015), http://dx.doi.org/10.1016/j.fishres.2015.02.005

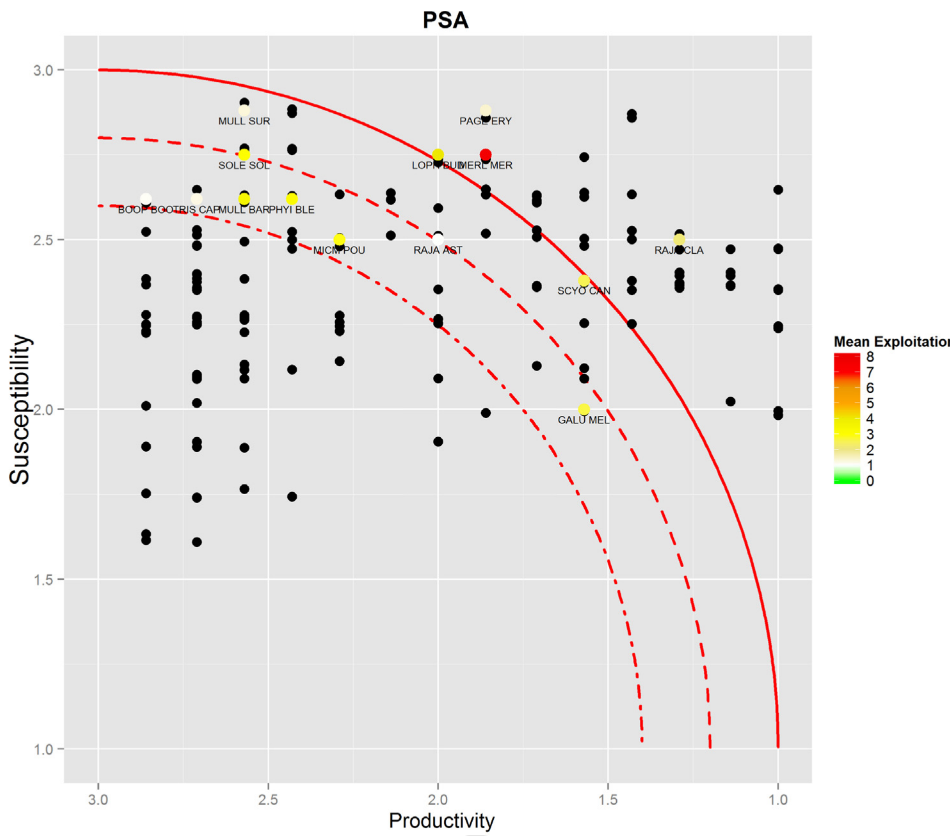

Fig. 1. Plot shows the results of the PSA analysis in comparison to the mean exploitation (F/F_{msy}) of the assessed stocks. The three contour lines are considered the limits between vulnerability (V) classes (low concern $V<1.6$ medium concern $V<1.8$, $1.8\leq$ high concern $1.8\leq V<2.0$ and major concern $V\geq 2.0$) exploitations being sustainable ($F/F_{msy}<1$) in green, unsustainable exploitation in respect to F_{msy} in red ($F/F_{msy}>1$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Comparison with annual rate of change methods

For a first comparison, we compared PSA-derived susceptibility (S) and productivity (P) scores to standardized annual rates of change estimated for cartilaginous fish from time series of scientific trawl surveys from the Tyrrhenian Sea (Ferretti et al., 2005) and Adriatic Sea (Ferretti et al., 2013). Yearly rates of change were estimated in the original papers by applying generalized linear models to catch per unit of effort (CPUE) data (numbers/swept area). The hypothesis is that species with high vulnerability scores are more likely to have declined in abundance over the past 50 years.

To investigate this hypothesis, the rates of change reported in Ferretti et al. (2005, 2013) were modeled, using generalized additive mixed models, as a function of susceptibility, productivity, and area (Tyrrhenian and Adriatic Sea). These covariates were included to distinguish between two different areas, as well as separately for Productivity and Susceptibility scores, as they summarize all the scoring attributes of the PSA. Rates of change estimates were weighted by the inverse variance of the estimate derived from the original publications.

A second qualitative comparison with the PSA scores was performed against the IUCN red list classification (www.iucnredlist.org) which is structured in six levels of risk plus one for data-deficient species. The expectation is for a high correlation between PSA vulnerability and red list classification.

2.4. Comparison to F_{ratio} methods

For a third comparison, the estimated vulnerability of assessed data rich stocks was tested against the exploitation ratio assessed in the stock assessments (F_{year}/F_{msy}). This ratio was used as it scales the different Fs relative to F_{msy} so that comparisons could be made across stocks. The F_{year}/F_{msy} were estimated over the period 2008–2012 over which large changes in selectivity are not expected. Such shifts could cause change in F_{msy} estimation and other problems (Cordue, 2012). For the data rich stocks, all yearly fishing mortality (F_{year}) and fishing mortality reference points (F_{msy}) were extracted from the available stock assessment reports and are divided by GFCM Statistical area (GSA1–GSA25) and by year (2008–2012) [STECF reports (https://stecf.jrc.ec.europa.eu/reports/medbs)]. The estimated F/F_{msy} has a finer resolution (they are estimated for a given GSA and year) than the PSA scores (which were derived at Mediterranean Sea level and without a temporal component).

In this case, we hypothesize that stocks with the highest fishing mortality relative to F_{msy} scale positively with susceptibility and negatively with productivity. We assume that the differences in productivity and vulnerability across GSAs are negligible, or that there would be insufficient data to perform a PSA in each of the 27 Mediterranean GSA. To investigate this hypothesis, additive mixed models were fitted to susceptibility score, productivity score and area (GSA) to estimate the association with fishing mortality relative to F_{msy} of assessed stocks.

2.5. Predicting fishing mortality relative to F_{msy} (F/F_{msy}) for un-assessed stocks

Using the best model trained on the data rich assessed stocks, we predicted the F/F_{msy} for the un-assessed stocks, using productivity, susceptibility and area (GSA) as covariates. A similar approach, albeit with more covariates and stocks, was used by Costello et al. (2012) and by Thorson et al. (2012). Both of these authors used assessment results from the RAM legacy database (Ricard et al., 2012), landing time series and some life history parameters. In this analysis we used PSA scores, area and fishing mortality relative to F_{msy} and relied on the fact that we wanted to predict stock status (F/F_{msy}) of species that emerge from a group with similar properties in terms of habitat, fishing history and environmental conditions. The analysis involves the assumption that fishing effort applied to demersal stocks of commercial value in a given area generates an equivalent fishing mortality on the stocks that are part of the same multispecies fishery (Raetz et al., 2013) and are available to bottom trawl gear.

All models were fitted in R 3.0.3 (R Core) using the libraries gamm4 (Wood and Scheipl, 2013) and lme4 (Bates et al., 2013). Model fitting was by maximum likelihood with smoothers fitted as random effects (see Section 6.6.1). Model selection was performed by first fitting a full model, dropping random effect terms, followed by fixed effect terms. Smoothers were specified as thin plate regression splines with 4 degrees of freedom; in the case of 2-dimensional smooths this was a tensor product of cubic regression splines with 4 degrees of freedom in each dimension. The best model was selected based on minimum AIC where AIC was defined as $-2 \times \log \text{Likelihood} + 2 \times \text{model degrees of freedom}$. In the mixed effects construction, 1-d smoothers (regardless of wigglyness) contribute 2 degrees of freedom to the model: one for the variance of the random (wiggly) component and one for the fixed (linear) component, 2-d smoothers contribute 5 degrees of freedom. Once the 'best' model was identified, parameters were re-estimated using restricted maximum likelihood if any random effects remained, as this gives better parameter estimates (Zuur et al., 2008).

3. Results

3.1. PSA

The results of the PSA (Figs. 1 and 2), following the "best guess" scoring approach for the attributes of the species with low knowledge, showed that the range of productivity scores are wide, scoring from 1.0 to 2.86, compared to the susceptibility scores which ranged from 1.62 to 2.88 (Supplementary materials, file "psa_scores_Med.csv"). All the species considered in this analysis displayed a vulnerability score greater than 0.64, however, only 12 species were below 1.0. The maximum value of vulnerability (2.58) was recorded for the cartilaginous fish *Dalatias licha*. Of the 151 species analyzed, 58 species displayed low vulnerability, 20 medium vulnerability, 25 high vulnerability and 48 were considered of major concern. Only three species of cartilaginous fishes (*Mobula mobular, Mustelus punctulatus*, and *Galeus melastomus*) were assessed as moderately vulnerable ($1.6 < V < 1.8$) while the rest were of high and major concern ($V > 1.8$) (Fig. 2). When using the conservative PSA scoring approach for comparison, the PSA scores classified 40 species with low vulnerability, 22 with medium, 28 with high and 61 were of major concern (Fig. 1 in Appendix A). The conservative scoring approach classifies many stocks at high and major risk because of a lack of knowledge rather than true vulnerability. Since this PSA tends to over-classify species vulnerability, we deemed the "best guess" PSA to be more realistic and reliable. The main difference between the two PSAs is for 27 species with poor data. However, these species were classified with high productivity and medium vulnerability in the "best guess" PSA, so they are unlikely to be at risk. Since the impact on the subsequent analysis is not relevant, we retain the "best guess" approach for all the analysis in the manuscript and leave the conservative results of the PSA in the Appendix A.

Using results for the "best guess" PSA, six species out of the 14 species currently assessed in the Mediterranean Sea have medium vulnerability, and the rest have high or very high vulnerability. This means that there are species not being assessed by any management body, which displayed a higher vulnerability score compared to some of the assessed ones. When the estimated vulnerability scores are plotted against the mean exploitation for the assessed stocks, there is a good agreement for most species (Fig. 1), with the exception of *Raja clavata*.

One important result of the PSA analysis is the scoring of data quality. This ranking could be used to identify species with poor knowledge for which data collection should be improved. By comparing vulnerability scores with IUCN extinction risk categories, it appears that the species with the higher vulnerability are, with few exceptions, ranked as most threatened by the IUCN (Fig. 2, bottom right panel). This is indicative of a good qualitative agreement between the two different scoring methods. While some of the information used by IUCN and the PSA might be similar, the criteria to derive vulnerability are not. We therefore believe that the good concordance between the two approaches corroborates the results of the PSA.

3.2. Species rankings

The species ranking (using landings, species mean price and vulnerability) returned a list of 52 species (Fig. 3). The list is limited by availability of price data and by lack of landing information for rarely caught species. It therefore applies only for ranking principal commercial stocks. Seven of the top 15 ranked stocks are currently assessed (*M. merluccius, Mullus surmuletus, Mullus barbatus, Pagellus erythrinus, Solea solea, Boops boops* and *Micromesistius poutassou*), but the remaining eight stocks are not assessed despite having economic importance and potential vulnerability. This ranking could be a quantitative criterion for prioritizing future stock assessment efforts in the region. However, local targeting might need to be considered area by area if there are important differences. Due to the fact that 99 species were not included in the ranking for lack of data, more efforts should be allocated towards improving the knowledge on these species.

3.3. Comparison with annual rate of change

To test the relationship between the annual rate of population change of cartilagineous fish from trawl surveys with the PSA scores, we fitted generalized additive mixed models allowing for random effects in area and stock, and nonlinear effects on the interaction between susceptibility and productivity. The best model, selected using AIC (Table 1), was the linear model:

Rate of change ~ susceptibility + area, The best model (Table 3) retained susceptibility and area as predictors. Diagnostic plots (Fig. 2, Appendix A) show acceptable residual patterns. Overall the model has low explanatory power (R-squared = 0.164) and susceptibility increased with the rate of decline.

3.4. Comparison to F_{ratio} and prediction of fishing mortality relative to F_{msy} for un-assessed stocks

To test the effect of PSA scores and area on the exploitation ratio (F/F_{msy}), we applied additive mixed-effects models following the same methodology described above. Early model trials and variance to mean tests showed an increasing mean to variance relationship. Log transformation was thus necessary to homogenize the variance and was applied in all models. The best model, based on AIC (Table 2), was:

$$\log(\text{Exploitation ratio}) \sim \text{productivity} + \text{GSA}$$

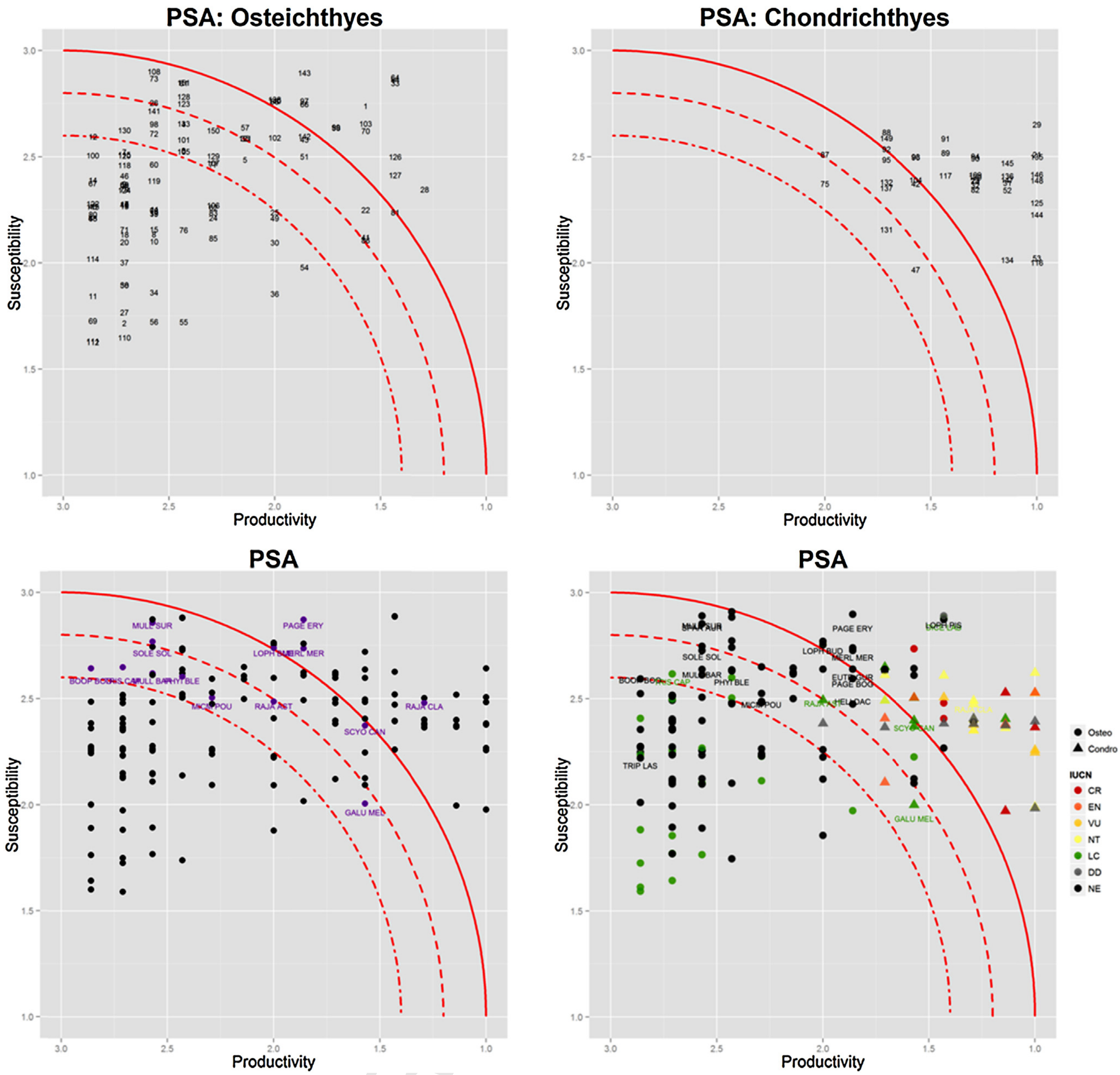

Fig. 2. Productivity and Susceptibility analysis for Mediterranean Demersal stocks subject to trawling, according to the "best guess" scoring of PSA attributes following Cope et al. (2011). Top left, bony fish, Top right cartilagineous fish, Bottom left, all species against assessed stocks, Bottom right all species in relation to IUCN red list classification where the symbols represent circles = Osteichthyes (bony fish), triangles = Chondrichthyes (cartilagineous fish).

where stock was treated as a random effect. The best model (Table 4) retained a linear effect of productivity as a significant predictor and GSA. Diagnostic plots (Fig. 3 in Appendix A) show acceptable residual patterns in QQ plot, histogram of residuals. Overall the model has an R-squared = 0.3971.

We used the best model to predict the ratio F/F_{msy} of the unassessed stocks using the fixed components (Productivity and

Table 1
Summary of the models for testing rate of change ~ PSA scores. Model specification is in R and degrees of freedom (df) and effective degrees of freedom (edf), Akaike Information Criterion (AIC) and Delta Akaike Information Criterion (ΔAIC) are reported for each model. Tensor product smooths (t2), smooth terms (s) are specified for the fixed terms and random indicates the variables used as random effects. Best model is in bold.

Fixed	Random	df	edf	AIC	ΔAIC
t2(Productivity, susceptibility, $k = 4$) + zone	(1|Stock)	10	0	9.63	11.64
s(Productivity, $k = 4$) + s(susceptibility, $k = 4$) + productivity × susceptibility + zone	(1|Stock)	9	0	7.63	9.64
s(Productivity, $k = 4$) + productivity × susceptibility + zone	(1|Stock)	8	0	5.63	7.64
Productivity × susceptibility + zone	(1|Stock)	7	NA	3.63	5.64
Productivity × susceptibility + zone		6	NA	1.63	3.64
Productivity + susceptibility + zone		5	NA	−0.37	1.64
Susceptibility + zone		**4**	**NA**	**−2.01**	**0**

Please cite this article in press as: Osio, G.C., et al., Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. Fish. Res. (2015), http://dx.doi.org/10.1016/j.fishres.2015.02.005

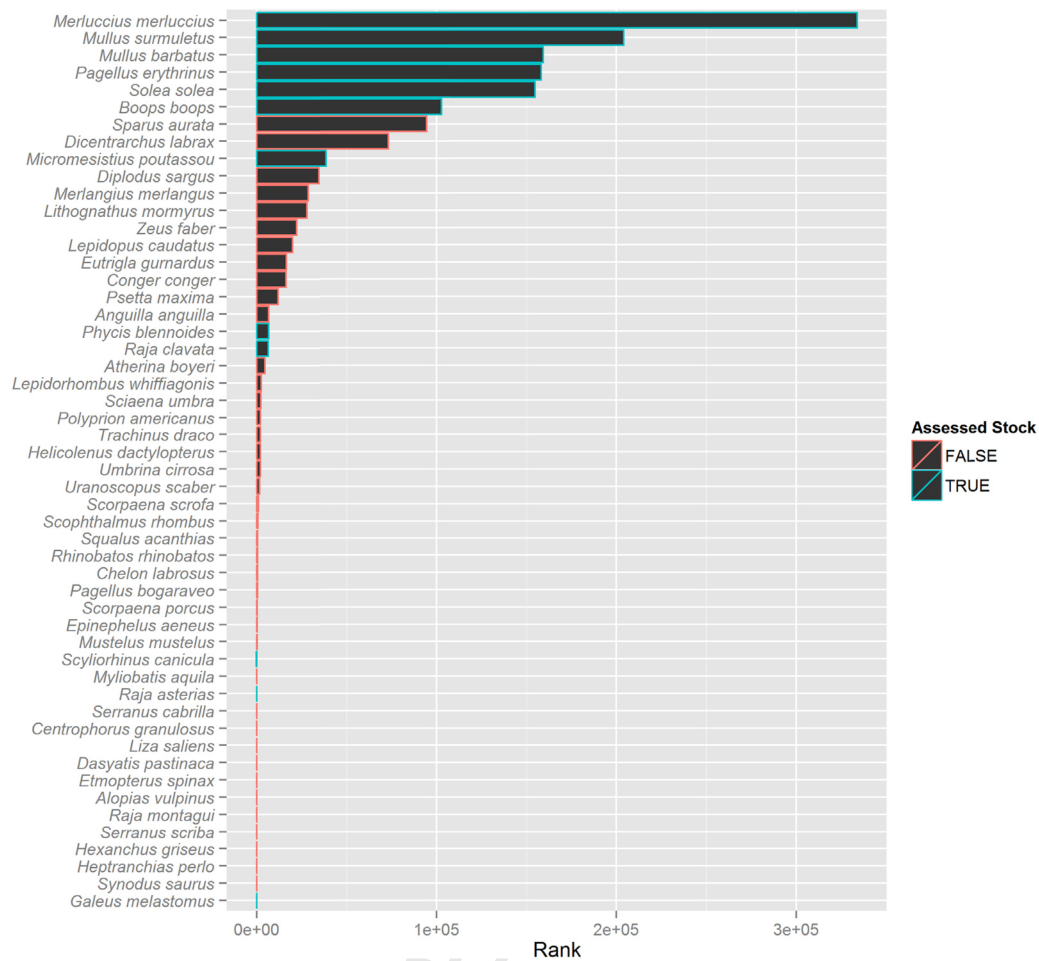

Fig. 3. Ranking of commercial stocks for which mean price, landings and vulnerability (derived from PSA) were available. In green stocks that have been assessed at least once between 2008 and 2012 and in red stocks never assessed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary of the models for testing F ratio ~ PSA scores. Model specification is in R and degrees of freedom (df) and where a smoother was fitted the effective degrees of freedom (edf) of the smooth component if given, Akaike Information Criterion (AIC) and Delta Akaike Information Criterion (ΔAIC) are reported for each model. Tensor product smooths (t2), smooth terms (s) are specified for the fixed terms and random indicates the variables used as random effects. Best model is in bold.

Fixed	Random	df	edf	AIC	ΔAIC
t2(Productivity, susceptibility, $k=4$) + GSA	(1| YS) + (1|Stock)	23	17	158.95	11.74
t2(Productivity, susceptibility, $k=4$) + GSA	(1|Stock)	22	17	157.09	9.89
t2(Productivity, susceptibility, $k=4$) + GSA	(1| YS)	23	18.49	157.14	9.94
s(Productivity, $k=4$) + s(susceptibility, $k=4$) + GSA	(1| YS) + (1|Stock)	21	16	154.95	7.74
s(Susceptibility, $k=4$) + GSA	(1| YS) + (1|Stock)	19	15	153.74	6.53
s(Productivity, $k=4$) + GSA	(1| YS) + (1|Stock)	19	15	151.05	3.85
s(Productivity, $k=4$) + GSA	(1|Stock)	18	15	149.20	2.00
s(Susceptibility, $k=4$) + GSA	(1| Stock)	18	15	152.04	4.83
s(Productivity, $k=4$)	(1| YS)	5	2	170.20	22.98
Productivity + GSA	**(1|Stock)**	**17**	**15**	**147.20**	**0**

GSA) based on the PSA scores of all the species. We predicted F/F_{msy} for 151 species in 14 GSAs for a total of 2114 species-areas combinations (Fig. 4). A stock is classified as being exploited unsustainably with respect to F_{msy} when $F/F_{msy} > 1$, as this is current practice in Europe. However it should be noted that higher rates than F_{msy} could be sustainable (capable of maintaining steady, albeit low, population sizes) but not providing the maximum sustainable yield.

Table 3
Testing of the yearly rate of change from trawl survey CPUE against PSA derived scores, results for the best model.

Parametric coefficients	Estimate	Std. Error	t Value	Pr(>|t|)
(Intercept)	−2.447	0.8237	−2.970	0.0048
Susceptibility	0.223	0.0980	2.275	0.0278
Zone Tyrrhenian	1.875	0.7889	2.376	0.0219
***R*-sq. (adj)**	0.164l			

Please cite this article in press as: Osio, G.C., et al., Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. Fish. Res. (2015), http://dx.doi.org/10.1016/j.fishres.2015.02.005

Table 4
Testing of the exploitation ratio (F/F_{msy}) of the assessed stocks against PSA derived scores, results for the best model (Fmod7g).

Random effects				
Groups	Name	Variance	Std. Dev.	
Stock	Intercept	0.07658	0.2767	
Residual		0.21720	0.4660	
Parametric coefficients	**Estimate**	**Std. error**	***t* Value**	**Pr(>|t|)**
(Intercept)	2.7718	0.81297	3.409	0.001045
productivity	−0.53861	0.34391	−1.566	0.121475
GSA5	−0.26019	0.31319	−0.831	0.408707
GSA6	−0.17435	0.28231	−0.618	0.538699
GSA7	−0.46582	0.28545	−1.632	0.106844
GSA9	−0.69858	0.26853	−2.601	0.011151
GSA10	−0.79105	0.29703	−2.663	0.009444
GSA11	−0.43313	0.29708	−1.458	0.148976
GSA15–16	−0.70646	0.29594	−2.387	0.019467
GSA17	−0.33946	0.30947	−1.097	0.276141
GSA18	−0.49665	0.31774	−1.563	0.12219
GSA19	0.07684	0.35994	0.213	0.83152
GSA20	−1.34881	0.36524	−3.693	0.000415
GSA22–23	−1.20328	0.3482	−3.456	0.000901
GSA25	0.01	0.41381	0.024	0.980774
***R*-sq. (adj)**	0.3971			

Number of obs: 91, groups: stock, 10.

Over all areas, only 39 species-area combinations are estimated as being exploited sustainably ($F/F_{msy} < 1$) while the remaining 2075 are exploited unsustainably with respect to F_{msy} ($F/F_{msy} > 1$). The species exploited sustainably are only in area 20 (Greece), and the area where the highest exploitation is predicted is area 19 (Italy). The predicted mean F/F_{msy} for the assessed stocks is well in line with the observed F/F_{msy}, although some observations of F/F_{msy} for *M. merluccius* are outside the prediction Confidence Intervals, but are at the same time extremely high (Fig. 4 in Appendix A). Full predictions are reported in Supplementary Materials (file "predicted_F_Fmsy.csv"). Overall we predict that ≈ 98% of the unassessed demersal fish species are potentially overexploited in the evaluated areas. The 95% confidence intervals on the estimates of F/F_{msy} are quite wide and reflect the uncertainty in the model. For 371 area-species combinations the stock could be exploited sustainably since the lower confidence interval falls below $F/F_{msy} < 1$.

Kernel densities estimates of the distribution of predicted exploitation were produced for each area (GSA) by grouping the species in their Superfamily (Fig. 5). The groups of Torpediniformes, Squaliformes and Rajiformes have the highest predicted exploitation in all areas and span a wider range of exploitation ratios

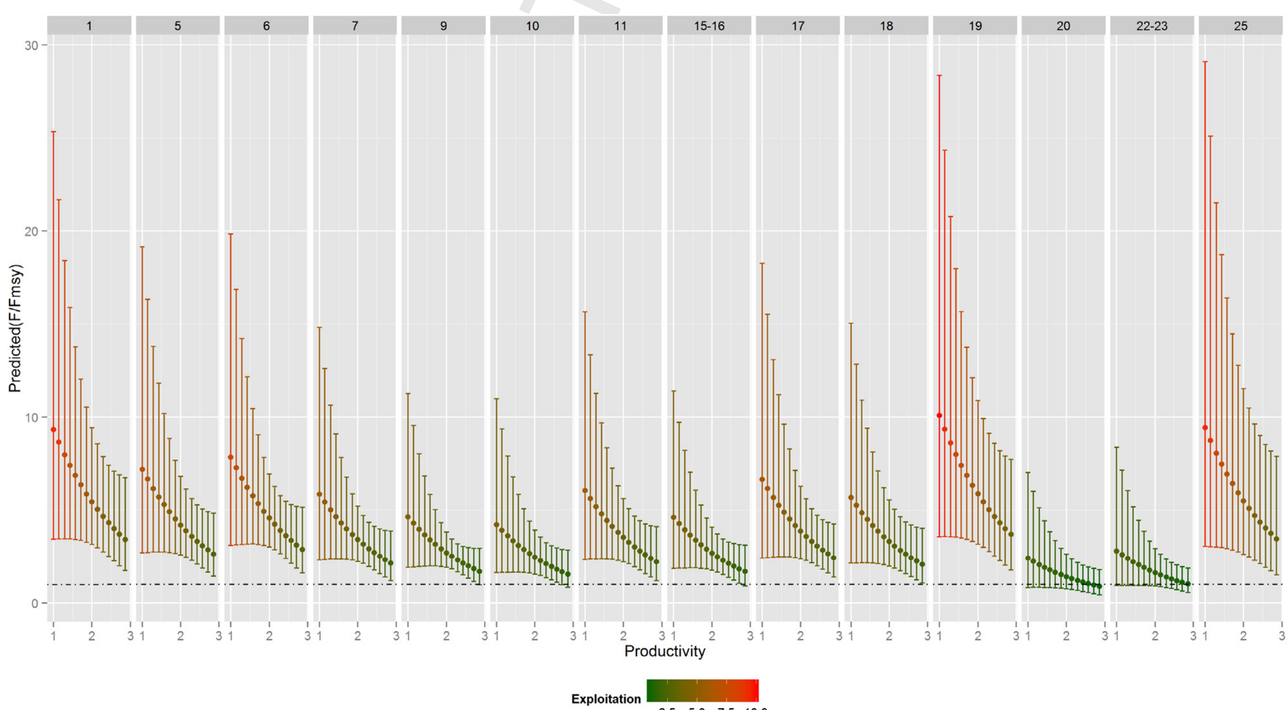

Fig. 4. Predicted exploitation levels where each panel is one GFCM statistical units GSA (1–25) or joint areas, with 95% Confidence Intervals, from the best model with the productivity estimates derived in the PSA. The horizontal line at $y = 1$ separates exploitations predicted being sustainable ($F/F_{msy} < 1$) from the unsustainable in respect to F_{msy} one ($F/F_{msy} > 1$).

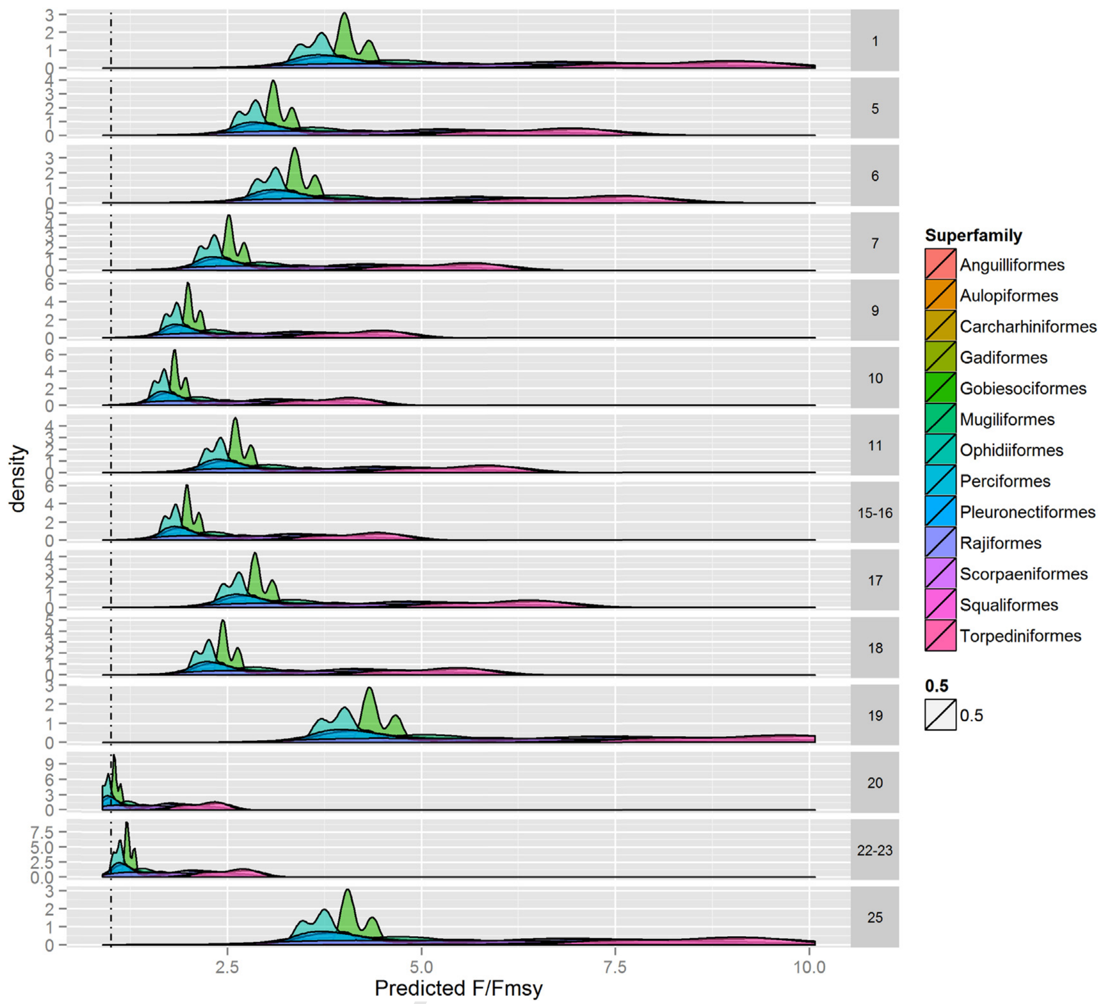

Fig. 5. Kernel density of predicted exploitation levels where each panel is one GFCM statistical units GSA (1–25) or joint areas, from the best model, grouped by Superfamily. The vertical line at $x = 1$ separates exploitations being sustainable ($F/F_{msy} < 1$) from the unsustainable in respect to F_{msy} one ($F/F_{msy} > 1$).

than Mugiliformes and Gobesciformes. Superfamilies with only one species could not be visualized in Fig. 5.

4. Discussion

4.1. PSA

The PSA approach is conceptually similar to other semi-quantitative risk assessments that evaluate extinction risk based upon biological productivity and categorization of life-history parameters (e.g. Musick, 1999; Roberts and Hawkins, 1999; Cheung et al., 2005). However, PSA differs from these approaches in that it addresses vulnerability to overfishing by considering not only the biological productivity of the stock, but also the degree to which fisheries can impose mortality upon the stock. While the utility of PSA is more limited than fully quantitative methods, such as the Sustainability for Fishing Effects model (Zhou and Griffiths, 2008), it is more widely applicable in situations where information is limited (Ormseth and Spencer, 2011).

The restricted range of susceptibility scores from the present analysis could be rectified by modifying the scoring thresholds to generate greater contrast among stocks. However, we do not choose to this here, because the goal of this analysis is to estimate vulnerability in relation to an overall standard appropriate for the range of managed species. In our study, a lack of contrast in susceptibility scores may simply reflect a fisheries behavior where targeting is concurrent on many species.

Certain species (for example *Dicentrarchus labrax*, *Lophius piscatorius*, *Eutrigla gurnardus* and *Zeus faber*) are classed as highly vulnerable and belong to the species for which EU Member States are obliged to collect data but are currently not being assessed in the Mediterranean Sea. Here the PSA indicates both high risk and need of assessing these stocks.

The PSA analysis clearly shows the high risk for most of the elasmobranchs (Fig. 2, top right panel). This is not surprising given the life history traits of this subclass (Cope et al., 2011). From a fisheries management perspective, the high vulnerability, and evidence that many species have already disappeared from different Mediterranean areas (Ferretti et al., 2005, 2013), calls for prompt conservation measures and additional analysis.

4.2. Comparison with annual rate of change

For the analysis of the rate of change of elasmobranchs population based on survey CPUE in relation to PSA scores, the best fitted model explains a small portion of total variance. This result is similar to Ferretti et al. (2005) who regressed life history traits against yearly rates of change in CPUE and found low correlation between the two.

In this analysis, we included cartilagineous fishes for which the rate of change had been estimated by Ferretti et al. (2005, 2013),

Please cite this article in press as: Osio, G.C., et al., Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. Fish. Res. (2015), http://dx.doi.org/10.1016/j.fishres.2015.02.005

and this prior study did not estimate the rate of change for any bony fishes. Restricting analysis to cartilaginous fishes limited the range of productivity (2.2–1.0) and susceptibility (2.0–3.0) (Fig. 2, top right panel) to the, respectively, low and high part of the spectrum, thus without great contrasts. If decline rates of bony fish were also available, the relationship between rate of decline (from trawl survey data) and productivity/susceptibility might have been more significant.

In general, availability of survey CPUE indices would be a more robust approach to determine if some stocks are at risk of collapse. Ferretti et al. (2005, 2013) is unique in presenting available trends in CPUE since the 1940s. Only one standardized survey has been performed in the Mediterranean since 1994 (MEDITS) and it could be used to explore trends in abundance. However, using indices from this survey would be severely biased because, in 1994, the exploitation had already been high for the previous 30–40 years and the trends would not be very informative (see Ferretti et al., 2013).

4.3. Modeling F/F_{msy} in relation to PSA scores and area

The method proposed here to predict F/F_{msy} is novel in using PSA scores, but at the same time relies on prior analysis sharing a similar meta-analytical philosophy (Costello et al., 2012; Thorson et al., 2012; Thorson et al., in press), and on the "Robin Hood" approach (Punt et al., 2011). It depends on a number of assumptions that we have listed to clarify strengths and potential weaknesses. The first assumption is that stock assessments and F reference points are correct and, if they are not, all the predictions are biased. The assessment results used here are the biggest and only body of assessments available and are used for current management.

The second assumption is that assessed stocks are a random subset of all stocks. If there is bias in selecting the stocks (Thorson et al., in press) for assessment, this might reflect on the predictions. Based on the PSA results, the assessed stocks cover a wide range in terms of productivity but a narrower range for susceptibility (Fig. 1). There are few assessments for stocks at high and low vulnerability; in particular, cartilagineous fish have only two assessments. This could generate a problem of extrapolating outside the area where the model is parameterized. To test the goodness of prediction for highly vulnerable species, we included in the PSA species that were present in the past but are now very rare or eradicated, such as sturgeons (Acipenseriformes) and angel sharks (Squatiniformes). The predicted exploitation for these species ranges between 6 and 10 (Supplementary Materials (file "predicted_F_Fmsy.csv")). This indicates that these species would not withstand current levels of exploitation. The predictions for less susceptible stocks might be overly pessimistic, and including in the training set some assessments for low susceptibility stocks would improve the confidence in the results for these species. Therefore, it would be advisable to perform additional stock assessments for low susceptibility species as well as for more cartilagineous fish.

A third assumption is that fisheries targeting is on the demersal assemblage as a whole and not on specific stocks. We believe this assumption is not violated, given the high number of commercial demersal stocks in the Mediterranean and the fishery being essentially a mixed fishery (Raetz et al., 2013). There might be slight area differences in targeting, but these are, to a certain degree, accounted for with the F ratios of the assessed stocks.

The level of exploitation in a GSA strongly affects the prediction. If all the assessed stocks are overexploited, predicted status of the unassessed will depict the same situation. The predicted F ratios are more or less robust depending on the number of stock assessments performed in each area. In the case of the Greek areas 20 and 22–23, three stocks had analytical assessments in each area (*M. merluccius*, *M. barbatus* and *M. surmuletus*). In this case, the predictions for 151 species in the two areas are based on only six assessments for three species. In other areas, predicted F/F_{msy} are more robust since more stock assessment data was used to train the model. For example, in GSA 9 (Ligurian-North Tyrrhenian Sea), 14 assessment results were used.

The confidence intervals of the predicted exploitation reflect the uncertainty entering in the model from the variability in F ratio of the stocks in each area, but do not account for the uncertainty in the estimates of F and F_{msy}. Uncertainty is not estimated in most of the original stock assessments since they are performed with virtual population analysis and F_{msy} (in most cases $F_{0.1}$) is derived by Yield per Recruit analysis. Therefore, uncertainty around the predictions is underestimated.

We cannot properly include uncertainty in stock assessment estimates of exploitation ratios until integrated assessments are conducted in the Mediterranean region. However, in regions with integrated assessments that estimate uncertainty in exploitation ratios, the prediction of F ratio could properly propagate uncertainty if it is available from assessed stocks. In these cases, it should enter in the prediction model either via a weighting function in the regression model or via a parametric bootstrap.

We performed the PSA at a Mediterranean basin level to try to address the need of knowing the vulnerability of all the unassessed demersal fish stocks. Additionally we proposed a new method to predict stock status and applied it to all the areas for which we had some assessments. Since some small differences between areas can exist in terms of fisheries targeting or discarding, our prediction might not be precise at species/area level but we believe this paper brings enough evidence to support the fact that the wider picture is correct. More localized PSAs could be performed (similarly to Abella et al., 2011) in many areas and would likely return results with finer resolution. However, performing 25 PSAs to cover all Mediterranean areas would be a daunting task. In particular, regional PSAs would still need to borrow information from other areas, given the scarcity of data, and it would not be possible to use a meta-analysis approach such as the one taken here.

The PSA combined with the prediction model proposed here is a first step towards measuring the vulnerability of Mediterranean demersal fish. While there could be further validation of this approach with simulation testing and an expansion of the training dataset, we believe that it is valid to estimate whether an un-assessed stock is exploited sustainably or unsustainably with respect to Fmsy. However, given the high uncertainty associated with the method proposed, derived results should be used only for ranking species regarding future research, assessment prioritization and precautionary management.

As the number of assessed stocks will increase in the different areas as well as the quality of some PSA scores, future updates of the current analysis will return better predictions on exploitation ratios. The model for exploitation rate based on PSA scores will continue to not have much information for cartilagineous fish unless more analytical assessments become available. The method proposed here is not meant to replace stock assessment, which remains the most robust way of assessing stock status, but to complement it when stock assessment can't be performed.

5. Conclusions

Many new assessments need to be performed in the Mediterranean Sea to achieve the MSY target of the Common Fisheries Policy by 2015–2020 as well as MSFD descriptor-3 goals. Clearly, having full analytical assessments for more than 100 species in all the Mediterranean GSAs is an impossible target due to lack of data and scientific man power. The first step to address this need is to prioritize the stocks that deserve more attention. For this we applied a PSA analysis to 151 Mediterranean demersal fish species. Out of 151 species, 58 displayed low vulnerability, 20 medium vulnerability 25 high vulnerability and 48 were considered of major concern. Most of the cartilagineous fish fell in the high and major risk areas but implementing strong conservation measures should be a clear policy target, even if performing analytical assessments of these is practically impossible or not defensible in terms of investing man power. To derive a ranking of priority stocks to be assessed, vulnerability scores were scaled with landings and mean price per stock. This new method balances vulnerability and fisheries importance and the estimated list appears robust for new assessment selection.

We regressed vulnerability scores against rates of change from survey CPUEs for cartilagineous fish and found a significant relationship although variance-explained was low. We regressed exploitation ratio (F/F_{msy}) of assessed stocks against PSA scores and area and found a significant relationship with higher variance explained. Given this result, assessed stocks were used as a training set to predict the exploitation of un-assessed stocks, based on area and productivity scores. This prediction model, with some limitations, can be used to predict fishing mortality relative to F_{msy} when no information on stock status is available. Our model predicts that approximately 98% of the unassessed demersal fish species are potentially overexploited in the evaluated areas.

We believe that approaches like PSA and the prediction of exploitation ratio based on PSA scores could be applied to the most data-poor situations where not even landings time series are available. This should be a first step in a tiered approach that could be quickly applied to all unassessed stocks. If landings are available, catch only methods, like the ones tested in a recent FAO report (Rosenberg et al., 2014), as well as catch curve stock-reduction analysis (Thorson and Cope, 2015), could be applied to identify B/Bmsy. When a survey index (either length or age disaggregated) is also available, simple statistical catch at age or length models should be applied, such as the newly developed “a4a” model (Jardim et al., 2014). With these three increasingly data demanding and robust methods, it will be easier to determine the status of the many unassessed Mediterranean fish stocks. Achieving MSY by 2015–2020 will strongly depend on management and political commitment to drastically reduce fishing effort from the current levels. In the NE Atlantic this reduction already happened and many stocks are recovering (http://ices.dk/community/advisory-process/Pages/Latest-Advice.aspx). It is time that strong management action is now taken in the North Mediterranean to move away from a situation where 95% of the assessed and potentially 98% of the unassessed demersal fish are overexploited.

Q8 Uncited references

Bax and Knuckey (1996), Beverton (1992), Dankel et al. (2008), Davis (2002), European Commission (2012), European Commission, 2013, Froese and Binohlan (2000), Hoenig (1983), ICES (2013), Pauly et al. (1998), Simpfendorfer et al. (2008), Thompson (1993), Wood (2011).

Acknowledgments

We are grateful to two anonymous reviewers and the editors for constructive comments and suggestions that greatly improved the paper. We thank EC JRC for supporting the authors during the analysis, STECF EWG MED for producing the stock assessments results used in this paper, Finlay Scott, Iago Mosqueira, Ernesto Jardim, Franca Contini and Dimitiros Damalas for constructive discussion.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2015.02.005.

References

Abella, A., Mancusi, C., Serena, F., 2011. Sustainability of by-catch of sharks and finfish in a Norway lobster fishery. In: GFCM Workshop on Stock Assessment of Selected Species of Elasmobranchs, Brussels.

Astles, K.L., Holloway, M.G., Steffe, A., Green, M., Ganassin, C., Gibbs, P.J., 2006. An ecological method for qualitative risk assessment and its use in the management of fisheries in New South Wales, Australia. Fish. Res. 82, 290–303.

Bates, Douglas, Maechler, Martin, Bolker, Ben, 2013. lme4: Linear mixed-effects models using S4 classes. In: R package Version 0. 999999-2, ⟨http://CRAN.R-project.org/package=lme4⟩.

Bax, N.J., Knuckey, I., 1996. Evaluation of selectivity in the south-east fishery to determine its sustainable yield. In: Final Report to the Fisheries Development Corporation Project 1996/40.

Bertrand J. A., L. Gil de Sola, C., Papaconstantinou, G. Relini & A. Souplet, 2000. An international bottom trawl survey in the Mediterranean: the Medits programme, Demersal resources in the Mediterranean. Proceedings of the symposium held in Pisa, 18-21 March 1998. J.A. Bertrand & G. Relini eds. Ifremer, Plouzané. Actes de Colloques 26: 76-93.

Beverton, R.J.H., 1992. Patterns of reproductive strategy parameters in some marine teleosts fishes. J. Fish Biol. B 41, 137–160.

Broadhurst, M.K., Suuronen, P., Hulme, A., 2006. Estimating collateral mortality from towed fishing gear. Fish Fish. 7, 180–218.

Cheung, W.W.L., Pitcher, T.J., Pauly, D., 2005. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. Biol. Conserv. 124, 97–111.

Cordue, P.L., 2012. Fishing intensity metrics for use in overfishing determination. ICES J. Mar. Sci. J. Cons., http://dx.doi.org/10.1093/icesjms/fss036.

Cope, J.M., DeVore, J., Dick, E.J., Ames, K., Budrick, J., Erickson, D.L., Grebel, J., Hanshew, G., Jones, R., Mattes, L., Niles, C., Williams, S., 2011. An approach to defining stock complexes for U.S. west coast groundfishes using vulnerabilities and ecological distributions. N. Am. J. Fish. Manage. 31 (4). Q9

Costello, C., Ovando, D., Hilborn, R., Gaines, S.D., Deschenes, O., Lester, S.E., 2012. Status and solutions for the world's unassessed fisheries. Science 338 (6106), 517–520.

Dankel, D.J., Skagen, D.W., Ulltang, O., 2008. Fisheries management in practice: review of 13 commercially important fish stocks. Rev. Fish Biol. Fish. 18, 201–233.

Davis, M.W., 2002. Key principles for understanding fish bycatch discard mortality. Can. J. Fish. Aquat. Sci. 59, 1834–1843.

European Commission, 2012. The 2012 Annual Economic Report on the EU Fishing Fleet (STECF-12-10).

European Commission Regulation No. 1380/2013. ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:354:0022:0061:EN:PDF⟩. Q10

Ferretti, F., Myers, R., Sartor, P., Serena, F., 2005. Long term dynamics of the Chondrichthyan Fish Community in the Upper Tyrrhenian Sea ICES. Theme Session on Elasmobranch Fisheries science (N). ICES Document CM 2005/N:25 (25 pp).

Ferretti, F., Osio, G.C., Jenkins, C.J., Rosenberg, A.A., Lotze, H.K., 2013. Long-term change in a meso-predator community in response to prolonged and heterogeneous human impact. Sci. Rep. 3.

Froese, R., Binohlan, C., 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. J. Fish Biol. 56, 758–773.

Hobday, A.J., Smith, A., Stobutzki, I., 2004. Ecological risk assessment for Australian Commonwealth fisheries, final report. In: Report R01/0934 to the Australian Fisheries Management Authority. Australian Fisheries Management Authority, Canberra, Australia, ⟨http://www.afma.gov.au/research/reports/2004/r01_0934.pdf⟩ (72 p.).

Hobday, A.J., Smith, A., Webb, H., Daley, R., Wayte, S., Bulman, C., Dowdney, J., Williams, A., Sporcic, M., Dambacher, J., Fuller, M., Walker, T., 2007. Ecological risk assessment for the effects of fishing: methodology. In: Report R04/1072 for the Australian Fisheries Management Authority. Australian Fisheries Management Authority, Canberra.

Hobday, A.J., Smith, A.D.M., Stobutzki, I.C., Bulman, C., Daley, R., Dambacher, J.M., Deng, R.A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S.P., Johnson, D., Kenyon, R., Knuckey, I.A., Ling, S.D., Pitcher, R., Sainsbury, K.J., Sporcic, M., Smith, T., Turnbull, C., Walker, T.I., Wayte, S.E., Webb, H., Williams, A., Wise, B.S., Zhou, S., 2011. Ecological risk assessment for the effects of fishing. Fisheries Research 108 (2–3), 372–384.

Hoenig, J.M., 1983. Empirical use of longevity data to estimate mortality rates. Fish Bull. 82, 898–902.

ICES, 2013. ICES WKLIFE III, ⟨http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2013/WKLIFE3/Report%20WKILFE%20III.pdf⟩.

Jardim, E., Millar, C.P., Mosqueira, I., Scottl, F., Osio, G.C., Ferretti, M., Alzorriz, N., Orio, A., 2014. What if stock assessment is as simple as a linear model? The a4a initiative. ICES J. Mar. Sci., http://dx.doi.org/10.1093/icesjms/fsu050 (Journal du Conseil).

Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akcakaya, H.R., Leader-Williams, N., Milner-Gulland, E.J., Stuart, S.N., 2008. Quantification of extinction risk: IUCN's system forfor classifying threatened species. Conserv. Biol. 22, 1424–1442.

Milton, D.A., 2001. Assessing the susceptibility to fishing of populations of rare trawl bycatch: sea snakes caught by Australia's Northern Prawn Fishery. Biol. Conserv. 101, 281–290.

Musick, J.A., 1999. Criteria to define extinction risk in marine fishes. Fisheries 24 (12), 6–14.

NOAA (2010). NOAA Assessment toolbox. Productivity and Susceptibility Analysis (PSA) - Version 1.4.

Ormseth, O.A., Spencer, P.D., 2011. An assessment of vulnerability in Alaska groundfish. Fish. Res. 112, 127–133.

Osio, G.C., 2012. The historical fisheries in the Mediterranean Sea: a reconstruction of trawl gear. In: Effort and Trends in Demersal Fish Stocks. University of New Hampshire, New Hampshire (PhD dissertation).

Patrick, W.S., Spencer, P., Ormseth, O., Cope, J., Field, J., Kobayashi, D., Gedamke, T., Cortés, E., Bigelow, K., Overholtz, W., Link, J., Lawson, P., 2009. Use of productivity and susceptibility indices to determine stock vulnerability, with example applications to six U.S. fisheries. In: U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-101 (90 p.).

Q11 Patrick, Wesley S., Spencer, Paul, Link, Jason, Cope, Jason, Field, John, Kobayashi, Donald, Lawson, Peter, Gedamke, Todd, Cortés, Enric, Ormseth, Olav, Bigelow, Keith, Overholtz, William, 2010. Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. Fish. Bull. 108 (3), 305–322.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, F., 1998. Fishing down marine food webs. Science 279, 860–863.

Ricard, D., Minto, C., Jensen, O.P., Baum, J.K., 2012. Examining the status of commercially exploited marine species with the RAM Legacy Stock Assessment Database.
Q12 Fish Fish..

Roberts, C.M., Hawkins, J.P., 1999. Extinction risk in the sea. Trends Ecol. Evol. 14, 241–248.

Simpfendorfer, C., Cortés, E., Heupel, M., Brooks, E., Babcock, E., Baum, J.K., McAuley, R., Dudley, S.F.J., Stevens, J.D., Fordham, S., Soldo, A., 2008. An integrated approach to determining the risk of over-exploitation for data-poor pelagic Atlantic sharks. An Expert Working Group Report. Lenfest Ocean Program, Washington, DC (22 p.).

Stobutzki, I.C., Miller, M.J., Jones, P., Salini, J.P., 2001a. Bycatch diversity and variation in a tropical Australian penaeid fishery: the implications for monitoring. Fish. Res. 53, 283–301.

Stobutzki, I., Miller, M., Brewer, D., 2001b. Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. Environ. Conserv. 28, 167–181.

Thompson, G.G., 1993. A proposal for a threshold stock size and maximum fishing mortality rate. In: Smith, S.J., Hunt, J.J., Rivard, D. (Eds.), Risk Evaluation and Biological Reference Points for Fisheries Management, vol. 120. Can. Spec. Pub. Fish. Aquat. Sci., pp. 303–320.

Thorson, J.T., Branch, T.A., Jensen, O.P., 2012. Using model-based inference to evaluate global fisheries status from landings, location, and life history data. Can. J. Fish. Aquat. Sci. 69, 645–655.

Thorson, J.T., Cope, J., Kleisner, K., Shelton, A., Samhouri, J., Ward, E., In press. Giants' shoulders 15 years later: Lessons, challenges, and guidelines in fisheries meta-analysis. Fish Fish. doi:10.1111/faf.12061.

Thorson, J.T., Cope, J.M., 2015. Catch curve stock-reduction analysis: an alternative solution to the catch equation. Fish. Res.

Wood, S., 2006. Generalized Additive Models: An Introduction with R. Chapman & Hall/CRC Press (410 pp.). Q13

Wood, S., 2011. gamm4: Generalized additive mixed models using mgcv and lme4. In: R package version 0., pp. 1–5.

Wood, S., Scheipl, F., 2013. gamm4: Generalized additive mixed models using mgcv and lme4. In: R package version 0, ⟨http://CRAN.R-project.org/package=gamm4⟩ (2-2).

Zhou, S., Griffiths, S.P., 2008. Sustainability Assessment for Fishing Effects (SAFE): a new quantitative ecological risk assessment method and its application to elasmobranch bycatch in an Australian trawl fishery. Fish. Res. 91, 56–68.

Zuur, A.F., Ieno, N.I., Walker, N.J., Saveliev, A.A., Smith, G.M., 2008. Mixed Effect Models and Extensions in Ecology with R, 2008. Springer (547 pp.).