Fisheries Research 171 (2015) 87–100

Contents lists available at ScienceDirect

Fisheries Research

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

Having confidence in productivity susceptibility analyses: A method for underpinning scientific advice on skate stocks?

Sophy R. McCully Phillips[a,*], Finlay Scott[b], Jim R. Ellis[a]

[a] Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, UK
[b] European Commission—Joint Research Centre, Via Enrico Fermi 2749, I-21027 Ispra, VA, Italy

ARTICLE INFO

Article history:
Received 31 March 2014
Received in revised form 8 January 2015
Accepted 10 January 2015
Handling Editor Prof. A.E. Punt
Available online 12 February 2015

Keywords:
Productivity susceptibility analysis (PSA)
Celtic Sea
Elasmobranch
Skate
Data-limited

ABSTRACT

National and European shark conservation plans aim to manage elasmobranch stocks sustainably. However uncertainties and deficiencies with available data hamper traditional, quantitative assessment methods of stock status to inform those plans, and thus effective management. The International Council for the Exploration of the Sea (ICES) Expert Groups have explored a range of data deficient assessment methods that may be used to support management advice, including Productivity Susceptibility Analysis (PSA). This method was applied to the demersal elasmobranch fauna (21 species) of the Celtic Sea to explore how such approaches could inform the management of skates (Rajidae). This species complex is an important catch component for demersal trawl and gillnet fisheries and is currently managed under a mixed species total allowable catch (TAC). PSAs were conducted on both of these fisheries, by four experts from three countries to introduce independence, and to quantify the range in perceptions of each stock. Confidence scoring of attributes was incorporated and probability distributions generated to model uncertainty in the expert responses to susceptibility attributes. Results showed that three shark species (tope, *Galeorhinus galeus*; angel shark, *Squatina squatina* and spurdog, *Squalus acanthias*) were the most vulnerable species in both fisheries (a consequence of their life history strategy and large size), followed by two skates (otter trawl) and three skates (gillnet). All of these species have some form of restrictive management and, apart from tope, are either currently listed as prohibited species or have a zero TAC in the area. Blonde ray, *Raja brachyura* was ranked as the next most vulnerable member of the commercially exploited skate complex. This adaptation of the PSA approach enabled skate species of higher and lower risk to be ranked and thus inform where management efforts should be focussed, whilst giving a novel consideration to uncertainty through canvassing expert opinion.

1. Introduction

In European waters, scientific agencies have only been able to assess the size of fish stocks, fishing mortality rates and catch levels for just over one third of commercial stocks (e.g. CEC (2009a) 224, Annex II). This is often because scientific advice and assessments are hampered by inaccurate commercial data (e.g. landings, discards and effort), limited biological knowledge (e.g. age and growth, natural mortality and reproductive output), or limitations of fishery-independent survey data. For example fishery-independent surveys were designed to monitor stocks of commercially important roundfish and flatfish, thus the fishing gears used, seasons and areas sampled are sub-optimal for capture of many elasmobranch species. Some groups of fish that are not assessed currently (e.g. because they are deemed of less commercial importance in overall landings) can be highly susceptible to the impacts of fishing and there is an increased focus to consider and advise on such species under the ecosystem approach to fisheries management (EU, 2013). The UK's 'Shark, Skate and Ray Conservation Plan' (Defra et al., 2011) aims: "*To manage elasmobranch stocks sustainably so that depleted stocks recover and that those faring better are fished sustainably*", yet to progress towards such targets for data deficient species, despite the inherent uncertainties, novel and robust assessment and management procedures are required.

Following the United Nations Code of Conduct for Responsible Fisheries (FAO, 1995), the "*best scientific evidence available*" should be used to evaluate the state of any fisheries to support decisions, while the precautionary approach to fisheries management requires a formal consideration of uncertainty. In order to address such principles, various risk-based approaches have been considered for data-limited, multi-species scenarios. These include Ecological Risk Assessments (ERAs), which attempt to evaluate the

* Corresponding author. Tel.: +44 0 1502 527754.
E-mail address: sophy.mccully@cefas.co.uk (S.R. McCully Phillips).

http://dx.doi.org/10.1016/j.fishres.2015.01.005

vulnerability of a species or stock to overfishing based on its biological sensitivity or productivity, and its susceptibility to the main fisheries operating over their geographic range.

Within an ERA framework a hierarchical approach may be taken to evaluate the effects of fishing. The approach moves from a largely qualitative analysis of risk that can involve stakeholder judgement (level one), through a semi-quantitative approach (e.g. Productivity Susceptibility Analysis (PSA), level two) to a fully quantitative approach (level three), which requires appropriate data to be available (Hobday et al., 2011). In this way, the vulnerability of a species to a fishery (and fishing gear) is assessed (Fletcher, 2005; Griffiths et al., 2006). ERA approaches have expanded from single species applications to help implement the ecosystem-based approach for fisheries management (Smith et al., 2007; Zhou et al., 2009), allowing rapid assessment of the potential species at risk within an ecosystem to particular fisheries and gears, including within multispecies fisheries (Stobutzki et al., 2002; Hobday et al., 2011).

Elasmobranchs are generally considered as vulnerable to overfishing (Ellis et al., 2008 and references cited therein), as they are often long-lived, slow growing and of low fecundity.

While there are, or have been some directed fisheries for these species in the Northeast Atlantic, many of these species represent ‘bycatch’, a proportion of which is retained. The commercial importance of the various species, which is related to the market value, size and condition of individual fish, and technical regulations (e.g. quota availability and minimum landing sizes) influences discard/retention patterns in commercial fisheries (Silva et al., 2012). There is frequently limited information on the biology of many elasmobranch species, in particular key Northeast Atlantic skate species, and on their interactions with commercial gears and discard survival rates. As a result, analytical assessments have been possible for only a few elasmobranch species. In fact, ICES (The International Council for the Exploration of the Sea) has only benchmarked[1] one elasmobranch assessment—spurdog, *Squalus acanthias* (De Oliveira et al., 2013); with management advice for other species based primarily on temporal trends in relative abundance from scientific trawl surveys. Nevertheless, given the requirements for precautionary management, and the introduction of the European Commission’s Community Plan of Action for sharks (CEC, 2009b), there is an increasing need to provide some form of advice for a wider group of elasmobranch species.

‘Semi-quantitative’ PSAs have been considered for elasmobranch species around the world (see Gallagher et al., 2012 for a review), including pelagic elasmobranchs in the Atlantic Ocean (Simpfendorfer et al., 2008; Cortés et al., 2010; Arrizabalaga et al., 2011) and for those taken in the deepwater fishery to the west of the British Isles (Watling et al., 2011; Dransfeld et al., 2013). These examples vary both in the number and range of taxa through to their methodological interpretation of a PSA. Similarly, the extent to which expert opinion is canvassed, and the method by which this is achieved (blind scoring or through consultation) varies, as does the consideration of uncertainty in such scores. The importance of quantifying uncertainty and canvassing expert opinion to improve decision making was emphasised by Aspinall (2010). While this variability implies that a ‘one size fits all’ approach may not be operationally optimal, some level of testing and standardisation is required to allow direct comparison, and to incorporate the PSA method into the provision of management advice.

[1] An intense process for evaluating the current data and assessment methodology. The aim of a benchmark is consensus agreement on an assessment methodology that is to be used in future update assessments, laid down in a stock annex. The result will be the ‘best available’ method on which ICES advice can be based on (ICES website—21 February 2013).

The level to which PSAs may feed into management measures varies, but as a minimum they can help identify the most vulnerable species within a fishery, and thus where future management efforts and advice should be directed. They may also have a role in exploring the efficacy of management options designed to reduce the susceptibility of species of concern. The advantages of any management measures, however, would be specific to the fishery examined and could also depend on factors such as the fixed biological characteristics of the most vulnerable species, political drivers, data availability, industry compliance and feasibility.

Until 2012, assessing and advising on stocks of uncertain status and limited data was not achievable within ICES through their traditional frameworks. ICES provides advice for over 200 stocks, yet ICES (2012a) determined that 122 do not have population estimates from which catch options can be derived using the existing MSY framework, and are considered ‘data-limited’ (ICES, 2012b). Given the drive to provide and implement some form of quantitative management advice for increasing numbers of stocks, ICES developed a framework of data-limited approaches in 2012 (ICES, 2012a,c). Within this framework there are six categories of data deficiency, with associated methodological recommendations made at each level, with PSA’s recommended for both category five (‘data-poor stocks’) and six (‘negligible landings stocks and stocks caught in minor amounts as bycatch’) stocks (ICES, 2012c). However, this approach can also be applied across the board to include data rich stocks, as a means to identify the relative vulnerability of species to fisheries, and to distinguish species of high and low risk. Some data-limited methods by their nature adopt a precautionary approach, where decreasing information increases the margin of precaution, thus moving the stock in the direction of sustainable exploitation, whilst having due regard for the species’ biological characteristics and uncertainty in the information (ICES, 2012b).

Two ICES expert groups investigated the application of PSAs in their 2013 meetings (ICES, 2013a,b); including demersal elasmobranchs in the Celtic Sea, which were considered a category six stock (ICES, 2012c). In this paper we undertake a level two PSA (Hobday et al., 2011), with emphasis on the skate complex of the Celtic Sea, in order to evaluate the utility of the PSA approach to multi-species fisheries management, whilst incorporating expert scoring and probability modelling of uncertainties.

2. Materials and methods

2.1. PSA framework and attributes

To evaluate the skate complex of the Celtic Sea, an existing PSA framework was updated, based upon biological productivity characteristics and their susceptibility to the fisheries that catch them. The NOAA toolbox (http://nft.nefsc.noaa.gov/index.html) PSA framework (Patrick et al., 2009) was used to assess nine data-limited rajid stocks (for which ICES provides advice) from the Celtic Sea ecoregion in two demersal fisheries (otter trawl and gillnet), with an additional four prohibited skates and eight other elasmobranch taxa included for comparison. These additional species, for which greater information were available, were used for ‘ground-truthing’.

As per Patrick et al. (2009), vulnerability was assumed to be influenced by two components: the productivity or biological sensitivity of the stock (related to its biological characteristics) and its fisheries susceptibility (related to the likely impact of the specific fishery/gear on the stock). Each of these components comprised a number of different traits or factors.

Several different attributes and approaches were examined throughout the PSA process. After consultation with fisheries

Table 1
Productivity attributes used in the PSA. Those in normal font were as used in the NOAA PSA framework (Patrick et al., 2009), attributes modified from NOAA are shown in **bold**, and additional attributes shown in ***bold italics***.

Productivity attributes	Low (1)	Moderate (2)	High (3)
R	<0.16	0.5–0.16	>0.5
Maximum age	>30 years	10–30 Years	<10 Years
Maximum size	>150 cm	60–150 cm	<60 cm
von Bertalanffy growth coefficient (*k*)	<0.15	0.15–0.25	>0.25
Estimated natural mortality	<0.20	0.20–0.40	>0.40
Measured fecundity	**<10**	**10–100**	**>100**
Breeding strategy	**Live bearer**	**Demersal egg layer**	**Broadcast spawner**
Breeding cycle (female)	***Bi/Triennial***	***Annual cycle with a seasonal peak***	***Annual cycle with protracted breeding season or with multiple broods per year***
Recruitment pattern	infrequent recruitment success (<10% of year classes are successful)	moderately frequent recruitment success (between 10% and 75% of year classes are successful)	highly frequent recruitment success (>75% of year classes are successful)
Age at maturity	>4 years	2–4 years	<2 years
Mean trophic level	>3.5	2.5–3.5	<2.5
Genetic distinctness	***In this region, this species is the only one in its family***	***In this region, this species is the only one in its genus***	***In this region, this species is one of several in its genus***

managers and biologists in the ICES community, it was decided to form this PSA on the criteria used in the NOAA toolbox (Patrick et al., 2009) as a baseline, whilst also recognising that each application of a PSA may require modification to improve the relevance to particular stocks and management areas. Therefore the attributes used were modified slightly to better address some of the biological characteristics more specific to elasmobranchs. Twelve productivity attributes were employed in this PSA (Table 1). Two of these attributes (measured fecundity and breeding strategy) were modified from the default NOAA toolbox, to better distinguish between the life history strategies of elasmobranchs. Two new attributes (breeding cycle and genetic distinctness) were also added to the assessment.

Similarly, the majority of susceptibility attributes within the NOAA PSA approach were used. Thirteen attributes were included (Table 2), of which three (fishery importance, management applicable and monitoring (or assessment) of status) were added attributes. These three attributes, which were considered discrete issues, were used to replace the single ‘management strategy’ attribute used in the NOAA toolbox. Another attribute (‘fishing rate relative to M’) was excluded, as this is unknown for all species included in this assessment. A small modification was made to ‘value of fishery’ to remove the actual dollar or retention values, and make the scoring more qualitative in terms of desirability without giving exact monetary definitions. Given the international fishing occurring in these waters, and that experts from three different

Table 2
Susceptibility attributes used in the PSA. Those in normal font were as used in the NOAA PSA framework (Patrick et al., 2009), attributes modified from NOAA are shown in **bold**, and additional attributes shown in ***bold italics***.

Susceptibility Attributes	Low (1)	Moderate (2)	High (3)
Fishery	***Non-commercial species in this fishery***	***Important bycatch in mixed fisheries and/or targeted in seasonal/localised fisheries***	***Important target fisheries operate or have operated in recent times (for this metier)***
Management applicable	***Landings or catches strictly regulated for much of the stock area***	***Landings or catches partly regulated for the stock area***	***No management measures for the species/species-complex***
Monitoring (or assessment) of stocks	***Appropriate monitoring to inform on stock status***	***Limited data can inform on trends in catches or landings***	***Insufficient data to evaluate status***
Areal overlap	<25% of stock occurs in the area fished	Between 25% and 50% of the stock occurs in the area fished	>50% of stock occurs in the area fished
Geographic distribution	Continuous: stock is distributed in >50% of the range of the fishery	Restricted: stock is distributed in 25% to 50% of the range of the fishery	Fragmented: stock is distributed in <25% of the range of the fishery
Vertical overlap	<25% of stock occurs in the depths fished	Between 25% and 50% of the stock occurs in the depths fished	>50% of stock occurs in the depths fished
Biomass of spawners (SSB) or other proxies	B is >40% of B0 (or maximum observed from time series of biomass estimates)	B is between 25% and 40% of B0 (or maximum observed from time series of biomass estimates)	B is <25% of B0 (or maximum observed from time series of biomass estimates)
Seasonal migrations	Seasonal migrations decrease overlap with the fishery	Seasonal migrations do not substantially affect the overlap with the fishery	Seasonal migrations increase overlap with the fishery
Schooling/aggregation and other behavioural responses	Behavioural responses decrease the catchability of the gear	Behavioural responses do not substantially affect the catchability of the gear	Behavioural responses increase the catchability of the gear [i.e., hyperstability of CPUE with schooling behaviour]
Morphology affecting capture	Species shows low selectivity to the fishing gear.	Species shows moderate selectivity to the fishing gear.	Species shows high selectivity to the fishing gear.
Survival after capture and release	Probability of survival >67%	33%< probability of survival <67%	Probability of survival <33%
Desirability/value of the fishery	**stock is not highly valued or desired by the fishery**	**stock is moderately valued or desired by the fishery**	**stock is highly valued or desired by the fishery**
Fishery impact to EFH or habitat in general for non-targets	Adverse effects absent, minimal or temporary	Adverse effects more than minimal or temporary but are mitigated	Adverse effects more than minimal or temporary and are not mitigated

Table 3
Data quality scores (adapted from Patrick et al., 2009).

Data quality score	Description
1	**Best data:** Information based on collected data for the stock and area of interest that is both established and substantial.
2	**Adequate data:** Information with limited coverage and corroboration, or not wholly reliable.
3	**Limited data:** Estimates with high variation and limited confidence, or based on similar taxa.
4	**Very limited data:** Expert opinion or based on general literature review from wide range of species, or from outside study area.
5	**No data:** No information to base score on.

countries contributed their scores, a common currency was not available or suitable in this case.

Each individual biological productivity or susceptibility attribute was given a score of between 0–3 for each species (with bridging values of 1.5 and 2.5 permitted). Each attribute was also given a 'weight' (i.e. how much consideration is given to this attribute in the assessment). Following Patrick et al. (2009), the default score was two (where each attribute would be given equal importance), with a range of zero (i.e. excluded from the assessment) to four (of greatest importance). The weights assigned to each attribute remained constant across all species within an assessment and for each fishery assessed. The attribute score multiplied by the weight gives the 'weighted attribute score'. Furthermore, for each attribute scored per species, the 'data quality' was also scored between zero and five (Table 3).

2.2. Incorporating expert judgement

Given that biological productivity does not change between fisheries and that these attributes are less subjective, the authors scored these attributes based on literature and expert opinion, and they were not sent out to the national experts to score independently. However, to ensure accuracy, these scores were verified by an internationally renowned European expert for elasmobranch biology (with over 30 years of experience), and consensus achieved.

Four national experts (from three European countries, with between six and 20 years in elasmobranch research) scored the susceptibility attributes. Experts scored 13 attributes for the 21 species in both the demersal otter trawl and gillnet fleets. They also provided a data quality score (Table 3), and assigned weightings (between zero and four, the higher the score, the more 'weight' that attribute carries within the assessment) that they believed appropriate to each of the 13 attributes. Weightings were assigned to attributes using the modal values attained, and did not change between species within a gear, or between the two gears themselves.

2.3. Incorporating confidence

The NOAA PSA includes a 'Data Quality' score, which implies the overall quality of the data or belief in the score rather than the actual type of data used in the analysis (Patrick et al., 2010). This results in five tiers, ranging from the best data (or high belief in the score) to no data (or little belief in the score) (Patrick et al., 2010). In this study, the authors wanted to tease apart the two elements, and score the quality of the data (giving the 'Data Quality' score) independently from the confidence of each expert in the score they assigned to the attributes (giving an additional 'Confidence' score). Given the geographic spread and varying levels of fishery knowledge of the experts involved, we wanted to capture this information, whereby an expert can be more confident in a score than available data would suggest, and vice versa. Therefore, as an alternative, a 'Confidence Score' (adopted from the Intergovernmental Panel on Climate Change, IPCC, 2005) was added. These had the values: low, medium, high, very high, which represented a degree of confidence of being correct as 0.2, 0.5, 0.8 and 0.9 respectively (Table 4). Each susceptibility attribute for each species was given an individual confidence score by all assessors for each gear type (Fig. 1).

Table 4
Confidence scoring (adapted from IPCC, 2005). 'Very Low' score omitted, as assessors would not score a species or an attribute they had such low confidence in.

Terminology	Degree of confidence in being correct
Low	About 2 out of 10 chance of being correct
Medium	About 5 out of 10 chance of being correct
High	About 8 out of 10 chance of being correct
Very high	About 9 out of 10 chance of being correct

The confidence scores were used to model the susceptibility attribute scores as beta probability distributions (Holt et al., 2014). The susceptibility scores were rescaled from their original values to between 0 and 1 (i.e. scores of 1, 1.5, 2, 2.5 and 3 were rescaled to 0.167, 0.333, 0.5, 0.667 and 0.833). These rescaled attribute scores were used as the modes of the distributions. The confidence scores (0.2, 0.5, 0.8 and 0.9, see Table 4) were used as the area under the probability distribution function (pdf) in the range around the mode $\pm 1/12$ (the distance between modes divided by 2), i.e. when sampling a value from the distribution, the more confident the expert is, the more likely the value will be closer to the mode (the rescaled attribute score) (Fig. 2). A distribution was generated for all of the 20 combinations of susceptibility attribute score and confidence level.

2.4. Modelling confidence of expert responses

The weightings (0–4) assigned to each attribute were incorporated with the susceptibility attribute distributions to generate distributions for the weighted susceptibility scores by species and gear. This was carried out by calculating the weighted susceptibility (sum (weight × score)/sum (weight)) value for each expert, then averaging across experts to get the 'final' weighted susceptibility distribution.

This followed the method employed by Uusitalo et al. (2005) who noted: "*the probability distributions of the experts were combined by simple average since there is evidence that simple combinational methods outperform group judgements* (Gigone and Hastie, 1997) *compared with more complex combinational rules* (Clemen and Winkler, 1999)". By treating the expert's probabilities equally and symmetrically, they can also be considered exchangeable (Clemen and Winkler, 1999). This method allowed examination of how the weighted susceptibility scores differed between experts.

For each species and gear combination, 500 samples were taken from each individual attribute distribution of each expert. These were rescaled back to the original attribute score range (0–3) and used to calculate 500 weighted susceptibility scores by each expert. These were then averaged across experts to give a distribution of weighted susceptibility. Each expert was given equal weight in the analysis.

2.5. Combining weighted susceptibility and productivity scores

The weighted productivity score was combined with our samples from the weighted susceptibility score to calculate the overall

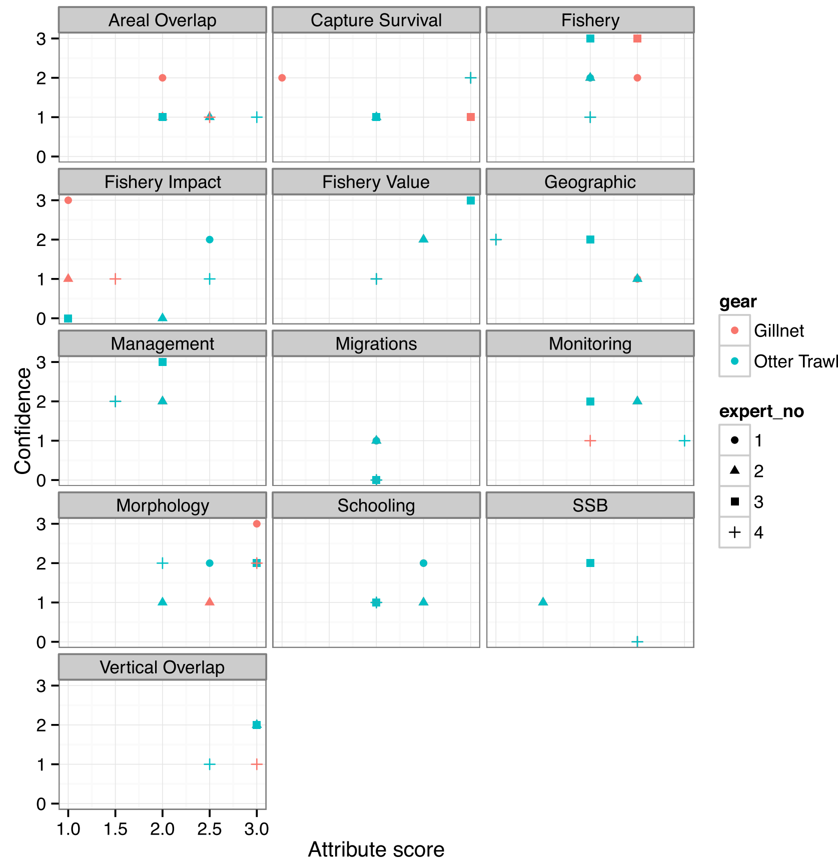

Fig. 1. Example confidence and susceptibility attribute scores by expert for blonde ray.

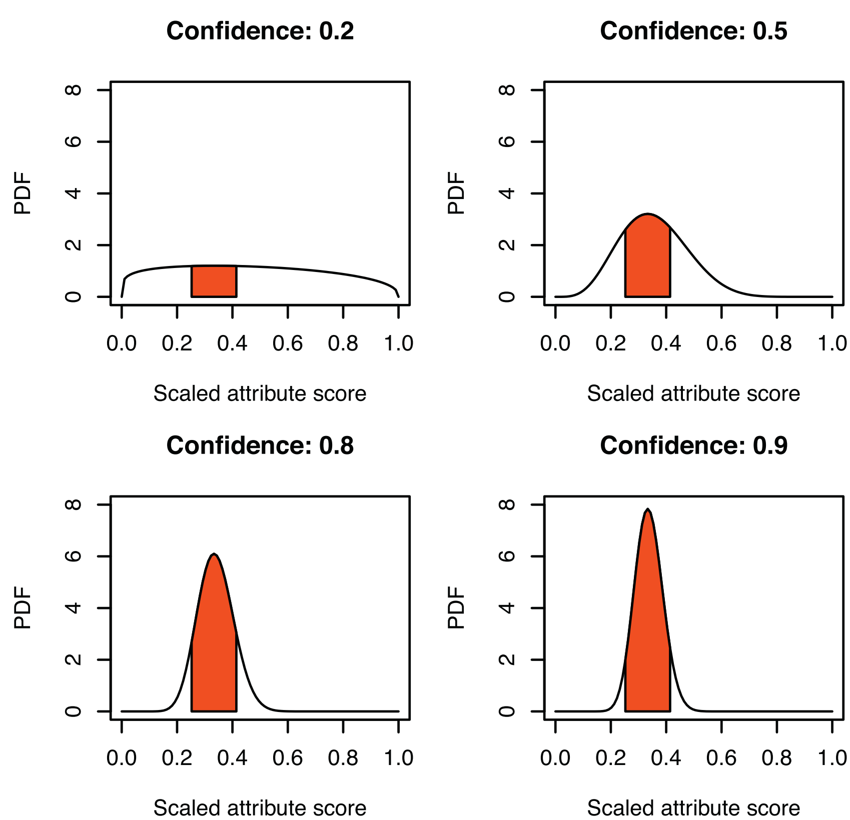

Fig. 2. Beta distribution for attribute score of 1.5 (mode = 0.33). The coloured region shows the area of probability distribution that contains the attribute score. As confidence increases, the distribution tightens around the mode.

PSA (i.e. vulnerability) score. This vulnerability score (v) is defined as the Euclidean distance of the weighted productivity (p) and weighted susceptibility (s) scores from the origin on the scatter plot (i.e. 3.0, 1.0) using the equation (Patrick et al., 2009, 2010):

$$v = \sqrt{(p-3)^2 + (s-1)^2}.$$

The vulnerability scores were input into the NOAA toolbox PSA spreadsheet, to give the final PSA scatter plots, where productivity scores are plotted (x-axis) in reverse (3 to 1) against susceptibility scores (y-axis), allowing the most vulnerable species (i.e. low productivity and high susceptibility) to be identified in the top right hand corner of the plot.

3. Results

3.1. PSA rankings

The relative vulnerabilities (final PSA score) of all species considered were ranked in terms of most to least vulnerable in relation to gillnet (Table 5, Fig. 3) and otter trawl fisheries (Table 5, Fig. 4). In the gillnet fishery, the most vulnerable species was tope, *Galeorhinus galeus* (score of 2.00), which was followed closely by five other species, all of which are currently designated as prohibited or zero TAC in the Celtic Seas ecoregion. Given the rationale of this study to look at species contained within the mixed ‘skate and ray’ TAC, the most vulnerable member of this complex was blonde ray, *Raja brachyura*, ranking eighth most vulnerable, with a vulnerability score of 1.75. Blonde ray was followed by two large bodied *Dipturus* spp. (long-nose skate, *D. oxyrinchus* and Norwegian skate, *D. nidarosiensis*)—both deeper water species for which knowledge of their biology is limited. Results in the otter trawl fishery were broadly similar, with angel shark, *Squatina squatina* ranking as the most vulnerable (1.98), followed by tope and then three prohibited or zero TAC species (spurdog, white skate, *Rostroraja alba* and flapper skate *Dipturus* cf. *intermedia*), with blonde ray again deemed to be the most vulnerable member of the mixed skate TAC complex (1.74) for this gear.

The data quality score for biological productivity (which is the same over both gears) ranged from low (e.g. angel shark) to high. Spurdog was the only species that achieved a ‘high’ data quality score for productivity (and the only species to have a robust quantitative stock assessment). Nine species scored ‘low’ and eleven scored as ‘medium’ data quality. Within fisheries susceptibility, all species in both fisheries achieved a data quality score of ‘medium’.

The expert scores for productivity varied very little, and consensus was achieved easily. The range of scores for fisheries susceptibility also varied relatively little, and the only attribute where a ‘high’ and ‘low’ score was achieved simultaneously was for ‘Desirability/value of the fishery’, which was simply a misinterpretation of prohibited/zero TAC species (and a lack of clear scoring instructions for this attribute, under changing management regimes) and was quickly rectified following a clarification by the lead author.

3.2. Modelling confidence of expert responses

The beta distributions resulting from the attribute score and confidence, for each species by expert and gear were plotted to examine the spread of these data. Example distributions for three contrasting species (blonde ray; lesser-spotted dogfish, *Scyliorhinus canicula* and angel shark) are shown (Fig. 5). Where only two or three distributions are evident, more than one expert gave the same combination of attribute and confidence score.

In some cases the agreement was very high, for example blonde ray ‘fishery’ attribute, where all experts concluded the same attribute score, but with slightly different levels of confidence, but

Table 5
Results of the PSA vulnerabilities and overall rankings for elasmobranchs in the gillnet and otter trawl fisheries in the Celtic Sea.

Species	FAO code	Both gears		Otter trawl		Gillnet		Otter trawl		Gillnet	
		Productivity		Susceptibility		Susceptibility		Vulnerability		Vulnerability	
		Weighted attribute score	Weighted data quality Score	Weighted attribute score	Weighted data quality Score	Weighted attribute score	Weighted data quality Score	Score	Rank	Score	Rank
Tope (*Galeorhinus galeus*)	GAG	1.33	2.88	2.07	2.85	2.11	2.80	1.98	2	2.00	1
Angel shark (*Squatina squatina*)	AGN	1.29	3.82	2.00	3.22	1.97	3.07	1.98	1	1.97	2
Spurdog (*Squalus acanthias*)	DGS	1.39	1.97	2.06	2.00	2.12	1.94	1.93	3	1.96	3
White skate (*Rostroraja alba*)	RJA	1.52	3.55	2.10	3.37	2.16	3.48	1.85	4	1.88	4
Flapper skate (“*Dipturus intermedia*”)	RJB1	1.50	2.79	2.06	2.98	2.12	2.98	1.83	5	1.87	5
Electric ray (*Torpedo nobiliana*)	TTO	1.48	4.06	1.93	3.00	1.95	3.06	1.78	6	1.79	7
Common skate (“*Dipturus batis* (cf. *flossada*)”)	RJB2	1.65	2.94	2.13	2.77	2.18	2.72	1.76	7	1.79	6
Blonde ray (*Raja brachyura*)	RJH	1.76	3.03	2.22	2.61	2.24	2.63	1.74	8	1.75	8
Long-nosed skate (*Dipturus oxyrinchus*)	RJO	1.71	4.00	2.16	3.32	2.14	3.31	1.73	9	1.72	10
Norwegian skate (*Dipturus nidarosiensis*)	JAD	1.65	3.88	2.04	3.35	2.10	3.36	1.70	10	1.74	9
Starry smooth-hound (*Mustelus asterias*)	SDS	1.70	2.91	2.10	2.42	2.12	2.45	1.70	11	1.72	11
Shagreen ray (*Leucoraja fullonica*)	RJF	1.77	3.76	2.14	2.91	2.19	2.86	1.67	12	1.71	12
Sandy ray (*Leucoraja circularis*)	RJI	1.77	3.76	2.12	3.42	2.14	3.47	1.66	13	1.68	13
Small-eyed ray (*Raja microocellata*)	RJE	1.80	3.03	2.10	2.56	2.12	2.60	1.63	14	1.64	15
Marbled electric ray (*Torpedo marmorata*)	TTR	1.67	3.82	1.93	3.02	1.95	3.09	1.63	15	1.64	16
Undulate ray (*Raja undulata*)	RJU	1.86	2.88	2.12	2.84	2.19	2.78	1.60	17	1.65	14
Thornback ray (*Raja clavata*)	RJC	1.89	2.24	2.18	2.44	2.11	2.44	1.61	16	1.56	17
Spotted ray (*Raja montagui*)	RJM	1.98	2.55	2.10	2.55	2.10	2.56	1.50	18	1.50	18
Cuckoo ray (*Leucoraja naevus*)	RJN	1.98	2.42	2.06	2.46	2.07	2.51	1.46	19	1.48	19
Greater spotted dogfish (*Scyliorhinus stellaris*)	SYT	1.98	3.88	1.92	2.80	1.90	2.79	1.37	20	1.35	20
Lesser spotted dogfish (*Scyliorhinus canicula*)	SYC	2.09	2.67	1.91	2.03	1.82	2.02	1.29	21	1.22	21

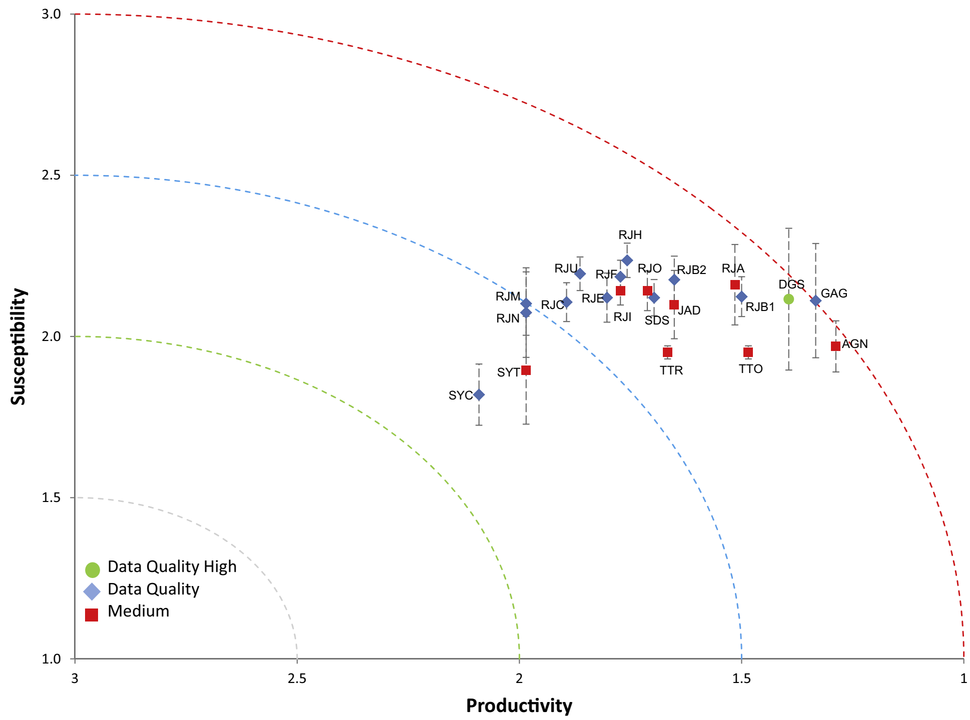

Fig. 3. PSA plot of vulnerabilities for Celtic Sea skates (and other elasmobranchs) in the demersal gillnet fishery. See Table 5 for species codes.

in other cases, like the 'monitoring' attribute, the experts returned a spread of attribute scores.

Further examination of these data was undertaken by plotting the distributions for the weighted susceptibility scores by species and gear (Figs. 6 and 7), to see how these scores differed between experts. Trends in scores could be identified across experts, for example expert four had the lowest confidence in their scores for all species and both fisheries assessed, while expert one was usually more confident in their scores. Trends in confidence also varied within individual experts depending upon the species—for example, expert one was more confident in relation to spurdog (DGS, in Fig. 6), but very unsure of the susceptibility scores for Norwegian skate (JAD) in both fisheries.

There was a striking resemblance between both fisheries assessed, with the average probability distributions (Fig. 8) mirroring each other. While some species were considered more

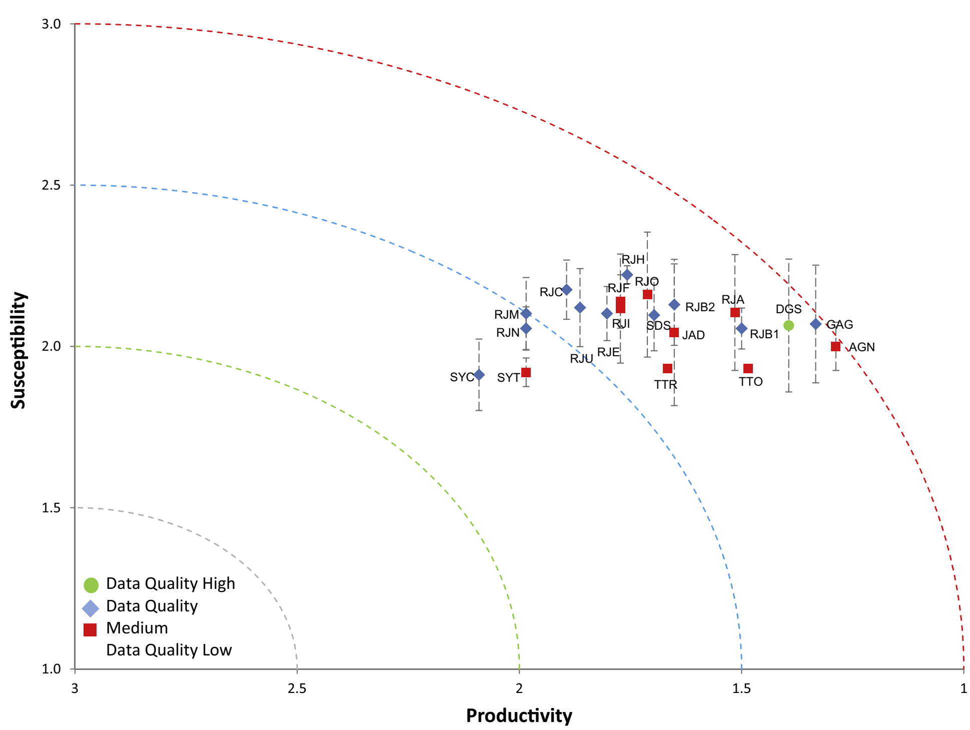

Fig. 4. PSA plot of vulnerabilities for Celtic Sea skates (and other elasmobranchs) in the demersal otter trawl fishery. See Table 5 for species codes.

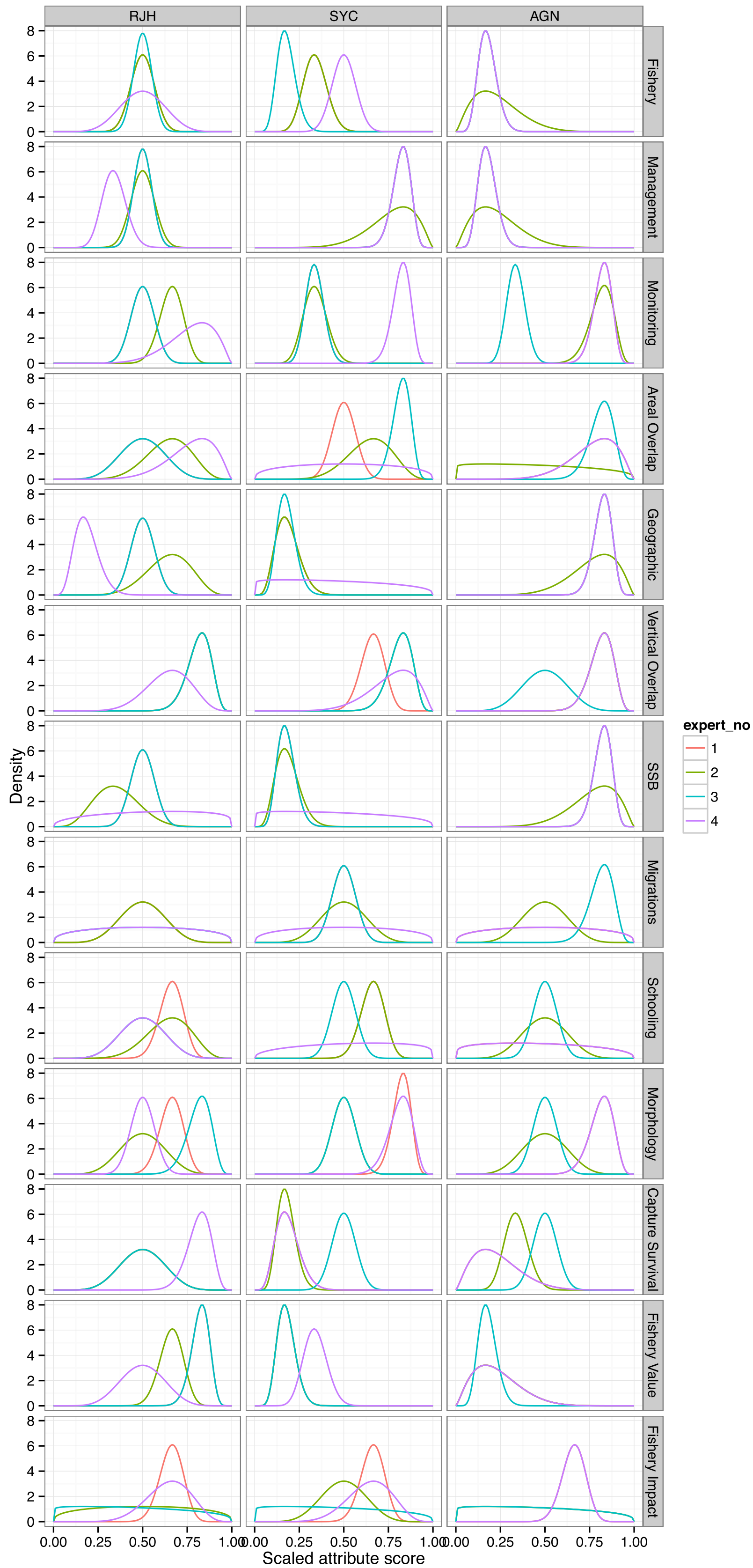

Fig. 5. Beta distributions for the attribute susceptibility score for three example species, blonde ray (RJH), lesser-spotted dogfish (SYC) angel shark (AGN), given by experts in relation to otter trawl fisheries.

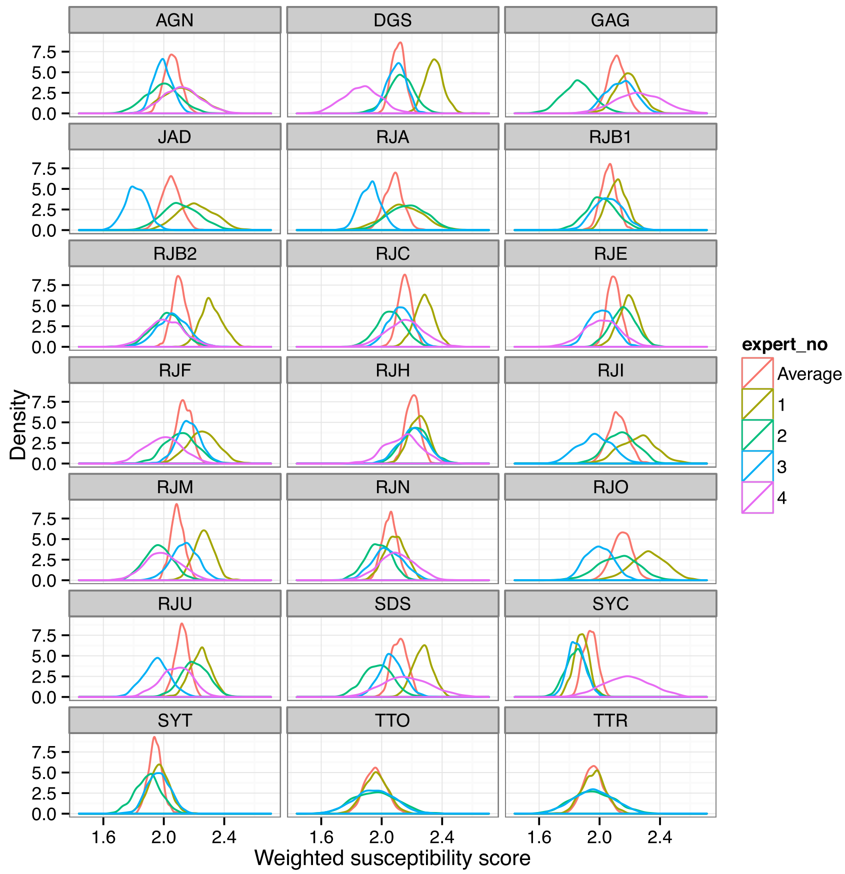

Fig. 6. Distribution of the weighted susceptibility scores by expert and averaged across experts for elasmobranchs taken in otter trawl fisheries. See Table 5 for species codes.

susceptible in gillnet fisheries than otter trawl fisheries, and vice versa, the actual probability curves were almost identical in most cases. Fifteen of the 21 species assessed were considered more vulnerable in gillnet fisheries than otter trawl, however in five of these cases, the vulnerability score was just 0.01 more. Five species were considered to be more vulnerable in otter trawl fisheries, including three species of shark (lesser- and greater-spotted dogfish, *Scyliorhinus stellaris* and angel shark). The largest variation in vulnerability score received between the two fisheries was lesser-spotted dogfish (SYC), which was the most biologically productive species in this assessment, and ranked least vulnerable overall in both fisheries. The most commercially important skate for the UK, in terms of quantities landed, is thornback ray, *Raja clavata* (RJC), which was considered to be more vulnerable in otter trawls than gillnets.

4. Discussion

4.1. PSA rankings

This assessment was conducted primarily to assess the relative vulnerabilities of the various skates, caught in mixed fisheries, currently managed under a common TAC in the Celtic Seas ecoregion. The inclusion of other elasmobranchs allowed comparison to be drawn between six different families of elasmobranch, thereby allowing slightly different life histories to be included. A previous study (McCully et al., 2012) investigated whether data rich teleosts with quantitative stock assessments could be used to 'ground-truth' the elasmobranch results. Those results, however, were inconclusive, with elasmobranchs clustered together on the PSA plot as a result of their life history being so different to most teleosts. It was for this reason that the PSA developed here was conducted on just elasmobranchs with the attributes selected to better reflect their biological differences and so tease them apart.

That tope ranked as the most vulnerable of the case study species in the gillnet fishery and second in otter trawl fisheries is initially surprising, as neither of these fishing methods would be used to target this species in practice. Although tope represent a small proportion of the bycatch in both fisheries, their large size and extremely low reproductive potential (1.33) renders them most vulnerable in this assessment. Tope fishing around the UK has been largely recreational, with occasional bycatch being landed; numbers caught were never great enough to sustain a target fishery. Given their low numbers and productivity, conservative precautionary management was put in place in UK waters, in the form of the 'Tope (Prohibition of Fishing) Order (2008)', with measures including the prohibition of fishing for tope (other than by rod and line), a 45 kg per day limit on tope that are brought onboard, and the prohibition of persons to land tope in England that are beheaded or captured from rod and line. Angel shark (ranking most vulnerable in the otter trawl- and second in the gillnet assessment) is a very rare species, extirpated from much of its former range (Rogers and Ellis, 2000). This species would only very occasionally be caught accidentally, yet its low reproductive potential (1.29) and large uncertainties surrounding much of its biology lead to a high overall vulnerability. Angel shark is subject to the highest form of protection in UK waters through their listing on the Wildlife and Countryside Act, and also being on the list of prohibited species, where it is prohibited for EU vessels to fish for, to retain on board, to tranship and to land angel shark in EU waters (Council Regulations (EC) 23/2010, 57/2011, 43/2012, 39/2013 and 43/2014).

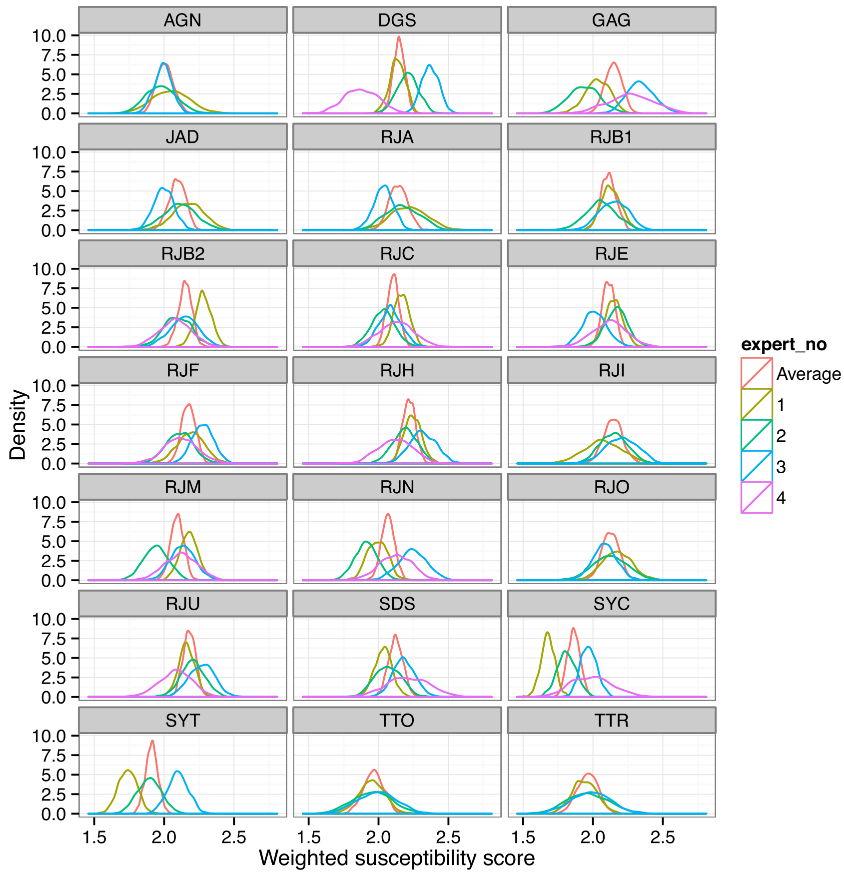

Fig. 7. Distribution of the weighted susceptibility scores by expert and averaged across experts for elasmobranchs taken in gillnet fisheries. See Table 5 for species codes.

Following tope and angel shark (both under strict management) in the rankings, were four species that are all either currently listed as prohibited species or a zero TAC species (spurdog, the common skate-complex and white skate). Similarly, the remaining species included to ground-truth the commercial skate, at the other end of the spectrum also generated intuitive rankings. Lesser-spotted dogfish ranked the least vulnerable in both fisheries. This species is widespread throughout the British Isles, is one of the most fecund elasmobranchs and has been increasing in fishery dependent surveys since at least the early 1990s. Its sister species, the greater-spotted dogfish, was ranked next least vulnerable. Other species including electric ray, *Torpedo nobiliana*, starry smooth-hound, *Mustelus asterias*, and marbled electric ray, *Torpedo marmorata*, ranked between sixth and sixteenth. Again these rankings all appear credible given their respective body sizes, largely non-commercial nature, fecundity and distributions. With earlier attempts to 'ground truth' this PSA in mind, it is reassuring that the stocks considered the most depleted and for which restrictive management has been introduced recently, were ranked as most vulnerable.

The relative rankings for the commercial skate species landed within the generic TAC also appear plausible, with the larger bodied and less widespread species (e.g. blonde ray, long-nosed skate, Norwegian skate, shagreen ray, *Leucoraja fullonica*, and sandy ray, *Leucoraja circularis*), for which no appropriate monitoring is available, being ranked higher (eighth to thirteenth), than others within the assemblage. The most commercially important ray, thornback ray was ranked 16th and 17th most vulnerable in the otter trawl and gillnet fisheries respectively. This species, although relatively large bodied, is more productive than its compatriots, is widespread across the area, and unlike many of the other skate and rays has appropriate monitoring through fisheries independent surveys, from which trends in stock status can be estimated. Credibly, the smaller bodied, widely distributed species also with informative stock trends (i.e. spotted ray, *Raja montagui*, and cuckoo ray, *Leucoraja naevus*) ranked lowest in the skate and ray assemblage.

Of course, as a data-limited method, there are several drawbacks within it, including a limit on the many aspects of a complex system of biology and fisher behaviour that can be considered. Devine et al. (2012) exposed several weaknesses in the PSA technique and scoring of attributes, stating that the "*susceptibility criteria need to be re-evaluated*". ICES (2012b) stated that "*these weaknesses need to be further explored within the context of stocks for which ICES provides advice*". However, some of the 'weaknesses' identified by Devine et al. (2012) were mitigated against in our PSA application, by better tailoring the attributes to the species being assessed. For example, the 'management strategy' attribute (included by Patrick et al., 2009) was modified to address three distinct attributes (commercial nature of the stock, management in place and stock monitoring) to better reflect the state of the population rather than just whether management strategies are in place. Fisher behaviour was considered in this assessment under the introduced 'Fishery' attribute, detailing whether stocks were non-commercial, important bycatch or highly commercial and targeted—an essential attribute to be accounted for with respect to fisher discard and retention patterns.

A limitation in the current application is the disregard of selectivity varying by life history stage. There is clearly varying size selection of species in different gears. Currently species are assessed irrespective of actual body size (rather their maximum attainable size) or life history stage, when, for example, a juvenile ray would be more susceptible to capture in otter or beam trawl than large meshed gillnets, whilst larger skates may not be caught in beam

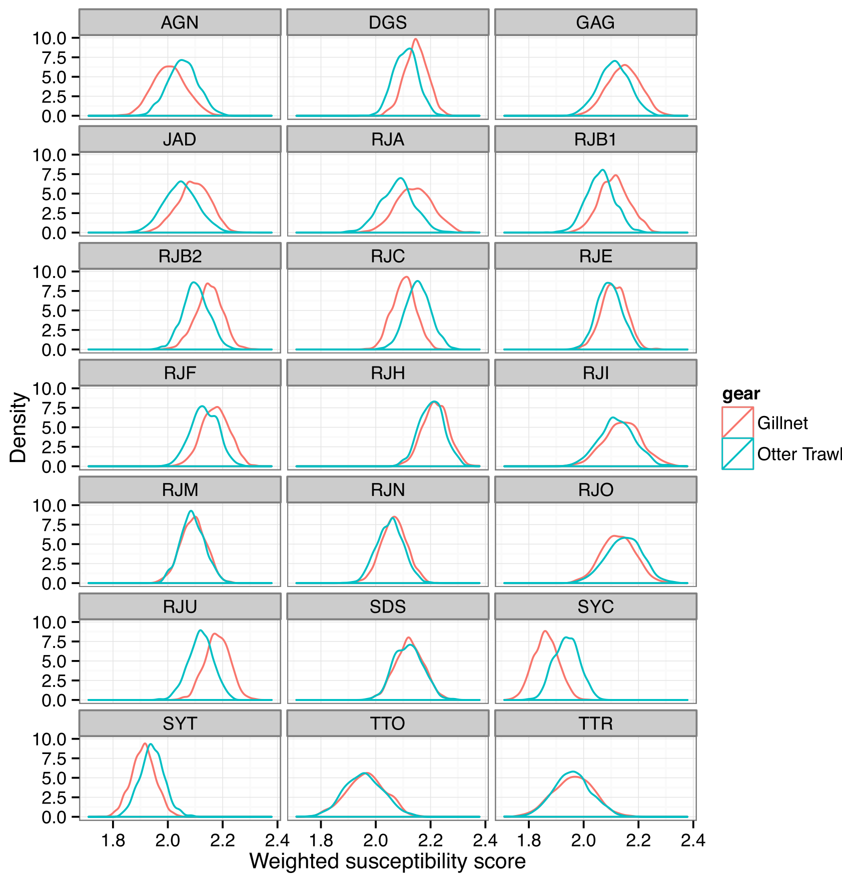

Fig. 8. Distribution of the averaged weighted susceptibility scores in otter trawl and gillnet fisheries. See Table 5 for species codes.

trawls (Silva et al., 2012). This could be incorporated in future assessments, with species broken down into juveniles and adults as a minimum and assessed separately. This could further assist where necessary in subsequently identifying effective management interventions.

This study chose to assess the otter trawl and gillnet fisheries, as these are the main gears catching skates and rays in this area. Although the susceptibility attributes were given due consideration and modification, they did not discriminate well from one another (Figs. 3, 4 and 8; Table 5) as they are both similar in terms of their area of operation, depth and target species. Additionally given that most of these species also occur on broadly similar habitat types and sediments, and have comparable morphology affecting capture, the main differences in susceptibility will be derived from differences in spatial distribution in this particular case study.

Although modifying attributes to fit a specific species assemblage or on a fishery by fishery basis will not allow direct comparison between PSAs, it will make each assessment more robust and appropriate for defining vulnerability of a stock relative to its compatriots. Given that species *x* is assessed relative to species *y*, in each assessment, it would be unwise to compare across different applications anyway, given the different experts involved and potential variations in PSA methodologies (e.g. Field et al., 2010).

One of the attributes introduced here was 'genetic distinctness', as some authors have suggested that taxa with low rates of speciation may be more prone to extinction (Heard and Mooers, 2000). Whilst expert opinion did not rank this attribute highly in terms of fisheries management, it may be ranked more highly if such PSA approaches are used to address biodiversity considerations, especially since monotypic families may also be deemed of greater importance in the maintenance of phylogenetic diversity (Vézquez and Gittleman, 1998). Conversely, breeding cycle was weighted of high importance to elasmobranchs by the experts, given that the fecundity attribute does not provide any indication of the frequency of breeding, which can range from multiple broods per year to triennial cycles.

4.2. Modelling confidence of expert responses

In this study the distributions of the trait scores are assumed to be independent. However, it is known that some life history traits are correlated (for example, species with high growth rates tend to also have a low age at maturity) and the same may well be true of ratings within an individual expert's assessment. The analyses would, therefore, be improved if these correlations could be quantified and incorporated into the analysis. Doing so might well lead to an increase in the 'true' uncertainty of the scores, but estimating the covariance structure of the scores would require a much larger sample size. It may therefore be better to view the differences between individual assessments as a measure of variation between the experts we used rather than an estimate of the variation in a larger population of experts or an indicator of some 'true' value of uncertainty.

The scoring of biological attributes can be agreed by a small group of experts with appropriate knowledge of life history and biology. Given the use of published material and research study results, there is no need for a large group of people to all repeat the same exercise, although here the productivity sheets were made available to all experts for review. However, it was felt more important to collate the range of views on susceptibility attributes, where a lack of published data means the scores are much more open to interpretation and scores can be more subjective.

The range in the distribution of susceptibility scores and associated confidences highlights the importance of collating a range of independently derived expert opinions, to allow these subjectivities to be 'smoothed' out. If there is a range of expertise within chosen experts, some could have their scores down-weighted, and other up-weighted. This procedure was not investigated in this study, as it was initially believed that the confidence score would allow for the spread of knowledge and quantified in this way. However Aspinall (2010) highlights the potential bias that can accompany expert confidence, where those with lowest confidence rated better in their (known-answer) seed questions (to calibrate proficiency), and thus were given more 'weight' overall in the analysis, than those who had greater confidence.

The spread of the geographic location of experts appears to have a bearing on these assessments. Although all experts were selected based on their knowledge of these species and/or fishing area, all experts will have some preconceived ideas based on their 'local' fisheries in which they have the greatest understanding. In this case, one of the experts did not score all species and several requests for expert opinion were rejected due to their lack of confidence in the area. The geographic influence needs to be given due consideration–especially as there is a wide range of species which are only targeted commercially in certain areas, and also as there can be different national and regional fishery regulations in coastal waters.

The most geographically remote expert (number four), had the lowest scoring confidence for every species and in both fisheries assessed. This indicates that possibly they were either unsure of the overall method or had limited understanding of the fisheries operating in that region. Conversely, expert one (more local to the Celtic Sea) had a much greater confidence in the species' susceptibility but less so for the less frequently encountered species.

The similar average probability distributions (Fig. 8) indicated that the experts are more confident in their knowledge of a particular species than with the more subtle technical differences in catchability of demersal gears. The incorporation of more varied fisheries (e.g. longline and beam trawl) into the assessment would provide a useful comparison, with a wider spread in susceptibility scores expected. Furthermore, in order to evaluate the potential effectiveness of management methods, all fishing pressures exerted on these species need to be given due consideration.

The overall vulnerability rankings for species based on the susceptibilities perceived by the four independent assessors, showed them to be relatively consistent (Table S1). There were only minor differences in placing, and the three assessors who scored all 21 species included the 10 highest ranking species (from the final assessment) in their individual top 14 places. The greatest difference in ranks between individual assessors was seven positions, and this was found for Norwegian skate in the gillnet assessment and starry smooth-hound in the otter trawl assessment. In the case of Norwegian skate, two of the three assessors who scored this species gave the same ranking (seventh), with the third assessor placing its vulnerability seven ranks lower (fourteenth). Given that this large bodied deepwater species was placed ninth and tenth most vulnerable overall in the gillnet and otter trawl assessments respectively, this seven rank discrepancy highlights the value of canvassing a range of expert opinions, whereby either a consensus score can be achieved following discussions, or discrepancies smoothed by averaging over scores.

4.3. Application of PSA in management of skate fisheries

These assessments have allowed the highest priority species within the skate complex to be identified, using probability modelling to convey expert opinion. The main challenge from this point is utilising such assessments to inform management advice. While the approach helps highlight where knowledge gathering and management action should be prioritised, PSAs do not have the ability to calculate the maximum sustainable yield (MSY) or an appropriate quota. That said, in the U.S.A., information generated during the PSA process has been shown to be useful in setting acceptable biological catch (ABC), for data-limited species where reliable catch data are available. A tiered approach is used to define precautionary catch limits that account for scientific uncertainty in the estimate of a stock's overfishing limit (OFL), so less productive species are managed with more precaution and a larger buffer between the ABC and OFL (Berkson et al., 2011; Carmichael and Fenske, 2011). Further potential utilisation of PSAs in assessment, could be in the incorporation of information (such as productivity estimates) in the development of priors, including intrinsic growth rate (McAllister et al., 2001; Martell and Froese, 2013), depletion (Cope et al., 2015) and fishing mortality rates (Osio et al., 2015).

For some potential methods to derive catch limits, which may employ PSA information (e.g. setting an ABC using depletion-based stock reduction analysis), a time-series of catch is required. The skate species examined in this PSA have only a very short time series of reliable catch data, as up until 2008, skates and rays were reported in generic categories, rather than to species level. Since 2008 (for the North Sea), and 2009 (for the Celtic Seas), the European Commission has obliged member states to provide species-specific landings data for the major skate and ray species, in order to improve understanding of skate stocks in the area (CEC, 2008, 2009c). Compliance with this legislation has varied from 0 to 100% by region and member state and, whilst improving, there are some data quality and species identification issues (ICES, 2013b).

With the reform of the Common Fisheries Policy (CFP) already underway in EU waters, which promotes an increase in regionalised management (CEC, 2013), and in order to meet initiatives to eliminate discards and protect sensitive species, such as elasmobranchs, there may conceivably be a move away from such high reliance on quota systems. More regionalised management could employ technical measures and effort restrictions, and PSA approaches may help promote discussions with stakeholders on how best to introduce appropriate and pragmatic management measures.

In this assessment, five of the top ranked species already have some form of restrictive management in place (prohibited status or zero TAC), based on perceived stock depletion. Therefore, managers can focus consideration on the next high ranking species to ensure that monitoring is fit for purpose, and where necessary make proactive precautionary management decisions. In the case of the skate and ray assemblage caught in mixed fisheries and managed under the generic skate TAC at present, future advice may need to be better geared towards managing the most vulnerable member of the complex (e.g. blonde ray). Managers must also remain vigilant to those species in the more intermediate rankings, whilst collecting more data for future assessments. Future management scenarios could be tested using PSAs to re-score under alternative management options (e.g. maximum landing length, minimum landing size, spatial or temporal restrictions, reduced soak time or tow duration, depth restrictions) and help identify the effects these interactions will have across all species rather than just the main target commercial or important bycatch species (e.g. Watling et al., 2011).

It may also be emphasised that, whilst PSA approaches may be useful in the initial evaluation of certain management options, it is important that fishers from relevant sectors of the fleet can be involved in such processes. Engaging stakeholders to identify the merits of those measures they deem most pragmatic would enhance the iterative process of applying PSA approaches within regional management.

5. Conclusions

This PSA approach, which incorporates the modelling of uncertainty in expert responses, has identified the relative vulnerability risk for elasmobranch species within two fisheries in the Celtic Sea. Currently this PSA cannot be used to identify appropriate catch levels. However, by expanding management to the most vulnerable commercial species (e.g. blonde ray) within a complex such as this, which is currently managed under a generic quota system, this approach can provide a starting point for investigating alternative management options. The innovative incorporation of expert opinion, probability scoring, and uncertainty modelling adds independent robustness to any rankings and subsequent advice or management priorities and measures resulting from this assessment.

Acknowledgements

The methodologies employed have been developed with the financial assistance of the UK Department for Environment, Food and Rural Affairs (projects: M1205, M1206, MA011 and M5201C), the project Defineit under the MariFish ERA-NET (ERAC-CT-2006-025989) and CEFAS project DP227W. Thanks to the anonymous national experts who assisted the scoring, to colleagues at NOAA for their assistance and the provision of their PSA spreadsheet, and to Graham Pilling, Kieran Hyder, Alastair Grant and the anonymous referees for commenting on the draft manuscript.

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.2015.01.005.

References

Arrizabalaga, H., De Bruyn, P., Diaz, G.A., Murua, H., Chavance, P., De Molina, A.D., Gaertner, D., Ariz, J., Ruiz, J., Kell, L.T., 2011. Productivity and susceptibility analysis for species caught in Atlantic tuna fisheries. Aquat. Living Resour. 24, 1–12.
Aspinall, W., 2010. A route to more tractable expert advice. Nature 463, 294–295.
Berkson, J., Barbieri, L., Cadrin, S., Cass-Calay, S.L., Crone, P., Dorn, M., Friess, C., Kobayashi, D., Miller, T.J., Patrick, W.S., Pautzke, S., Ralston, S., Trianni, M., 2011. Calculating acceptable biological catch for stocks that have reliable catch data only (only reliable catch stocks—ORCS). In: NOAA Technical Memorandum NMFS-SEFSC-616, 56 P.
Carmichael, J., Fenske, K. (Eds.), 2011. Third National Meeting of the Regional Fisheries Management Councils' Scientific and Statistical Committees. Report of a National SSC Workshop on ABC Control Rule Implementation and Peer Review Procedures. October 19–21, 2010. South Atlantic Fishery Management Council, Charleston, SC.
CEC, 2008. Council Regulation (EC) No 40/2008 of 16 January 2008 fixing for 2008 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in Community waters and, for Community vessels, in waters where catch limitations are required. Off. J. Eur. Communities L19, 1–203, Available at ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:019:0001:0203:EN:PDF⟩.
CEC, 2009a. Communication from the Commission: Consultation on Fishing Opportunities for 2010. Brussels, 12.5.2009 COM (2009) 224 final., pp. 16, Available at ⟨http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0224&from=EN⟩.
CEC, 2009b. On a European Community Action Plan for the Conservation and Management of Sharks. Brussels, 5.2.2009, COM (2009) 40 final., pp. 15, Available at ⟨http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0040&from=EN⟩.
CEC, 2009c. Council Regulation (EC) No 43/2009 of 16 January 2009 fixing for 2009 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in community waters and, for community vessels, in waters where catch limitations are required. Off. J. Eur. Communities L22, 1–205, Available at ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:022:0001:0205:EN:PDF⟩.
CEC, 2013. Regulation (EC) No 1380/2013 of the European parliament and of the council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. Off. J. Eur. Union, Available at ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:354:0022:0061:EN:PDF⟩.
Clemen, R.T., Winkler, R.L., 1999. Combining probability distributions from experts in risk analysis. Risk Anal. 19, 187–203.
Cope, J.M., Thorson, J.T., Wetzel, C.R., Devore, J.D., 2015. Evaluating a prior on relative stock status using simplified age-structured models. Fish. Res. 171, 101–109.
Cortés, E., Arocha, F., Beerkircher, L., Carvalho, F., Domingo, A., Heupel, M., Holtzhausen, H., Santos, M.N., Ribera, M., Simpfendorfer, C., 2010. Ecological risk assessment of pelagic sharks caught in Atlantic pelagic longline fisheries. Aquat. Living Resour. 23, 25–34.
De Oliveira, J.A.A., Ellis, J.R., Dobby, H., 2013. Incorporating density dependence in pup production in a stock assessment of NE Atlantic spurdog *Squalus acanthias*. ICES J. Mar. Sci. 70, 1341–1353.
Defra, 2011. Shark, Skate and Ray Conservation Plan. Defra, Available at ⟨http://archive.defra.gov.uk/environment/marine/documents/interim2/shark-conservation-plan.pdf⟩.
Devine, J.A., Watling, L., Cailliet, G., Drazen, J., Durán Muñoz, P., Orlov, A.M., Bezaury, J., 2012. Evaluation of potential sustainability of deep-sea fisheries for grenadiers (*Macrouridae*). J. Ichthyol. 52, 709–721.
Dransfeld, L., Gerritsen, H.D., Hareide, N.R., Lorance, P., 2013. Assessing the risk of vulnerable species exposure to deepwater trawl fisheries: the case of orange roughy *Hoplostethus atlanticus* to the west of Ireland and Britain. Aquat. Living Resour. 26, 307–318.
Ellis, J.R., Clarke, M.W., Cortés, E., Heessen, H.J.L., Apostolaki, P., Carlson, J.K., Kulka, D.W., 2008. Management of elasmobranch fisheries in the North Atlantic. In: Payne, A.I.L., Cotter, A.J., Potter, E.C.E. (Eds.), Advances in Fisheries Science. 50 Years on from Beverton and Holt. Blackwell Publishing, Oxford, pp. 184–228.
EU, 2013. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. Off. J. Eur. Union L354, 22–61.
FAO, 1995. Code of Conduct for Responsible Fisheries. FAO, Rome.
Field, J., Cope, J., Key, M., 2010. A descriptive example of applying vulnerability evaluation criteria to California nearshore finfish species. In: Starr, R., Culver, C., Pomeroy, C., McMillan, S., Barnes, T., Aseltine-Neilsen, D. (Eds.), Managing Data-Poor Fisheries: Case Studies, Models and Solutions. California Sea Grant Program, 1. University of California, San Diego, La Jolla, CA, pp. 229–240.
Fletcher, W.J., 2005. The application of qualitative risk assessment methodology to prioritise issues for fisheries management. ICES J. Mar. Sci. 62, 1576–1587.
Gallagher, A.J., Kyne, P.M., Hammerschlag, N., 2012. Ecological risk assessment and its application to elasmobranch conservation and management. J. Fish Biol. 80, 1727–1748.
Gigone, D., Hastie, R., 1997. Proper analysis of the accuracy of group judgements. Psychol. Bull. 121, 149–167.
Griffiths, S., Brewer, D., Heales, D., Milton, D., Stobutzki, I., 2006. Validating ecological risk assessments for fisheries: assessing the impacts of turtle excluder devices on elasmobranch bycatch populations in an Australian trawl fishery. Mar. Freshwater Res. 57, 395–401.
Heard, S.B., Mooers, A.Ò., 2000. Phylogenetically patterned speciation rates and extinction risks change the loss of evolutionary history during extinctions. Proc. R. Soc. London, Ser., B: Biol. Sci. 267, 613–620.
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. Fish. Res. 108, 372–384.
Holt, J., Leach, A.W., Schrader, G., Petter, F., MacLeod, A., Gaag, D.J., Baker, R.H.A., Mumford, J.D., 2014. Eliciting and combining decision criteria using a limited palette of utility functions and uncertainty distributions: illustrated by application to pest risk analysis. Risk Anal. 34, 4–16.
ICES, 2012a. Report of the Workshop on the Development of Assessments based on LIFE history traits and exploitation characteristics (WKLIFE), 13–17 February 2012. In: ICES CM 2012/ACOM:36. ICES, Lisbon, Portugal, pp. 122.
ICES, 2012b. Report of the ICES Advisory Committee 2012. ICES Advice, 2012., pp. 156, Book 1.
ICES, 2012c. ICES implementation of advice for data-limited stocks in 2012 in its 2012 advice. In: ICES CM 2012/ACOM 68. ICES, 42pp.
ICES, 2013a. Report of the Working Group on Biology and Assessment of Deep-sea Fisheries Resources (WGDEEP), 14–20 March 2013. In: ICES CM 2013/ACOM:17. ICES, Copenhagen, Denmark, 963 pp.
ICES, 2013b. Report of the Working Group on Elasmobranch Fishes (WGEF), 17–21 June 2013. In: ICES CM 2013/ACOM:19. ICES, Lisbon, Portugal, 649 pp.
IPCC, 2005. Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties. IPCC.
Martell, S., Froese, R., 2013. A simple method for estimating MSY from catch and resilience. Fish Fish. 14, 504–514.
McAllister, M.K., Pikitch, E.K., Babcock, E.A., 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci. 58, 1871–1890.
McCully, S.R., Scott, F., Ellis, J.R., Pilling, G.M., 2012. Productivity and susceptibility analysis: application and suitability for data poor assessment of elasmobranchs in northern European Seas. Collective Volume of Scientific Papers ICCAT, 69., pp. 1679–1698.

Osio, G.C., Orio, A., Millar, C.P., 2015. Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status. Fish. Res. 171, 110–121.

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: NOAA Tech. Memo. NMFS-F/SPO-101. U.S. Dep. Commer., pp. 90p.

Patrick, W.S., Spencer, P., Link, J., Cope, J., Field, J., Kobayashi, D., Lawson, P., Gedamke, T., Cortés, E., Ormseth, O., Bigelow, K., Overholtz, W., 2010. Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. Fish. Bull. 108, 305–322.

Rogers, S.I., Ellis, J.R., 2000. Changes in the demersal fish assemblages of British coastal waters during the 20th century. ICES J. Mar. Sci. 57, 866–881.

Silva, J.F., Ellis, J.R., Catchpole, T.L., 2012. Species composition of skates (Rajidae) in commercial fisheries around the British Isles, and their discarding patterns. J. Fish Biol. 80, 1678–1703.

Simpfendorfer, C., Cortés, E., Heupel, M., Brooks, E., Babcock, E., Baum, J., McAuley, R., Dudley, S., Stevens, J.D., Fordham, S., Soldo, A., 2008. An integrated approach to determining the risk of over-exploitation for data-poor pelagic Atlantic sharks. In: Expert Working Group Report. ICCAT.

Smith, A.D.M., Fulton, E.J., Hobday, A.J., Smith, D.C., Shoulder, P., 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES J. Mar. Sci. 64, 633–639.

Stobutzki, I.C., Miller, M.J., Heales, D.S., Brewer, D.T., 2002. Sustainability of elasmobranchs caught as by-catch in a tropical prawn (shrimp) trawl fishery. Fish. Bull. 100, 800–821.

Tope (Prohibition of Fishing) Order, 2008. Statutory Instrument No. 691. (Sea Fisheries, England), Available at ⟨http://www.legislation.gov.uk/uksi/2008/691/pdfs/uksi_20080691_en.pdf⟩.

Uusitalo, L., Kuikka, S., Romakkaniemi, A., 2005. Estimation of Atlantic salmon smolt carrying capacity of rivers using expert knowledge. ICES J. Mar. Sci. 62, 708–722.

Vézquez, D.P., Gittleman, J.L., 1998. Biodiversity conservation: does phylogeny matter? Curr. Biol. 8, 379–381.

Watling, L., Haedrich, R.L., Devine, J., Drazen, J., Dunn, M.R., Gianni, M., Baker, K., Cailliet, G., Figueiredo, I., Kyne, P.M., Menezes, G., Neat, F., Orlov, A., Duran, P., Perez, J.A., Ardron, J.A., Bezaury, J., Revenga, C., Nouvian, C., 2011. Can ecosystem-based deep-sea fishing be sustained? Report of a Workshop Held 31 August-3 September 2010, 11–11. University of Maine, Darling Marine Center, Walpole, ME, pp. 84p, Darling Marine Center Special Publication. ⟨http://digitalcommons.library.umaine.edu/sms_facpub/145/⟩.

Zhou, S., Griffiths, S.P., Miller, M., 2009. Sustainability assessment for fishing effects (SAFE) on highly diverse and data-limited fish bycatch in a tropical prawn trawl fishery. Mar. Freshwater Res. 60, 563–570.

Further reading

http://nft.nefsc.noaa.gov/index.html.