The MSY concept in a multi-objective fisheries environment - Lessons from the North Sea

Kempf Alexander [1, *], Mumford John [2], Levontin Polina [2], Leach Adrian [2], Hoff Ayoe [3], Hamon Katell [4], Bartelings Heleen [4], Vinther Morten [5], Staebler Moritz [1], Poos Jan Jaap [6], Smout Sophie [7], Frost Hans [3], Van Den Burg Sander [4], Ulrich Clara [5], Rindorf Anna [5]

[1] Thunen Inst Sea Fisheries, Palmaille 9, D-22761 Hamburg, Germany.
[2] Univ London Imperial Coll Sci Technol & Med, Ctr Environm Policy, Silwood Pk Campus, Ascot SL5 7PY, Berks, England.
[3] Univ Copenhagen, Dept Food & Resource Econ, Rolighedsvej 25, DK-1958 Frederiksberg C, Denmark.
[4] LEI Wageningen, Alexanderveld 5, NL-2585 DB The Hague, Netherlands.
[5] Tech Univ Denmark, DTU Aqua, Jaegersborg Alle 1, DK-2920 Charlottenlund, Denmark.
[6] Wageningen IMARES, Inst Marine Resources & Ecosyst Studies, POB 68, NL-1970 AB Ijmuiden, Netherlands.
[7] Scottish Oceans Inst, St Andrews KY16 8LB, Fife, Scotland.

* Corresponding author : Alexander Kempf, email address : alexander.kempf@ti.bund.de

Abstract :

One of the most important goals in current fisheries management is to maintain or restore stocks above levels that can produce the maximum sustainable yield (MSY). However, it may not be feasible to achieve MSY simultaneously for multiple species because of trade-offs that result from interactions between species, mixed fisheries and the multiple objectives of stakeholders. The premise in this study is that MSY is a concept that needs adaptation, not wholesale replacement. The approach chosen to identify tradeoffs and stakeholder preferences involved a process of consulting and discussing options with stakeholders as well as scenario modelling with bio-economic and multi-species models. It is difficult to intuitively anticipate the consequences of complex trade-offs and it is also complicated to address them from a political point of view. However, scenario modelling showed that the current approach of treating each stock separately and ignoring trade-offs may result in unacceptable ecosystem, economic or social effects in North Sea fisheries. Setting F-MSY as a management target without any flexibility for compromises may lead to disappointment for some of the stakeholders. To treat FMSY no longer as a point estimate but rather as a "Pretty Good Yield" within sustainable ranges was seen as a promising way forward to avoid unacceptable outcomes when trying to fish all stocks simultaneously at FMSY. This study gives insights on how inclusive governance can help to reach consensus in difficult political processes, and how science can be used to make informed decisions inside a multi-dimensional trade-off space. (C) 2016 Elsevier Ltd. All rights reserved.

Highlights

► Implementing MSY or MEY leads to a multi-dimensional trade-off space ► Ignoring trade-offs may result in unacceptable outcomes ► "Pretty Good Yield" may be a better concept than a pure MSY or MEY approach ► Inclusive governance and science can help to resolve trade-offs

Keywords : MSY, MEY, Bio-economic, Mixed fisheries, Multi species, North Sea

1. Introduction

The use of the Maximum Sustainable Yield (MSY) concept as a fisheries management objective aims to get the most from a resource over a long time period (Schaefer 1954, Beverton and Holt 1957). The MSY definition in the European Common Fisheries Policy (CFP, EU 2013) is *"the highest theoretical equilibrium yield that can be continuously taken on average from a stock under existing average environmental conditions without significantly affecting the reproduction process"*. The applicability of this definition in practice is likely to be limited to a single species with fairly stable dynamics. There are well-documented problems with the definition and performance of MSY targets in fisheries, even for a single-species if there are natural deviations from theoretical equilibrium assumptions (Mace 2001). Where there are multiple interacting species and/or multiple objectives it becomes even more difficult to simultaneously evaluate the trade-offs that inevitably occur and establish any overall optimised outcome. For management involving complex biological interactions and diverging objectives, the MSY concept may be inherently inappropriate (Matsuda and Abrams 2004, 2006; Walters et al. 2005; Mackinson et al. 2009). Larkin (1977) recognized that single species MSY cannot be achieved for all species inside an ecosystem simultaneously when biological interactions (such as predator-prey relationships) are considered. Likewise, technical interactions in mixed fisheries create major difficulties in obtaining maximum sustainable yields for several species simultaneously when species are caught together (Kraak et al. 2013). The implementation of a landing obligation (EU 2013; Article 15) renders the issue even more complex, because it is generally difficult to exhaust the individually advised quotas for all species at the same time in mixed fisheries and the most limiting quota becomes limiting for the entire fishery (Batsleer et al. 2013, Ulrich et al. 2011), the so-called "choke-species" effect.

Article 2 of the CFP (EU 2013) calls for long-term sustainability of marine resources as well as economic, social and employment benefits. The CFP also requires a precautionary and ecosystem based approach to fisheries to minimise the negative impacts of fishing activities on the marine ecosystem. Therefore, the CFP sets out a regime in which the economic and social constraints must

3

56 be respected and precaution pre-empts maximisation, leading to further potential conflicts between

57 objectives.

58 There has been a long search for alternatives to MSY that would allow for more effective fisheries

59 management. The Maximum Economic Yield (MEY) concept includes the cost of fishing and the

60 income gained, and aims to maximise profit. In single species fisheries, the fishing mortality at which

61 MEY occurs is usually at a lower fishing effort than that required for MSY (Clark 1990, Hersoug 1996,

62 Grafton et al. 2007), and typically corresponds to a limited number of fishing vessels each with large

63 profits. The shift to an economic objective still aims at maximisation of some defined and relatively

64 stable equilibrium value (Gordon 1954, Grafton et al. 2007). Subsequent to the development of MEY,

65 scientists have noted the importance of addressing wider social concerns, reflecting a desire to

66 ensure more equitable distribution of economic benefits (Hilborn 2007, Macinko and Bromley 2002).

67 The "Pretty Good Yield" concept outlined by Hilborn (2010) is an example of an attempt to

68 compromise between ecological, economic and social goals, while retaining some technical rigour.

69 Multiple objectives are difficult to address from a political and scientific perspective. Often decisions

70 must be made based on uncertain scientific results, and compromises between different

71 stakeholders must be found. Expert and preference elicitation is a way to integrate the subjective

72 opinion of different stakeholders and experts to provide decision support in conservation

73 management (Mardle et al. 2004, Smith et al. 2007, Martin et al. 2011). If decisionsare to be fully

74 accepted then opinions of stakeholders should be included in the process to help ensure legitimacy

75 of the management (Smith et al. 1999, Mardle et al. 2004, Röckmann et al. 2012).

76 A large pan-European research project (MYFISH, www.myfishproject.eu) was launched in 2012, to

77 investigate the MSY concept in depth by gathering the opinion of different stakeholders on issues

78 and trade-offs linked to various options. The project aimed to get a better understanding of the

79 applicability and the impact of alternative MSY definitions. This study describes the approach taken

80 in MYFISH to identify and evaluate alternative decision frameworks that could offer more relevant

81 management guidance than MSY (in its original definition) when applied to North Sea fisheries. The

82　focus was on the European legislation because all countries with fishing rights in the North Sea are

83　EU members, apart from Norway. The study proceeds with the premise that MSY is a positive

84　concept that needs adaptation, not wholesale replacement. Particularly the issues of (i) trade-offs in

85　objectives, (ii) the need to evaluate the whole rather than the particular, and (iii) considering

86　acceptable ranges of uncertain outcomes - not just the optimum - were addressed by combining

87　aspects of expert and preference elicitation with multi-species and mixed fisheries scenario

88　modelling. Problems that can be anticipated when implementing the MSY policy in the North Sea

89　mixed fisheries were highlighted.

90　## 2. Materials and Methods

91　The task of implementing MSY-related principles in a multi-species environment with diverging

92　objectives among different stakeholder groups is complex. The approach, directed at the specific

93　case of the North Sea fisheries, involved a process of consulting and discussing options with

94　stakeholders in four steps:

95　　1. A problem framing workshop to identify MSY objectives and constraints and determine a
96　　　ranking of options
97　　2. Two management reflection workshops to discuss the rankings and refine options
98　　3. Scenario modelling of preferred options to prepare Decision Support Tables
99　　4. A decision support workshop for stakeholder feedback and validation, based on modelling of
100　　　scenarios in which preferred options were implemented.

101　A specific issue linked to using a stakeholder-elicitation approach is to ensure that relevant

102　stakeholders attend the workshops. Systematic efforts were made throughout the project to inform

103　and invite a broad range of stakeholders. However, attendance at the various workshops remained

104　unequal in terms of number and composition of stakeholder groups (Figure 1), and composition

105　varied between workshops. The workshop records are therefore treated as a 'snapshot' of opinions.

106 **[Figure 1 here]**

107 **2.1 Problem framing workshop**

108 The problem framing workshop was held in April 2012 and was designed to establish the feasibility of

109 a range of objectives (in terms of yield or other outcomes) which could be maximised, and a range of

110 sustainability indicators that could be used to define constraints. The North Sea problem framing

111 workshop was held as part of a larger scale MSY workshop including industry representatives, NGO

112 representatives, and scientists covering several regions. As a starting point, groups with participants

113 from all European sea regions defined a list of potential objectives and constraints. These lists were

114 the basis for parallel regional groups to determine how to rank the different options. The group

115 addressing problem framing in the North Sea consisted of 12 persons (Figure 1).

116 The methodology for eliciting stakeholder views used in this workshop combined elements of open

117 group interviews and specialized elicitation tools to record opinions, reflecting both consensus and

118 differences of opinion amongst workshop attendees (Leach et al. 2014). A specially designed Excel-

119 based graphical tool was used to facilitate discussions and the documentation of conclusions.

120 Potential objectives to be maximised were listed, and participants were asked to provide ratings (R)

121 of importance for each option and to document the degree of uncertainty or disagreement in the

122 group (U) on each option. For MSY objectives (What should be maximised?), ratings and uncertainty

123 were required with respect to three aspects: i) Does the necessary information exist? ii) How

124 informative is it in relation to the objective? and iii) Is it likely that management measures will result

125 in meeting the objective? For MSY constraints only the overall importance in the region was rated.

126 An example set of plots showing distributions of ratings from the graphical tool are shown in Figure

127 2. The tool was particularly helpful for groups to visualise consensus or disagreement about different

128 aspects of an option and each participant could see that individual opinions were included within the

129 distribution. The Rating and Uncertainty for each option from the various stakeholder groups were

130 combined into a unique utility index using a matrix method (Holt et al. 2014).

131

6

132   [Figure 2 here]

133

134   **2.2 Management reflection workshops**

135   The results of the problem framing workshop were presented at two subsequent meetings in

136   October 2012 (ICES/MYFISH WKM-TRADE; ICES WKM-TRADE 2012) and in February 2013

137   (ICES/Nordic Council of Ministers (NCM) Workshop; Rindorf et al. 2013). There were 17 and 38

138   participants in these two management reflection workshops, respectively (Figure 1). While the

139   problem framing workshop was dominated by scientists, the management reflection workshops

140   included more managers, fishing industry representatives and Non-Governmental Organisations

141   (NGOs). Therefore, they provided a good forum to discuss the findings of the first workshop and to

142   determine whether the rankings are representative for a different group of stakeholders. The

143   workshops were structured with short presentations reflecting the preferred objectives and

144   constraints indicated by the Problem framing workshop followed by plenary discussions. No specific

145   elicitation tool was used in these workshops.

146   **2.3 Scenario modelling of preferred options**

147   The stakeholder opinions on objectives and constraints derived from the workshops were used to

148   identify relevant scenarios to be included in Decision Support Tables (DSTs). In these DSTs

149   stakeholders can use selected indicators to compare management decisions based on likely impacts.

150   Three DSTs were created for the North Sea demersal fisheries, focusing on different issues and types

151   of fisheries in different areas of the North Sea. The best available model was selected for each case

152   and updated to address the topic. Two DSTs focused on the mixed demersal gadoid fishery as a case

153   study (mainly distributed in the central and northern North Sea) and one on the mixed flatfish and

154   brown shrimp fishery in the southern North Sea. For simplicity, it was decided to look at trade-offs

155   resulting from biological interactions separately to those arising from technical interactions in mixed

156   fisheries. A hierarchical organisation of DSTs was used focusing first on biological interactions, then

157   on technical interactions in mixed fisheries and finally on trade-offs taking also into account the

7

158   sustainable exploitation of by-catch species and the size structure in the ecosystem (technical

159   interactions and Good Environmental Status (GES)). In all three cases, the two generic MSY objectives

160   of maximising total landings in weight and in Euros were analysed. Additional case-specific

161   optimisation scenarios were added, as described below. The scenarios tested cover extreme trade-

162   offs likely to be encountered and should be interpreted as being indicative of the broad scale

163   direction of change. All trade-offs of the various cases and scenarios were visualised using

164   standardised graphical outputs such as icon arrays that have been demonstrated to be more easily

165   understood by non-scientists while conveying a large amount of complex information (Ancker et al.

166   2006, Spiegelhalter et al. 2011).

167   ***MSY accounting for species predator-prey interactions (DST1)***

168   The effect of species interactions on long term yield and sustainability was assessed by producing

169   100 year forecasts with the stochastic multi-species model SMS (Lewy and Vinther 2004, ICES

170   WGSAM 2012). The model can produce a full stochastic forecast of stock size and catch under the

171   assumption that fish are consumed by other fish according to observed stomach contents from

172   around two hundred thousand stomachs and a diet selection model. The model describes catches of

173   the interacting species cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock (*Melanogrammus*

174   *aeglefinus*), whiting (*Merlangius merlangus*), herring (*Clupea harengus*), sprat (*Sprattus sprattus*),

175   Norway pout (*Trisopterus esmarkii*) and sandeel (*Ammodytes spec.*). Cod and saithe are top

176   predators feeding on all other species and, in the case of cod, younger conspecifics. Whiting is a mid-

177   level prey and predator feeding on juvenile cod, haddock and whiting as well as herring, sprat,

178   Norway pout and sandeel of all ages. Haddock feeds on sandeel and Norway pout only. In addition to

179   the two generic MSY scenarios, a third scenario was examined aiming for a yield in tonnes close to

180   the maximum of each species (at least 95% of maximum yield) while assuring that no species are

181   exploited unsustainably ("Pretty Good Yield" scenario). To evaluate the performance of management

182   options, for each species it was determined whether the average spawning stock biomass at

183   equilibrium was above the reference points B_{lim} (below B_{lim} there may be impaired recruitment

184 because of a low spawning stock) and B_{pa} (precautionary reference point taking into account the

185 uncertainty in the assessments to ensure that the stock was above B_{lim} with high probability). In the

186 standard MSY scenarios uncertainty was included and multiple simulations run. Outputs were tested

187 against the criterion that 95% of results had stocks staying above B_{lim} and B_{pa} . For the "Pretty Good

188 Yield" scenario only deterministic simulations and outputs were computationally feasible. B_{lim} and B_{pa}

189 were the officially agreed reference points from ICES (ICES WGNSSK 2013) - or in the case of whiting

190 – from the ICES advice on multi-species considerations for the North Sea (ICES Multi 2013).

191 ***MSY accounting for mixed-fisheries technical interactions (DST2)***

192 The multi-species multi-fleet model FISHRENT (Salz et al. 2011, Frost et al. 2013) was used to study

193 how to maximise yield under the assumption that the advised total allowable catches (TAC) are set

194 separately in a single species context but a landing obligation is implemented and fleets have to stop

195 when the first quota is exhausted. The model included 12 North Sea fishing fleets and 10 species

196 including the four gadoids cod, haddock, saithe and whiting as well as Norway pout, sandeel, herring,

197 sprat, plaice (*Pleuronectes platessa*) and sole (*Solea solea*). Given the single species F_{MSY} targets and

198 associated overall total allowable catch (TAC) of each species, the distribution of quotas over the

199 fleets was optimized to reach given objectives. The TAC for each stock was set in the model in

200 accordance with the single species F_{MSY} defined by ICES or in the case of cod the target fishing

201 mortality from the current management plan (ICES WGNSSK 2013, ICES Multi 2013, EU 2008). The

202 relative stability condition between countries, i.e. each country obtains a fixed share of the TAC, was

203 respected and only a redistribution of quotas between fleets inside a country was allowed. The two

204 generic MSY-scenarios were investigated focusing on the four gadoid target species cod, whiting,

205 haddock and saithe. In relation to MEY, a maximisation of the net present value (NPV) of the profit

206 (remuneration discount rate of 3.5% after remuneration of capital and labour) over 25 years was

207 carried out including the dynamics, moving from the present situation to the optimal situation. The

208 three scenarios were contrasted to a fourth "traditional management" scenario based on fixed quota

209 shares where no maximisation and redistribution of quotas between fleets inside a country was

210   allowed. All scenarios were constrained by the assumptions (i) that catches of all species were kept

211   below the single species TACs each year, (ii) that a landings obligation was implemented and all

212   catches were landed and sold, (iii) the maximum TAC change per year was +/- 15%, and (iv) because

213   of technological constraints, the maximum average increase in capacity (number of vessels) was

214   restricted to +4% of the capacity in the previous year. Fish prices and costs were kept constant at the

215   average 2008-2010 level throughout the 25 years simulation period. Prices and costs were extracted

216   from the account statistics of the Scientific, Technical and Economic Committee for Fisheries (STECF

217   2013).

218   ***MSY accounting for technical interactions and Good environmental status (GES) (DST3)***

219   In a third case study the long-term consequences of aiming for different objectives in the flatfish

220   (plaice and sole) and brown shrimp (*Crangon crangon*) fisheries in the Southern North Sea were

221   evaluated. An approach with paired models was chosen. The spatially explicit bio-economic model

222   Simfish (Bartelings et al. 2015) based on FISHRENT (Salz et al. 2011) and the ecosystem model

223   Ecopath with Ecosim (EwE; Christensen and Walters 2004, Christensen et al. 2008) were utilized in

224   parallel. Optimisations were carried out in Simfish and afterwards the optimized fishing effort was

225   transferred to EWE to evaluate the impact on GES related criteria for bycatch species and a large fish

226   indicator (LFI).

227   Simfish was parameterized for the fisheries targeting sole, plaice and brown shrimps including

228   German, Dutch and UK trawl fleets. In addition to the two generic MSY scenarios, a third MEY

229   scenario investigated the maximisation of the net present value of the fleet profits (discount rate

230   3.5%) over 40 years. The profit is defined as the revenue minus variable and fixed costs. In a fourth

231   "MEY constrained" scenario the fishing effort was constrained to ensure a sustainable exploitation of

232   bycatch species such as turbot and elasmobranchs (see below). The following assumptions were

233   made during the optimisation: i) to avoid unrealistic variation of effort from year to year the change

234   in effort is limited to +/-5% per year for each fleet and is fixed after 10 years of simulation to reach

235   equilibrium levels of catch, ii) total effort is constrained but the spatial distribution of fleets in the

236   North Sea is free, iii) the landings obligation is not implemented because there is still uncertainty

237   how it will be applied in the flatfish and shrimp fisheries (the brown shrimp fishery is already

238   exempted) and a fixed proportion of undersized catch is discarded and iv) the fleet capacity is

239   derived from the total effort, dividing the total days-at-sea per fleet by the initial average days at sea

240   per vessel. Fish prices and costs were extracted from the European fisheries economic database

241   (STECF 2013). Costs and prices of plaice were kept constant at the average 2008-2010 values

242   throughout the simulation period but price elasticity was assumed for sole and brown shrimp prices

243   to account for the observed relationship between landed volumes and prices (de Wilde 2003, ICES

244   WKCCM 2013). The dynamics of the fish stocks were simulated with logistic productivity functions for

245   flatfish and a polynomial function for shrimp using data from ICES WGNSSK 2012 and ICES WGCRAN

246   2012.

247   Stäbler et al. (2016) parameterized an EwE model of the southern part of the North Sea (ICES areas

248   IVb and IVc). The model represents all parts of the ecosystem including primary producers,

249   zooplankton, benthos, demersal and pelagic fish, rays and sharks, marine mammals and seabirds.

250   The fishery is represented by eleven fleets typical for the southern part of the North Sea (e.g.,

251   demersal trawls and seines, beam trawls, shrimp trawlers and static gears). It was tested whether the

252   fishing mortality for turbot (*Scophthalmus maximus*) was kept below the F_{MSY} proxy of 0.34 (ICES

253   WGNSSK 2013). As further indicator species the elasmobranchs thornback ray (*Raja clavata*), spotted

254   ray (*Raja montagui*) and starry ray (*Amblyraja radiata*) were chosen. These species occur regularly in

255   the southern and central part of the North Sea. It was tested whether the optimized effort levels are

256   sufficient to lead to catches in line with the ICES advice for these species (ICES advice 2013; +20% in

257   TAC for thornback and spotted ray; -36% in TAC for starry ray). The ICES advice was taken as proxy

258   for GES because official long-term target reference levels do not yet exist. Next to this a LFI as further

259   potential GES indicator was calculated representing the proportion of demersal fish species with a

260   maximum length above 40 cm. The threshold of 40 cm was also used by Greenstreet et al. (2011)

261   analysing LFIs for the North Sea fish community.

2.4 Decision support workshop

A decision support workshop was held in July 2014 to determine informed preferences of the participants for different scenarios. The joint workshop with the North Sea Advisory Council (NSAC) had 23 participants (Figure 1). Similar to the problem framing workshop, the priorities of stakeholders for different MSY/MEY objectives and their response to constraints were identified. However, this time stakeholders were confronted with modelling results summarized in the DSTs and they were asked to indicate their preferences given the trade-offs emergent in the modelling results. Therefore, this workshop helped to validate the original outcomes of the Problem framing workshop and the DSTs provided the basis for further discussions.

For each of the DSTs the background of the scenarios and a brief description of the modelling approach and its shortcomings were presented. In contrast to the problem framing workshop, the preferences were collected through questionnaires and not via the Excel tool. While group elicitation methods enable sharing of information and offer a sense of equitable treatment with the opportunity for individual voices to be heard and reflected in a transparent manner (Romakkaniemi 2015), equitability in a group setting, although desirable, is not automatic. Some individuals can assert their dominance and be seen to unfairly influence group-based outcomes. Such bias can also arise from a subgroup of individuals who share a particular background and might therefore hold similar views. In such cases their influence on the group opinion might be judged by others to be unsuitably dominating. Concerns on such group interaction effects had been raised during the problem framing workshop. To minimize these concerns, participants (not including scientists) were asked to indicate their preferences individually for each of the scenarios presented in the DSTs (suitability; score 1 = very poor to 5 = very good). They were also asked how certain they were about their rating (uncertainty; score 1= low uncertainty to 4= high uncertainty). Finally, there was opportunity for them to give the main reasons for their ratings (in free text format). The questionnaires were analysed by taking the individual answers, converting them to distributions approximating the discrete scheme of the Excel tool adopted in the problem framing workshop (Fig.

288   2) and then averaging the samples into single distributions. This was consistent with the methods

289   used in the problem framing workshop and it synthesised all individual views on the suitability of

290   various management scenarios and the uncertainty surrounding those views. In addition, the DSTs

291   were discussed in a plenary meeting and minutes on the main points raised during the discussions

292   were taken.

293   3. Results

294   3.1 Problem framing workshop

295   Responses to MSY /MEY objectives and constraints were ranked according to expected utility values

296   and the outcomes are presented in Table 1 and 2 respectively. These were binned into 5 equally-

297   sized expected utility groups, on an interval [0,4], resulting in the thresholds 0.0-0.8 for the first

298   priority, and so forth. Lower utility index values correspond to preferred options. The top-ranked

299   objective was "Maximise inclusive governance" (Table 1). Other priority objectives were "Maximise

300   yield in value of key commercial species" and "Maximise yield in tonnes of key commercial species".

301   "Maximise yield of fish/litre of fuel (or CO_2) or similar energy unit" and "Maximising net present

302   value" were ranked as the most preferred MEY related objectives (Table 1). In the top group of

303   objectives "Maximise consumer welfare/happiness" can be also found. While MSY and MEY related

304   objectives can be predicted with models, the maximisation of inclusive governance was interpreted

305   as maximisation of stakeholder involvement during the definition and implementation of an MSY

306   policy. Consumer welfare and happiness were also difficult to define and criteria for happiness and

307   welfare most likely change through time and between social groups.

308

309   [Table 1 here]

310

311 Good environmental status (GES) related constraints were ranked highest (Table 2). This also

312 included constraints to ensure sustainable mortality rates for non-target species. In general, there

313 was a wide variety of opinions on most constraints and often ratings ranged from very good to very

314 poor. This led to similar expected utilities for many constraints (Table 2). Relative stability and area

315 closures, such as wind parks and Natura 2000 sites, were also seen as important constraints. This

316 should not be seen as an agreement to relative stability or area closures but more as a political

317 constraint because participants felt that it is not possible to change these things in the near future.

318 Socio-economic constraints were generally ranked low. "Profits above a minimum level" was seen as

319 the most important economic constraint. Typical social constraints such as "Maintaining small

320 communities at a specified level" or "Employment above a specified level" were ranked low.

321

322 [Table 2 here]

323

324 **3.2 Management reflection workshops**

325 In general, the participants of the two workshops considered that the aim of fisheries management

326 must be compatible with the stocks being maintained above precautionary limits, e.g. limits below

327 which recruitment of the stock is impaired (ICES WKM-TRADE 2012, Rindorf et al. 2013). Within the

328 area defined as compatible with sustainability, scientists are expected to provide advice on the

329 relevant trade-offs between different yield and ecosystem aspects. However, they should not be

330 responsible for making decisions on the exact trade- off of different objectives in an automated

331 fashion such as through trading a kilo or a euro landed value of one fish species against that of

332 another. Such information may be presented to guide decision makers but should not be considered

333 as legally binding in the decision process. In the second of the two workshops (Rindorf et al. 2013), it

334 was considered that it would not be politically feasible to reach a consensus on decisions where one

335 country would have to loose yield in order for the summed European yield to be maximised. A

336　structure where scientists provide advice on the combination of management targets which were

337　considered sustainable and which would provide yields reasonably close to single species MSY was

338　considered to be a potentially useful route forward. The impression that GES related constraints are

339　most important was also the result of these two workshops. As long as these constraints are fulfilled,

340　science should give options and highlight possible trade-offs as demonstrated in the DSTs.

341　**3.3 Scenario modelling of preferred options (DSTs)**

342　*Biological interactions (DST1)*

343　In cases where fish eat other fish, the yield in weight is generally highest when the predatory fish,

344　which otherwise would eat smaller fish, are removed (Gislason 1999). This was also the result in the

345　North Sea case examined here (DST1, Figure 3). Hence, obtaining the maximum weight of landings is

346　achieved by fishing with a higher fishing mortality of the two top predators (cod and saithe). This

347　does not provide a substantially higher yield of the two species, but does require a higher fishing

348　effort on these species leading to lower stock sizes. The higher the fishing mortality on the top

349　predators, the higher the abundance of their prey (i.e. whiting and haddock), which leads to an

350　increased probability of the Norway pout stock being below precautionary limits. To obtain

351　maximum total yield in weight or Euros, a substantially higher fishing mortality than that leading to

352　single species MSY of cod and saithe is required and a cost in the form of a cod stock below

353　precautionary limits and a higher fishing effort is the consequence. In contrast, the "Pretty Good

354　Yield" scenario leading to all stocks being retained above biological limits (above B_{lim}) has a fishing

355　effort on cod which is in between that leading to MSY of cod in a single species environment and that

356　leading to the maximum total landings in the North Sea. Long-term yield of predatory fish is only

357　mildly affected by the differences in fishing mortality and hence appear to be virtually identical

358　between scenarios.

359

360　[Figure 3 here]

361

362 *Technical interactions (DST2)*

363 The comparison between the traditional management scenario (distribution of quotas determined by

364 historic landings shares alone) and the three optimisation scenarios (allowing quotas to be

365 redistributed between fleets inside a country) revealed that at the scale of the entire fishery, MEY

366 gives considerably more profit compared to traditional management (Figure 4). Redistribution is also

367 favoured with respect to MSY-related objectives (yield in weight and yield in Euros), the reasons

368 being that traditional management is constrained by being subject to fixed fleet shares of the quotas

369 based on historical landing shares. This leads to a situation where fleets have to stop fishing under a

370 landing obligation relatively early in the year when the first quota is exhausted. However,

371 management based on maximising yield does not take into account the costs of using excessive

372 effort to maximise catch in weight or value. Only in the MEY scenario is the usage of quotas

373 optimised while minimising fishing effort, leading to lower costs. The reduced effort comes at the

374 cost of reduced employment.

375

376 [Figure 4 here]

377

378 *Technical interactions and GES (DST3)*

379 The DST for the southern North Sea case study shows similar trade-offs (DST3, Figures 5 and 6). The

380 current definition of MSY (maximise yield in weight) is not optimal from an economic and

381 conservation point of view. It leads to a substantialy lower profit compared to the other scenarios

382 and risks the unsustainable exploitation of by-catch species. Regarding target species, neither plaice

383 nor sole were predicted to be below B_{pa} in any scenario. It could be shown that economic efficiency

384 and ecosystem sustainability are not mutually exclusive. Aiming for MEY leads to a relatively low

385 fishing effort and therefore to a relatively low by-catch and because of lower fishing mortalities to a

386 better size structure in the ecosystem. The loss in profit caused by the protection of by-catch species

387 (MEY constrained scenario) was only marginal. However, economic optimization and the protection

388 of by-catch species were achieved with much lower catch and at a high social cost (low employment).

389

390 [Figure 5 here]

391 [Figure 6 here]

392

393 **3.4 Decision support workshop**

394 Eleven participants (three NGOs, six fishing industry representatives, two policy representatives)

395 filled out the questionnaire for the first DST on multi-species trade-offs (see Figure 3). The scenario

396 "Pretty Good Yield" was evaluated to be most suitable (Figure 7). Arguments from stakeholders at

397 the workshop included that it allows more fishermen to continue fishing because yield is distributed

398 more evenly over the different species. It also leaves room for negotiation because there are no

399 hardwired maximisation objectives. Criticism included the fact that it is not quite clear how such a

400 concept could work out under the current legislation. To maximise yield in weight or Euros was rated

401 considerably less suitable (Figure 7) although it was recognized by workshop participants that these

402 MSY objectives are closer to the current political reality. In the discussion after the presentation of

403 DST1, stakeholders pointed towards the high uncertainty of results, e.g. trends in recruitment

404 success and the complex simulation of biological multi-species interactions. Discussions also picked

405 up the difficulty to reach consensus between member states when trade-offs because of predator-

406 prey interactions become obvious. Each EU member state has different fisheries and therefore

407 different priorities on which species' yield should be maximised (i.e. the yield from the predator or

408 the prey?).

409 The questionnaire for DST2 on technical interactions in the mixed roundfish fishery (Figure 4) was

410 filled in completely by seven respondents (three NGOs; three fishing industry representatives, one

411 policy). Another three respondents (fishing industry representatives) evaluated only part of the

412 scenarios. Including all responses, the results show that the scenario "MEY maximise net present

413 value" was deemed most suitable (Figure 7). The explanations for the relatively high rating include

17

414 the high income. The loss in employment was the main argument against this objective. Traditional

415 management and MSY based on weight were least preferred. The large fleet and low income speak

416 against these scenarios. The "Maximise yield in Euros" scenario was rated in between the MEY and

417 the other two scenarios. The focus of the discussions during plenary was on the appropriateness of

418 the assumption on constant prices and costs. It was also discussed how to deal with the situation in

419 models that fleets continue fishing despite making a loss for a number of years. This situation occurs

420 in reality and was explained by fishing industry representatives with a reluctance of fishermen to

421 close family companies and to lose status.

422 Regarding the third DST (Figure 5), the appropriateness of limiting fisheries because of sustainability

423 constraints for by-catch species like turbot was discussed at the workshop next to discussions on pros

424 and cons to choose MEY instead of MSY as management targets especially in relation to social

425 constraints. The questionnaire for the third DST was filled in completely by six respondents (three

426 NGOs; two fishing industry representatives; one policy). Another two respondents (fishing industry

427 representatives) evaluated only part of the scenarios. Including all responses, the results show that

428 the "MEY constrained" scenario received highest scores (Figure 7). Arguments for this scenario

429 included no overfishing of turbot and elasmobranchs. The main argument against was the negative

430 effect on employment (despite high income).

431

432 [Figure 7 here]

4. Discussion

4.1 Main conclusions

435 Multiple trade-offs occur when implementing the MSY concept in the North Sea because of biological

436 interactions, technical interactions, and social constraints. Trade-offs related to biological

437 interactions were identified by managers in the management reflection workshops as being an issue

438 of high potential conflict, with single species management still preferred. The current definition of

439   MSY to maximise the yield in weight from a stock or community leads to a loss in profit and the

440   relatively high fishing effort needed to fish out the associated quotas increases the potential for

441   conflict with environmental constraints. MEY seems to be an appropriate concept to cover wider

442   objectives, however, employment and the activity of fishing fleets might suffer when aiming for MEY

443   instead of MSY. Although addressing trade-offs is complicated from a political point of view, the

444   motivation to address them may change if the current approach of ignoring trade-offs results in

445   unacceptable ecosystem, economic, or social effects. Overall, a "Pretty Good Yield" concept may be

446   more suitable than trying to reach the absolute maximum of one particular objective.

447   Often decisions and compromises are needed that go beyond science when dealing with trade-offs

448   and participants indicated that inclusive governance is of great importance. One important outcome

449   of the management reflection workshops was the view that scientists should not make the decisions,

450   but should only give advice on the range of potential options within a sustainable exploitation space.

451   It is then up to the other stakeholder groups to make final decisions. In our approach, we tried to

452   include different stakeholder groups from the start to enable discussions on difficult trade-offs and

453   to provide options for sustainable exploitation. In the following sections the different aspects of

454   lessons learned from this exercise are discussed in detail.

455

456   **4.2 Uncertainties of model results and recommendations for visualisation**

457   When providing advice for fisheries management, a major source of uncertainty is related to the

458   scenario modelling. Different modelling approaches may not only change the apparent weight of

459   trade-offs, but also the direction of change for a given key decision variable. Such problems are

460   encountered regularly and diversified scientific approaches are encouraged, for instance with the

461   growing use of ensemble modelling (Murphy et al. 2004, Thorpe et al. 2016). Often resources are not

462   available to construct a variety of models for the same problem (as in our case here) and this can

463   lead decision makers to wrongly assume that the advice they give is robust, whereas a more

464   comprehensive modelling effort might have revealed the same advice as being contingent upon

465   model assumptions and sensitive to a range of uncertainties. Visualisation techniques, such as icon

466   arrays, can make comparisons among several sets of modelling results easier, but they can also

467   contribute to a false sense of certainty. Thus the problem of subjectivity – presenting a single model

468   outcome from a set of possible scientifically valid conclusions – can be made more acute by

469   representing these results effectively and memorably using pictograms. Similarly, visualisation of

470   expert preferences and uncertainties associated with those values as done in the stakeholder

471   workshops is subject to linguistic uncertainty related to the lack of consistency of definitions such as

472   'good' or 'very poor' across stakeholders. Comparatively, the sensitivity to the parameterization of

473   distributions representing opinions is a relatively minor issue (Holt et al 2014).

474   At the decision support workshop the uncertainties regarding the modelling approaches were clearly

475   expressed during presentations and the comments from stakeholders during the discussions show

476   that these uncertainties were recognized and taken seriously. Our predictions were sensitive to

477   various assumptions. For example, assumptions on the future productivity of stocks may determine

478   whether stocks are predicted to be above or below biomass reference points. Market prices for fish

479   and fuel prices may also change in the future and therefore influence the profit of fleets. There are

480   many other sources of uncertainty, e.g. food web dynamics or assumptions on future catchabilities

481   under the landing obligation. In general, the famous quote "All models are wrong, but some are

482   useful" (Box and Draper 1987) also holds true for the three case studies presented. Under this

483   premise, it was not the aim to predict what will happen exactly in the future, but to highlight general

484   trade-offs and to find out the preferences of stakeholders when confronted with such trade-offs

485   based on the current situation. The model results only show likely conflicts which stakeholders need

486   to consider. The management itself must be carried out in an adaptive way, based on the decisions

487   on general objectives.

488   **4.3 What are the main trade-offs?**

489   According to our results, one main trade-off in setting long term management targets for an

490   interacting fish community is the trade-off between maintaining a large stock of predators, which

20

491   provide a large and valuable yield, versus reducing the predatory stocks to achieve a higher yield of

492   prey fish. Similar results using different types of multi-species and ecosystem models have been

493   obtained for a range of ecosystems (Gislason 1999; Matsuda and Abrahms 2004, 2006; Jacobsen et

494   al. 2014, Thorpe et al. 2016) suggesting some generality of the result.

495   The main distinction between MEY and MSY objectives is that the MEY scenarios represent a

496   maximisation of the profit from the fish stocks to society when the profit to the fishermen and the

497   capital are embodied in the cost function, that the prices and costs are estimated as financial costs

498   rather than opportunity costs (best alternative use) and that external effects such as positive or

499   negative impact on the ecosystem are disregarded. In the MSY scenarios catch quantity or value is

500   maximised but this will not lead to maximisation of the resource rent to society. However, as catch

501   quantity and fishing effort is higher at the MSY level compared to the MEY level it is likely that

502   employment in the fisheries sector is higher and that supplies of fish to processors and consumers

503   are higher. This trade-off has also been discussed in other literature (e.g., Hilborn 2007, Christensen

504   2010, Sumaila and Hannesson 2010). Thus the question raised by the MEY vs. MSY dichotomy is what

505   benefits society most in the long run, either that the fishery contributes most economically, i.e. with

506   the highest catch value to the lowest costs, or that higher employment and higher food supply can be

507   maintained. Before answering this question, alternative employment opportunities must be taken

508   into account. For fisheries in remote communities, alternative opportunities for employment and

509   development may be limited (Mardle et al. 2004).

510   The requirement for impacts on by-catch species to be sustainable can lead to additional trade-offs

511   between the maximisation of yield from the target species and conservation targets. In the test case

512   for the southern North Sea, the loss in profit as a result of preventing by-catch for the modelled

513   species was only marginal, but catches that could be taken from target stocks and employment were

514   substantially constrained. MEY is often considered to be more environmentally beneficial in terms of

515   reduced bycatch and habitat damage due to lower fishing effort (Grafton et al. 2007; Dichmont et al.

516   2008). This conclusion is also supported by our modelling results.

517　So called "choke species" constrain mixed fisheries under a landing obligation due to an obligation, if

518　strictly implemented, to close the fishery when their quotas are exhausted. Similar to our results for

519　North Sea demersal fisheries, several "choke species" were identified in analyses of the Scientific,

520　Technical and Economic Committee for Fisheries (STECF 2014) and the ICES working group

521　WGMIXFISH (ICES WGMIXFISH 2014). Resolving the "choke species" problem is complicated in

522　Europe because of the relative stability principle. This principle ensures that each year countries get

523　the same quota shares based on historical fishing rights. In some countries even national quotas are

524　distributed based on relative stability criteria. The traditional management scenario in the second

525　DST (see Fig 4) mimics this approach by not allowing any redistribution of quota shares between

526　fleets. The losses in yield and NPV were substantial in comparison to a system where at least

527　redistributions inside a country were allowed. It can be deduced from these results that with a

528　complete removal of the relative stability principle, allowing redistribution freely, even better

529　economic results may be achieved, albeit possibly at the expense of greater inequality between

530　countries and the fear that a few large companies will monopolize quotas. Currently a system of

531　quota swapping is used to overcome the limitations caused by the principle of relative stability

532　(Hoefnagel *et al.* 2015). However, it is unclear how such a system of voluntary quota exchanges will

533　function under the landing obligation.

534　**4.4 Resolving the trade-offs**

535　*What were the main priorities for stakeholders?*

536　A key priority for stakeholders was that harvest strategies must be sustainable. In the problem

537　framing workshop GES related constraints were ranked as most important. This is in line with the

538　new CFP where the implementation of an ecosystem approach is an important objective. However,

539　the achievement of GES could lead to additional constraints for North Sea fisheries.

540　In addition, participants of the different workshops considered a successful implementation of MSY

541　to depend critically on viable fisheries, and MEY was ranked highest in the decision support

542　workshops where possible. While social aspects played only a small role during the problem framing

543   workshop, social aspects were also raised by stakeholders after confronted with the results from the

544   DSTs. Often expressed was the desire to find a compromise between economic optimisation and

545   social constraints (e.g., employment, food security). In other studies, Wattage et al. (2005) used a

546   choice experiment, whereas Mardle et al. (2004) applied the analytical hierarchy process (AHP) to

547   elicit stakeholder preferences in North Sea and Eastern Channel fisheries. Both approaches also

548   demonstrated that maintaining regional employment and the sustainable exploitation of stocks were

549   key concerns. Therefore, results in this study are similar despite differences in stakeholder groups

550   and elicitation methods.

551   A suitable compromise could be the "Pretty Good Yield" concept that was also favoured from the

552   DST on biological interactions. In mixed fisheries of the North Sea the individual MSYs/MEYs cannot

553   be achieved for all species simultaneously because of biological and technical interactions

554   (Mackinson et al. 2009). Sustainable ranges for F_{MSY} in accordance with the "Pretty Good Yield"

555   concept are one option to minimize this problem. The aim would be to keep all stocks within their

556   individual sustainable ranges leading to pretty good yield (e.g., at least 95% of the maximum) instead

557   of trying to fish all stocks simultaneously at their stock specific F_{MSY} point estimate. This means a less

558   strict interpretation of the MSY concept because ranges could also include sustainable fishing

559   mortalities above F_{MSY}. But this gives room to find compromises and reduces the limiting effect of

560   choke species under the landing obligation.

561   *Inclusive governance*

562   Inclusive governance was identified by stakeholders as most important in the problem framing

563   workshop. Inclusive governance can be seen as an essential part of fisheries management because of

564   the need for a balanced and stable outcome on all three dimensions of sustainability – ecological,

565   economic and social (Rice 2011). The historic failure to include the major stakeholders in meaningful

566   decision-making has long been seen as one of the causes of failures in fisheries management

567   (Cochrane 1999) while increased stakeholder participation helps establish trust, resolves conflicts,

568 enhances the legitimacy and acceptance of management policies and increases the likelihood of

569 compliance (Jentoft and McCay 1995, Berghofer et al. 2008).

570 A challenge and strength of inclusive governance lies in the consideration of interests from different

571 participants in the governance process (Rochet and Rice 2005). Scientists, fishing industry, policy-

572 makers and NGOs often gave different weights to the different features of a decision (not shown in

573 the results because of privacy protection). During the elicitations for this study all participants got an

574 equal say. Although it was ensured that representatives from each stakeholder group (Industry,

575 NGO's, Managers, Scientists) participated in the elicitation process, composition of workshop

576 participants may have biased the results to some extent. It was the diversity of views that was most

577 interesting for this study and therefore the different views are highlighted in the discussion and not

578 only the most preferred ones. The main outcome of the stakeholder elicitation was that there is no

579 simple solution satisfying the objectives of all stakeholders at the same time. Therefore, setting F_{MSY}

580 or F_{MEY} as management target without any flexibility for compromises may lead to disappointment

581 for some stakeholders. This conclusion is robust to any potential bias in the composition of workshop

582 participants. A well-structured decision making process with clear responsibilities is therefore

583 needed in fisheries management to resolve trade-offs and find compromises. This is an important

584 point because inclusive governance alone may also lead to a management system that is blocked by

585 too many conflicting views. The elicitation process carried out for this study can be used also in

586 practice to deal with difficult trade-offs. However, a more targeted stakeholder screening may be

587 needed before the start of the process and participants should not change in between the different

588 steps. The final decision making is an additional task that was not in the scope of this scientific study.

589 Perspectives

590 The CFP (EU 2013) states that management decisions should take into account the difficulty of fishing

591 all stocks in a mixed fishery at maximum sustainable yield at the same time and that multiannual

592 plans should cover the interactions between fish stocks, fisheries, and marine ecosystems. The

593 general principle of treating F_{MSY} not as a point estimate but to use sustainable ranges to find a

594   compromise between the various objectives and trade-offs has been explicitly acknowledged by the

595   European authorities (Task force 2014). ICES has been tasked with identifying these ranges for a

596   number of stocks using a standardised framework (ICES WKMSYREF III 2014). These elements may be

597   an important element of the regional mixed-fisheries management plans currently being developed.

598   For the North Sea, STECF evaluated that F_{MSY} ranges could lead to more flexible sustainable

599   management of mixed-fisheries, provided that TACs are not blindly set at the maximum of the range

600   each year across all species in the fishery (STECF 2015). However, discussions are ongoing whether

601   F_{MSY} ranges can be compatible with the basic regulation of the CFP (EU 2013) and the Marine

602   Strategy Framework Directive (MSFD; EU MSFD 2008) or if single species point estimates of F_{MSY}

603   should be considered an upper limit. The yield and profits from North Sea fisheries will depend on

604   agreed reference levels and how GES indicators from the MSFD influence the CFP. A harmonised

605   approach between the CFP and MSFD is a prerequisite for a successful implementation of the MSY

606   concept inside an ecosystem-based approach. This study gives insights on how inclusive governance

607   and appropriate elicitation tools can help in such difficult political processes to reach consensus and

608   how science can be used to make informed decisions inside a multi-dimensional trade-off space. The

609   results of this study also highlight problems that can be anticipated when implementing the MSY

610   policy in the North Sea, suggesting that MSY is a useful concept but that a pragmatic adaptation may

611   be needed to reconcile the diverse and often conflicting views regarding fisheries management in

612   Europe.

613

614

5. Acknowledgement

615

616

617

618

619

620

6. References

J.S. Ancker, Y. Senathirajah, R. Kukafka, J.B. Starren, Design features of graphs in health risk communication: a systematic review, Journal of American Medical Informatics Association 13 (2006) 608-618.

H. Bartelings, K.G. Hamon, J. Berkenhagen, F.C. Buisman, Bio-economic modelling for marine spatial planning application in North Sea shrimp and flatfish fisheries, Environmental Modelling & Software 74 (2015) 156-172.

J. Batsleer, J.J. Poos, P. Marchal, Y. Vermard., A.D. Rijnsdorp, Mixed fisheries management: Protecting the weakest link, Marine Ecology Progress Series 479 (2013) 177-190.

A. Berghofer, H. Wittmer, F. Rauschmayer, Stakeholder participation in ecosystem-based approaches to fisheries management: a synthesis from European research projects, Marine Policy 32 (2008) 243–253.

R.J.H. Beverton, S.J. Holt, On the Dynamics of Exploited Fish Populations, Fishery Investigations Series II Vol. XIX, Ministry of Agriculture, Fisheries and Food, Great Britain, 1957.

G.E.P. Box, N.R. Draper, Empirical Model-Building and Response Surfaces, John Wiley & Sons, New York, 1987.

V. Christensen, C.J. Walters, Ecopath with Ecosim: methods, capabilities and limitations, Ecological Modelling, 172 (2004) 109-132.

V. Christensen, C.J. Walters, D. Pauly, R. Forrest, Ecopath with Ecosim version 6 user guide, Lenfest Ocean Futures Project, University of British Columbia, Vancouver, 2008.

V. Christensen, MEY = MSY, Fish and Fisheries 11 (2010) 105-110.

C.W. Clark, Mathematical Bioeconomics: The Optimal Management of Renewable Resources, 2nd edition, John Wiley & Sons, New York, 1990.

K.L. Cochrane, Complexity in fisheries and limitations in the increasing complexity of fisheries management, ICES Journal of Marine Science 56 (1999) 917–926.

646   J.W. de Wilde, The 2001 North Sea cod recovery measures: economic consequences for the Dutch

647   fishing fleet, Proceedings of the 15th EAFE Conference, Session 6, Brest, 2003.

648   C.M. Dichmont, A Deng, A.E. Punt, N. Ellis, W.N. Venables, T. Kompas, Y. Ye, S. Zhou, J. Bishop,

649   Beyond biological performance measures in management strategy evaluation: Bringing in

650   economics and the effects of trawling on the benthos, Fisheries Research 94 (2008) 238–250.

651   EU 2008. Council Regulation (EC) No 1342/2008 of 18 December 2008 establishing a long-term

652   plan for cod stocks and the fisheries exploiting those stocks and repealing Regulation (EC)

653   No 423/2004.

654   EU 2013. REGULATION (EU) No 1380/2013 OF THE EUROPEAN PARLIAMENT AND OF THE

655   COUNCIL of 11 December 2013 on the Common Fisheries Policy, amending Council

656   Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations

657   (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC.

658   EU MSFD 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June

659   2008 establishing a framework for community action in the field of marine environmental

660   policy (Marine Strategy Framework Directive).

661   H. Frost, P. Andersen, A. Hoff, Management of complex fisheries: Lessons learned from a

662   simulation model, Canadian Journal of Agricultural Economics 61(2) (2013) 283-307.

663   H. Gislason, Single and multispecies reference points for Baltic fish stocks, ICES Journal of Marine

664   Science 56 (1999) 571–583.

665   H.S. Gordon, The economic theory of a common-property resource: The fishery, J. Polit. Econ. 62

666   (1954) 124–142.

667   S.P.R. Greenstreet, S.I. Rogers, J.C. Rice, G.J. Piet, E.J. Guirey, H.M. Fraser, R.J. Fryer,

668   Development of the EcoQO for the North Sea fish community, ICES Journal of Marine Science

669   68 (2011) 1-11.

670   R.Q. Grafton, T. Kompas, R.W. Hilborn, Economics of overexploitation revisited,

671   Science 318 (2007) 1601.

672   R. Hilborn, Defining success in fisheries and conflicts in objectives, Marine Policy 31(2) (2007)

673   153-158.

674   R. Hilborn, Pretty Good Yield and exploited fishes, Marine Policy 34 (2010) 193-196.

675   E. Hoefnagel, B. de Vos, E. Buisman, E, Quota swapping, relative stability, and transparency,

676   Marine Policy 57 (2015) 111-119.

677   J. Holt, A.W. Leach, G. Schrader, F. Petter, A. MacLeod, D.J. van der Gaag, R.H.A. Baker, J.D.

678   Mumford, Eliciting and Combining Decision Criteria Using a Limited Palette of Utility

679   Functions and Uncertainty Distributions: Illustrated by Application to Pest Risk Analysis. Risk

680   Analysis. 34 (2014) 4-16

681   ICES Advice, Rays and skates in Divisions and Subarea IIIa, IV, and VIId, e (Kattegat, Skagerrak,

682   North Sea, and English Channel), ICES Advice 2013, Book 6.

683   ICES-Multi, Multi species considerations for North Sea stocks, ICES Advice 2013, Book 6.

684   ICES WGCRAN, Report of the Working Group on Crangon Fisheries and Life History (WGCRAN),

685   ICES CM 2012/SSGEF: 09.

686   ICES WGMIXFISH, Report of the Working Group on Mixed Fisheries Advice for the North Sea

687   (WGMIXFISH-NS), ICES CM 2014/ACOM: 22.

688   ICES WGNSSK, Report of the working group on the assessment of demersal stocks in the North

689   Sea and Skagerrak (WGNSSK), ICES CM 2012/ACOM: 13.

690   ICES WGNSSK, Report of the Working Group on the Assessment of Demersal Stocks in the North

691   Sea and Skagerrak (WGNSSK), ICES CM 2013/ACOM: 13

692   ICES WGSAM, Report of the working group on Multi Species Assessment Methods (WGSAM),

693   ICES CM 2012/SSGSUE: 10.

694   ICES WKCCM, Report of the Workshop on the Necessity for Crangon and Cephalopod

695   Management (WKCCM), ICES CM 2013/ACOM: 82.

696   ICES WKMSYREF III, Report of the Joint ICES-MYFISH Workshop to consider the basis for FMSY

697   ranges for all stocks (WKMSYREF III), ICES CM 2014/ACOM: 64.

698   ICES WKM-TRADE, Report of the Workshop on North Sea and Baltic Sea Multispecies Trade-offs

699   (WKM-Trade), ICES CM 2012/ACOM: 71.

700   N.S. Jacobsen, H. Gislason, K.H. Andersen, The consequences of balanced harvesting of fish

701   communities. Proceedings of the Royal Society B 281 (2014) 20132701,

702   http://dx.doi.org/10.1098/rspb.2013.2701

703   S. Jentoft, B. McCay, User participation in fisheries management—lessons drawn from

704   international experiences, Marine Policy 19 (1995) 227–46.

705   S.B.M. Kraak, N. Bailey, M. Cardinale, C. Darby, J.A. De Oliveira, M. Eero, N. Graham, S.J. Holmes, T.

706   Jakobsen, A. Kempf, E. Kirkegaard, J. Powell, R.D. Scott, E.J. Simmonds, C. Ulrich, W. Vanhee, M.

707   Vinther, Lessons for fisheries management from the EU cod recovery plan, Marine Policy 37

708   (2013) 200-213.

709   P.A. Larkin, An epitaph for the concept of maximum sustained yield, Transactions of the

710   American Fisheries Society 106 (1977) 1-11.

711   A.W. Leach, P. Levontin, J. Holt, L.T. Kell, J.D. Mumford, Identification and prioritization of

712   uncertainties for management of Eastern Atlantic bluefin tuna (Thunnus thynnus), Marine

713   Policy 48 (2014) 84–92.

714   P. Lewy, M. Vinther, A stochastic age-length-structured multispecies model applied to North Sea

715   stocks, ICES CM 2004/ FF: 20.

716   P.M. Mace, A new role for MSY in single-species and ecosystem approaches to fisheries stock

717   assessment and management, Fish and Fisheries 2 (2001) 2-32.

718   S. Macinko, D.W. Bromley, Who owns America's Fisheries? Island Press, Washington DC, 2002.

719   S. Mackinson, D. Barrie, D. Beveridge, J. Casey, Mixed-fishery or ecosystem conundrum?

720   Multispecies considerations inform thinking on long-term management of North Sea

721   demersal stocks, Canadian Journal of Fisheries and Aquatic Sciences 66(7) (2009) 1107-

722   1129.

723   S. Mardle, S. Pascoe, I. Herrero, Management objective importance in fisheries: An evaluation

724   using the Analytic Hierarchy Process (AHP), Environmental Management, Vol. 33 (1) (2004) 1-

725   11.

726   T.G. Martin, M.A. Burgman, F. Fidler, P.M. Kuhnert, S. Low-Choy, M. Mcbride, K. Mengersen,

727   Eliciting Expert Knowledge in Conservation Science, Conservation Biology, Vol. 26 (1) (2011)

728   29–38.

729   H. Matsuda, P.A. Abrams, Effects of predator-prey interactions and adaptive change on

730   sustainable yield, Canadian Journal of Fisheries and Aquatic Sciences. 61 (2004) 175-184.

731   H. Matsuda, P.A. Abrams, Maximal yields from multi-species fisheries systems: Rules for

732   harvesting top predators and systems with multiple trophic levels, Ecological Applications 16

733   (2006) 225-237.

734   M. Murphy, D.M.H. Sexton, D.N. Barnett, G.S. Jones, M.J. Webb, M. Collins, D.A. Stainforth,

735   Quantification of modelling uncertainties in a large ensemble of climate change simulations,

736   Nature 430 (2004) 768-772.

737   J. Rice, Managing fisheries well: delivering the promises of an ecosystem approach, Fish and

738   Fisheries 12 (2011) 209-231.

739   A. Rindorf, J. Schmidt, B. Bogstadt, S. Reeves, Y. Walther, A Framework for Multispecies

740   Assessment and Management, ICES/NCM Background Document (2013) ISBN 978-92-893-

741   2584-4.

742   M.-J. Rochet, J. Rice, Do explicit criteria help selecting indicators for ecosystem-based fisheries

743   management? An experimental test, ICES Journal of Marine Science 62 (2005) 528–539.

744   A. Romakkaniemi (Ed.), Best practices for the provision of prior information for Bayesian stock

745   assessment, ICES Cooperative Research Report No. 328 (2015) 93 pp.

746   C. Röckmann, C. Ulrich, M. Dreyer, E. Bell, E. Borodzicz, P. Haapasaari, K.H. Hauge, D. Howell, S.

747   Mäntyniemi, D. Miller, G. Tserpes, M. Pastoors, The added value of participatory modelling in

748   fisheries management – what has been learnt?, Marine Policy Vol. 36(5) (2012) 1072-1085.

749   P. Salz, E. Buisman, K. Soma, H. Frost, P. Accadia, R. Prellezo, FISHRENT Bio-economic simulation

750   and optimization model for fisheries, LEI-report (2011) 2011-024.

751   M.B. Schaefer, Some aspects of the dynamics of populations, important for the management of

752   the commercial fisheries, Bulletin of the Inter-American Tropical Tuna Commission Vol. 1(2)

753   (1954) 27-56.

754   A. D. M. Smith, K. J. Sainsbury, R. A. Stevens, Implementing effective fisheries-management

755   systems – management strategy evaluation and the Australian partnership approach, ICES

756   Journal of Marine Science 56 (1999) 967-979.

757   C. Smith, A. L. Howes, B. Price, C. A. McAlpine, Using a Bayesian belief network to predict suitable

758   habitat of an endangered mammal – the Julia Creek dunnart (*Sminthopsis douglasi*), Biological

759   Conservation 139 (2007) 333–347.

760   U. R. Sumaila, R. Hannesson, Maximum economic yield in crisis? Fish and Fisheries Vol. 11(4)

761   (2010) 461 – 465.

762   D. Spiegelhalter, M. Pearson, I. Short, Visualizing uncertainty about the future, Science 333

763   (2011) 1393-1400.

764   M. Stäbler, A. Kempf, S. Mackinson, J.J. Poos, C. Garcia, A. Temming, Combining efforts to make

765   maximum sustainable yields and good environmental status match in a food-web model of

766   the southern North Sea, Ecological Modelling (2016)

767   http://dx.doi.org/10.1016/j.ecolmodel.2016.01.020

768   STECF, Scientific, Technical and Economic Committee for Fisheries (STECF). The 2013 Annual

769   Economic Report on the EU Fishing Fleet (STECF-13-15). Publications Office of the European

770   Union, Luxembourg (2013) doi:10.2788/23331.

771   STECF, Scientific, Technical and Economic Committee for Fisheries (STECF). Landing Obligations

772   in EU Fisheries - part 4 (STECF-14-19). Publications Office of the European Union,

773   Luxembourg (2014) doi:10.2788/050499.

774   STECF, Scientific, Technical and Economic Committee for Fisheries (STECF) – Evaluation of

775   management plans: Evaluation of the multi-annual plan for the North Sea demersal stocks

776   (STECF-15-04). Publications Office of the European Union, Luxembourg (2015)

777   doi:10.2788/547608.

778   Task Force 2014, Task Force on multiannual plans. Final report April 2014. Downloaded from

779   http://www.europarl.europa.eu/meetdocs/2009_2014/documents/pech/dv/taskfor/taskfo

780   rce.pdf , last access 13.10.2015.

781   R.B. Thorpe, P.J. Dolder, S. Reeves, P. Robinson, S. Jennings, Assessing fishery and ecological

782   consequences of alternate management options for multispecies fisheries, ICES Journal of

783   Marine Science (2016) doi: 10.1093/icesjms/fsw028.

784   C.J. Walters, V. Christensen, S.J. Martell, J.F. Kitchell, Possible ecosystem impacts of applying MSY

785   policies from single-species assessment, ICES Journal of Marine Science 62 (2005) 558-568.

786   P. Wattage, S. Mardle, S. Pascoe, Evaluation of the importance of fisheries management

787   objectives using choice-experiments, Ecological Economics 55 (2005) 85-95.

Figure captions

Figure 1. Composition of workshop participants in the 4 workshop events. Total number of participants are given in white at the bottom of each bar.

Figure 2. Graphical tool to record ratings. If the group rates (R) an aspect 'Very good (VG)' and the uncertainty (U) or disagreement is very low, the resulting distribution shows a high column in 'Very good (VG)' and a small column in 'Good (G)'. Keeping 'U' constant at 'Very low' while changing 'R' to 'Medium (M)' or 'Very poor (VP)' retains the narrow distribution but shifts the mode towards the right. In contrast, increasing 'U' to 'High' leads to a larger spread.

Figure 3. Decision support table showing three scenarios to investigate the effect of fish eating other fish on MSY: maximise the total landings in tonnes, maximise the total landings in Euros and an iterative process where it is attempted to get a yield in tonnes close to the maximum of each species while assuring that no species are exploited unsustainably (Pretty Good Yield). Catch is indicated by the number of fish of each species and the number in each cell. Colour indicates whether the average spawning stock biomass (SSB) of all species is above the precautionary biomass reference point Bpa (green), whether the SSB of at least one species is below Bpa but above Blim (yellow) or below Blim (red). Empty cells mean zero catch. Even a small catch leads to a stock collapse of whiting with high probability in the respective scenarios.

Figure 4: Decision support table on the comparison between traditional management (distribution of quotas determined by historic landings shares) and three optimisation scenarios in the mixed demersal roundfish fishery. Catch in thousand tonnes is indicated by the number of fish of each species. The net present value (NPV) in million Euros is indicated by the number of Euro signs. Employment in full time equivalents (fte) is indicated by the number of people. Effort in days at sea is

indicated by number of vessels. Yellow colour indicates spawning stock biomass (SSB) below $B_{pa.}$ but above $B_{lim.}$ Green colour indicates SSB above Bpa.

Figure 5: Decision Support Table (DST) on the consequences of aiming for different MSY/MEY objectives in the main fisheries of the southern North Sea. Catch in thousand tonnes is indicated by the number of fish of each species. The profit in million Euros is indicated by the number of Euro signs and negative profit is red. Employment in full time equivalents (fte) is indicated by the number of people. Effort in days at sea is indicated by number of vessels. Green colour indicates SSB above Bpa. For brown shrimp (*Crangon crangon*) no reference points are defined.

Figure 6: a) Consequences of aiming for different MSY/MEY objectives in the main fisheries of the southern North Sea for the sustainable exploitation of selected bycatch species. b) Impact on a modelled large fish indicator based on the percentage of biomass from demersal species with length infinity above 40 cm.

Figure 7: Stakeholder frequency of ratings on options given in the three DSTs. Top row: DST1 on biological interactions. Middle row: DST2 on traditional vs. MSY/MEY management. Bottom row: DST3 on MSY/MEY objectives in the southern part of the North Sea. VG=very good; G=good; M=Medium; P=poor; VP= very poor.
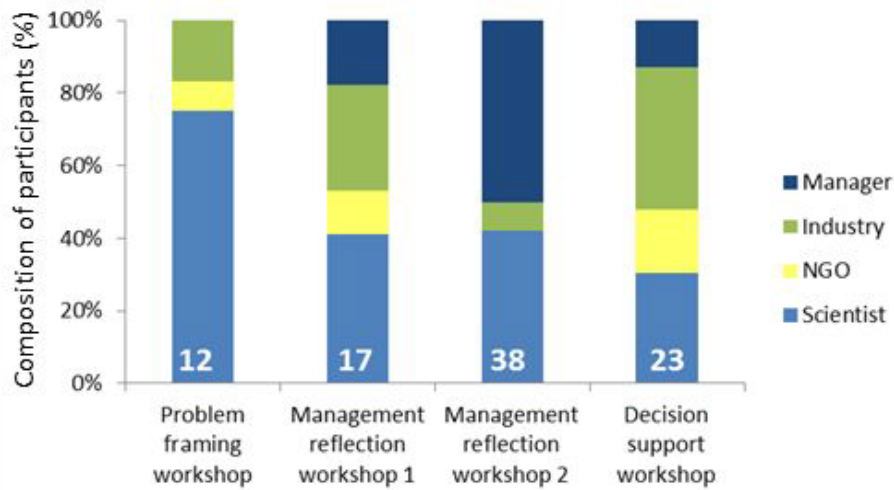
Fig-. 1
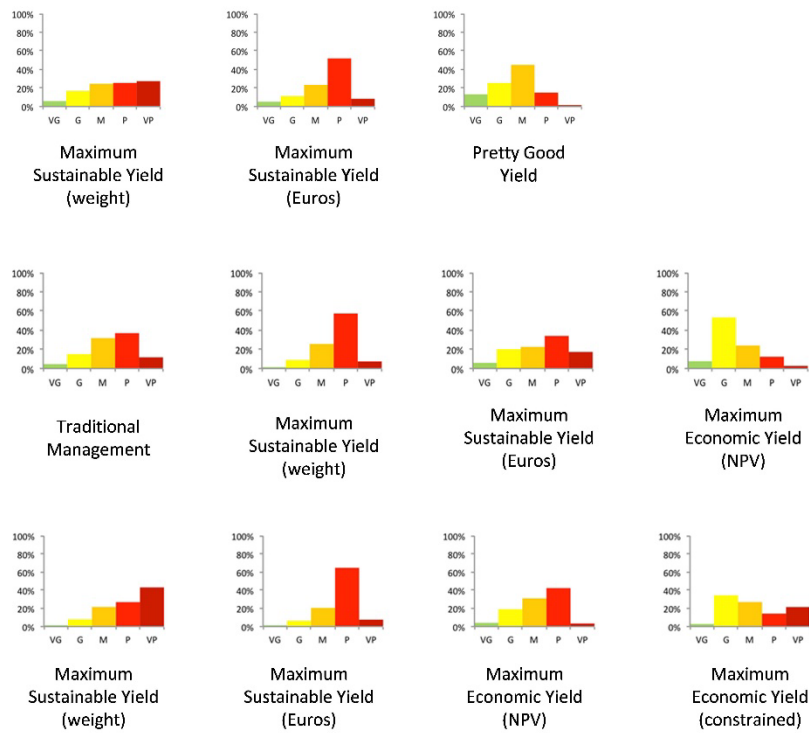
Fig. 2
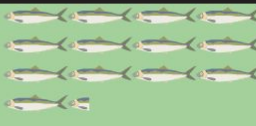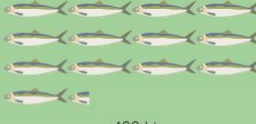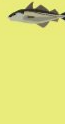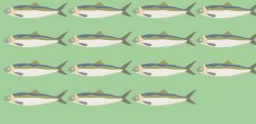
Scenario	Cod	Whiting	Haddock	Saithe	Herring		Industrial (Sandeel, Norway Pout and Sprat)
Maximum Sustainable Yield (Weight)	90 kt		40 kt	120 kt	400 kt		400 kt
Maximum Sustainable Yield (Euros)	100 kt		40 kt	120 kt	400 kt		100 kt
Pretty Good Yield	90 kt	30 kt	30 kt	130 kt	450 kt		840 kt

Fig. 3

Scenario	Cod	Whiting	Haddock	Saithe	NPV	Employment	Effort
Traditional Management	35 kt	20 kt	35 kt	60kt	15 mil	31000 fte	300 thousand days
Maximum Sustainable Yield (Weight)	35 kt	25 kt	40 kt	70 kt	11 mil	50000 fte	1.2 mil days
Maximum Sustainable Yield (Euros)	35 kt	25 kt	40 kt	70 kt	17 mil	54000 fte	1.5 mil days
Maximum Economic Yield (NPV)	35 kt	25 kt	40 kt	60 kt	31 mil	13000 fte	500 thousand days

Fig. 4
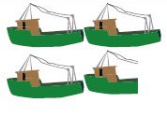
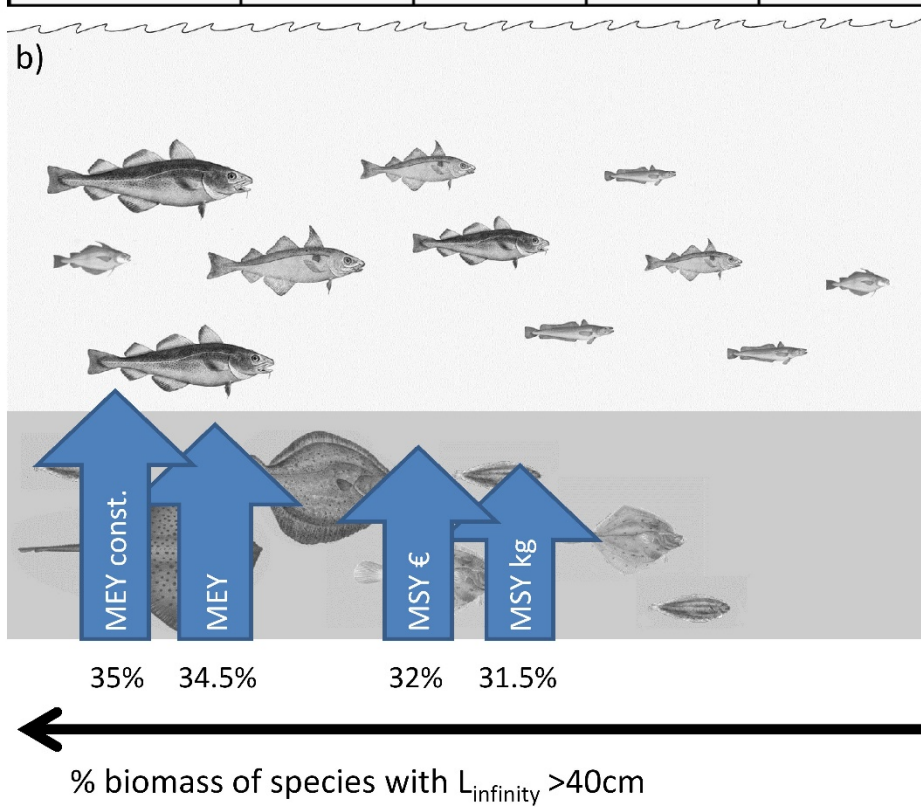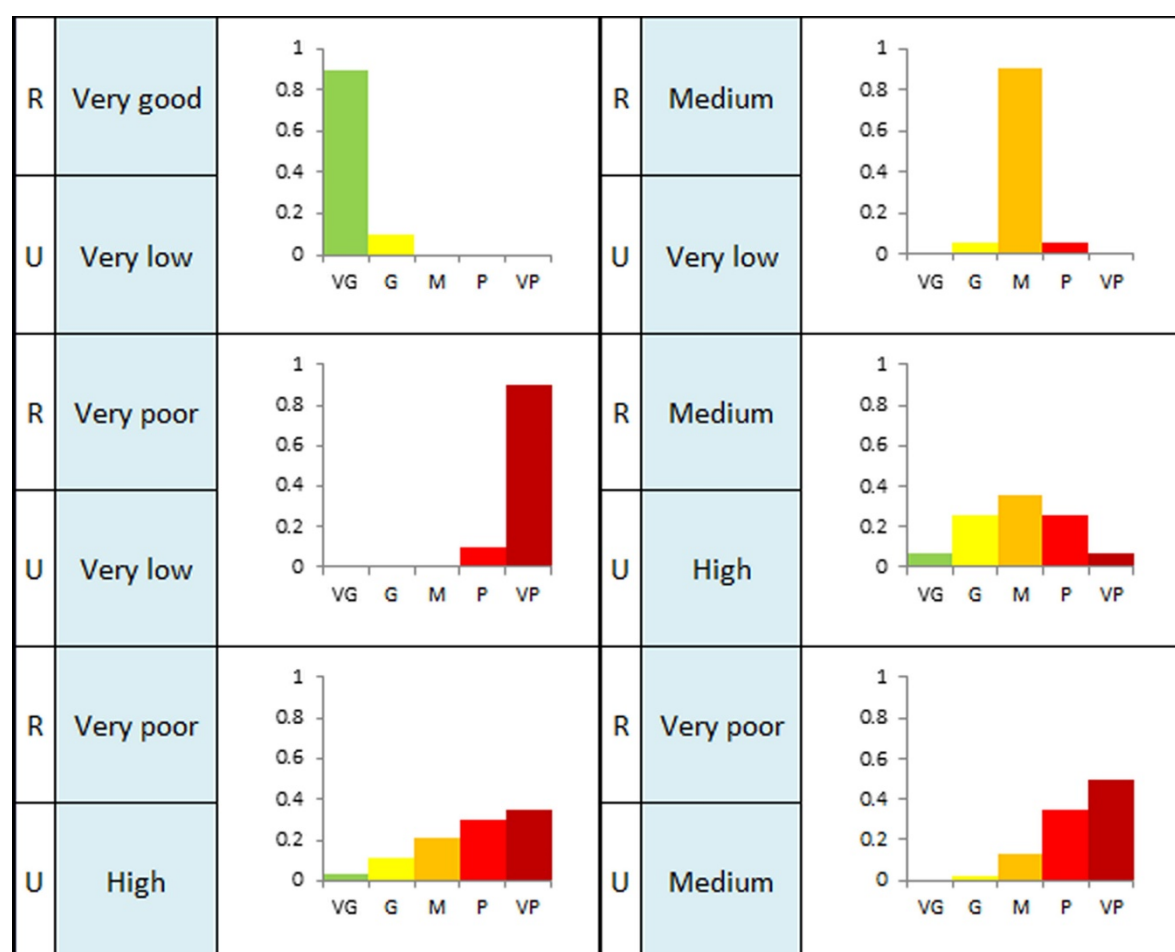| Scenario	Plaice	Sole	Crangon	Employment	Profit (total)	Effort (total)
Maximum Sustainable Yield (Weight)	198 kt	17 kt	50 kt	2350 fte	-2.5 mil	81 thousand days
Maximum Sustainable Yield (Euros)	188 kt	18 kt	51 kt	2250 fte	27 mil	72 thousand days
Maximum Economic Yield	123 kt	14 kt	49 kt	450 fte	88 mil	34 thousand days
Maximum Economic Yield (constrained)	121 kt	14 kt	49 kt	400 fte	87 mil	32 thousand days

Fig. 5

Fig. 6

Fig. 7

Table 1. Ranking of MSY objectives by participants of the problem framing workshop. Lower utility values correspond to preferred options.

Priority	MSY objectives	Expected utility
1	Maximise inclusive governance	0.46
	Maximise yield of fish/litre of fuel (or CO2) or similar energy unit	0.47
	Maximise yield in value of key commercial species	0.53
	Maximise consumer welfare/happiness	0.62
	Maximise yield in value	0.77
	Maximise yield in tonnes of key commercial species	0.77
	Maximise stability	0.78
2	Maximise Net Present Value	0.82
	Maximise Gross Value Added	1.14
	Maximise fisher welfare/happiness	1.52
	Maximise Gross Value Added over the entire value chain	1.57
3	Maximise yield in tonnes	1.66
	Maximise useful knowledge	1.78
	Maximise Social Yield	1.80
	Maximise willingness to invest in the future fisheries	1.87
	Maximise fishing community viability	1.93
	Maximise resilience	2.22
4	Maximise stability of stocks	2.41
	Maximise Resource Rent	3.12

Table 2. Ranking of constraints by participants of the problem framing workshop. Lower utility values correspond to preferred options.

Priority	Constraint	Expected utility
1	GES descriptors of commercial species above reference level	0.10
	GES descriptors of biodiversity above reference level	0.10
	GES descriptor of food web functioning above reference level	0.10
	GES descriptors of seafloor integrity above reference level	0.10
	Areas with fishing restrictions (e.g., Natura 2000)	0.10
	Mortality of PET and other vulnerable species below specified level	0.10
	Discard of non-target species below specified level	0.10
	Legislation adhered to/compliance	0.10
	Maintain relative stability	0.10
	Human accidents at sea below a specified level	0.10
	Maintain trust among industry participants	0.67
2	Profits above a minimum level	1.04
	Carbon footprint less than specified level	1.06
	Maintain trust among all stakeholders	1.06
	Equity of income	1.06
	Increase level of self-determination for fishing actions by fishers	1.06
	Maintain fishing rights and ownership	1.21
3	Stability of landings	2.00
	Retain subsidies	2.00
	Maintain small communities at specified level	2.00
	Maintain vessel size distribution at a certain level	2.00
	Maintain consumer choice for different kinds and sources of fish	2.00
4	Maintain human food supply above specified level	2.96
5	Management costs below specified level of Gross Values Added	3.90
	Technical selectivity unaltered	3.90
	Employment above a specified level	3.90
	Increase status of fishers	3.90
	Reduce barriers to mobility in the fishing industry (to join or leave)	3.90