

---

## Estimating the economic loss of recent North Atlantic fisheries management

Gorka Merino<sup>a, b, \*</sup>, Manuel Barange<sup>b</sup>, Jose A. Fernandes<sup>b</sup>, Christian Mullon<sup>c</sup>, William Cheung<sup>d</sup>,  
Verena Trenkel<sup>e</sup>, Vicky Lam<sup>f</sup>

<sup>a</sup> AZTI-Tecnalia, Herrera Kaia, Portualdea, z/g, Pasaia (Gipuzkoa), 20110, Spain

<sup>b</sup> Plymouth Marine Laboratory, Prospect Place, PL1 3DH, Plymouth, UK

<sup>c</sup> IRD, Unité de Recherche Ecosystèmes Marins Exploités, Avenue Jean Monnet, 34200, Sète, France

<sup>d</sup> Fisheries Centre, University of British Columbia Fisheries Centre, Vancouver, B.C., V6T 1Z4, Canada

<sup>e</sup> Ifremer, rue de l'île d'Yeu, BP 21105, 44311 Nantes cedex 3, France

<sup>f</sup> Fisheries Economics Research Unit, Fisheries Centre, University of British Columbia Fisheries Centre, Vancouver, B.C., V6T 1Z4, Canada

\*: Corresponding author : Gorka Merino, tel.: +34 667-174-456 ; email address : [gmerino@azti.es](mailto:gmerino@azti.es)

[maba@pml.ac.uk](mailto:maba@pml.ac.uk) ; [w.cheung@fisheries.ub.ca](mailto:w.cheung@fisheries.ub.ca) ; [Verena.Trenkel@ifremer.fr](mailto:Verena.Trenkel@ifremer.fr) ; [v.lam@fisheries.ub.ca](mailto:v.lam@fisheries.ub.ca)

---

### Abstract:

It is accepted that world's fisheries are not generally exploited at their biological or their economic optimum. Most fisheries assessments focus on the biological capacity of fish stocks to respond to harvesting and few have attempted to estimate the economic efficiency at which ecosystems are exploited. The latter is important as fisheries contribute considerably to the economic development of many coastal communities. Here we estimate the overall potential economic rent for the fishing industry in the North Atlantic to be B€ 12.85, compared to current estimated profits of B€ 0.63. The difference between the potential and the net profits obtained from North Atlantic fisheries is therefore B€ 12.22. In order to increase the profits of North Atlantic fisheries to a maximum, total fish biomass would have to be rebuilt to 108 Mt (2.4 times more than present) by reducing current total fishing effort by 53%. Stochastic simulations were undertaken to estimate the uncertainty associated with the aggregate bioeconomic model that we use and we estimate the economic loss NA fisheries in a range of 2.5 and 32 billion of euro. We provide economic justification for maintaining or restoring fish stocks to above their MSY biomass levels. Our conclusions are consistent with similar global scale studies.

### Highlights

► The economic loss of North Atlantic fisheries in 2010 was B€ 12.2. ► Fish stocks would have to recover to levels 2.4 times larger than present to achieve maximum profits. ► Macroscale assessments of governance require simplifications and assumptions. ► Stochastic simulations estimate NA fisheries loss in a range from B€2.5 to B€32. ► Securing that stocks biomass are above MSY is economically justified despite uncertainty on results.

**Keywords** : Economic assessment ; Fisheries, North Atlantic ; Management efficiency ; Uncertainty

52  
53  
54  
55

56 Marine fisheries are an important source of food and livelihood opportunities worldwide  
57 (Allison et al., 2009; Garcia & Rosenberg, 2010; Rice & Garcia, 2011). The exploitation state of  
58 fish stocks is hotly debated (Branch et al., 2011; Pauly et al., 2002; Worm et al., 2009), but there  
59 is a general consensus that marine fisheries food production potential is not achieved (Branch et  
60 al., 2011; FAO, 2012). North Atlantic fisheries are nowadays yielding less fish than in recent  
61 decades and despite significant improvements (Fernandes and Cook 2013), the state of many of  
62 its stocks remains poor. Traditionally, the efficiency of biomass production has been the basis of  
63 fisheries management. Therefore, different regulations have aimed at maintaining fish stocks at  
64 levels at which they could produce their *Maximum Sustainable Yield (MSY)*, i.e. the exploitation  
65 rate where the response of the stocks to fishing through individual growth and recruitment  
66 operates at its maximum capacity. In a deterministic sense, at this level, average fish biomass  
67 remains stable over time and the amount of fish that can be sustainably extracted is maximized  
68 (Schaefer, 1954). Classic approaches assume that these dynamics operate at a particular stock  
69 level, depending on the species' life history and thus, should fisheries management succeed in  
70 maintaining each of them at their MSY, the maximum potential of food production from marine  
71 ecosystems would be achieved. Using Economic Exclusive Zone (EEZ) and fish species data  
72 from the Sea Around Us database, the food production potential wasted due to ineffective  
73 management was estimated, i.e., the difference between catch observations and their MSY  
74 estimated from historic catch series (Srinivasan et al., 2010). Srinivasan et al. (2010) estimated  
75 that catch losses amounted to 7-36% of the reported annual catch, resulting in a landed value  
76 loss between \$6.4 billion and \$36 billion.

77

78 In reality, it is ecologically impossible to simultaneously maximize sustainable yield for all  
79 species in a multiple species fishery (Link, 2009). Therefore, the productivity of marine  
80 ecosystems is expected to be lower than predicted by the sum of single stocks' MSY (Link et  
81 al., 2012). The overall productivity and state of exploitation of marine ecosystems have been  
82 investigated previously with complex ecosystem models and indicators (Blanchard et al., 2012;  
83 Blanchard et al., 2009; Coll et al., 2008; Cury et al., 2008; Merino et al., 2012; Shin et al.,  
84 2005), and with single species models applied to entire exploited communities (Guillen et al.,  
85 2013; Link et al., 2012; Mueter & Megrey, 2006; Sparholt & Cook, 2009; Worm et al., 2009).  
86 For example, 'surplus production models' (SPM), have been used to produce simple  
87 representations of the key ecological processes underlying fisheries (Link et al., 2012). SPM can

88 be used to estimate biological reference points (BRP's) such as the biomass level and the rate of  
89 exploitation to achieve the MSY of single fish stocks or marine ecosystems.  
90  
91 SPM have allowed the extension of fisheries assessment into other disciplines beyond ecology.  
92 For example, the seminal paper by Gordon (1954) introduced the concept of *Maximum*  
93 *Economic Yield (MEY)*, the bioeconomic reference point at which the economic profits of a  
94 fishery are maximized. This concept relies on fish stocks' productivity described by SPM  
95 (Schaefer, 1954), the market price of fish and the costs of fishing. A derivation of this model  
96 was used to assess the economic efficiency at which the world's fisheries are exploited  
97 (Arnason et al., 2009), from which global MEY was estimated based on world's catch, value  
98 and costs databases. Arnason et al (2009) highlight the vast economic consequences of  
99 inefficient fisheries management and the economic benefit of maintaining fish stocks at healthy  
100 levels. Due to the high uncertainty in the data and the simplified model used, the numeric results  
101 of Arnason et al (2009) study were presented with caution and with wide confidence intervals.  
102 Nonetheless, the global cost of sub-optimal management was estimated to be in a range between  
103 \$37-67 billion in 2004, with an historic accumulated loss of \$2.2 trillion between 1974 and  
104 2004. Arnason et al. (2009) did not explicitly evaluate the cost of rebuilding fish stocks, i.e., the  
105 cost of the necessary transition until stocks are recovered and more economic profit is obtained  
106 with less fishing effort. More recent research shows that the benefit of rebuilding global  
107 fisheries outweighs costs (Sumaila et al., 2012) and that investing in restoring overexploited  
108 stocks is economically sound (Crilly & Esteban, 2012). However, it is important to clarify that  
109 not all fish stocks are overexploited. For example, forty-three percent of assessed EU stocks  
110 were considered overfished in 2012 (Fernandes & Cook, 2013; European Union 2012). In any  
111 case, when fishing yields do not correspond to MSY this does not automatically mean a stock is  
112 overfished (Hilborn & Stokes, 2010). Hilborn and Stokes (2010) suggest that it would be  
113 reasonable to adopt a definition of being overfished as any stock size where the expected yield  
114 is 80% or less than MSY, which is the level at which reductions of fishing mortality towards  
115 MSY would produce measurable catch increases.  
116  
117 The North Atlantic basin is a dynamic environment for physical and biological processes  
118 (Beaugrand et al., 2002; Marshall et al., 2001; Parsons & Lear, 2001) and is home to some of  
119 the largest populations of commercially exploited stocks (Trenkel et al., 2013). With this at the  
120 background and due to the importance of North Atlantic global climate, BASIN (Wiebe et al.,  
121 2009) is a joint EU/North American research initiative with the goal of elucidating the  
122 mechanisms underlying observed changes in the North Atlantic ecosystems and their services,  
123 and Euro-BASIN is a programme to implement this vision funded by the European Commission  
124 7<sup>th</sup> Framework Programme (St. John et al. *introduction article of this issue*). In the context of

125 Euro-BASIN, this article aims to reflect the economic relevance of fisheries within the North  
126 Atlantic basin using some of the methods described above to estimate the economic cost of  
127 ineffective fisheries management, defining ‘ineffective’ as a deviation from maximum  
128 economic rent (Arnason et al., 2009). To do so, we tested alternative aggregations of fisheries  
129 production and economic indicators and parameterized a simple bioeconomic model. The scope  
130 and scale of this study is vast and complex and requires simplifications. The ecological  
131 complexity, regional differences and dynamics of individual fish stocks in the North Atlantic  
132 are simplified in an aggregated single stock of fish, which is exploited by an aggregated single  
133 fishery. While this approach has significant ecological difficulties, aggregated fisheries  
134 production functions are not new, and have been used to assess the economic efficiency of  
135 global fisheries as a single exploited unit (Arnason et al., 2009), at ecosystem level (Crilly &  
136 Esteban, 2012; Link et al., 2012; Sparholt & Cook, 2009) and at species-EEZ level (Srinivasan  
137 et al., 2010). The implications of this approach and justification for the use of an aggregated  
138 model will be discussed in detail throughout the manuscript. Furthermore, we explore the  
139 possible impact of parameter uncertainties and the assumptions made to obtain our numeric  
140 results. Finally, we discussed the use of multidisciplinary approaches in analyzing marine  
141 resources at the basin scale. These results provide background context to the work conducted in  
142 Euro-BASIN in the Bio-economic modeling (WP7) and Living resources (WP5) workpackages.

143

144

## 145 **2. Material and Methods**

146

### 147 *2.1. The data*

148

149 - *Biological parameters:* Catch data from ICES FishStatPlus database ([www.ices.dk](http://www.ices.dk)),  
150 FAO Fishery Statistics ([www.fao.org](http://www.fao.org)) and Sea Around Us catch database  
151 ([www.seaaroundus.org](http://www.seaaroundus.org)) were used to estimate the biological parameters of the surplus  
152 production model of the North Atlantic (NA) fisheries from 1950 to 2010. The data  
153 used comprise 59 ICES stocks, 18 species and 2 habitats exploited in the North Atlantic  
154 for the ICES area (see Table 1). These data were used to explore how alternative levels  
155 of stock and taxonomic aggregation could lead to different MSY estimates and indicate  
156 the uncertainty that the aggregation process undergone for the NA bioeconomic model.  
157 The overall NA basin MSY was estimated using datasets from FAO and was used as  
158 input for the bioeconomic model. A series of all the species landed in the NA was used.

159

160 - *Economic parameters:* Three main sources of information were used to obtain the  
161 economic parameters of the NA fisheries. First, the Sea Around Us database was used

162 to obtain the value of the NA fishery as a whole. Second, a global fishing costs database  
163 at fleet segment level (Lam et al., 2011) was used to estimate countries total profits  
164 (Table 2). These estimates showed significant differences with the ones reported in the  
165 Annual Economic Report of the European Fishing Fleets (JRC, 2012).

166

## 167 2.2 The models

168

169 - *Biological parameters estimation:* We used a relatively simple method to obtain  
170 plausible MSY estimates and other biological parameters from catch data, based on  
171 assumptions on resilience (corresponding to the intrinsic growth rate  $r$  in the SPM) and  
172 the plausible range of relative stock sizes at the beginning of the time series (Martell &  
173 Froese, 2010). We used a medium resilience range as defined by Martell & Froese, i.e.  
174  $0.2 < r < 1$ , and an initial (in 1950) relative stock size range of 50-90% of carrying  
175 capacity  $K$  or pristine biomass for all stocks (except for 'ghl-arct' ICES stock which  
176 was considered of 'low' resilience,  $0.05 < r < 0.5$ ), and all species, habitat and the total  
177 NA. The identification of pairs of  $r$ - $K$  values compatible with the catch time series and  
178 the above assumptions was performed using the R-code for batch processing made  
179 publicly available in [http://www.fishbase.de/rfroese/CatchMSY\\_2.r](http://www.fishbase.de/rfroese/CatchMSY_2.r) for 59 ICES stocks  
180 ('ICESct2.csv', catch file processed and also made available by Martell and Froese), for  
181 the 18 species targeted in the ICES areas and for the entire NA basin from FAO catch  
182 data. The aggregation was a simple summation of catches of all the stocks of each of the  
183 18 species, of all demersal and pelagic species and of all ICES stocks. Similarly, for the  
184 NA estimation, all NA species catches were summed to obtain a single catch time  
185 series. For each plausible  $r$ - $K$  pair, an estimate is obtained as  $MSY = 1/4 r K$ . This MSY  
186 estimation algorithm has been validated against analytical fish stock assessment  
187 estimates of MSY (Martell & Froese, 2010). Good agreement was found between stock  
188 assessment MSY estimates and the geometric mean of MSY values calculated from the  
189 plausible  $r$ - $K$  pairs (Martell & Froese, 2010).

190

191 - *Aggregated bioeconomic model* (Arnason, 2007; Arnason et al., 2009). This model  
192 assumes that the stocks exploited by global fisheries can be modeled as a single fish  
193 stock with an aggregate biomass growth function and a fishing industry operating  
194 exclusively in the area. The economic performance from fisheries is estimated with the  
195 value of the global landings calculated with an aggregated harvest function (SPM by  
196 Schaefer 1954) and an aggregated fishing cost function relating current fishing effort to  
197 fisheries costs. Incorporating NA fisheries into a single fishery allows for a model with  
198 a manageable number of parameters. This model requires 4 biological parameters: (i)

199 Global MSY, (ii) total ‘carrying capacity’ or ‘unexploited biomass level’, (iii) fish  
200 biomass growth in the last year and, (iv) a ‘schooling’ parameter; and 5 economic  
201 parameters from the fishing industry: (i) Landings, (ii) value of landings and, (iii) total  
202 profits from fishing in the last year, (iv) ‘fixed costs ratio’ and, (v) ‘elasticity of  
203 demand’ with respect to total biomass. The MSY has already been explained and  
204 ‘unexploited biomass’, fish biomass growth, landings, value of landings and profits are  
205 self-explanatory. The ‘schooling’ parameter describes the spatial distribution behavior  
206 of fish and ranges between 0 and 1. The lower the parameter the more aggregated the  
207 fish, e.g., small pelagic stocks like anchovies, sardines, mackerel etc. When this  
208 parameter is close to 1, fish are homogeneously distributed in space, e.g., demersal  
209 species such as hake or plaice. For our analysis we fixed this parameter as 1, to assume  
210 that all fish are homogeneously distributed throughout the NA. However, the impact of  
211 this parameter on the final calculations is explored in the Appendix. The ‘fixed costs  
212 ratio’ describes the fraction of the total costs incurred by the fishing industry that are  
213 not originated by labor, fuel, capital and other factors of production such as  
214 maintenance, repair, supplies and gear costs. We considered this ratio to be 0 as in the  
215 global study (Arnason et al., 2009). Assuming a zero value means that fishing effort is  
216 measured as the size of fishing industry and not by its activity (if inactive, fleets would  
217 still generate fixed fishing costs). The elasticity of demand to biomass expresses the  
218 price of fish as dependent on the global marine commercial fish biomass. This elasticity  
219 is positive: when there is overexploitation, biomass is at a low level, the proportion of  
220 low value fish is higher and mean price is smaller; in the other direction, if fish stocks  
221 recover from overexploitation, the average size and trophic level of caught fish  
222 increased and price does so likewise. This is a manifestation of the “fishing down the  
223 food web” effect (Pauly et al 1997).

224 The bioeconomic model also required additional input that was obtained as follows:  
225 from the FAO catch data series we obtained catches in 2010 ( $Y_{2010}$ ) and biomass growth  
226 in 2010 ( $G(x)_{2010}$ ). We used the difference between  $Y_{2010}$  and  $Y_{2009}$  as  $G(x)_{2010}$  which  
227 assumes that catch changes were only caused by abundance changes rather than  
228 management or other factors. For the value of catches, the Sea Around Us database was  
229 used to complement FAO data ( $Value_{2010}$ ). The profits of NA fisheries in 2010 was  
230 obtained summing the national profits (Table 2) obtained from Lam et al (2011) applied  
231 to NA value of catch.

232

233 (# Insert Table 2 #)

234



235 We plot the classical equilibrium catch-biomass curve (Schaefer, 1954) and different  
 236 potential profit curves ( $iso\_P$ ) defined by the profits in 2010 ( $P_{2010}$ ), price at  
 237 equilibrium ( $p_{eq}$ ), costs of fishing per unit of effort ( $c$ ) and biomass at equilibrium  
 238 (equation 1).

$$239 \quad iso\_P = \frac{P_{2010}}{p_{eq} - c \cdot B_{eq}} \quad (\text{equation 1})$$

240 The points where  $iso\_P$  trajectories meet the catch and biomass equilibrium curve are a  
 241 feasible sustainable profit, catch and biomass equilibrium points. The maximum feasible  
 242  $iso\_P$  is searched to identify the *MEY* of North Atlantic fisheries. Further  
 243 transformations of the basic equations by Gordon-Schaefer required to plot the curves  
 244 are explained in the Appendix. Economic loss is then calculated as the difference  
 245 between this *MEY* value and realized profits in 2010.

246  
 247 *Stochastic simulations:* The economic loss estimated with the deterministic model for 2010  
 248 was re-estimated allowing for uncertainty on the input parameters (Table 3): (i) random values  
 249 in a range of  $\pm 30\%$  of the initial parameters ('sim 1'), (ii) lognormal distributions for *MSY* and  
 250 *K* as provided by the Martell and Froese (2010) estimation model and random for the others  
 251 ('sim 2'), (iii) lognormal distributions for *MSY* and *K* and random for Catch 2010 ('sim 3') and,  
 252 (iv) random within  $\pm 30\%$  for all parameters but *MSY*, *K* and Catch 2010 which were kept  
 253 constant ('sim 4'). For all stochastic simulations the model was run for  $10^5$  iterations to  
 254 equilibrium.

255

### 256 3. Results

257

258 The total *MSY* for all the ICES stocks combined was estimated to be between 6.68 and 9.75  
 259 million tonnes, depending on the level of catch aggregation from which the estimates were  
 260 calculated (Table 1 and Figure 1).

261 Biological parameters were estimated for each of the ICES stocks and were then aggregated into  
 262 species, habitat and total ICES areas. The total *MSY* estimate for the ICES fisheries decreases  
 263 exponentially with the level of aggregation, with *MSY* estimates 30% lower when using ICES  
 264 area aggregation (largest aggregation) compared to estimates from stock level aggregation  
 265 (lowest aggregation). Although we don't use the estimated *MSY* by ICES area for the basin-  
 266 scale analysis, the differences between estimates arising from different levels of aggregation  
 267 were used to calculate the confidence limits of *MSY* in the North Atlantic, which were used as  
 268 inputs for the bioeconomic model.

269

270 (# Insert Figure 1 #)

271 (# Insert table 1 #)

272

273 We used the time-series of total aggregated NA landings applied to the algorithm by Martell and  
274 Froese (2010) to estimate an MSY of 13.7 Mt (s.d.=0.04) (Figure 2). Historically North Atlantic  
275 fisheries were considered to be under development up to 1970s, when total landings started to  
276 exceed MSY considerations. From 1980 until the early 2000s, the total catch has fluctuated near  
277 this estimated global MSY. Since then landings have decreased to levels approximately 80% of  
278 basin MSY. This model also estimated the carrying capacity parameter (K) or unfished biomass  
279 for North Atlantic fish resources to be 170 Mt (Table 3).

280

281 (# Insert Figure 2 #)

282

283 The bioeconomic model estimated that NA fisheries could generate B€ 12.85 of profits  
284 compared to the current B€ 0.63 (Figure 3). In addition, this equilibrium model shows the  
285 biomass level (45Mt, 26% of K) if current profits were to be maintained. In summary, this  
286 figure indicates that allowing stocks to rebuild to the biomass consistent with MEY (108 Mt,  
287 63.5% of the unexploited biomass) would allow multiplying profits 20 fold. In other words, NA  
288 fisheries are only generating 5% of their economic potential. It must be noted that the catch at  
289 MEY is estimated to be 12.66 Mt, only 25% larger than the catch level in 2010.

290

291 (# Insert Table 3 #)

292 (# Insert Figures 3 and 4 #)

293

294 Using the classic revenue-cost against fishing effort curve by Gordon (1954) (Figure 4), the  
295 effort level that would lead to the economic maximization of North Atlantic fisheries is  
296 estimated to be 47% of current effort. Thus, should fishing effort increase 10% above current  
297 levels, the NA fisheries would incur economic losses. Figure 4 also shows that assuming  
298 equilibrium conditions NA fisheries in 2010 were near the “Bioeconomic Equilibrium” (BE),  
299 the point at which the fishery rents are dissipated as fishing costs are equal to the revenues from  
300 fishing.

301

302 (# Insert Figure 5 #)

303

304 The computations above are subject to uncertainties, and thus we added a level of stochasticity  
305 to our model’s input parameters, which indicated that the economic loss of North Atlantic  
306 fisheries in 2010 ranged between B€2.5 and B€32 when all parameters were randomly  
307 fluctuating with a 30% coefficient of variation (Figure 5). MSY and  $Y_{2010}$  are the most



308 important sources of variation when estimating the economic losses of fisheries (Arnason, 2007;  
309 Arnason et al., 2009) and Figure A.1 (Appendix). Besides, significant uncertainty was  
310 propagated into estimates of stocks' carrying capacity ( $sdLog=0.24$ ). Therefore, specific  
311 simulations investigating the impact of those three parameters were performed. Uncertainty in  
312 estimation was moderately reduced by varying the three parameters through lognormal  
313 distributions and generating random values with a uniform distribution with bounds  $\pm 30\%$  for  
314 the others ('sim 2') or assuming them constant ('sim 3'). The simulations 'sim 3' and 'sim 4'  
315 confirmed that these parameters generated the largest uncertainty on the final estimates of  
316 economic loss. For 'sim 4', fixing  $MSY$ ,  $K$  and  $Y_{2010}$  the variability of the loss estimate was  
317 reduced significantly, ranging between B€ 6 and 19 with 95% confidence. The most important  
318 result from these simulations is that the model is more sensitive to biological parameters and  
319 therefore, biological parameterization is more important than economic parameterization.

320

#### 321 4. Discussion

322

323 We have provided an assessment of the economic losses due to the choices taken in the  
324 management of North Atlantic fisheries. We have used methods previously implemented in the  
325 assessment of the economic losses of global fisheries (Arnason et al., 2009). Such a focus on the  
326 North Atlantic, in the context of the Euro\_BASIN project, is motivated by the fact that its  
327 fisheries have a long history and economic importance, with significant catch-independent and  
328 dependent data sets, which are managed at different scales and with different degrees of success  
329 and failure.

330

331 The catch and value of North Atlantic fisheries have declined significantly in the last decade,  
332 partially due to management restricting catches (see below). The economic opportunity lost  
333 through the inefficient management of North Atlantic fisheries in 2010 was estimated to be B€  
334 12.2. This echoes the results of a bioeconomic model built imposing strong assumptions on  
335 North Atlantic basin biological productivity and economic data of the fishing fleets operating in  
336 the area. Arnason et al 2009 estimated the global economic loss of marine fisheries due to  
337 overexploitation to be in a range of \$B 37-67. North Atlantic landings correspond to  
338 approximately 12% of global catches and the economic loss of NA fisheries represents ~33% of  
339 global losses. This may be caused by the relative larger price of NA fisheries in comparison to  
340 other areas (Sumaila et al., 2007) and by the historical overfishing history of North Atlantic  
341 fisheries (FAO, 2012). For the North East Atlantic, Crilly and Esteban (2012) estimate that  
342 restoring fish stocks could deliver up to £4.43 billion per year in profits, approximately 41% of  
343 our estimate for the entire NA.

344

345 Fisheries assessment provides information on the state of exploitation of marine resources and is  
346 generally performed at stock level, a harvested unit which dynamics are driven by recruitment,  
347 growth, natural mortality and fishing. Because of the limited number of fish stocks with stock  
348 assessment data at the basin-scale, the catch based approach employed in this study allow us  
349 to include a wider range of fish stocks. However, the catch based approach is based on the  
350 assumption that catch reflects fish abundance and productivity. This principle is controversial,  
351 especially when management interventions change through the history of catch time-series  
352 (Pauly et al., 2013). However, catch-based methods are widely used to assess data-poor fisheries  
353 and to produce large scale overviews of the state of fisheries (Fernandes et al., 2013; FAO,  
354 2012; Lleonart & Maynou, 2003; Pauly et al., 2003, Vasconcellos and Cochran, 2005). Data on  
355 North Atlantic fisheries' are abundant, especially for ICES-assessed stocks. A specific problem  
356 arises because data are not available at the basin scale, one of the challenges that the Euro-  
357 BASIN project tries to address. Also, the proportion of assessed stocks in relation to total catch  
358 differs across regions of the NA. For example, more than 90% of the North Sea catch (areas  
359 IVa-c) corresponds to assessed stocks but in the Celtic Sea (VIIe-k) this number is less than  
360 40% (Gascuel et al., 2012). Using data that are only available from ICES statistical area may  
361 thus provide a biased view of the status of fisheries in the NA basin. Besides, multi-species  
362 MSY is less than the sum of single stocks', as demonstrated in this and other studies (Link et al.,  
363 2012; Sparholt & Cook, 2009). Multi-species MSY could have been estimated with ecosystem  
364 models as well. Fish species dynamics are regulated through trophodynamic interactions and  
365 energetic fluxes across trophic levels (Pauly et al., 2000; Shin & Cury, 2004), which are  
366 reflected in the ecosystem's size spectra (Blanchard et al., 2009). For example, capelin, cod and  
367 herring interact in the Barents Sea food web (Lindstrøm et al., 2009). However, these models  
368 are relatively complex in relation to SPM (Coll et al., 2008). We favor the use of a simplified  
369 aggregated surplus production model because these models can produce robust estimates of  
370 multispecies environments (Sparholt & Cook, 2009) allowing for comparison across areas  
371 towards the practical implementation of the ecosystem-based fisheries management (Link et al.,  
372 2012). Also, this model provides a consistent platform to produce a macro scale assessment of  
373 North Atlantic fisheries in combination with economic information.

374

375 We acknowledge that the use of an aggregated economic model requires significant  
376 simplifications of complex ecological processes, and masks geographical differences in  
377 ecosystems productivity and management efficiency. For example, let us look at two cod stocks  
378 in the Irish and Icelandic Seas. Recent annual landings of Irish Sea cod have been lower than 5  
379 k t with prospects for zero catch in 2013 and a stock which is currently outside biological limits  
380 (ICES 2012a). In contrast, the Icelandic cod's TAC for 2012 was 177 k t and the stock is

381 considered inside safe biological limits (ICES 2012b). The overall fishing effort recommended  
382 to achieve MEY for NA fisheries would not be expected to be applied homogeneously to all  
383 stocks. The aggregative approach by-passes stock-specific responses and assumes that fishing  
384 effort reductions would have to focus those stocks catalogued as “overexploited” or “under  
385 overexploitation”, and that benefits from adequate fishing management will be especially  
386 notable for the most productive areas of the North Atlantic.

387

388 Based on our analysis, North Atlantic fisheries remained within the estimated MSY range from  
389 1964 to 2005. Then, total landings declined significantly and the estimation model associates  
390 this to overall overexploitation of NA resources. However, marine ecosystems are driven by  
391 multiple drivers that change over time; therefore, a constant historical MSY may not be  
392 realistic. The constant MSY estimated in the first part of this work is used for the subsequent  
393 economic assessment and should be considered with caution. Catch reductions can be caused by  
394 multiple factors, including overexploitation, environmental variability or implementation of  
395 catch restrictions. Overexploitation is defined by Hilborn and Stokes (2010) when catches are  
396 below 80% MSY, which equates to when declining yields are obtained with increased fishing  
397 effort (Schaefer 1954). The same is concluded from the biomass-catch diagram shown in  
398 Figure 3. When MSY is exceeded for extended periods and if fishing effort is maintained  
399 beyond the level corresponding to MSY, yield will decrease as the available biomass has fallen  
400 below the point at which MSY is achieved (50% of its unexploited level, in this case). That is,  
401 biomass decreases with increasing catch until the point when biomass reductions will result in  
402 lower catches if fishing effort is not increased. In multispecies fisheries apparent MSY levels  
403 can be maintained by targeting previously undeveloped fisheries simultaneously with declining  
404 stocks. Using theoretical models, it has been shown that this feature can precede a sequential  
405 collapse of geographically distant fisheries (Merino et al., 2010; Merino et al., 2011).

406

407 This model does not consider environmental effects on the productivity of the NA basin. In  
408 reality, fish stocks, especially small pelagic fish (70-80% of total NA catch), are highly  
409 vulnerable to environmental variability (Barange et al., 2009; Chavez et al., 2003; Fernandes et  
410 al., 2010; Hsieh et al., 2009). However, it is also evident that the impacts of particular  
411 environmental conditions differ between species. For example, Icelandic capelin catch averaged  
412 1 Mt from 1979 to 2002 (13% the yields from ICES assessed stocks) when it started declining to  
413 15 kt in 2008. This decline is reflected in the overall NA trend and it could be caused by  
414 temperature changes (Carscadden et al., 2013 (In press)). However, other stocks such as herring  
415 (yielding ~2Mt in the last decade) seem to be favored by current conditions and have recovered  
416 from overexploitation faster than expected (Nash et al., 2009), which could counterbalance the  
417 negative environmental impact on capelin on the basin scale trend. Another example is blue

418 whiting whose catches have displayed a dramatic “boom and bust” dynamic over the past two  
419 decades (ICES, 2011). Landings during the 1980s and early 1990s were typically between 500  
420 and 1000 kt, but increased to 2400 kt in 2004 as a result of a suite of good year classes. At this  
421 point, blue whiting was the largest fishery in the North Atlantic, ahead of herring, and the third  
422 largest marine capture fishery in the world (FAO, 2010). The subsequent decline of the fishery  
423 has, however, proved to be equally dramatic (ICES, 2011). The alternation between warm and  
424 cold regimes is associated to alternative species proliferation (Chavez et al., 2003), including  
425 multidecadal regime shifts (Alheit et al., 2009). However, investigating each of the  
426 environmental drivers affecting fish stocks in the North Atlantic in order to better estimate  
427 individual MSYs would mean losing focus on the principal objective of this study and its scale.

428  
429 A third factor resulting in catch reduction is management restriction. Generally, closures and  
430 drastic catch limitations are the consequence of overexploiting resources and subsequent fishery  
431 crises (Finlayson, 1994; Lazkano et al., 2012; Nøstbakken & Bjørndal, 2003; Worm et al.,  
432 2009). Historically, fish stocks have collapsed due to a myriad of unfavorable environmental  
433 conditions and excessive fishing pressure (Alheit et al., 2009; Chavez et al., 2003; Merino et al.,  
434 2013; Watson et al., 2006) and which triggered consequent catch restrictions (Worm et al.,  
435 2009). However, we would like to stress that, particularly the catch reduction in the last ten  
436 years of the data series, should be attributed not only to historical overfishing but also to  
437 management driven catch limitations. For example, under the EU framework, the Common  
438 Fishery Policy and the Financial Instrument for Fisheries Guidance (FIFG) a remarkable  
439 reduction of fishing boats has been accomplished (Fernandes and Cook 2013). In addition, since  
440 2005 emergency and recovery plans have applied under the EU adopted MSY framework  
441 aiming to reduce fishing mortality towards achieving MSY for different stocks which is already  
442 improving fisheries economic indicators (Cardinale et al., 2013). Furthermore, this approach is  
443 followed by the International Council of the Exploration of the Sea (ICES) and other  
444 international agreements (FAO, 2012). To sum up, some of the catch reductions reflected in the  
445 basin scale trend (Figure 2) are aligned to the implementation of international efforts to restore  
446 fish stocks and this can potentially bias the parameter estimation procedure used in this study by  
447 estimating as economic loss what in reality may be a short term economic loss “invested” in  
448 stocks recovery towards more profitable fisheries.

449  
450 The parameters used in the bioeconomic model can be controversial too: For example,  
451 classically, the supply-demand relation is considered as inverse: the lesser the catch, the higher  
452 the price. However, the positive elasticity parameter used here was taken from Arnason et al  
453 (2009) which aligns with a global perspective of the state of marine fisheries, as the “Fishing  
454 down the food web” concept (Pauly et al 1997) does. However, this is expected to have low

455 impact in our numeric results: The estimated catch increase when moving towards MEY would  
456 be small, so the expected price changes would be small too. A different matter is the potential  
457 impact of exogenous variables on North Atlantic fish demand and therefore, in the price  
458 equation used in this document. We do not consider the impact of aquaculture expansion on the  
459 price of wild fish nor the impact of imports that might act as less priced substitutes to North  
460 Atlantic fish. Both factors could presumably reduce the price of North Atlantic fish and  
461 therefore, the potential economic profit of North Atlantic fisheries would be reduced. Finally,  
462 our model is based on estimates of current profits of NA fisheries, estimated with value and  
463 fishing costs databases, and without considering the effects of subsidies. According to Sumaila  
464 et al (2012), 31% of landed value in world fisheries is subsidized and therefore, the current  
465 profits for the fishing companies are presumably larger than the B€0.63 used to parameterize  
466 our bioeconomic model.

467

468 The implementation of ecosystem-based fisheries management (EBFM) requires the  
469 development of models to assess the economic performance of the fishing industry in  
470 combination with their impact upon marine ecosystems (Gascuel et al., 2012). The bioeconomic  
471 model used here was parameterized with a global estimate of NA ecosystems productivity and  
472 the sum of the economic performance indicators of the countries operating in its waters. In  
473 contrast to the biological part, the aggregation of the economic parameters was additive, we  
474 estimated the NA value of catch and net economic profits as the sum of the national estimates.  
475 The values shown in table 2 were obtained collating catch and value data from the Sea Around  
476 Us database and estimating the fleet specific costs of fishing using costs per tonne estimates  
477 from Lam et al (2011). Fishing costs and net profit values were also available from alternative  
478 reports. For example, the Annual Economic Report (AER) on the EU fishing fleet (JRC, 2012)  
479 provides estimates of many fishing indicators of EU countries. However, this report aggregates  
480 all EU countries fishing operations in waters beyond the NA. Using costs of fishing per tonne of  
481 catch in the NA allows for assigning the fishing costs only to the operations targeting North  
482 Atlantic fish. However, the cost structure provided in the AER is more detailed than in our  
483 approach. The net profit of EU fleets operating in the NA estimated in the AER is B€-0.236.  
484 Had this value been used as input to our bioeconomic model, our estimated loss would have  
485 been even larger. Additional sources of information on the economic performance of Russian,  
486 Norwegian, US and Canadian fleets (FAO, 2007; Kitts et al., 2010; NOAA, 2011) could  
487 improve the economic parameter estimation process. However, as seen in Figure 5, the most  
488 determinant set of parameters are those related to ecosystems productivity.

489

490 Our approach is based on deviations from biological and economic reference points. The  
491 economic loss pivots around the concept of *Maximum Economic Yield*, an equilibrium point

492 where the net economic return from a fishery can be maximized sustainably, as assumed in  
493 previous studies (Arnason et al., 2009; Crilly & Esteban, 2012; Sumaila et al., 2012). This  
494 reference point is estimated with a graphical procedure (Figure 3). Large benefits will be  
495 considered as unsustainable as they do not meet the parabola and; lower than the optimal will  
496 cross it twice, one for high levels of biomass and the other at biomass levels below that  
497 corresponding to MEY. It is important to note that the recovery of the stocks towards MEY  
498 biomass would not produce major changes in the overall catch from the NA. In 2010 10.8Mt of  
499 fish was landed whereas for the MEY total catch would be 12.66 Mt. Therefore, a catch increase  
500 of 26% would produce a net economic gain of 2000%, but would require a 53% reduction in  
501 fishing effort. According to this, the economic benefit of restoring stocks would outweigh its  
502 potential food security implications (Garcia & Rosenberg, 2010; Rice & Garcia, 2011;  
503 Srinivasan et al., 2010). By reducing the fishing effort, costs would reduce linearly as revenues  
504 would increase potentially until the MSY peak. Then, further effort reductions would make  
505 revenues reduce too until its gradient equals fishing costs lines slope. As a result, a fishing effort  
506 reduction would produce a logarithmic increase in profits. Therefore, the profit increase would  
507 be more substantial at the initial stages of reduction. For example, if total fishing effort was  
508 reduced to 70% of current levels, total fish biomass (not each and every stock) would recover to  
509 MSY and profits would increase up to B€10.8 (1725% more than in 2010). Therefore, accepting  
510 the hard transition of reducing the size of the industry to 47% of current level, it is important to  
511 note that moderate reductions would also produce large economic benefits as well as improving  
512 resource conservation significantly.

513 The reduction of fishing effort will have negative short term costs in the form of reduction of  
514 catch towards stocks recovery, loss of a notable number of current jobs provided by fisheries  
515 and costs to dismantle a number of the fishing boats currently operating in the North Atlantic.  
516 Therefore, it will require investments to reallocate fishermen in alternative activities, scrap  
517 fishing vessels and other compensations to the fishing industry. Crilly and Esteban (2012) and  
518 the work by Sumaila et al. (2012) demonstrate that after a short transition the benefits of  
519 restoring fish stocks outweighs the costs incurred and investments required to reduce fishing  
520 mortality. This conclusion holds notwithstanding the high uncertainty in estimates and the  
521 assumptions made to enable large scale assessments of governance (Cash & Moser, 2000;  
522 Christensen & Walters, 2004; Jennings et al., 2008; Wilbanks & Kates, 1999). In addition,  
523 restoring fish stocks would avoid reducing the risk of fisheries collapses and its dramatic  
524 economic consequences. For example, the collapse of cod produced an increase of 30% of  
525 unemployment in some areas of Newfoundland and more than \$3 billion were spent to  
526 restructuring adjustments for workers in the fishing sector, among other social implications  
527 (Hamilton and Butler, 2001). However, it is also true that fishing mortality reductions haven't  
528 always produced the stocks' recovery predicted by fisheries assessment models. For example, a



529 combination of environmental changes and fishing pressure are responsible of Atlantic cod  
530 populations failure to recover (Hilborn and Litzinger, 2009).

531

532 A single estimate of economic loss is intuitive but can be simplistic given the number of  
533 parameters involved in the computation. In order to add consistency to our results and to offset  
534 the uncertainty associated with our methods, four stochastic experiments were conducted with  
535 the bioeconomic model. The results of these experiments provide two conclusions: First,  
536 allowing as much as a 30% random variation in the input parameters, the estimated economic  
537 loss of North Atlantic fisheries is measured in billions of euro. Second, the model is particularly  
538 sensitive to three biological parameters: MSY, K and catch in the last year. Reducing the  
539 uncertainty on these parameters reduces the standard deviation of the estimates significantly. In  
540 contrast, fixing the other five parameters produces only moderate reductions of variability on  
541 the economic loss of fisheries. Therefore, we emphasize the relevance of adequate commercial  
542 and fishery independent data collection programs in order to improve the stock assessment  
543 process. Despite uncertainties on the current scale of North Atlantic basin productivity, we  
544 conclude that an overall fishing effort reduction is recommended, with not only ecological  
545 benefits but significant and demonstrable economic consequences.

546

547 To conclude, our analysis supports the work conducted under the Euro-BASIN project by  
548 providing a basin-scale framework for the economic analysis of the efficiency of North Atlantic  
549 fisheries management. In the future this analysis needs to take into consideration the way  
550 European fisheries management, in particular, is evolving. The reform of the European  
551 Common Fisheries Policy identifies MSY as a management target, consistent with our analysis.  
552 It also highlights the need to implement a discard ban, which should come hand in hand with the  
553 needed improvement in the monitoring and reporting of fishing activities. While our analysis is  
554 conducted at the basin scale, regionalization of management is a process that would need to be  
555 considered in future monitoring programs and modeling approaches. Significantly, the CFP  
556 reform also identifies the need to collect environmental, social and economic data and use these  
557 as criteria to allocate fishing rights. Future Euro-BASIN initiatives would have to consider the  
558 above in developing their workprogramme, as well as approaches to better understand market  
559 price formation (exports and competition with products from other areas) and how to influence  
560 consumer demand for species that traditionally have been less preferred.

561

562

563 **Acknowledgments**

564

565 This research was supported by European Union seventh framework programme through the  
 566 project EURO-BASIN (264933). We than Dr. Froese for making publicly available the MSY  
 567 estimation algorithm used in this study. We also thank Francesc Maynou, Hilario Murua, Gerry  
 568 Scott for the valuable comments in the preparation of this manuscript.

569

## 570 Appendix

571

572 Table A1. Necessary transformations to run the bioeconomic model using the parameters shown  
 573 in Table 3 (Arnason, 2007; Arnason et al., 2009; Gordon, 1954; Schaefer, 1954).

574

575 {Insert Table A1}

576

577 Figure A1. Sensitivity analysis of the economic loss in 2010 for different parameters.

578

579 {Insert Figure A1}

## 580 References

581

- 582 • Alheit, J., Roy, C., Kifani, S., 2009. Decada-scale variability in populations. In D.  
 583 Checkley, J. Alheit, Y. Oozeki, C. Roy (Eds.), *Climate Change and Small Pelagic Fish*  
 584 *Stocks* (p. 382): Cambridge University Press.
- 585 • Allison, E.H., Perry, A.L., Badjeck, M.C., Adger, W.N., Brown, K., Conway, D., Halls,  
 586 A.S., Pilling, G., Reynolds, J.D., Andrew, L.N., Dulvy, N., 2009. Vulnerability of  
 587 national economies to the impacts of climate change on fisheries. *Fish and Fisheries*,  
 588 10, 173-196.
- 589 • Arnason, R., 2007. Loss of economic rents in the global fishery. *XVIIIth Annual EAFE*  
 590 *Conference*. Reykjavik, Iceland: www.eafe-fish.eu.
- 591 • Arnason, R., Kelleher, K., Willman, R., 2009. The Sunken Billions: The economic  
 592 justification for fisheries reform. *Agriculture and rural development* (p. 100): The  
 593 World Bank and Food and Agriculture Organization.
- 594 • Barange, M., Bernal, M., Cercole, M.C., Cubillos, L., Cunningham, C.L., Daskalov,  
 595 G.M., De Oliveira, J.A.A., Dickey-Collas, M., Hill, K., Jacobson, L., Køster, F.W.,  
 596 Masse, J., Nishida, H., Ñiquen, M., Oozeki, Y., Palomera, I., Saccardo, S.A.,  
 597 Santojanni, A., Serra, R., Somarakis, S., Stratoudakis, Y., van der Lingen, C.D., Uriarte,  
 598 A., Yatsu, A., 2009. Current trends in the Assessment and Management of Small  
 599 Pelagic Fish Stocks. In D. Checkley, J. Alheit, Y. Oozeki, C. Roy (Eds.), *Climate*  
 600 *Change and Small Pelagic Fish Stocks* (p. 382): Cambridge University Press.
- 601 • Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, J.A., Edwards, M., 2002. Reorganization  
 602 of North Atlantic marine copepod biodiversity and climate. *Science*, 296, 1692-1694.
- 603 • Blanchard, J., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, I., Holt, J., Dulvy,  
 604 N., Barange, M., 2012. Potential consequences of climate change for primary  
 605 production and fish production in large marine ecosystems. *Philosophical Transactions*  
 606 *of the Royal Society B*, 367, 2979-2989.

- 607 • Blanchard, J., Jennings, S., Law, R., Castle, M.D., McCloghrie, D., Rochet, M.J.,  
608 Benoît, E., 2009. How does abundance scale with body size in coupled size-structured  
609 food webs? *Journal of Animal Ecology*, 78, 270-280.
- 610 • Branch, T.A., Jensen, O.P., Ricard, D., Ye, Y., Hilborn, R., 2011. Contrasting global  
611 trends in marine fishery status obtained from catches and stock assessments.  
612 *Conservation Biology*, 25, 777-786.
- 613 Cardinale, M., Dorner, H., Abella, O., Andersen, J.L., Casey, J., Doring, R., Kirkegaard,  
614 E., Motova, A., Anderson, J., Simmonds, E.J., Stransky, C., 2013. Rebuilding EU fish  
615 stocks and fisheries, a process under way? *Marine Policy*, 39, 43-52.
- 616 • Carscadden, J.E., Gjørseter, H., Vilhjálmsson, H., 2013 (In press). A comparison of  
617 recent changes in distribution of capelin (*Mallosus villotus*) in the Barents Sea, around  
618 Iceland and in the Northwest Atlantic. *Progress In Oceanography*.
- 619 • Cash, D.W., Moser, S.C., 2000. Linking global and local scales: designing dynamic  
620 assessment and management processes. *Global Environmental Change*, 10, 109-120.
- 621 • Coll, M., Libralato, S., Tudela, S., Palomera, I., Pranovi, F., 2008. Ecosystem  
622 Overfishing in the Ocean. *PLoS ONE*, 3, e3881.
- 623 • Crilly, R., Esteban, A., 2012. No catch investment: Investing to restore European fish  
624 stocks. In N.E. Foundation (Ed.). London, UK.
- 625 • Cury, P.M., Shin, Y.-J., Planque, B., Durant, J.M., Fromentin, J.M., Kramer-Schadt, S.,  
626 Stenseth, N.C., Travers, M., Grimm, V., 2008. Ecosystem oceanography for global  
627 change fisheries. *Trends in Ecology and Evolution*, 23, 338-346.
- 628 • Chavez, F.P., Ryan, J., Lluch-Cota, S.E., Niquen C, M., 2003. From anchovies to  
629 sardines and back: multidecadal change in the Pacific ocean. *Science*, 299, 217-221.
- 630 • Christensen, V., Walters, C.J., 2004. Trade-offs in ecosystem scale optimization of  
631 fisheries management policies. *Bulletin of Marine Science*, 74, 549-562.
- 632 • European Union. 2012. Communication from the Commission to the Council  
633 concerning a consultation on Fishing Opportunities for 2013. COM(2012) 278 final, 17  
634 pp.
- 635 • FAO, FISHSTAT Statistical collections. FAO.
- 636 • FAO, 2007. National fishery sector overview: The Russian Federation. (p. 17).
- 637 • FAO, 2010. Statistics and Information Service of the Fisheries and Aquaculture  
638 Department. FAO yearbook. Fishery and Aquaculture Statistics 2008. Rome, Italia.  
639 72p.
- 640 • FAO, 2012. The State of World Fisheries and Aquaculture. In FAO (Ed.). Rome.
- 641 • Fernandes J.A., Cheung W.W.L., Jennings S., Butenschön M., de Mora L., Frölicher  
642 T.L., Barange M., Grant A., 2013. Modelling the effects of climate change on the  
643 distribution and production of marine fishes: accounting for trophic interactions in a  
644 dynamic bioclimate envelope model. *Global Change Biology* 19(8), 2596-2607.
- 645 • Fernandes, P.G., Cook, R.M., 2013. Reversal of fish stock decline in the Northeast  
646 Atlantic. *Current Biology*, 23(15), 1432-1437.
- 647 • Fernandes J.A., Irigoien X., Goikoetxea N., Lozano J.A., Inza I., Pérez A, Bode A.,  
648 2010. Fish recruitment prediction, using robust supervised classification methods.  
649 *Ecological Modelling*, 221(2), 338-352.
- 650 • Finlayson, A.C., 1994. *Fishing for truth: A sociological analysis of northern cod stock*  
651 *assessments from 1977-1990*. St. John's, Newfoundland, Canada: Memorial University  
652 of Newfoundland.

- 653 • Garcia, S.M., 2009. Rising to depletion? Towards a dialogue on the state of national  
654 marine fisheries. Preliminary report. In T.W. Bank (Ed.), *Global Program on Fisheries*  
655 (*PROFISH*) (p. 65).
- 656 • Garcia, S.M., Rosenberg, A.A., 2010. Food security and marine capture fisheries:  
657 characteristics, trends, drivers and future perspectives. *Philosophical Transactions of*  
658 *the Royal Society B*, 365, 2869-2880.
- 659 • Gascuel, D., Merino, G., Döring, R., Druon, J.N., Goti, L., Guénette, S., Macher, C.,  
660 Soma, K., Travers-Trolet, M., Mackinson, S., 2012. Towards the implementation of an  
661 integrated ecosystem fleet-based management of European fisheries. *Marine Policy*, 36,  
662 1022-1032.
- 663 • Gordon, H.S., 1954. The economic theory of a common-property resource: the fishery.  
664 *Journal of Political Economy*, 62, 124-142.
- 665 • Guillen, J., Macher, C., Merzéréaud, M., Bertignac, M., Fifas, S., Guyader, O., 2013.  
666 Estimating MSY and MEY in multi-species and multi-fleet fisheries, consequences and  
667 limits: an application to the Bay of Biscay mixed fishery. *Marine Policy*, 40, 64-74.
- 668 • Hamilton, L.C., Bulter, M.J., (2001) Outport adaptations: social indicators through  
669 Newfoundland's cod crisis. *Research in Human Ecology*, 8(2), 1-11.
- 670 • Hilborn, R., Stokes, K., 2010. Defining overfished stocks: Have we lost the plot?  
671 *Fisheries*, 35, 113-120.
- 672 • Hsieh, C.-H., Kim, H.J., Watson, W., Di Lorenzo, E., Sugihara, G., 2009. Climate  
673 driven changes in abundance and distribution of larvae of oceanic fishes in the southern  
674 California region. *Global Change Biology*, 15, 2137-2152.
- 675 • ICES, 2011. Report of the Working Group on Widely Distributed Stocks (WGWISE).  
676 ICES CM 2011/ACOM:15. 624 pp.
- 677 • ICES. 2012b. Report of the ICES Advisory Committee 2012. ICES Advice, 2012. Book  
678 5. 459 pp.
- 679 • ICES. 2012b. Report of the ICES Advisory Committee 2012. ICES Advice, 2012. Book  
680 2. 114 pp.
- 681 • Jennings, S., Mélin, F., Blanchard, J.L., Forster, R.M., Dulvy, N.K., Wilson, R.W.,  
682 2008. Global-scale predictions of community and ecosystem properties from simple  
683 ecological theory. *Proceedings of the Royal Society B: Biological Sciences*, 275, 1375-  
684 1383.
- 685 • JRC, 2012. The 2011 Annual Economic Report on the EU fishing fleet. In J. Anderson,  
686 J. Guillen, J. Virtanen (Eds.), *Scientific, technical and economic committee for fisheries*.
- 687 • Kitts, A., Bing-Sawyer, E., Walden, J., Demarest, C., McPherson, M., Christman, P.,  
688 Steinback, S., Olson, J., Clay, P., 2010. Performance of the Northeast multispecies  
689 (groundfish) fishery. In N.N.M.F. Service (Ed.). Woods Hole, MA.
- 690 • Lam, V.W.Y., Sumaila, R.U., Dyck, A., Pauly, D., Watson, R., 2011. Construction and  
691 first applications of a global cost of fishing database. *ICES Journal of Marine Science*,  
692 68, 1996-2004.
- 693 • Lazkano, I., Nøstbakken, L., Prellezo, R., 2012. Past and future management of a  
694 collapsed fishery: The bay of Biscay anchovy. *Natural Resource Modeling*.
- 695 • Lindstrøm, U., Smoutb, S., Howelc, D., Bogstad, B., 2009. Modelling multi-species  
696 interactions in the Barents Sea ecosystem with special emphasis on minke whales and  
697 their interactions with cod, herring and capelin. *Deep-Sea Research Part II: Topical*  
698 *Studies in Oceanography*, 56, 2068-2079.

- 699 • Link, J.S., 2009. *Ecosystem-Based Fisheries Management: Confronting Tradeoffs*. New  
700 York: Cambridge University Press.
- 701 • Link, J.S., Gaichas, S., Miller, T.J., Essington, T., Bundy, A., Boldt, J., Drinkwater, K.,  
702 Moksness, E., 2012. Synthesizing lessons learned from comparing fisheries production  
703 in 13 northern hemisphere ecosystems: emergent fundamental features. *Marine Ecology*  
704 *Progress Series*, 459, 293-302.
- 705 • Leonart, J., Maynou, F., 2003. Fish stock assessments in the Mediterranean: state of the  
706 art. *Scientia Marina*, 67 (Suppl. 1), 37-49.
- 707 • Marshall, J., Kushnir, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J.,  
708 McCartney, M., Saravanan, R., Visbeck, M., 2001. North Atlantic climate variability:  
709 phenomena, impacts and mechanisms. *International Journal of Climatology*, 21, 1863-  
710 1898.
- 711 • Martell, S., Froese, R., 2010. A simple method for estimating MSY from catch and  
712 resilience. *Fish and Fisheries*.
- 713 • Merino, G., Barange, M., Mullon, C., Rodwell, L., 2010. Impacts of global  
714 environmental change and aquaculture expansion on marine ecosystems. *Global*  
715 *Environmental Change*, 20, 586-596.
- 716 • Merino, G., Barange, M., Rodwell, L., Mullon, C., 2011. Modelling the sequential  
717 geographical exploitation and potential collapse of marine fisheries through  
718 economic globalization, climate change and management alternatives. *Scientia Marina*,  
719 75, 779-790.
- 720 • Merino, G., Barange, M., Blanchard, J., Harle, J., Holmes, R., Allen, I., Allison, E.H.,  
721 Badjeck, M.C., Dulvy, N., Holt, J., Jennings, S., Mullon, C., Rodwell, L., 2012. Can  
722 marine fisheries and aquaculture meet fish demand from a growing human population in  
723 a changing climate? *Global Environmental Change*,  
724 <http://dx.doi.org/10.1016/j.gloenvcha.2012.03.003>.
- 725 • Merino, G., Barange, M., Mullon, C., 2013. Role of reduction fisheries in the world  
726 fishmeal production. In K. Ganas (Ed.), *Biology and ecology of anchovies and*  
727 *sardines*. Enfield, New Hampshire, USA: Science Publishers.
- 728 • Mueter, F.J., Megrey, B.A., 2006. Using multi-species surplus production models to  
729 estimate ecosystem-level maximum sustainable yields. *Fisheries Research*, 81, 189-  
730 201.
- 731 • Nash, J.F., Dickey-Collas, M., Kell, L.T., 2009. Stock and recruitment in North Sea  
732 herring (*Clupea harengus*); compensation and depensation in the population dynamics.  
733 *Fisheries Research*, 95, 88-97.
- 734 • NOAA, 2011. Fisheries Economics of the United States 2009. In U.D.o. Commerce  
735 (Ed.), Vol. NMFS-F/SPO-118: National Oceanic and Atmospheric Administration.
- 736 • Nøstbakken, L., Bjørndal, T., 2003. Supply functions for North Sea herring. *Marine*  
737 *Resource Economics*, 18, 345-361.
- 738 • Parsons, L.S., Lear, W.H., 2001. Climate variability and marine ecosystem impacts: a  
739 North Atlantic perspective. *Progress In Oceanography*, 49, 167-188.
- 740 • Pauly, D., Alder, J., Bennett, E., Christensen, V., Tyedmers, P., Watson, R., 2003. The  
741 future for fisheries. *Science*, 302, 1359-1361.
- 742 • Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, Jr. F. 1997. Fishing down  
743 marine food webs. *Science*, 278, 860-863.



- 744 • Pauly, D., Christensen, V., Guenette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J.,  
745 Watson, R., Zeller, D., 2002. Towards sustainability in world fisheries. *Nature*, 418,  
746 689-695.
- 747 • Pauly, D., Christensen, V., Walters, C.J., 2000. Ecopath, Ecosim, and Ecospace as tools  
748 for evaluating ecosystem impact of fisheries. *ICES Journal of Marine Science*, 57, 697-  
749 706.
- 750 • Pauly, D., Hilborn, R., Branch, T.A., 2013. Fisheries: Does catch reflect abundance?  
751 *Nature*, 694, 303-306.
- 752 • Rice, J.C., Garcia, S.M., 2011. Fisheries, food security, climate change and biodiversity:  
753 characteristics of the sector and perspectives of emerging issues. *ICES Journal of*  
754 *Marine Science*, 68(6), 1343-1353.
- 755 • Schaefer, M., 1954. Some aspects of the dynamics of populations important to the  
756 management of the commercial Marine fisheries. *Bulletin of the Inter-American*  
757 *Tropical Tuna Commission*, 1, 27-56.
- 758 • Seijo, J.C., Defeo, O., Salas, S., 1998. *Fisheries bioeconomics. Theory, modelling and*  
759 *management*. Rome.
- 760 • Shin, Y.-J., Bundy, A., Shannon, L.J., Blanchard, J.L., Chuenpagdee, R., Coll, M.,  
761 Knight, B., Lynam, C., Piet, G.J., Richardson, A.J., Group, a.t.I.W., 2012. Global in  
762 scope and regionally rich: an Indiseas workshop helps shape the future of marine  
763 ecosystem indicators. *Reviews in Fish Biology and Fisheries*, 22, 835-845.
- 764 • Shin, Y.-J., Cury, P.M., 2004. Using an individual-based model of fish assemblages to  
765 study the response of size spectra to changes in fishing. *Canadian Journal of Fisheries*  
766 *and Aquatic Sciences*, 61, 414-431.
- 767 • Shin, Y.-J., Rochet, M.-J., Jennings, S., Field, J.G., Gislason, H., 2005. Using size-  
768 based indicators to evaluate the ecosystem effects of fishing. *ICES Journal of Marine*  
769 *Science*, 62, 384-396.
- 770 • Sparholt, H., Cook, R., 2009. Sustainable exploitation of temperate fish stocks. *Biology*  
771 *Letters*.
- 772 • Srinivasan, U.T., Cheung, W.W.L., Watson, R., Sumaila, R.U., 2010. Food security  
773 implications of global marine catch losses due to overfishing. *Journal of Bioeconomics*,  
774 12, 183-200.
- 775 • Sumaila, R.U., Cheung, W.W.L., Dyck, A., Gueye, K., Huang, L., Lam, V., Pauly, D.,  
776 Srinivasan, T., Swartz, W., Watson, R., Zeller, D., 2012. Benefits of rebuilding global  
777 marine fishereis outweigh costs. *PLoS ONE*, 7, e40542.
- 778 • Sumaila, R.U., Marsden, A.D, Watson, R., Pauly, D., 2007. A Global ex-vessel fish  
779 price database: Construction and Applications. *Journal of Bioeconomics*, 9, 29-51.
- 780 • Trenkel, V.M., Huse, G., MacKenzie, B.R., Alvarez, P., Arrizabalaga, H., Castonguay,  
781 M., Goñi, N., Grégoire, F., Hátun, H., Jansen, T., Jacobsen, J.A., Lehodey, P.,  
782 Lutcavage, M., Mariani, P., Melvin, G.G., Neilson, J.D., Nøttestad, L., Óskarsson, G.J.,  
783 Payne, M.R., Richardson, D.E., Senina, I., Speirs, D.C., 2013 (*In press in this issue*).  
784 Comparative ecology of widely distributed pelagic fish species in the North Atlantic:  
785 implications for modelling climate and fisheries impacts. *Progress in Oceanography*.
- 786 • Vasconcellos, M., Cochrane, K., 2005. Overview of world status data-limited fisheries:  
787 inferences from landings statistics, In: *Fisheries assessment and management in data-*  
788 *limited situations*. Proceedings; Lowell Wakefield Symposium, 21, Anchorage, AK  
789 (USA), 22-25 Oct 2003. Kruse, G.H. (ed.) Gallucci, V.F. (ed.) Hay, D.E. (ed.) Perry,  
790 R.I. (ed.) Peterman, R.M. (ed.) Shirley, T.C. (ed.) Spencer, P.D. (ed.) Wilson, B. (ed.)



- 791 Woodby, D. (ed.) / Alaska Univ., Fairbanks (USA). Alaska Sea Grant College Program,  
792 2005, p. 1-20.
- 793 • Watson, R., Alder, J., Pauly, D., 2006. Fisheries for forage fish, 1950 to the present. In  
794 J. Alder, D. Pauly (Eds.), *On the multiple uses of forage fish: from ecosystems to*  
795 *markets* (pp. 1-20).
- 796 • Wilbanks, T.J., Kates, R., 1999. Global change in local places: how scale matters.  
797 *Climatic Change*, 43, 601-628.
- 798 • Wiebe, P.H., Harris, R.P., St. John, M.A., Werner, F.E., de Young, B., 2009. P.P.E.  
799 (Eds.), 2009. *BASIN: Basin-scale Analysis, Synthesis and Integration. Science Plan and*  
800 *Implementation Strategy*.
- 801 • Worm, B., Hilborn, R., Baum, J.K., Branch, T.A., Collie, J.S., Costello, C., Fogarty,  
802 M.J., Fulton, E.A., Hutchings, J.A., Jennings, S., Jensen, O.P., Lotze, H.K., Mace, P.M.,  
803 McClanahan, T.R., Minto, C., Palumbi, S.R., Parma, A.M., Ricard, D., Rosenberg,  
804 A.A., Watson, R., Zeller, D., 2009. Rebuilding Global Fisheries. *Science*, 325, 578-585.  
805

806 **Figure captions**

807

808 Figure 1. Maximum Sustainable Yield estimates for the stocks assessed by ICES at different  
809 aggregation levels. The aggregation level is the number of units considered: 59 stocks, 18  
810 species, 2 habitats and 1 for all the ICES stocks as a single fishery. Boxes show the geometric  
811 mean of the estimate, 0.25 and 0.75 quantiles. The intervals limit the estimate to a 99.5%  
812 confidence (see text).

813

814 Figure 2. Top: Historical landings of North Atlantic fisheries according to FAO and estimated  
815 corresponding MSY. Below: Density distribution of annual total landings and distribution of  
816 plausible total MSY values using the approach by Martell and Froese (2013).

817

818 Figure 3. Graphical estimation of North Atlantic fisheries Maximum Economic Yield. The  
819 crossing point between different potential profit trajectories ( $iso_{\Psi}$ ) and the biomass-catch  
820 equilibrium curve determines the catch and biomass level that will lead to MEY. The MEY for  
821 North Atlantic fisheries is B€ 12.85. The  $iso_{\Psi} = 0.63B€$  corresponds to profits in 2010.

822

823 Figure 4. Gordon-Schaefer's model equilibrium for North Atlantic fisheries. Current (2010) and  
824 economically optimum fishing efforts indicated with dotted lines. Net profits are calculated as  
825 the difference between value of catch and costs of fishing. MEY is the *Maximum Economic*  
826 *Yield*, i.e. the maximum difference between value of catch and costs of fishing.

827

828 Figure 5. Results of stochastic estimates of the economic loss of North Atlantic fisheries in  
829 2010: 'sim 1' random fluctuation ( $\pm 30\%$ ) of the parameters of the bioeconomic model (see table  
830 3); 'sim 2' log-normally distributed MSY, K and  $Y_{2010}$  and random fluctuation for the others  
831 ( $\pm 30\%$ ); 'sim 3' same as previous but with other parameters kept constant at values shown in  
832 table 3; 'sim 4' MSY, K and  $Y_{2010}$  constant and random fluctuation for the others ( $\pm 30\%$ ).

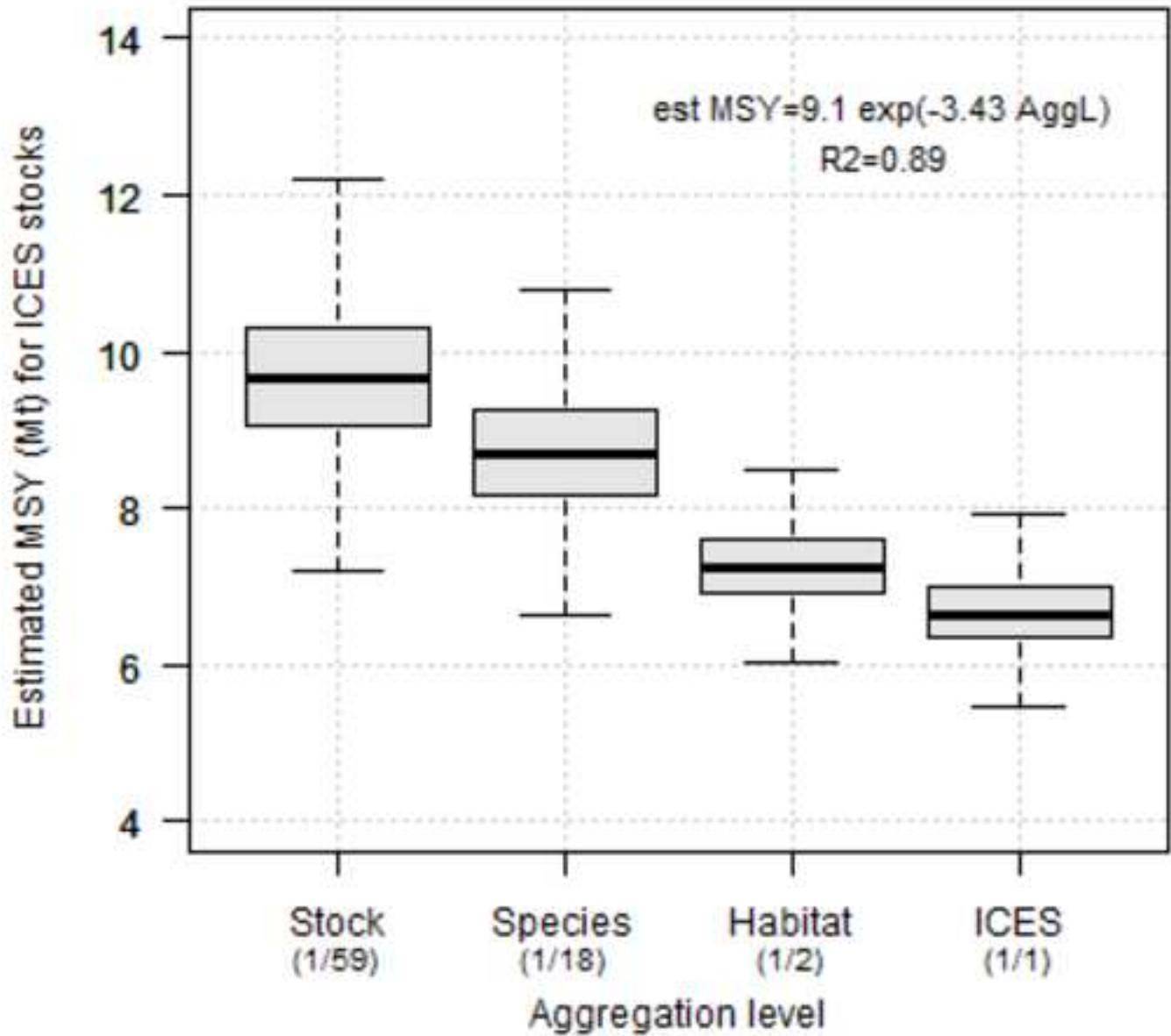
833

834

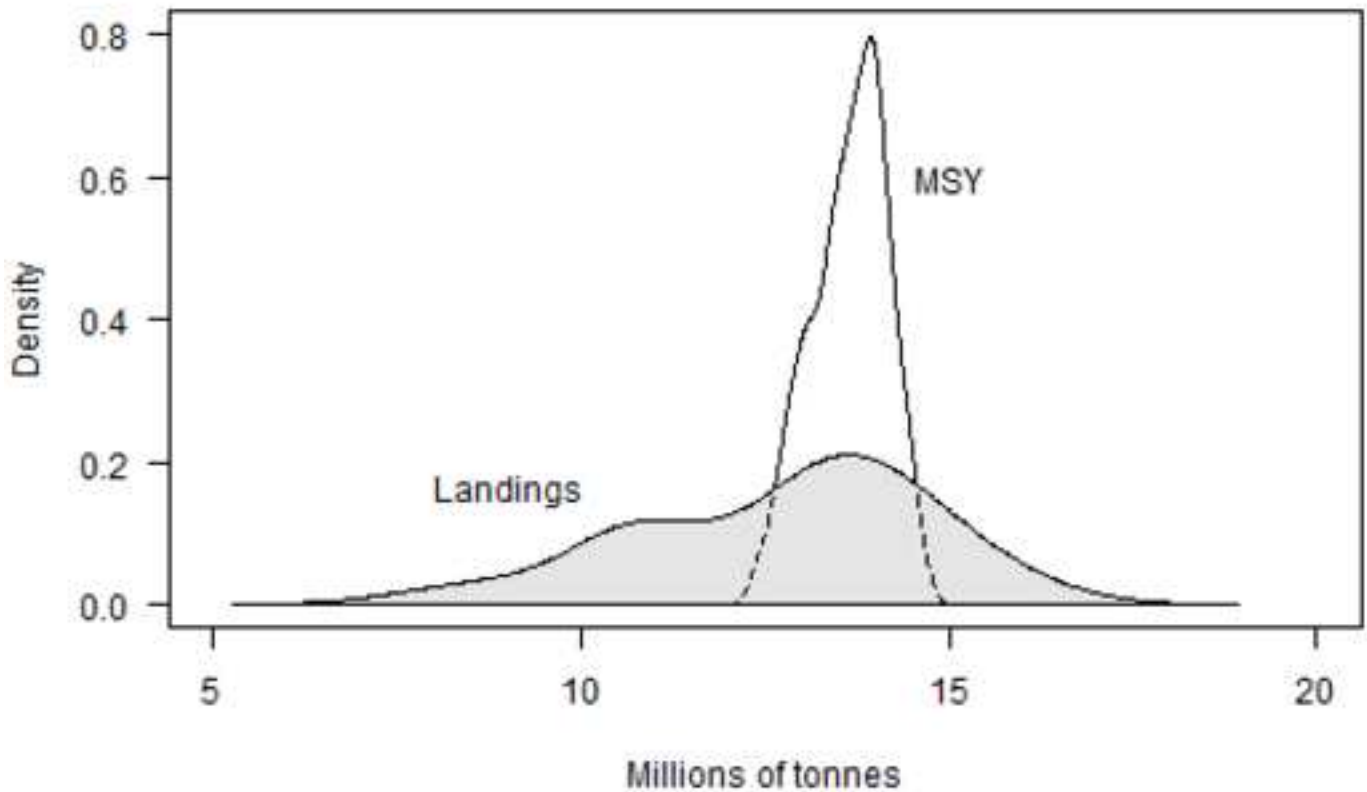
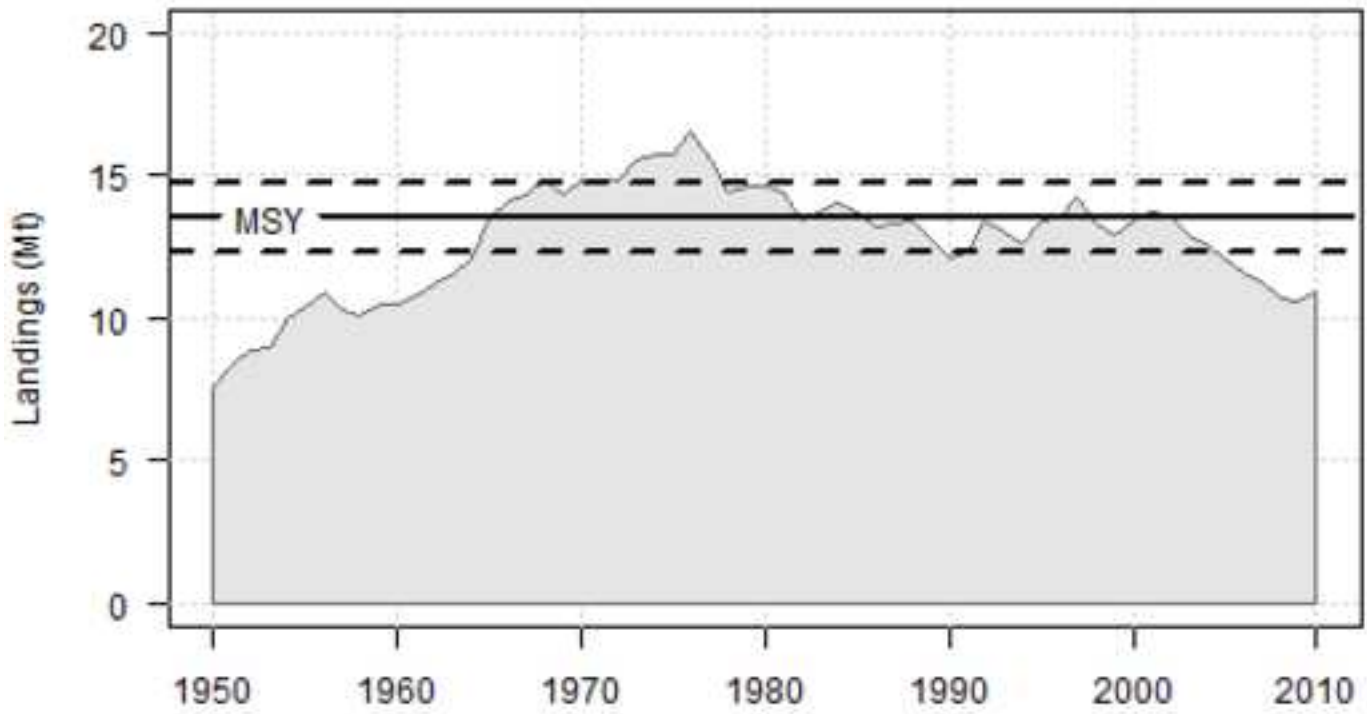
835 Figure A1. Sensitivity analysis of the economic loss in 2010 for different parameters.

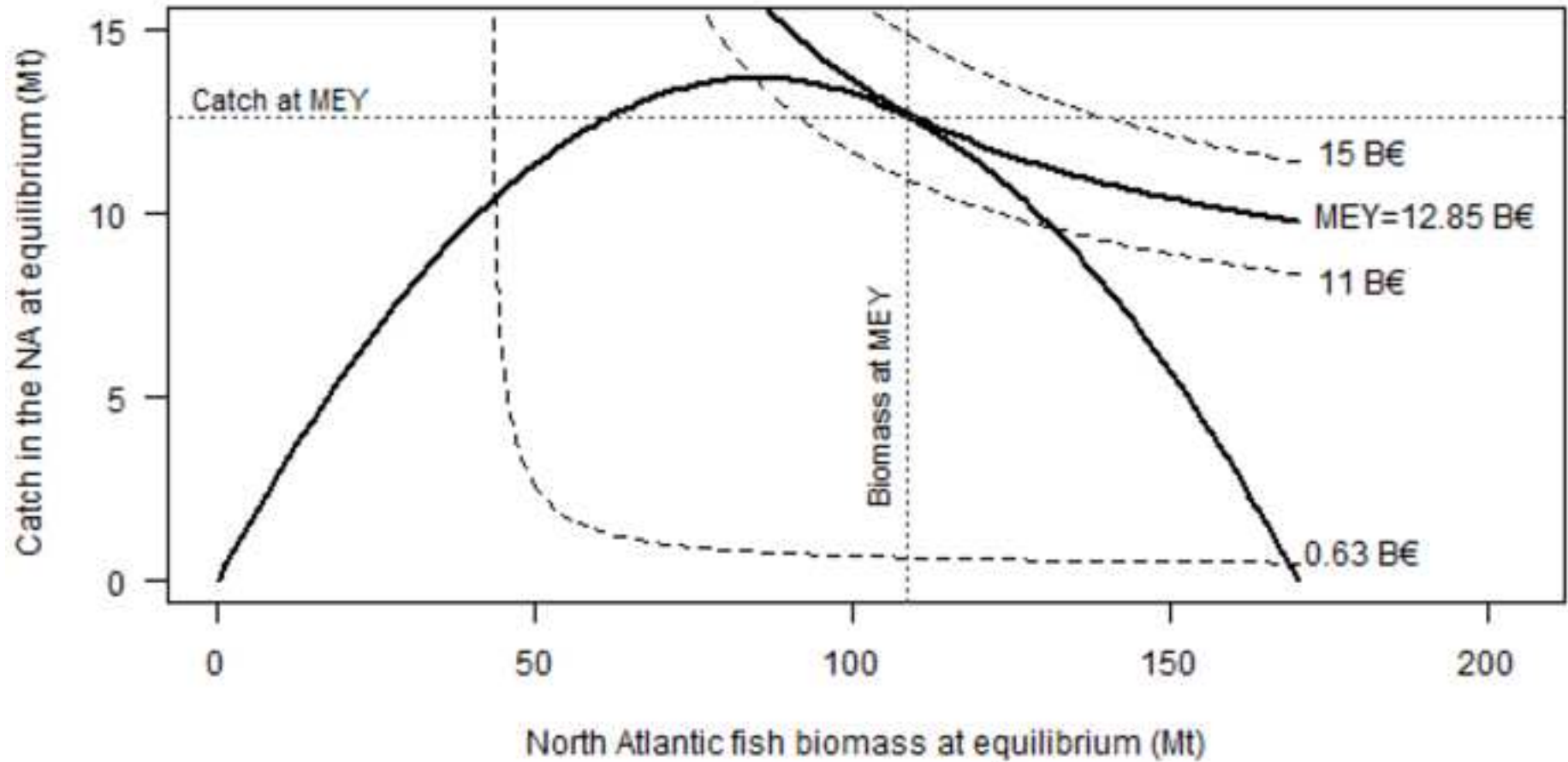
836

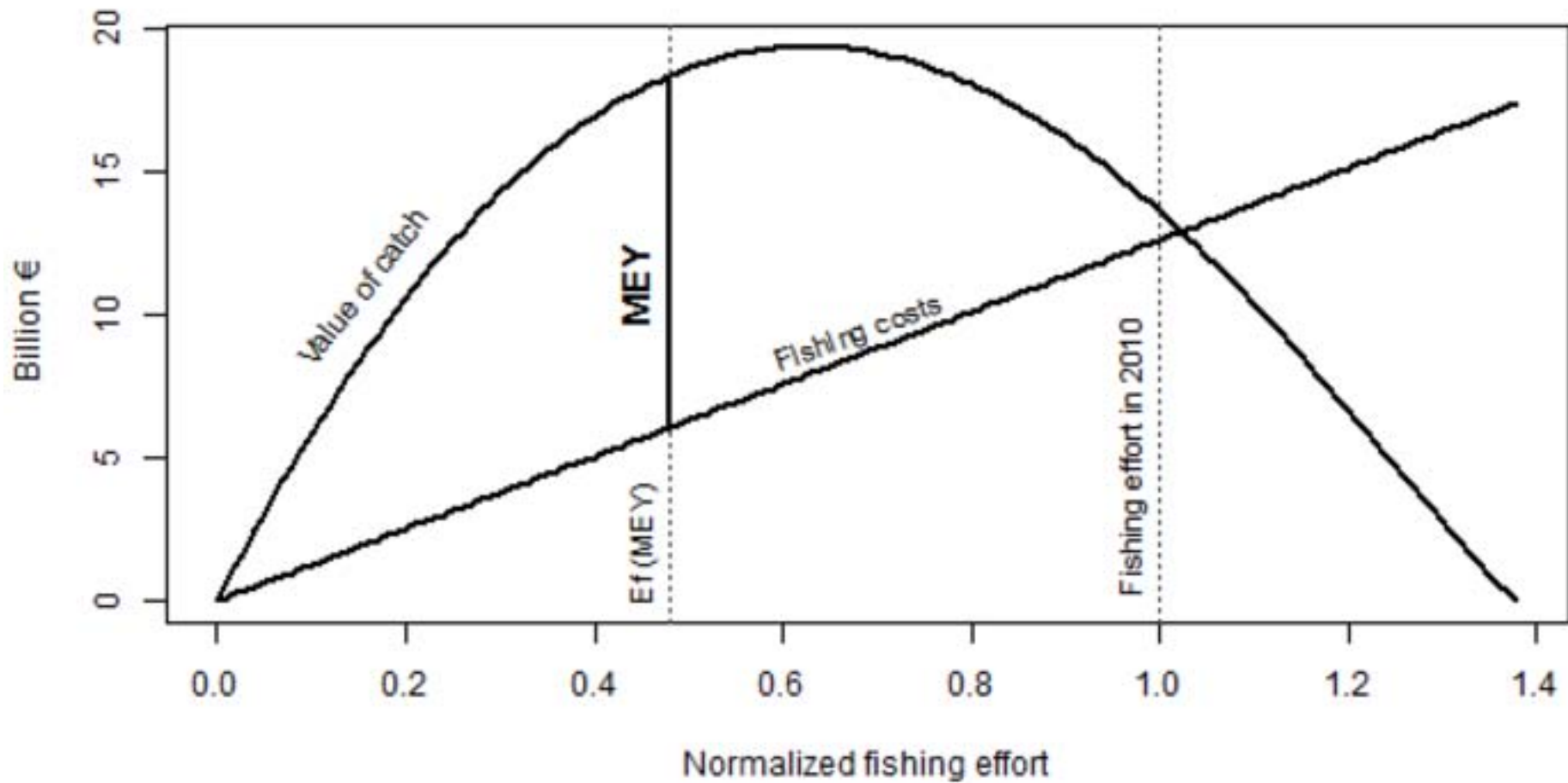
837



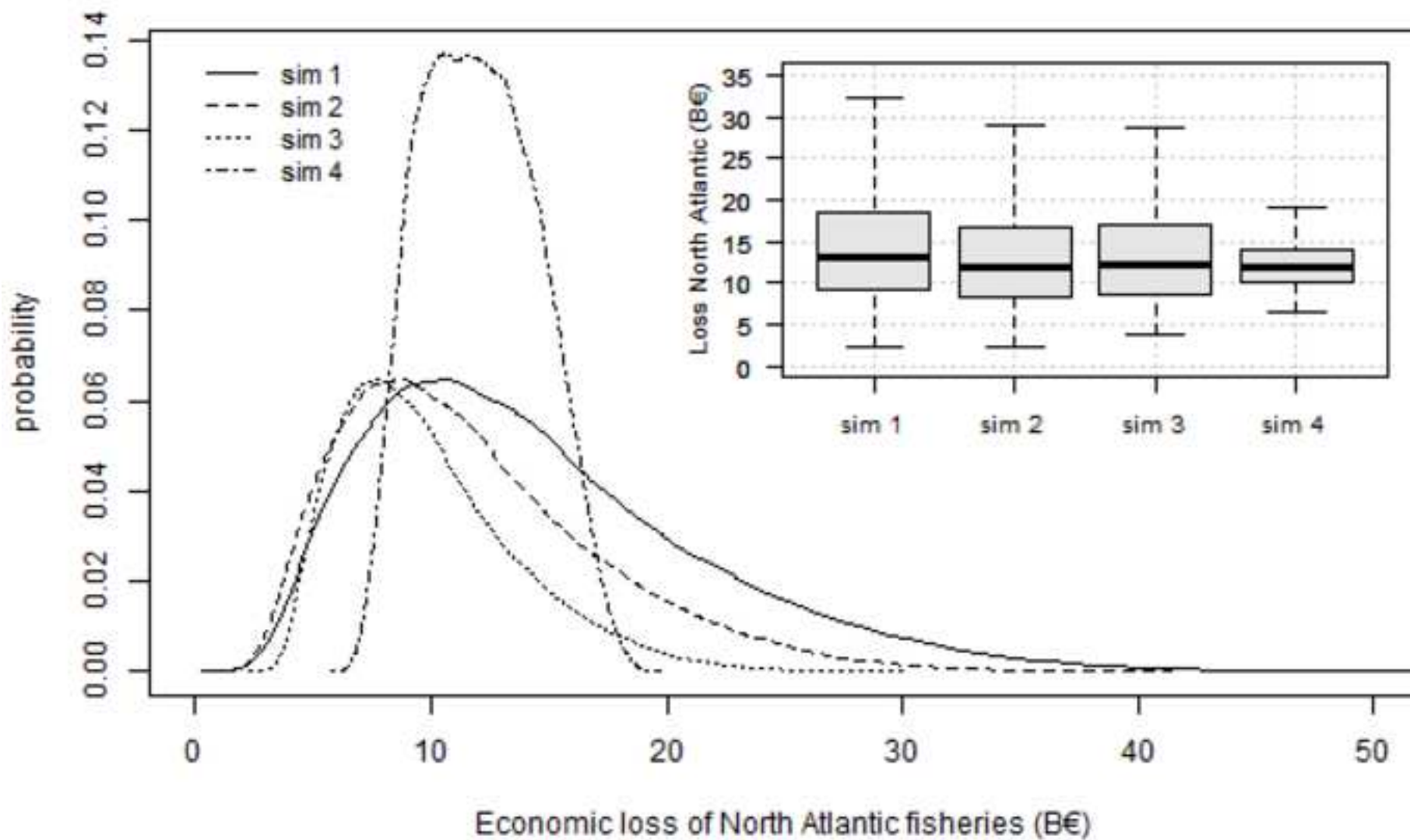
## North Atlantic landings (FAO) and MSY estimates



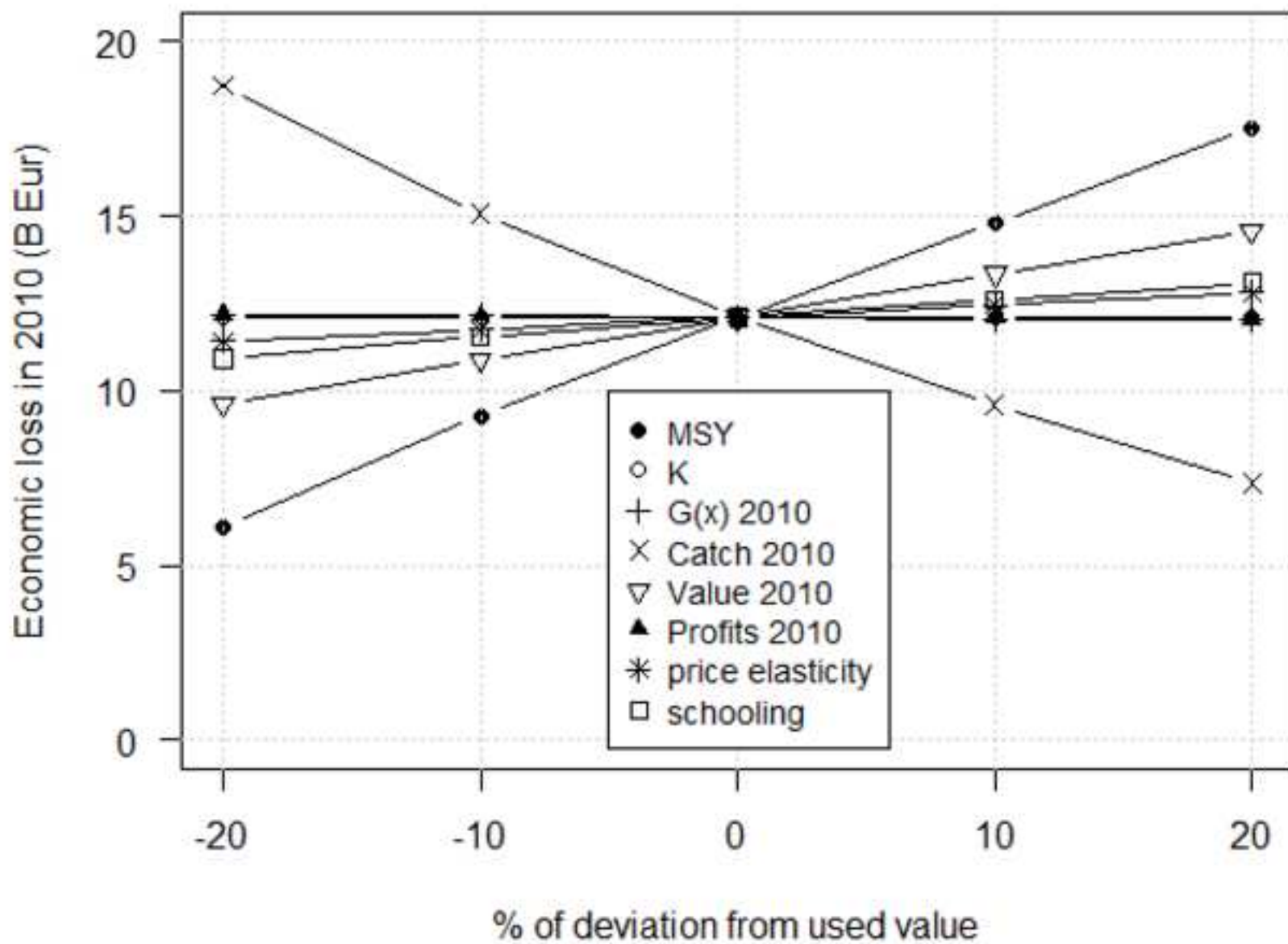








## Sensitivity to input paramaters



838  
839  
840  
841  
842  
843

### Tables

Table 1. Estimated Maximum Sustainable Yield for different levels of aggregation of ICES-stocks.

<i>Total</i> <i>MSY (Mean Mt, sdLog)</i>	<i>Habitat</i> <i>MSY (Mean Mt, sdLog)</i>	<i>Species</i> <i>MSY (Mean kt, sdLog)</i>	<i>ICES-Stock</i> <i>MSY (Mean kt, sdLog)</i>
ICES (6.68, 0.07)	Demersal (2.26, 0.03)	Cod (1364.61, 0.03)	cod-2224 (38.91, 0.09)
			cod-2532 (181.77, 0.06)
			cod-347d (256.87, 0.05)
			cod-arct (737.22, 0.05)
			cod-coas (59.71, 0.1)
			cod-farp (24.48, 0.05)
			cod-iceg (374.87, 0.06)
			cod-iris (8.72, 0.07)
		cod-scow (16.41, 0.12)	
		Greenland halibut (20.38, 0.20)	ghl-arct (20.16, 0.2)
		Haddock (419.40, 0.04)	had-34 (281.57, 0.07)
			had-7b-k (12.61, 0.18)
			had-arct (164.18, 0.13)
			had-faro (18.11, 0.06)
			had-iceg (81.20, 0.18)
			had-rock (4.67, 0.12)
		Megrim (1.23, 0.11)	mgb-8c9a (1.23, 0.11)
		Anglerfish (0.46, 0.14)	mgw-8c9a (0.46, 0.14)
		Nephrops (5.15, 0.09)	nep-8ab (5.68, 0.11)
			nop-34 (0.18, 0.13)
		Plaice (122.48, 0.04)	ple-celt (1.18, 0.07)
			ple-eche (4.32, 0.07)
			ple-echw (1.68, 0.08)
			ple-iris (3.38, 0.05)
		ple-nsea (114.97, 0.04)	
	Sole (31.93, 0.06)	sol-bisc (5.27, 0.08)	
		sol-celt (1.12, 0.06)	
		sol-eche (4.73, 0.11)	
		sol-echw (0.97, 0.05)	
		sol-iris (1.40, 0.08)	
sol-kask (0.77, 0.09)			
	sol-nsea (21.4, 0.04)		
Pelagic (4.99 Mt, 0.08)	Capelin (867.50, 0.07)	cap-icel (866.05, 0.07)	
	Herring (2028.94, 0.13)	her-2532-gor (245.28, 0.09)	
		her-30 (61.63, 0.15)	
		her-3a22 (121.54, 0.15)	

			her-47d3 (538.76, 0.07)
			her-irls (20.81, 0.05)
			her-noss (1202.19, 0.2)
			her-riga (33.45, 0.12)
			her-vasu (92.75, 0.09)
			her-vian (79.26, 0.06)
		Horse Mackerel (260.41, 0.09)	hom-west (259.44, 0.09)
		Mackerel (697.43, 0.07)	mac-nea (696.15, 0.07)
		Saithe (366.03, 0.04)	sai-3a46 (160.77, 0.06)
			sai-arct (193.75, 0.08)
			sai-faro (53.57, 0.15)
			sai-icel (68.40, 0.09)
		Sandeel (646.50, 0.08)	san-ns1 (357.36, 0.09)
			san-ns2 (72.04, 0.11)
			san-ns3(259.59, 0.09)
		Sardine (149.70, 0.10)	sar-soth (150.34, 0.1)
		Sprat (378.03)	spr-2232 (375.41, 0.13)
		Blue whiting (1254.76, 0.16)	whb-comb (1241.12, 0.16)
			whg-47d (37.18, 0.14)
		Whiting (39.74, 0.09)	whg-7e-k (13.09, 0.08)

844  
845

846 Table 2. Data used to parameterize the bioeconomic model. Catch and value were built  
 847 combining data from international databases (FAO and Sea Around Us). Cost parameters are  
 848 from Lam et al (2011). Additionally, the net profits of EU member states as reported in the  
 849 Annual Economic Report on the European Fishing Fleet (JRC, 2012).  
 850

Country	Catch (t) (2010)	Value of catch (MEur) (2010)	Operational costs (Eur/t)	Total Costs (Eur/t)	Estimated Op. profits (MEur)	Estimated Net Profits (MEur)	<i>Net Profits (AER, 2010)</i>
Belgium	21,907	78.40	1,007.9	2,139.1	56.32	31.54	-8.2
Denmark	827,936	309.88	1,001.4	1,147.4	-519.23	-640.12	-34.1
Estonia	89,752	32.61	765.2	936.1	-600.90	-742.46	8.1
Finland	121,169	24.54	980.1	1,176.7	-63.42	-81.07	1.2
France	312,162	731.22	1,053.5	1,259.9	603.58	578.57	-5.5
Germany	193,536	211.31	1,108.4	1,324.9	-134.68	-202.26	2.0
Iceland	1,057,988	697.00	1,119.6	1,352.6	480.32	435.23	-
Ireland	285,527	63.65	981.6	1,169.0	-974.82	-1,173.11	-33.4
Latvia	77,085	14.72	644.0	803.1	-169.16	-214.59	4.5
Lithuania	21,371	19.92	673.0	828.5	-31.96	-43.95	8.2
Netherlands	283,377	49.83	1,004.8	1,206.4	28.36	24.05	4.6
Norway	2,555,186	5,027.08	610.7	733.8	4,854.01	4,819.15	-
Poland	113,579	223.46	874.1	1,067.1	-2,009.95	-2,503.27	30.9
Portugal	201,730	102.33	801.4	949.8	11.31	-5.55	-38
Russian Fed	997,827	1,305.52	1,276.0	1,533.7	1,048.10	996.12	-
Spain	399,448	245.59	1,211.3	1,427.4	-963.10	-1,178.74	-250.2
Sweden	210,552	137.83	567.3	757.6	-88.77	-164.80	-1.5
UK	578,677	293.55	973.5	1,167.5	88.57	47.72	74.6
Canada	1,046,985	1,416.26	1,652.3	1,825.5	460.11	359.91	-
US	743,143	1,444.67	1,435.4	1,604.5	377.93	252.28	-

851  
 852  
 853  
 854

855 Table 3. Parameters for the bioeconomic model (Arnason, 2007; Arnason et al., 2009),  
 856 primarily derived from data for 2010 (see text).  
 857

<i>Parameter</i>	<i>Explanation</i>	<i>Value</i>	<i>Unit</i> <sup>858</sup>
MSY		13.7	Mt <sup>859</sup>
K	Carrying capacity	170	Mt <sup>860</sup>
$G(x)_{2010}$	Biomass growth	0.283	t/yr <sup>861</sup>
$Y_{2010}$	Fisheries catches	10.14	Mt
$Value_{2010}$	Value of catches	12.43	M€
$Price_{2010}$	Base price of catch	1.22	€/t
$Profits_{2010}$	Fishery profits	0.63	B€
$C_{2010}$	Cost of effort	11.8	M€
Price elasticity	Price elasticity	0.2	€/Mt
Schooling (b)	Schooling parameter	1	-
$Ef_{2010}$	Fishing effort	1	Normalized



862 Table A1. Necessary transformations to run the bioeconomic model using the parameters shown  
 863 in Table 3 (Arnason, 2007; Arnason et al., 2009; Gordon, 1954; Schaefer, 1954).  
 864

Biological parameters	$\alpha = 4 \cdot \frac{MSY}{K}; \beta = \frac{\alpha}{K}$
Biomass in 2010	$B_{2010} = (\alpha/2\beta) \cdot \left(1 - \left(1 - \frac{4\beta(Y_{2010} + G(x)_{2010})}{\alpha^2}\right)^{0.5}\right)$
Price in 2010	$p_{2010} = Value_{2010}/Y_{2010}$
Cost of unit of effort	$c = \frac{Value_{2010} - \Psi_{2010}}{Ef_{2010}}$
Catchability in 2010	$q_{2010} = Y_{2010}/(B_{2010} \cdot Ef_{2010})$
Biomass at equilibrium	$B_{eq} = (\alpha - q_{2010}Ef_{eq}) \cdot K/\alpha$
Catch at equilibrium	$Y_{eq} = q_{eq}Ef_{eq}B_{eq}^b$
Price at equilibrium	$p_{eq} = p_{2010} \left(\frac{B_{eq}}{B_{2010}}\right)^b$
Profits at equilibrium	$\Psi_{eq} = Y_{eq}p_{eq} - cEf_{eq}$

865

866

867