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1 An Indicator for Ecosystem Externalities in Fishing

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7 **Abstract**

8 Ecosystem externalities arise when one use of an ecosystem affects its other  
9 uses through the production functions of the ecosystem. We use simula-  
10 tions with a size-spectrum ecosystem model to investigate the ecosystem  
11 externality created by fishing of multiple species. The model is based upon  
12 general ecological principles and is calibrated to the North Sea. Two fleets  
13 are considered: a “forage fish” fleet targeting species that mature at small  
14 sizes and a “large fish” fleet targeting large piscivorous species. Based on  
15 the marginal analysis of the present value of the rent, we develop a benefit  
16 indicator that explicitly divides the consequences of fishing into internal and  
17 external benefits. This analysis demonstrates that the forage fish fleet has a  
18 notable economic impact on the large fish fleet, but the reverse is not true.  
19 The impact can be either negative or positive, which entails that for optimal  
20 economic exploitation, the forage fishery has to be adjusted according to the  
21 large fish fishery. With the present large fish fishery in the North Sea, the  
22 two fisheries are well adjusted; however, the present combined exploitation  
23 level is too high to achieve optimal economic rents.

24 *Keywords:* Ecosystem Externalities, Forage Fish, Benefit Indicator,

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26 **1. Introduction**

27       When a fish stock is fished, the impact of that fishing will also affect the  
28 other stocks in the ecosystem. For example, fishing piscivorous species should  
29 have a beneficial effect on their prey, whereas fishing forage species should  
30 have a detrimental effect on their predators. Fishing on a stock therefore  
31 incurs an opportunity cost on other fisheries in terms of a possible smaller  
32 outcome. In economic terms this means that a fishing fleet not only affects  
33 its own outcome but also, through the ecosystem, imposes externalities on  
34 other fleets and ecosystem users. If fishery management is to move beyond  
35 the traditional single stock approach, the opportunity cost of catch from  
36 different stocks has to be apparent. Our aim is to evaluate how one use of  
37 an ecosystem, here one fleet, indirectly affects other users, here other fleets,  
38 and to develop a benefit indicator that demonstrates this opportunity cost.  
39 By dividing the economic consequences into internal and external benefits  
40 we elucidate how the fishing fleets affect each other and thereby provide  
41 guidance into possible trade offs between fishing fleets in the exploitation of  
42 the ecosystem.

43       In fisheries there are traditionally identified three externalities: i) stock  
44 externalities ii) mesh externalities and iii) crowding externalities (Smith,  
45 1969). Stock externalities refer to the forgone further harvest caused by  
46 a decrease in stock, mesh externalities refer to the damage to the habitat  
47 made by the fisheries gear, and crowding externalities refer to the increase in  
48 operation costs caused by vessel congestion at the fishing ground. Crocker

49 and Tschirhart (1992) examined a predator-prey-grain system and use the  
50 term *ecosystem externality* for the part of the economic change originating—  
51 not from the direct manipulating of a species, but—through the ecosystem  
52 via other species. In this article we analyze the economic impact imposed  
53 by one fishery on other fisheries through the functionality of the ecosystem.  
54 As Crocker and Tschirhart (1992), we use the term *ecosystem externality* for  
55 this indirect impact and see it as a complement to the three other external-  
56 ities identified by Smith (1969). Ryan et al. (2014) use the term ecosystem  
57 externality for the change in future harvest generated by a change in underly-  
58 ing biological productivity of a fish stock by impacting the forage or habitat  
59 quantity or quality. While this may be covered by Crocker and Tschirhart’s  
60 (1992) definition, we note that the phenomena of Ryan et al. (2014) is similar  
61 to Smith’s (1969) mesh externalitiy.

62 Accounting for the interaction between fleets requires an ecosystem model  
63 that captures the multi-species nature of the ecosystem. Purely data-driven  
64 approaches, e.g., analysis of catch data, are unable to provide an understand-  
65 ing of the drivers and dynamics within an ecosystem. One approach in the  
66 fishery economics literature is to use simple conceptual models to obtain qual-  
67 itative insights on ecosystems (Hannesson, 1983, 2002). The most common  
68 approach is to investigate the interaction of two or more trophic levels using  
69 Lotka-Volterra-type predator-prey models, e.g., May et al. (1979); Flaaten  
70 (1988); Wilen and Wilen (2012). Such models capture the predator-prey in-  
71 teractions of different species, however, by characterizing each species by its  
72 biomass only, they fail to account for the large variation in size within each  
73 species. Individuals within a fish species varies in size from about 0.001 g

74 to their asymptotic size of between about 10 g for forage fish to between 10  
75 and 100 kg for the largest predatory fish. The size of individuals charac-  
76 terizes their interaction with other individuals (big individuals eat smaller  
77 ones), their bioenergetics, fisheries gear selectivity and, more important in  
78 this context, their economic value. To adequately resolve the ecological and  
79 the economic reality of the ecosystem we therefore use a size-based model of  
80 the ecosystem.

81 There is a growing literature describing different types of size-spectrum  
82 models (Benoît and Rochet, 2004; Pope et al., 2006; Hall et al., 2006; Hartvig  
83 et al., 2011) and their application to understanding how marine ecosystems  
84 respond to fishing (Pope et al., 2006; Hall et al., 2006; Andersen and Pedersen,  
85 2010; Blanchard et al., 2014). These models are based on a few simple and  
86 generally accepted assumptions at the level of the individual organisms and  
87 their dynamics are explicitly driven by predation and individual growth.  
88 Individuals in the model are characterized by their size (weight). As fishing  
89 gear is size-selective and the prices of landed fish also depend upon size, these  
90 models are ideally suited for economic reasoning and calculations. A central  
91 difference between a size-spectrum model and an unstructured Lotka-Volterra  
92 model is that it resolves the competition between individuals of the same  
93 size but from different species, e.g. the competition between an adult herring  
94 and a juvenile saithe. We use a previously developed and calibrated size-  
95 spectrum model to represent the ecological reality of the ecosystem (Hartvig  
96 et al., 2011; Andersen et al., 2015). We use the model to calculate how a  
97 change in fishing on one fleet affects the abundance and sizes of fish target  
98 by other fleets.

99 To illustrate the applicability of the benefit indicator we use the North  
100 Sea fishery as a case. For this system, data for the value of the different fish  
101 species, broken down into size groups, is available. To simplify the description  
102 we focus on the internal and external benefits of two fleets: the forage fleet  
103 targeting small species, and the consumer fleet targeting large species. We use  
104 the benefit indicator to show that the forage fish fleet has a notable economic  
105 impact on the large fish fleet, but that the reverse is not true. The impact  
106 can be either negative or positive depending upon the level of exploitation in  
107 the system, i.e. forage fishing may even have positive externality on the large  
108 fish fleet. For the North Sea we find that at the current level of large fish  
109 fishery, the level of the forage fish fishery leads to an adequate externality.  
110 To achieve the optimal total benefit from fishing the ecosystem, however, the  
111 present combined exploitation level must be reduced.

112 The structure of this paper is as follows. The biological model is briefly  
113 explained in section 2, the benefit indicator is derived in section 3, the eco-  
114 nomic model is developed in section 4, and our results are presented in section  
115 5 and discussed in section 6. In the electronic supporting material<sup>1</sup> there is  
116 additional information on: the estimation of the cost parameters (A), the es-  
117 timation of the price model (B), the details of the biological model (C), the  
118 sensitivity analysis of some of the cost parameters (D), and the sensitivity of  
119 the model to the choice of the control variable (E).

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<sup>1</sup>The supporting material is available at: [URL for the supporting material]

## 120 2. Ecosystem model

121 The size- and trait-based model is well described elsewhere (Hartvig et al.,  
122 2011; Andersen et al., 2015), and we only provide a general description of  
123 the basic principles here. The aim of a trait-based size-spectrum model is to  
124 calculate the abundance distribution of individuals,  $N(w, W)$ , as a function  
125 of the size of the individuals,  $w$ , and the asymptotic (maximum) size that  
126 the individual may reach,  $W$ .

127 The model is built upon a bioenergetic budget of an individual predator  
128 that connects somatic growth with the predation mortality inflicted on its  
129 prey. The model is based on three fundamental assumptions:

- 130 1. Trophic interactions (predation) are described by big individuals eating  
131 small individuals. A predator will prefer to eat prey that is roughly 100  
132 times smaller than themselves (Ursin, 1973; Jennings et al., 2001).
- 133 2. The main trait describing differences between species is the asymptotic  
134 size  $W$  (Pope et al., 2006; Andersen and Beyer, 2006). This difference  
135 is embodied in the description of somatic growth, where growth slows  
136 down as the individual matures and approaches the asymptotic size  
137 (Lester et al., 2004), in a manner consistent with a traditional “von  
138 Bertalanffy” growth curve commonly used to describe fish growth (An-  
139 dersen and Beyer, 2015). The asymptotic size is used as a continuous  
140 variable. This circumvents the need to represent specific species; the  
141 diversity of the fish community is instead characterized by the abun-  
142 dance of individuals in the  $W$  dimension of the abundance distribution  
143  $N(w, W)$ .
- 144 3. The impact of stock biomass and food on recruitment can be ignored.

145 This is achieved by fixing the density of fish of size  $10^{-3}$  g. This means  
146 that the model does not resolve “recruitment overfishing” occurring at  
147 high fishing pressures. This is purposefully done so that all effects can  
148 be traced back to the predator-prey interactions. Note that common  
149 age-based models of fish populations operate with recruitment at finite  
150 age, typically at age 1 year. The high pre-recruit mortality found in  
151 those models is explicitly represented in the present model. By resolv-  
152 ing the entire life from age 0 to the commonly used age of recruitment,  
153 the model explicitly resolves the high pre-recruit mortality prescribed  
154 in age-based models.

155 In addition to the central assumptions the model relies on minor as-  
156 sumptions related to the exact description of the predator-prey encounter  
157 (the functional response), and the bio-energetic budget (supporting mate-  
158 rial C). These follow commonly accepted methodology for modeling fish and  
159 predator-prey interactions. All of the parameters in the size-spectrum model  
160 are related to individual weight, which makes it possible to formulate the  
161 model with a small set of general parameters, prompting the labeling of the  
162 model as “charmingly simple” (Pope et al., 2006). The model simulates  $1 \text{ m}^3$   
163 of water, and output is scaled to the North Sea volume. The equations and  
164 parameters of the models are described in supporting material C.

165 The model resolves the entire life of individuals from a size  $w_0$  to the  
166 asymptotic size of all species (Fig. 1A). The predator-prey interaction leads  
167 to a decrease in prey abundances and to somatic growth (production) of  
168 predator individuals. The somatic growth in the model is equivalent to indi-  
169 viduals moving to the right on the size axis. All energy originates from the

170 plankton community, and it is the size of this that determines the produc-  
171 tivity of the system.

172 To resolve the opportunity costs of fishing at different trophic levels, the  
173 fishery is divided into two fleets: one targeting small forage fish and one  
174 targeting large piscivorous fish. In this context, forage fish refer to fish that  
175 are prey all of their life. The *forage fish fleet* is then characterized by catching  
176 small fish from fish species that mature at small sizes, and their harvest is  
177 used for industrial reduction into fishmeal and oil. The *large fish fleet* catches  
178 piscivorous fish, i.e., fish species that are relatively large when mature, and  
179 are sold for direct human consumption.

180 Fishing in the model is represented by the product of the overall fishing  
181 mortality,  $\mathcal{F}$ , and the selectivity as a function of size and trait,  $\omega(w, W)$ .  
182 The two fleets are characterized by the range of asymptotic sizes they target;  
183 the forage fish fleet targets species with  $W < 512$  g (solid lines Fig. 1A), and  
184 the large fish fleet targets  $W \geq 512$  g (dashed lines Fig. 1A). Hence the two  
185 fleets fishery are non-overlapping with respect to species. The overall fishing  
186 mortality rate of the two fleets,  $(\mathcal{F}_F, \mathcal{F}_L)$ , is the control variable in the model.  
187 The size-selectivity is modeled as a trawl selectivity curve with an S-shaped  
188 function (Fig. 1B). The output of the ecological model is the harvest with  
189 respect to fish size (Fig. 1C), which gives the revenue when multiplied by  
190 price and integrated over all sizes.

### 191 **3. Benefit indicator**

192 To value the ecosystem wide effects of fishing, we develop a benefit indi-  
193 cator. The indicator is the marginal change in the present value of the rent  
194 when the system is brought from one steady state to another, taking the

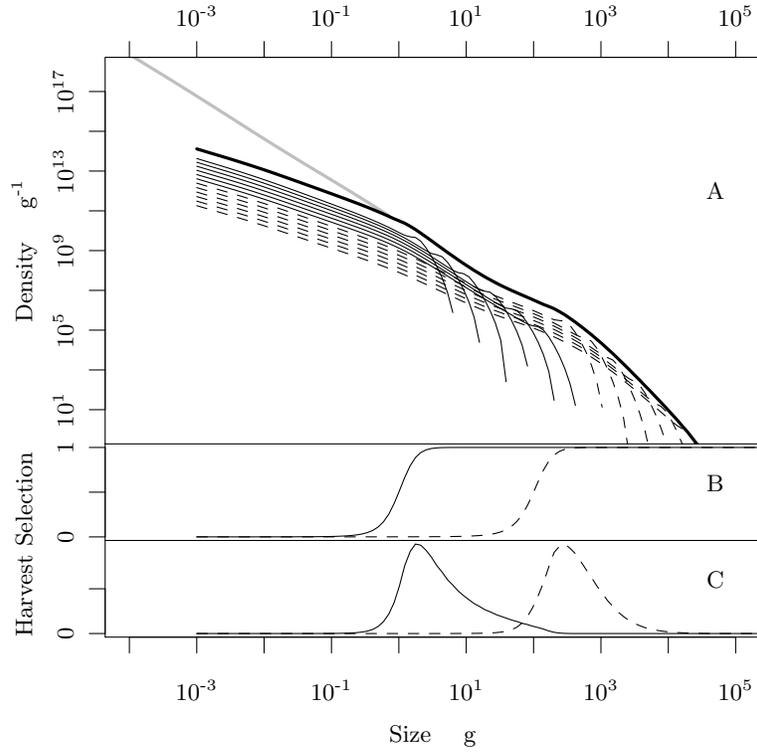


Figure 1: Run of the model with the fishing mortality of the two fleets set to correspond with the current exploitation of the North Sea. Solid lines represent the forage fish fleet, dashed lines the large fish fleet. A: Density of fish,  $N_i(w)$ , as a function of individual weight,  $w$ . Each thin line represents a population that is characterized by the maximum size,  $W$ , of individuals in the population. The thick black line is the sum of all of the populations. The smallest individuals feed on the plankton community (grey line). B: Fishing size-selection function,  $\omega(w)$ . C: The density of the harvest. The total harvest is the integral under the curves; however, as the abscissa represents the size on the logarithmic scale, the areas under the curves are scaled by the logarithm of their size to be visual comparable: the plotted line is  $\mathcal{F}\omega Nw \log(w)$ .

195 dynamic effects of the ecosystem during the change explicitly into considera-  
 196 tion. A change of state is prompted through a change in the fishing pressure  
 197 of one of the fishing fleets. The consequences of a change are characterized  
 198 by the *internal benefit* of the fleet that imposes the change and the *external*  
 199 *benefit* experienced by the other fleet.

200 Each fleet has one control variable, the overall fishing mortality rate  
 201  $(\mathcal{F}_F, \mathcal{F}_L)$ , where  $\mathcal{F}_F$  is for the fleet targeting forage fish and  $\mathcal{F}_L$  is for the  
 202 fleet targeting larger fish. We define *continue as usual* as keeping a constant  
 203  $\mathcal{F}$  and *an action* as changing  $\mathcal{F}$ . To generalize the method, the two fleets  
 204 are called  $i$  and  $j$ , where  $(i, j)$  can be either (F, L) or (L, F).

205 The ecosystem services generated by the fleets  $i$  and  $j$  are the harvests  
 206  $y_i$  and  $y_j$ —appraised by the rents (net values)  $\pi_i$  and  $\pi_j$ . Harvests and the  
 207 rents vary through time; to include the time component, the benefit of fleet  
 208  $i$  is summarized by  $Y_i$  and  $V_i$ , which are the present value of the harvest and  
 209 the rent, respectively, using the social discount rate  $\rho$  (equivalent for fleet  $j$ ):

$$Y_i := \int_0^{\infty} y_i(t) e^{-\rho t} dt \quad (1)$$

$$V_i := \int_0^{\infty} \pi_i(t) e^{-\rho t} dt \quad (2)$$

210 We consider a baseline situation where the ecosystem is in equilibrium  
 211 with its fleets and the outputs are constant. We consider a change in the  
 212 harvest of fleet  $i$  prompted by a change in  $\mathcal{F}_i$ ; the system will then no longer  
 213 be in equilibrium. Because of the restriction imposed by the ecosystem func-  
 214 tions, the change in fleet  $i$ 's harvest will lead to changes in the harvest and  
 215 rent for fleet  $j$  as well. As fleet  $j$  is *continue as usual*, the changes in this

216 fleet are an externality.

217 Because the change in  $V_j$  will depend upon  $\Delta y_i(t)$ , we use a concept from  
 218 cost-effectiveness analysis (Garber and Phelps, 1997; Kronbak and Vester-  
 219 gaard, 2013) and evaluate  $\Delta V_j / \Delta Y_i$ . We define the benefit indicator,  $B_{j/i}$ , of  
 220 fleet  $j$ 's rent per unit of fleet  $i$ 's harvest at the limit,  $\Delta Y_i \rightarrow 0$ .

221 This definition is incomplete in itself. To make it rigorous it has to be  
 222 combined with the previous definitions of *continue as usual* and *an action*.  
 223 We depart from  $\overset{\star}{N}(\mathcal{F}_i, \mathcal{F}_j)$  an ecosystem in equilibrium with  $(\mathcal{F}_i, \mathcal{F}_j)$ , that is  
 224 a situation where both fleets *continue as usual* for a very long time.

$$\text{Depart from: } N_{t=0} = \overset{\star}{N}(\mathcal{F}_i, \mathcal{F}_j) \quad (3)$$

225 At  $t = 0$  fleet  $i$  changes the fishing mortality while fleet  $j$  *continues as usual*.  
 226 To measure the indicator we expand the definition with the control variable:

$$B_{j/i} = \lim_{\Delta Y_i \rightarrow 0} \frac{\Delta V_j}{\Delta Y_i} \quad (4)$$

$$= \lim_{\Delta \mathcal{F}_i \rightarrow 0} \frac{\Delta V_j}{\Delta \mathcal{F}_i} \left( \frac{\Delta Y_i}{\Delta \mathcal{F}_i} \right)^{-1} \quad (5)$$

$$= \left( \lim_{\epsilon \rightarrow 0} \frac{V_j(\mathcal{F}_i + \epsilon, \mathcal{F}_j) - V_j(\mathcal{F}_i - \epsilon, \mathcal{F}_j)}{2\epsilon} \right) \cdot \left( \lim_{\epsilon \rightarrow 0} \frac{Y_i(\mathcal{F}_i + \epsilon, \mathcal{F}_j) - Y_i(\mathcal{F}_i - \epsilon, \mathcal{F}_j)}{2\epsilon} \right)^{-1} \quad (6)$$

$$= \lim_{\epsilon \rightarrow 0} \frac{V_j(\mathcal{F}_i + \epsilon, \mathcal{F}_j) - V_j(\mathcal{F}_i - \epsilon, \mathcal{F}_j)}{Y_i(\mathcal{F}_i + \epsilon, \mathcal{F}_j) - Y_i(\mathcal{F}_i - \epsilon, \mathcal{F}_j)} \quad (7)$$

227 As only  $i$  is doing *an action*, only  $\mathcal{F}_i$  is changed in line (5). The deviation  
 228 is expanded from both sides in line (6) to allow for more precision in the  
 229 numerical implementation.

230 The benefit indicator of the fleet itself,  $B_{i/i}$ , can be calculated in a similar  
231 fashion.  $B_{i/i}$  does not measure an externality,<sup>2</sup> but it is the net benefit to  
232 the fleet of removing one more fish, ignoring the externality of the fishing on  
233 the other fleet.

234 The total benefit indicator per unit of fleet  $i$ 's harvest is:

$$B_{\bullet/i} := B_{i/i} + B_{j/i} \quad (8)$$

235 where the  $\bullet$  indicates ‘summed over all fleets’. This benefit is the total  
236 net benefit of removing one more fish, including opportunity costs. Here,  
237 only two fleets are considered, but the expression can be generalized to an  
238 arbitrary number of fleets by summing over all of the fleets. The benefit will  
239 be a function of the current state of the ecosystem, and if the total benefit is  
240 positive (negative), then it will, from an economic point of view, be beneficial  
241 to increase (decrease) the harvest. If  $B_{\bullet/i} = 0$  for both fleets, then a marginal  
242 change in the harvest will leave the present value of the rent flow unchanged.  
243 Such a point is a candidate for a situation with optimal economic use of the  
244 ecosystem.

### 245 *3.1. Model simulations*

246 The deployed ecosystem model does not allow for an analytical solution  
247 for finding the benefit indicator. This section describes how the limit (7)  
248 is estimated with numerical experiments on the model, and how the con-  
249 tinuous formulation (1) and (2) are approximated with equivalent discreet  
250 formulation.

---

<sup>2</sup>Stock and crowding externalities (Smith, 1969) are included in  $B_{i/i}$ , however they are externalities vessels inflict on other vessels within the same fleet. Our viewpoint is the fleet, so these externalities are internal.

251 The estimation is performed by allowing the model to run with mortality  
 252 rates  $\mathcal{F}_i$  and  $\mathcal{F}_j$  until it converges to equilibrium  $\dot{N}^*(\mathcal{F}_i, \mathcal{F}_j)$ .<sup>3</sup> Two experi-  
 253 ments,  $A$  and  $B$ , that depart from the equilibrium are performed; in both  
 254 experiments, the fishing mortality of fleet  $j$  is fixed while the fishing mor-  
 255 tality of fleet  $i$  is changed:  $\mathcal{F}_i(A) = (1 - \epsilon)\mathcal{F}_i$  and  $\mathcal{F}_i(B) = (1 + \epsilon)\mathcal{F}_i$ . The  
 256 change in fishing mortality leads to a dynamic response of the ecosystem  
 257 model. The experiment is run for  $T = 50$  years, and the system converges  
 258 to a new equilibrium. We use  $\epsilon = 10^{-6}$  as a suitable compromise between  
 259 precision (close to the limit  $\epsilon \rightarrow 0$ ) and numerical noise (the signal is large  
 260 relative to rounding errors in computation).

261 The harvest flows,  $\mathbf{y}_i(A)$  and  $\mathbf{y}_i(B)$ , and the rent flows,  $\boldsymbol{\pi}_j(A)$  and  $\boldsymbol{\pi}_j(B)$ ,  
 262 are recorded (the bold symbols indicates that the flows are discrete in time  
 263 and represented as vectors  $\boldsymbol{\pi} = (\pi_0, \pi_{\Delta t}, \dots, \pi_T)$ ). All of the vectors are of  
 264 length  $(T/\Delta t + 1)$ , where  $\Delta t$  is the time step in the model. The changes in  
 265 the present values are then calculated as:

$$\Delta V_j = PV(\boldsymbol{\pi}_j(B) - \boldsymbol{\pi}_j(A)) \quad (9)$$

$$\Delta Y_i = PV(\mathbf{y}_i(B) - \mathbf{y}_i(A)) \quad (10)$$

266 The integrals involved in the present values are estimated as:

---

<sup>3</sup>In the model, the state variables, which are the density of the fish with respect to their size, exhibit the form of traveling waves with diminishing amplitudes when the controls are constant. The system is considered to converge to equilibrium when the coefficient of variation over 25 years in all points is less than  $10^{-8}$

$$PV(\boldsymbol{\pi}) = \sum_{t \in \{0, \Delta t, 2\Delta t, \dots, T - \Delta t\}} \rho^{-1} (e^{-t\rho} - e^{-(t+\Delta t)\rho}) \pi_t + e^{-T\rho} \frac{\pi_{T-\Delta t}}{\rho} \quad (11)$$

267 Here,  $\sum(\dots)$  calculates the present value from  $t = 0$  to  $t = T$ , and  $e^{-T\rho} \pi_{T-\Delta t} \rho^{-1}$   
 268 estimates the present value from  $t = T$  to  $t = \infty$ .

269 Finally the benefit indicator is estimated as

$$B_{j/i} = \frac{\Delta V_j}{\Delta Y_i} \quad (12)$$

## 270 4. Economic model

### 271 4.1. Two views on production in fisheries

272 In a traditional fisheries model (e.g. Getz and Haight, 1989, chap. 4), the  
 273 harvest is calculated by summing the contributions from all of the differently  
 274 sized groups that are fished. In the size-spectrum model, this is an integral  
 275 over the abundance distribution with respect to size,  $N(w)$ , weighted by the  
 276 size-selectivity of the fishing gear,  $\omega(w)$ :

$$y = \mathcal{F} \int_0^{\infty} \omega(w) N(w) w \, dw \quad (13)$$

277 where  $\mathcal{F}$  is the overall fishing mortality.

278 Fisheries economists tend to use a production model instead, where the  
 279 harvest,  $y$ , is the production of a fishing vessel with the factor inputs of effort,  
 280  $E$ , and stock,  $S$ , where the fish stock is an environmental variable.<sup>4</sup> The

---

<sup>4</sup>Stock is not a traditional production factor for the individual fisher as it is not under his control. It is more of an exogenous environmental variable. However, in aggregate, that is from a social viewpoint, the stock is endogenous and can be seen as a traditional production factor.

281 traditional approximation is to apply a Cobb-Douglas production function  
 282 (e.g., Clark, 1990, eq (2.8)):

$$y = qE^\alpha S^\gamma \quad (14)$$

283 Where  $q$  is the total factor productivity and  $\alpha$  is the output elasticity with  
 284 respect to effort, that is, how the harvest will relative increase (decrease)  
 285 with respect to a relative increase (decrease) in effort. The  $\gamma$  is the output  
 286 elasticity with respect to stock, and is normally expect to be found in the  
 287 range  $\gamma \in [0, 1)$ , and with smaller values for schooling fish compared to  
 288 benthic fish (e.g. Sandberg, 2006). The assumption of fixed catch per unit  
 289 effort (CPUE) found in some fishery models (e.g. Schaefer, 1954) is equivalent  
 290 to  $(\alpha, \gamma) = (1, 1)$  (in this context  $q$  is often called the catchability coefficient).  
 291 The Cobb-Douglas (14) is then a more sophisticated production view that  
 292 allows for declining productivity with respect to input factors.

293 The total production of the fleet is the sum of the productions of each  
 294 vessel. Assuming identical vessel and effort levels, total production will have  
 295 the same form as individual production:

$$\begin{aligned} y &= n q \left( \frac{E_{total}}{n} \right)^\alpha S^\gamma \\ &= q' E_{total}^\alpha S^\gamma \end{aligned} \quad (15)$$

296 where  $n$  is the number of vessels, and  $q' = n^{1-\alpha}q$ . Hence, the total harvest  
 297 function will be a scaled version of (14).

298 The two views on production can be unified by defining the stocks as:

$$S := \int_0^\infty \omega(w)N(w)w \, dw \quad (16)$$

299 and the overall fishing mortality rate as:

$$\mathcal{F} := q' E_{total}^\alpha S^{\gamma-1} \quad (17)$$

300 In this manner, the economic production view (15) and the model (13) will  
 301 give the same production,  $y$ .

302 The function  $S^{\gamma-1}$  in the overall fishing mortality rate (17) will, with  
 303 the expectation of  $\gamma \in [0, 1)$  being a convex decreasing function, indicating  
 304 declining productivity with respect to increasing stock.

#### 305 4.2. Cost model

306 Effort is an ambiguous concept; economists prefer to work with physical  
 307 input factors such as labour, fuel, and provision (see e.g. Squires, 1988):

$$y = q_1 x_1^{\alpha_1} x_2^{\alpha_2} \dots k^\beta S^\gamma \quad (18)$$

308 where  $x_1, x_2, \dots$  are input factors, and  $k$  is capital.  $\alpha_1, \alpha_2, \dots$  are output  
 309 elasticities with respect to the inputs factors, and  $\beta$  is the output elasticity  
 310 with respect to capital. Given (18), with corresponding prices  $p_i$  and a fisher  
 311 assumed to minimize cost, the input factors are applied such that

$$\frac{x_i}{x_j} = \frac{\alpha_i p_j}{\alpha_j p_i} \quad (19)$$

312 Equations (18) and (19) give a production cost relationship:

$$y = q_2 G^\alpha k^\beta S^\gamma \quad (20)$$

313 where

$$G = \mathbf{p} \cdot \mathbf{x} \quad (21)$$

$$\alpha = \sum \alpha_i \quad (22)$$

$$q_2 = q_1 \left( \sum \frac{p_i}{\alpha_i} \right)^\alpha \prod_i \left( \frac{\alpha_i}{p_i} \right)^{\alpha_i} \quad (23)$$

314 The production function (20) can replace (14) to allow for the estimation of  
 315 a production function based on the accounting statistics for the individual  
 316 vessel, which avoids the introduction of effort. It may seem equivalent to  
 317 a fixed price on effort, however, by assuming cost minimization, we allow  
 318 for substitution when relative prices between factors change (see supporting  
 319 material A).

320 Our objective is to analyze the ecosystem model from a long-run perspec-  
 321 tive. Therefore, we will derive a cost function under the assumption that all  
 322 of the factor inputs of the fishing fleet are completely variable, which allows  
 323 us to minimize both the operational and the capital costs.

324 With  $p_k$  as the price of capital, the total cost per vessel is  $C = G + kp_k$ .  
 325 If we assume that the ecosystem is in a steady state with a total harvest of  
 326  $y$ , then the cost minimization problem is to find the number of vessels,  $n$ ,  
 327 the operation cost,  $G$ , and the capital,  $k$ , such that:

$$(n, G, k) = \underset{n, G, k}{\operatorname{argmin}} n (G + kp_k) \Big|_{y = nqG^\alpha k^\beta S^\gamma} \quad (24)$$

328 By substituting  $n$

$$(n, G, k) = \underset{n, G, k}{\operatorname{argmin}} y \frac{G + kp_k}{qG^\alpha k^\beta S^\gamma} \Big|_{n = \frac{y}{qG^\alpha k^\beta S^\gamma}} \quad (25)$$

329 the cost minimization problem can be solved by first finding the operation  
 330 cost and capital level where the unit cost is minimized, and then the number  
 331 of vessels. Minimizing the unit cost implies that the input factors are applied  
 332 in the ratio:

$$\frac{G}{kp_k} = \frac{\alpha}{\beta} \quad (26)$$

333 and, because we are looking for the long-run optimal level of capital,  $\alpha + \beta =$   
 334 1. The total cost per vessel is then:

$$C = G + p_k k = G \left( 1 + \frac{\beta}{\alpha} \right) = \frac{G}{\alpha} \quad (27)$$

335 The unit costs are:

$$\frac{C}{y} = \frac{\frac{G}{\alpha}}{q \left( \frac{\beta}{\alpha p_k} \right)^\beta G^{\alpha+\beta} S^\gamma} = AS^{-\gamma} \quad (28)$$

336 Where

$$A = q^{-1} \beta^{-\beta} \alpha^{\beta-1} p_k^\beta \quad (29)$$

337 If we do the analysis from a long-run perspective and assume an ideal cost  
 338 minimizing fleet, we expect that the unit cost of harvesting will be of the form  
 339 (28) if changes in the harvest in the short-run are small. Because section 4.1  
 340 established a relationship between the biological production function (13) and  
 341 the economic production function (20), with the definition of stock given by

342 (16),  $\mathcal{F}$  can be used as the control variable in the model, and the cost can  
343 be calculated using (28).

#### 344 4.3. Cost model parameters

345 The parameters for the cost model for the two fleets (Tab. 1) are estimated  
346 for the North Sea on the basis of the accounting statistics, the landing statis-  
347 tics and the ICES (International Council for Exploration of the Sea) stock  
348 assessment summaries (ICES, 2010b) (see supporting material A). The unit  
349 cost model (28) has two parameters  $A, \gamma$  and one variable  $S$ . The value of  $\gamma$  is  
350 independent of how  $S$  is measured as long as it is proportional to the density  
351 of the fish in the sea. However, the value of  $A$  will depend upon the way  $S$  is  
352 measured, and there is no way to get from the spawning stock biomass, the  
353 metric of ICES, to the density of fish per  $\text{m}^3$ , the metric of the model. The  
354 approach taken is to calibrate the model to give a unit cost that is similar  
355 to the one observed in the data. However, the rent in today's fishery is zero  
356 (supporting material A Tab. 2 and 3). The fishery where transferable quotas  
357 were first introduced in Denmark was the herring and mackerel fishery (as a  
358 test in 2003, permanent since 2007); this is likely the most cost-efficient fish-  
359 ery in Denmark, and we assume that the other sectors would be as efficient  
360 if properly managed. Hence, the constant  $A$  is found by setting the rent to  
361 15.57% of the revenue in a fishery that resembles today's fishery in the North  
362 Sea.

#### 363 4.4. Price model

364 The price model is estimated using data from the Danish Landing Statis-  
365 tics (estimation details in supporting material B). Two price models are  
366 needed:  $p_F$  for the forage fish fleet, and  $p_L$  for the large fish fleet. The

Table 1: Parameter estimates for the price and cost models

Parameter	Estimate	Std Error	Units
$P$	0.1610	0.0053	€ kg <sup>-1</sup>
$\varrho$	4.830	0.51	€ kg <sup>-1</sup>
$b$	0.0295	0.00096	kg
$a$	5.38	0.25	kg
$\iota$	0.5230	0.0039	
$\gamma_{\text{F}}$	0.175	0.037	
$\gamma_{\text{L}}$	0.280	0.016	
$A_{\text{F}}$	0.05748	Calibrated	€ kg <sup>-1</sup>
$A_{\text{L}}$	0.2759	Calibrated	€ kg <sup>-1</sup>

367 forage fish fleet lands fish for reduction into fishmeal. Because there is no  
 368 size sorting in the landings, we assume a flat price with respect to the size of  
 369 the landed fish:

$$p_{\text{F}}(w) = P \quad (30)$$

370 The large fish fleet lands fish for human consumption. The prices depend  
 371 upon the size, grade and species. In the model, the size is presented as a  
 372 dimension; therefore, it is appropriate to give the price as a function of the  
 373 size:

$$p_{\text{L}}(w) = \begin{cases} \varrho(1 - \exp(-((w - b)/a)^{\iota})) & w \geq b \\ 0 & \text{else} \end{cases} \quad (31)$$

374 The function (31) is a scaled Weibull distribution function. Standard errors  
 375 (Tab. 1) are based on re-sampling (Efron and Tibshirani, 1993) leading to a  
 376 coefficient of variation below 0.004.

377 Revenue for fleet  $i$  are found as:

$$R_i = \mathcal{F}_i \int_0^\infty p_i(w)\omega_i(w)N(w)w \, dw \quad (32)$$

378 and rent:

$$\pi_i = R_i - y_i A_i S^{-\gamma_i} \quad (33)$$

379 with  $y_i$  and  $S_i$  as respectively (13) and (16).

## 380 5. Results

381 To illustrate the calculation of the benefit indicator, the state of the cur-  
382 rent North Sea fishery is examined. We assume that the mean landings over  
383 the period from 2001–2009 represent the sustainable harvest that the North  
384 Sea can deliver in its present state. The mean landing is 1 990 304 ton year<sup>-1</sup>  
385 (ICES, 2010a); half is assumed to be from the forage fish fleet and half from  
386 the large fish fleet. Our simulations depart from a model system in equi-  
387 librium with these services and the benefit indicators are calculated with a  
388 social discount rate of  $\rho = 3\%$  pa.

389 A change in the fishing mortality of the forage fish fleet impacts the pro-  
390 duction and rent of both fleets. Fig. 2 illustrates the data from the simulation  
391 explained in section 3.1. Initially, the harvest of the forage fish fleet shows  
392 a big increase, followed by a reduction that levels out at approximately half  
393 of the initial increase. The rent of the forage fish fleet increases initially, but  
394 eventually it levels out close to zero. The reason that the rent approaches  
395 zero, despite the increase in the harvest, is due to a slight decrease in the

396 density of fish; even though the elasticity of the unit cost with respect to  
397 the density is only  $\gamma = 0.175$ , the result is a slight increase in the unit cost  
398 that affects the harvest of the entire fleet. For the large fish fleet change in  
399 fishing mortality of the forage fish fleet results in a slight drop in the harvest  
400 followed by a sustained increase in harvest volume. Despite the increase in  
401 the harvest of the large fleet, the rent decreases. This decrease is due to a  
402 decrease in the size of the fish in the large fish fleet's harvest that leads to  
403 a lower market value. The benefit indicator for the two fleets per forage fish  
404 is calculated according to (12). The internal benefit to the forage fleet is a  
405 slight increase, but it is offset by the much larger decrease in external benefits  
406 to the large fish fleet. The total benefit of an increase in forage fishing in the  
407 North Sea today is, therefore, clearly negative.

408 The consequences of a change in the large fish fleet's fishing mortality  
409 rate can be evaluated in a similar manner (Fig. 3). The production of the  
410 large fish fleet shows the same pattern as the forage fish fleet, with an initial  
411 high extra harvest followed by oscillations and settling at approximately half  
412 of the initial amount. The harvest of the forage fish fleet increases initially  
413 due to the decreased predation pressure, but later it approaches zero as the  
414 predators again increase in number, although to a slightly smaller number  
415 than before. The change in the rent of the forage fish fleet is negligible, while  
416 the rent of the large fish fleet shows an initial increase (the dashed line start  
417 at positive values) followed by a drastic decrease. This decrease in the rent,  
418 despite the increase in harvest, is caused by two things: a slight decrease  
419 in the fish density, which increases the unit cost, and a decrease in size of  
420 the harvested fish, which decreases the market value. The total benefit of

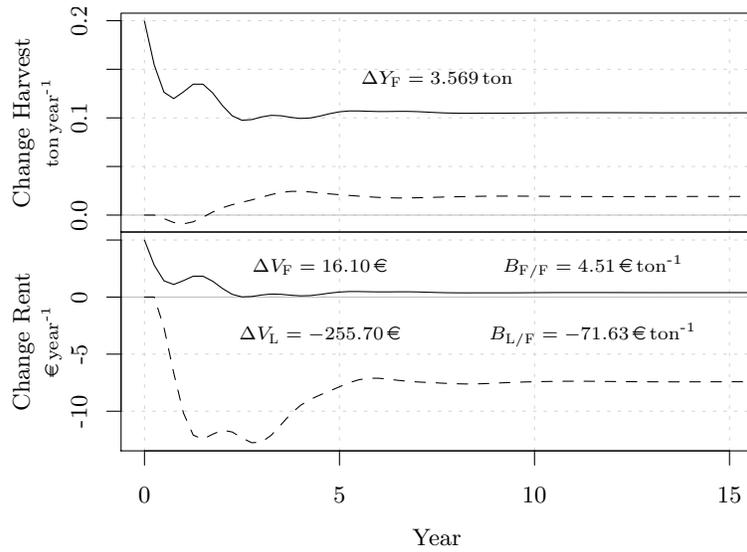


Figure 2: Calculation of the change in the benefit caused by a *change* in the forage fish fleet. The starting point of the calculation is a steady state. At time  $t = 0$ , the forage fish fleet fishing mortality is slightly changed (increased), while the fishing mortality of the large fish fleet is unchanged. The change in the fishing mortality leads to a change in the production (upper panel) and the rent (lower panel) of the forage fish fleet (solid lines) and the large fish fleet (dashed lines). All lines are changes, that is, deviations from the equilibrium situation before the change.

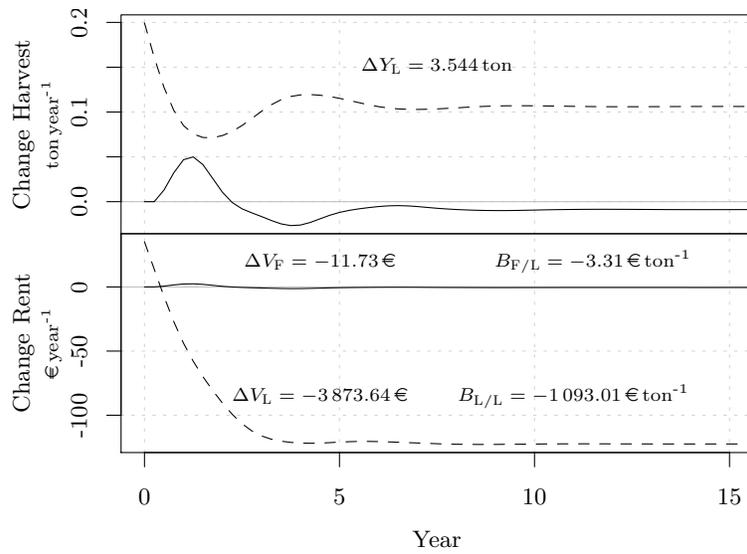


Figure 3: Illustration of the benefit indicator method caused by a *change* in the large fish fleet. The change in fishing mortality leads to a change in the production (upper panel) and the rent (lower panel) of the forage fish fleet (solid lines) and the large fish fleet (dashed lines). All lines are changes, that is, deviations from the equilibrium situation before the change.

Table 2: The benefit indicators of the present use of the North Sea.

With respect to	Forage fish fleet		Large fish fleet	
Internal Benefit	$B_{F/F}$	4.5 € ton <sup>-1</sup>	$B_{L/L}$	-1 093 € ton <sup>-1</sup>
External Benefit	$B_{L/F}$	-71.6 € ton <sup>-1</sup>	$B_{F/L}$	-3 € ton <sup>-1</sup>
Total Benefit	$B_{\bullet/F}$	-67.1 € ton <sup>-1</sup>	$B_{\bullet/L}$	-1 096 € ton <sup>-1</sup>

421 an increase in the large fish fleet in the North Sea today is negative and, in  
 422 magnitude, higher than the externality imposed by the forage fish fleet. Both  
 423 benefit indicators of the present use of the North Sea are negative (Tab. 2),  
 424 the benefit of the ecosystem services from the North Sea could be improved  
 425 by reducing both fleets' harvests.

426 Fig. 4 presents the internal and external benefit indicators calculated  
 427 with a discount rate of  $\rho = 3\%$  pa. The axis in the diagram is the sustainable  
 428 harvest, that is, the harvest from an ecosystem in equilibrium with constant  
 429 fishing mortality. The sustainable harvest is then an indicator for the state  
 430 of the ecosystem. The zero contour lines in the two internal panels cross one  
 431 another at point A. At this point society optimizes the benefit from the two  
 432 services but ignores the externality. The negative externalities amount to  
 433 -132 € ton<sup>-1</sup> inflicted on the large fish fleet for the marginal fish caught by  
 434 the forage fish fleet and -12 € ton<sup>-1</sup> on the forage fish fleet for the marginal  
 435 fish caught by the large fish fleet.

436 To find a global optimum, the total benefit indicator must be considered  
 437 (Fig. 5). The optimum is where the total benefit of the two fleets is zero  
 438 (point B). This point may be reached by approximately halving the harvests  
 439 of the two fleets.

440 The external benefit from the forage fish fleet (0–150 € ton<sup>-1</sup>) generally

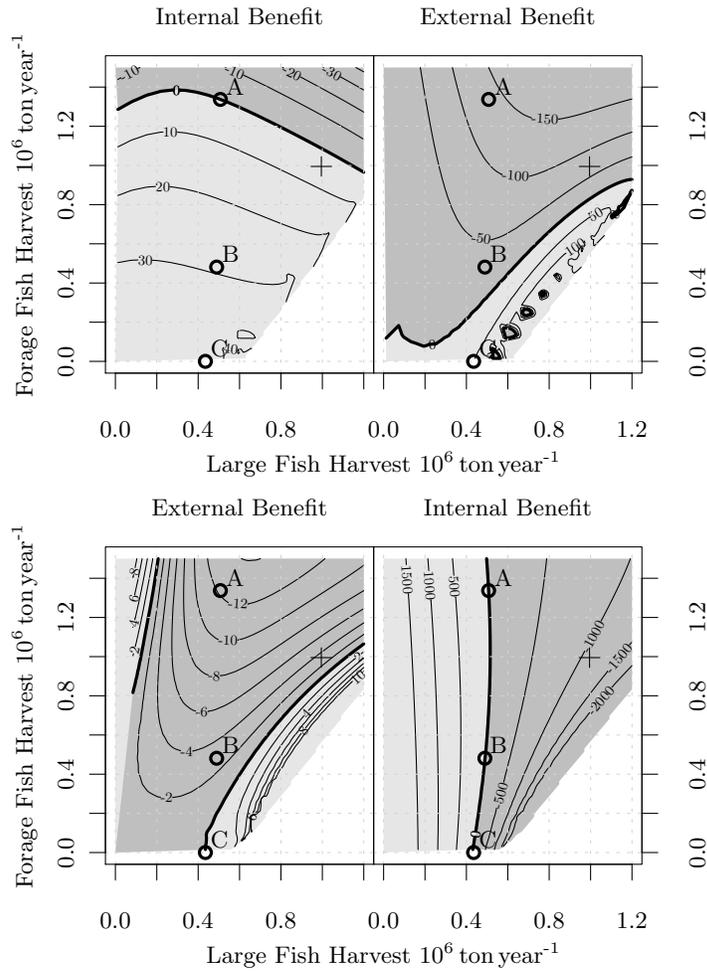


Figure 4: The benefit indicators ( $\text{€ ton}^{-1}$ ) for the North Sea forage fish fleet (top) and large fish fleet (bottom) divided into internal benefit,  $B_{i/i}$ , and external benefit,  $B_{i/j}$ . Four points of special interest are marked: the plus sign is the current state of the North Sea, A is where the internal benefits of the two fleets cross, B is where the total benefits of the two fleets cross (Fig. 5), and C is an arbitrarily chosen point where the externality on the large fish fleet from the forage fish fleet is positive

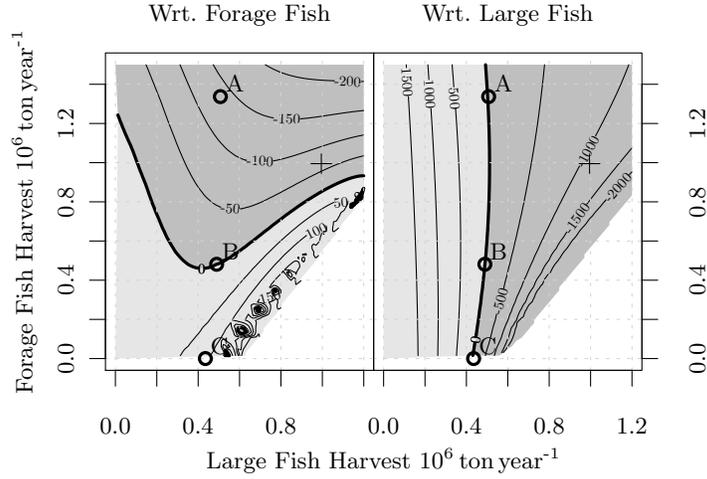


Figure 5: Total benefit indicator ( $\text{€ ton}^{-1}$ ) for the forage fish fleet,  $B_{\bullet/F}$  (left), and the large fish fleet,  $B_{\bullet/L}$  (right). The points marked are the same as in Fig. 4

441 far exceeds the internal benefit ( $0\text{--}30 \text{ € ton}^{-1}$ ). This phenomenon implies  
 442 that the management of the forage fish fleet should consider the large fish  
 443 fleet. The zero contour line of the total benefit indicator for the forage fish  
 444 fleet follows diagonals up left and right from point B (Fig 5). This result  
 445 indicates that the optimal forage fish harvest is dependent upon the volume  
 446 of the large fish fleet's harvest.

447 In contrast, in absolute values, the internal benefit of the large fish fleet  
 448 ( $0\text{--}1000 \text{ € ton}^{-1}$ ) generally dwarfs the external benefit ( $0\text{--}12 \text{ € ton}^{-1}$ ). Thus,  
 449 the influence of the large fish fleet on the forage fish fleet is rather small, and  
 450 it can, for practical purposes, be ignored. The zero contour line for the large  
 451 fish fleet in Fig 5 is vertical, indicating that the optimal harvest level of the  
 452 large fish fleet is independent of the forage fish fleet.

453 A striking result of Fig. 4 is that the forage fish fleet can create a positive  
 454 externality for the large fish fleet. To understand the mechanism behind this

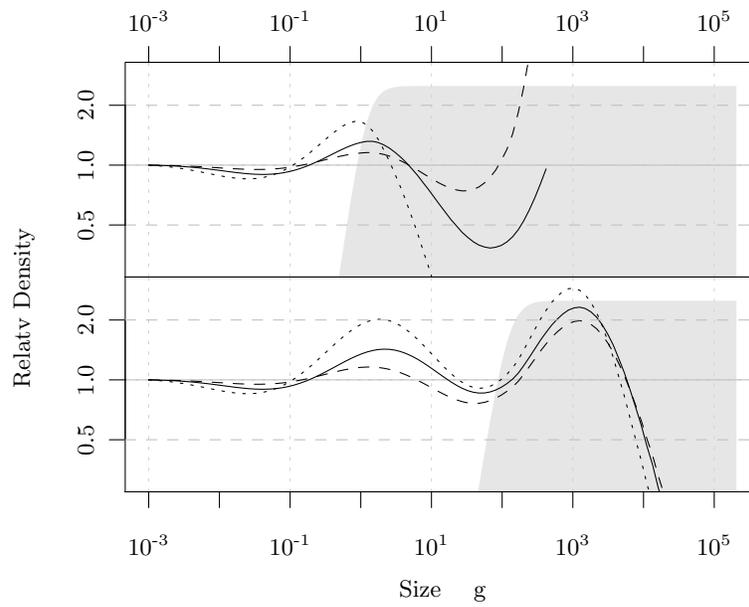


Figure 6: Abundance of fish as a function of individual size (both axes logarithmic) at the points A-C in Figs. 4 and 5; A is dotted, B is solid, and C is dashed. The abundance of forage fish (top) and large fish (bottom) is scaled relative to the unfished situation. The grey regions illustrate each fleet's selection function.

455 result, the population levels at three points, marked A, B, and C in Fig. 4  
456 and 5 are examined (Fig. 6). As the harvest of the forage fish is increased,  
457 i.e., moves from point C to B, the abundance of large forage fish within  
458 the size selection function decreases, as a response to the increased fishing  
459 pressure. The decreased abundance of the forage fish releases the predation  
460 pressure on smaller individuals in the size range of 1-10 g. The decreased  
461 abundance of large forage fish affects the large fish in two opposite ways: 1)  
462 it removes some of the food for the largest fish ( $> 1$  kg), and 2) it reduces  
463 the competition for food for the juvenile individuals of the large fish. Moving  
464 from C to B, the effect of the reduced competition appears most important  
465 because the large fish generally increase in abundance. Only when moving  
466 from B to A are the very large fish ( $> 5$  kg) negatively affected by the lower  
467 abundance of food from the forage fish. The impact on abundance is modest,  
468 but because the price of the large fish is high, this reduction is responsible  
469 for the negative externality at high harvest rates.

## 470 **6. Discussion and Conclusion**

471 We have developed a general methodology to analyze the internal and ex-  
472 ternal consequences of fishing an ecosystem in terms of the benefit indicator.  
473 The method has been applied to quantify the externalities that a forage fish  
474 fleet and a large fish fleet in the North Sea generate for one another. The  
475 generalization of the methodology to more than two ecosystem services is  
476 straightforward. Even though the model is calibrated to resemble the North  
477 Sea, it builds on analysis of size-spectra properties generally found across  
478 marine ecosystems. The results, therefore, have general value and may be  
479 applied to other systems, at least in qualitative terms.

480 Economic analyses often look at the first order derivative, known as the  
481 margin. This gives easy interpretative indicator, as for example Weitzman's  
482 (2003) stationary rate of return.<sup>5</sup> The Weitzman's (2003) stationary rate of  
483 return give an easy interpretable number to compared with the discount rate.  
484 We have here developed an indicator to inform about the trade-off when ex-  
485 ploiting a marine ecosystem based on marginal analysis, equation (4). As we  
486 define our indicator based on an equilibrium situation, our indicator resem-  
487 bles Weitzman's (2003) stationary approach. However the marine ecosystem  
488 is dynamic, and can not instantly go from one equilibrium situation to an  
489 other; there is a dynamic path that has economic implications. The indicator  
490 is designed to capture this dynamic, by discounting both the economic and  
491 physical changes.

492 While using the method of discounting seems to be widely accepted for  
493 aggregating the economic outcome for a (infinite) time flow, equation (2),  
494 using the method of discounting of the physical effect, equation (1), seems  
495 to encounter some skepticism.<sup>6</sup> This is, however, a method widely used in  
496 cost effectiveness analysis in health technology assessment, recommended for  
497 example by National Institute for Health and Care Excellence (NICE, 2012),  
498 and suggested for natural resource policy prioritizing (Kronbak and Vester-  
499 gaard, 2013). Discounting is time preference, that is, to get present utility,

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<sup>5</sup>If  $g(k, \dot{k})$  is the net cash flow as a function of capital  $k$  and investment  $\dot{k}$ , the stationary rate of return is

$$R(k) = -\frac{g_k}{g_{\dot{k}}}$$

That is, it is a ratio between the marginal cashflow with respect to capital and investment (Weitzman, 2003)

<sup>6</sup>Authors experience from presentations of the paper.

500 future benefit is weighted by a positive factor less than one, and declining  
501 the farther into the future the benefit is available. The rationale behind the  
502 time preference can be return on opportunity investment, society's produc-  
503 tivity growth, impatience and combinations of these factors. Irrespective of  
504 rationale the benefit we care about is the utility of goods and services. The  
505 money value is just a convenient concept for summing the utility into one  
506 value. If rational, it follows that it is the same time preference factor that  
507 is applied to all entities. It is then the same discount rate that has to be  
508 applied to monetary values and physical entities (for further explanation see  
509 Brent, 2003 and Kronbak and Vestergaard, 2013).

510 An alternative to our benefit indicator would be the discounted value of  
511 the cash flow with a change in fishing mortality rate or fishing effort. Both  
512 fishing mortality rate and fishing effort are model variables with no tangible  
513 physical realization, that is, they exist only as estimated variables in mod-  
514 els. It is impossible to show or measure fishing mortality in nature without  
515 the help from a model; people not familiar with fish models, e.g. fishers and  
516 politicians, will therefore have difficulties in interpreting an indicator based  
517 on fishing mortality. We therefore choose to use a well known physical en-  
518 tity, the quantity of removed fish, as denominator in our indicator. Another  
519 approach would be to find an implicit discount rate similar to the Weitz-  
520 man's (2003) stationary rate of return; similarly to the method applied in  
521 Ravn-Jonsen (2011). However, that will not give an indicator divided into  
522 external and internal effect, and it will only be computable for the part of  
523 the ecosystem states where there is an inter-temporal choice of exploitation  
524 (Ravn-Jonsen, 2011).

525 As defined in section 3, the benefit indicator rests upon a choice of control  
526 variable, as the control variable defines what *continue as usual* and *a change*  
527 signify. The choice of fishing mortality as control variable may be seen as  
528 representing the biologist's view of control variable, where as the natural  
529 choice for a manager or fisher may be either effort or the total harvest.  
530 Effort as control is known in fishery management as input control, and can  
531 for example be control over number of vessels, control over days at sea, control  
532 over motor power etc. Harvest as control is known as output control and is  
533 applied by setting total allowable catch for the fishery. To analyze the benefit  
534 of the different kinds of control in a real world fishery is beyond the scope of  
535 present analysis, however to test how sensitive the benefit indicator is to the  
536 choice of the control variable, the model was reformulated with two other  
537 types of control variables: harvest and fishing cost. Using cost as control is  
538 equivalent to having effort as control if factor input prices are constant. The  
539 results are presented in supporting material E and show consistency with  
540 the found benefit indicator, with the exception of the external benefit from  
541 the forage fish fleet. For the external benefit of the forage fleet, the zero  
542 contour line moves up so that the value for today's large fish fishery changes  
543 from  $-71 \text{ € ton}^{-1}$  with fishing mortality as the control to  $34 \text{ € ton}^{-1}$  with effort  
544 as the control to  $100 \text{ € ton}^{-1}$  with harvest as the control. Nevertheless, the  
545 general picture and the optimal point are convergent, which shows that the  
546 benefit indicator is a proper indicator of the net benefit, though the values  
547 for the external benefit at the present exploitation rate must be interpreted  
548 cautiously.

549 The intersection of the zero contour lines of the total benefit indicator in

550 Fig. 5 indicates the economic optimum. For simplicity, the decision variables  
551 have in the analysis only two dimensions: the two fishing mortality rates  
552 ( $\mathcal{F}_F, \mathcal{F}_L$ ). In the real world, there are many more possibilities for decision  
553 variables such as a change in the size selectivity, a change in the selectivity  
554 with respect to the traits, or a change in the fishing mortality over time.  
555 Therefore, it may be possible to increase the benefit by exploring other di-  
556 mensions of the decision space.

557 In current fishery management, securing the reproduction of the fish stock  
558 is considered to be an important goal. The ecological model has fixed repro-  
559 duction, that is, there is no feedback from the abundance of the adult fish  
560 onto the abundance of the offspring. This phenomenon is in line with the clas-  
561 sic yield-per-recruit analysis in fisheries science (Beverton and Holt, 1957).  
562 Thus, the opportunity cost of lost reproduction is not part of the benefits  
563 calculated in Fig. 4 and 5. This approach is taken to highlight only the  
564 trophic system, such that all of the effects stem from predation and growth  
565 of the individual. Therefore, our analysis cannot stand alone; reproduction  
566 must also be considered. The effects on reproduction would be mostly felt  
567 under “recruitment overfishing” at high fishing mortalities. The equilibrium  
568 points identified in our analysis are all at moderate fishing mortality and are  
569 therefore expected to only be weakly influenced by the lack of representa-  
570 tion of recruitment. The predictions of yields under high exploitation rates  
571 will be overpredicted by the model. However, the model indicates the bene-  
572 fit from a substantial reduction in the harvest, which would simultaneously  
573 reduce the probability of reproduction failure. The results are also depen-  
574 dent on the values of the parameters in the model. The qualitative behavior

575 model is, however, robust to changes in the parameters (e.g. those related  
576 to predator-prey interactions; Andersen and Pedersen (2010)). Changes to  
577 the parameters are therefore expected only to change the exact values of  
578 the equilibrium points, not the qualitative results regarding the interaction  
579 between fishing on small and large species.

580 The economic aspects of the model consist of a price model and a cost  
581 model. Both of these models are based on data from Denmark; however,  
582 because Danish fisheries are part of the global market, the models are generic.  
583 The price model is divided into two parts: one for forage fish, and one for  
584 large fish. Large fish are regarded as landed for direct human consumption,  
585 and we find in the supporting material B that price increases with size, with  
586 minor variations from year to year. We are confident that the price model  
587 reflects the willingness of the industry to pay with respect to size. However  
588 we notice that the price analysis is static, without the dynamic caused by  
589 supply and demand. We leave to future work to incorporate an economic  
590 market in the model.

591 The cost model is described as a power function of the biomass in the sea.  
592 The model needs two parameters for each fleet, the exponents  $\gamma_i$ , and the  
593 coefficients  $A_i$ . The value of the exponents differ between studies; e.g., Sand-  
594 berg (2006) found values in the range of 0.18 to 0.48 for different herring  
595 and cod fleets, and Eide et al. (2003) found 0.42 for cod. Compared to those  
596 studies, the values found in the present study (0.18 and 0.28) are on the low  
597 end. In supporting material D, the sensitivity of this parameter is tested  
598 by increasing the exponents by a factor of 1.5. The change in  $\gamma$  does not  
599 qualitatively change figures 4 or 5. The value of the benefit to the forage

600 fish fleet is slightly sensitive to a change in the exponent, while the large fish  
601 fleet is almost insensitive.

602 As our model does not use the same stock concepts as the ICES stock  
603 assessments, we have calibrated the coefficients in the cost model so that  
604 the present fishery gives 15.57% rent—the same as the best-managed fishery  
605 in Denmark. This is a rough estimate, as the present fishery yields zero  
606 rent (supporting material A Tab. 2 and 3). In supporting material D, the  
607 sensitivity of this calibration is tested by calibrating under the assumption of  
608 zero rent in the present fishery. Again, the figures do not change qualitatively;  
609 however, the value of the benefit to the forage fish fleet is more sensitive to  
610 this parameter than is the value to the large fish fleet. The reason for this  
611 difference in sensitivity between the two fleets stems from the underlying  
612 price structures: while the large fish fleet benefits from an increase in the  
613 price caused by the increase in the size of the fish as a result of the relieved  
614 exploitation level, the forage fish fleet has a flat price relative to the size of  
615 the fish. Since both fleets benefit from an increase in density as a result of the  
616 relieved exploitation levels in the form of a decreased unit cost. However, for  
617 large fish, the change in price dominates the change in cost. The economics  
618 of the forage fish fleet are then dominated by the density effect on the cost,  
619 and for the large fish fleet, the economics are dominated by the price response  
620 to the size of the fish.

621 The size-spectrum model has been used for ecological impact assessments  
622 of fishing on the ecosystem (Andersen and Pedersen, 2010; Houle et al., 2013;  
623 Jacobsen et al., 2014). One common impression from those analyses was that  
624 a fishery on the large fish imposed a positive influence on the forage fish, due

625 to the reduced predation pressure on the forage fish when the consumer fish  
626 were removed. In contrast, the results from present model, as presented in  
627 Fig. 4, uncover that the externality on the forage fish fleet generated by  
628 the large fish fleet is ignorable. The externality is ignorable because it is  
629 dwarfed by the intertemporal cost in the large fish fleet's own fishery if it is  
630 not managed close to the optimum. The contrast in interpretation between  
631 present model and the others highlights the importance of economic analyses  
632 over purely ecological analyses of the impact of fishing on an ecosystem.

633 Traditional Lotka-Volterra type models (e.g. May et al., 1979; Flaaten,  
634 1988) predict a positive externality from predator harvesting on forage fish  
635 harvest and a negative externality from forage fish harvest on predator har-  
636 vest. The total benefit of increased predator harvesting in these models will  
637 depend on model formulation and parameters; often when the predator is  
638 valuable, the externality to the prey is ignorable compared to the rent from  
639 the predator (e.g. Agnarsson et al., 2008). The reason for the positive ex-  
640 ternality is obvious: reduced predator abundance results in lower predation  
641 mortality on forage fish and thus increased productivity of the forage fishery;  
642 a reduction in forage fish, on the other hand, leads to less food for predators  
643 and consequently lower productivity and lower yield of the consumer fishery.  
644 The unstructured Lotka-Volterra equations are based on the assumption that  
645 only the adult parts of the fish populations matter. The size spectrum mod-  
646 els do not rely on this assumption, and explicitly model the entire life history,  
647 from eggs to adults. This extra degree of realism in the size spectrum model  
648 is the reason it predicts different externalities than Lotka-Volterra type of  
649 models.

650 Size spectrum models predict situations where the forage fish fleet gen-  
651 erates a negative externality on the large fish fleet, but there are situations  
652 where they generate a positive externality. The explanation for this phe-  
653 nomenon must be observed in the different functions the species fill for one  
654 another during their lifespan. If we focus on a mature forage fish that is  
655 approximately 100 g, it will fill three different functions with respect to the  
656 large fish species: 1) the function of a predator on larvae and juveniles, 2)  
657 the function of a competitor to similarly sized fish and 3) the function of prey  
658 for larger fish. The first two have a negative influence, while the last has a  
659 positive influence. The economic analysis shows that this triple functionality  
660 leads to a requirement of accommodating the harvest of forage fish to the  
661 exploration of the large fish. Traditional bioeconomic models have been cen-  
662 tered on the mature fish. The multi-species models that include interaction  
663 amongst mature levels that do exist, such as the Lotka-Volterra type model,  
664 are restricted to modeling predator-prey, competition or mutualism, but not  
665 all three at once. Consequently, these models disregard an important part of  
666 the ecological functionality.

### 667 *Concluding remarks*

668 Overall, this model shows that the exploitation of the forage species has  
669 a notable economic impact on the large species fishery, but the reverse is not  
670 true. The analysis shows that the naïve perception, where the forage species  
671 is only viewed as food for the large species, is too simple. The predation of the  
672 forage fish species on the juveniles of the large species and the competition  
673 between the forage fish species and the juveniles of the large species can, if the  
674 density of the forage fish is too high, dominate over the function of the forage

675 fish as prey. Thus, the harvest of the forage fish must be adjusted to the  
676 harvest of the large fish. The present management of the North Sea is, given  
677 the current exploitation rate of the large fish, not far from having the right  
678 forage fish harvest. However, the model's optimal point ( $481 \cdot 10^3$  ton year<sup>-1</sup>,  
679  $489 \cdot 10^3$  ton year<sup>-1</sup>) is approximately half of the current harvest in the North  
680 Sea, which indicates that the present exploitation is too high. To improve the  
681 utilization of the ecosystem, management must acknowledge the externalities  
682 that the fisheries impose upon one another.

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