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Ravn-Jensen, Lars; Andersen, Ken Haste; Vestergaard, Niels

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1 An Indicator for Ecosystem Externalities in Fishing

2 Lars Ravn-Jonsen^{a,*}, Ken H. Andersen^b, Niels Vestergaard^a

3 ^a*Department of Environmental and Business Economics, University of Southern*
4 *Denmark, Esbjerg*

5 ^b*Center for Ocean Life, Natl. Inst. of Aquatic Resources, Technical University of*
6 *Denmark, Charlottenlund*

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,

*Corresponding author
Preprint submitted to *Natural Resource Modeling*
E-mail address: lrj@sam.sdu.dk (Lars Ravn-Jonsen)

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 material¹ 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).

¹The 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 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

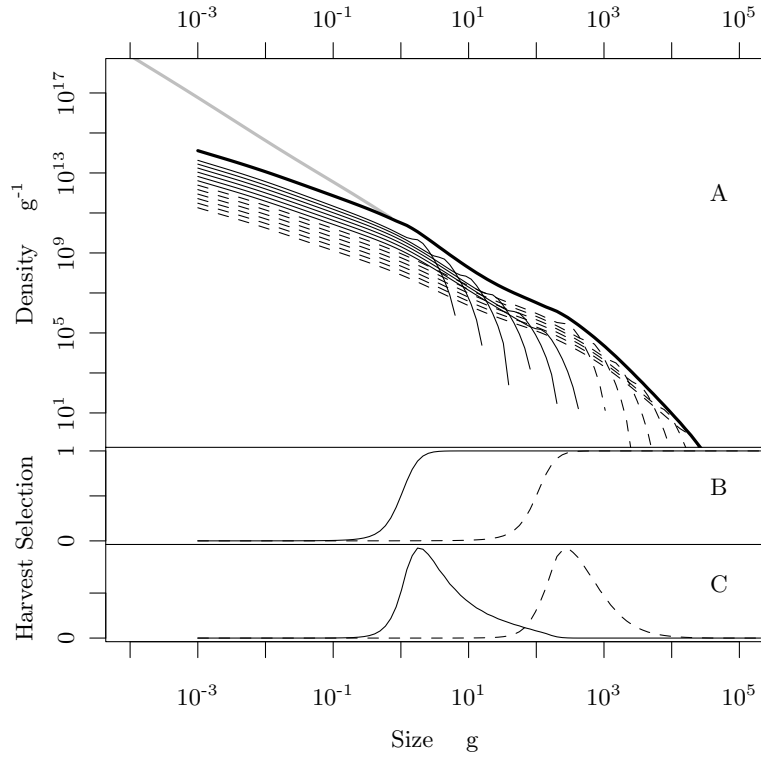


Figure 1: Run of the model with the fishing mortality of the two fleets set to correspond with the current exploitation of the North Sea. Solid lines represent the forage fish fleet, dashed lines the large fish fleet. A: Density of fish, $N_i(w)$, as a function of individual weight, w . Each thin line 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) π_i and π_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 ρ (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,² 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.

²Stock 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 $\dot{N}^*(\mathcal{F}_i, \mathcal{F}_j)$.³ 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 Δt 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:

³In 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.⁴ The

⁴Stock 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 α 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 γ 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 β 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, γ and one variable S . The value of γ 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 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 ⁻¹
ϱ	4.830	0.51	€ kg ⁻¹
b	0.0295	0.00096	kg
a	5.38	0.25	kg
ι	0.5230	0.0039	
γ_F	0.175	0.037	
γ_L	0.280	0.016	
A_F	0.05748	Calibrated	€ kg ⁻¹
A_L	0.2759	Calibrated	€ kg ⁻¹

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:

$$p_F(w) = P \tag{30}$$

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:

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

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⁻¹
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

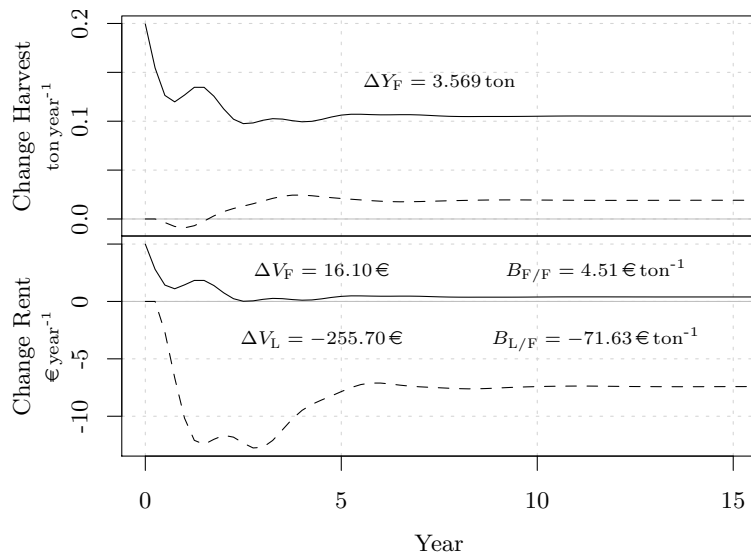


Figure 2: Calculation of the change in the benefit caused by a *change* in the forage fish fleet. The starting point of the calculation is a steady state. At time $t = 0$, the forage fish fleet fishing mortality is slightly changed (increased), while the fishing mortality of the large fish fleet is unchanged. 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.

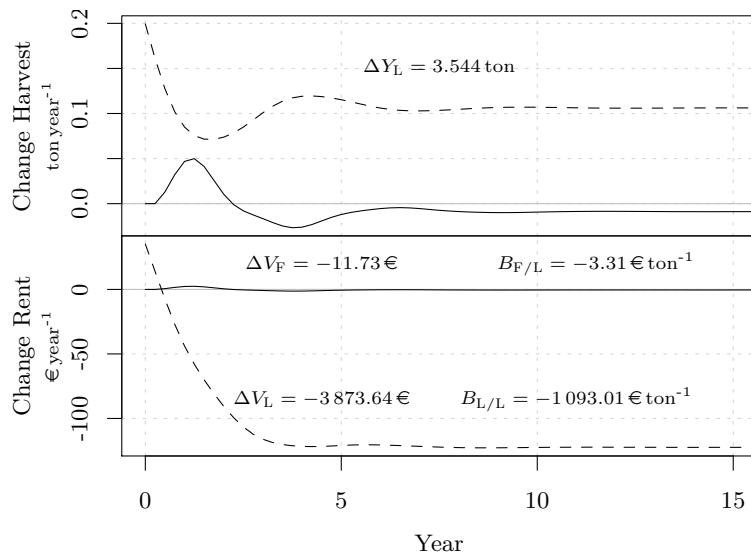


Figure 3: Illustration of the benefit indicator method caused by a *change* in the large fish fleet. The change in fishing mortality leads to a change in the production (upper panel) and the rent (lower panel) of the forage fish fleet (solid lines) and the large fish fleet (dashed lines). All lines are 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 ⁻¹	$B_{L/L}$	-1 093 € ton ⁻¹
External Benefit	$B_{L/F}$	-71.6 € ton ⁻¹	$B_{F/L}$	-3 € ton ⁻¹
Total Benefit	$B_{\bullet/F}$	-67.1 € ton ⁻¹	$B_{\bullet/L}$	-1 096 € ton ⁻¹

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⁻¹ inflicted on the large fish fleet for the marginal fish caught by
 434 the forage fish fleet and -12 € ton⁻¹ 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⁻¹) generally

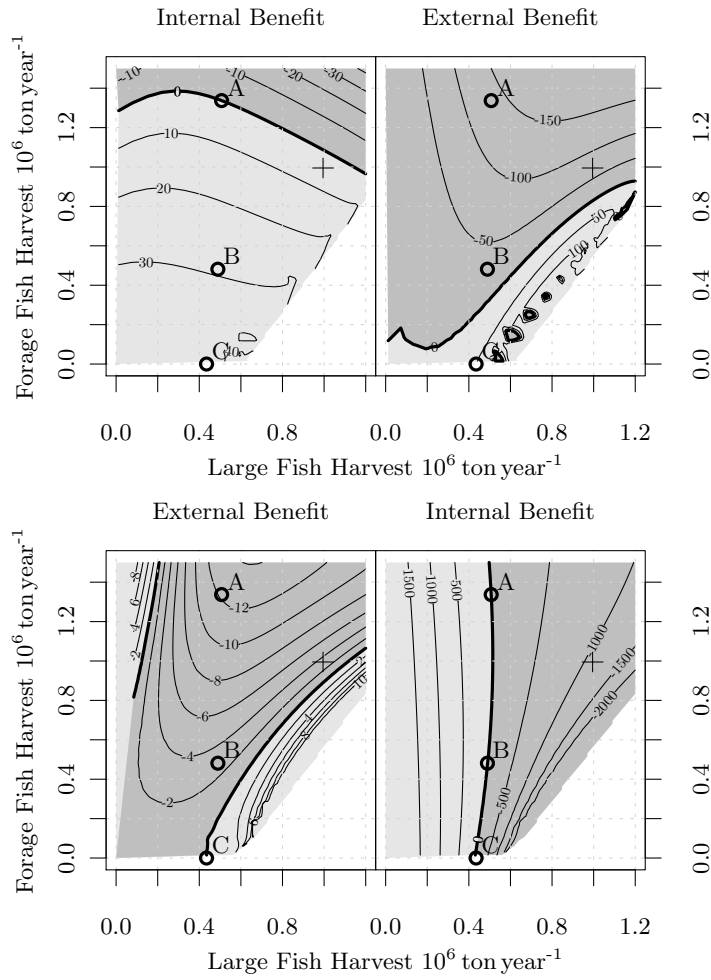


Figure 4: The benefit indicators (€ ton^{-1}) for the North Sea forage fish fleet (top) and large fish fleet (bottom) divided into internal benefit, $B_{i/i}$, and external benefit, $B_{i/j}$. Four points of special interest are marked: the plus sign is the current state of the North Sea, A is where 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

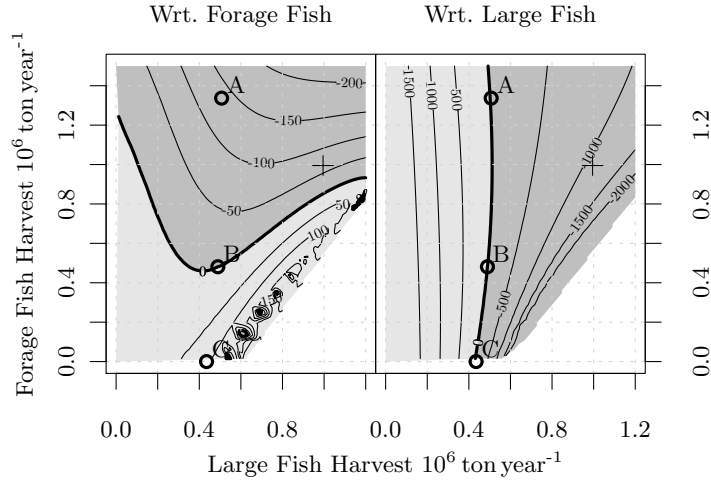


Figure 5: Total benefit indicator (€ ton^{-1}) for the forage fish fleet, $B_{\bullet/F}$ (left), and the large fish fleet, $B_{\bullet/L}$ (right). The points marked are the same as in Fig. 4

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

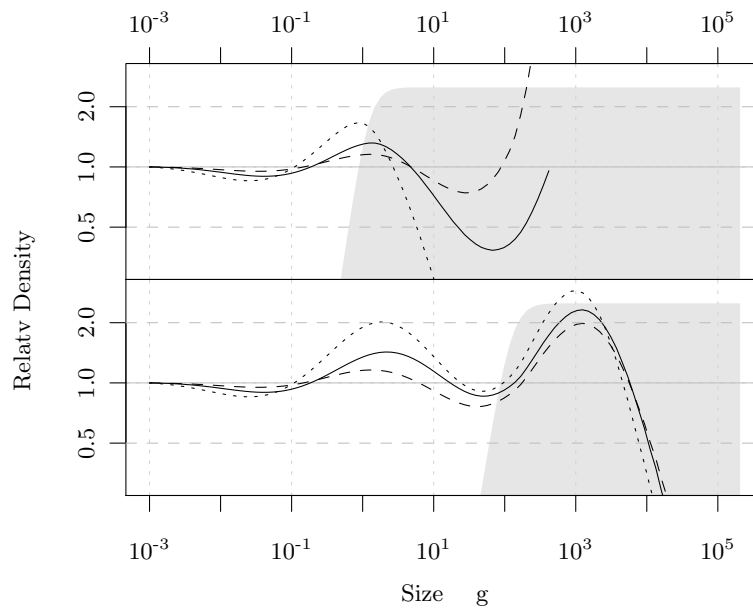


Figure 6: Abundance of fish as a function of individual size (both axes logarithmic) at the points A-C in Figs. 4 and 5; A is dotted, B is solid, and C is dashed. The abundance of forage fish (top) and large fish (bottom) is scaled relative to the unfished situation. The grey regions illustrate each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

⁵If $g(k, \dot{k})$ 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)

⁶Authors 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 € ton^{-1} with fishing mortality as the control to 34 € ton^{-1} with effort
544 as the control to 100 € 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 γ_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 γ 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⁻¹,
679 $489 \cdot 10^3$ ton year⁻¹) 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.

683 **Acknowledgement**

684 The research leading to these results has received funding from the Euro-
685 pean Community's Seventh Framework Program through the FACTS project.

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