Does size matter? A bioeconomic perspective on optimal harvesting when price is size-dependent

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Abstract

Body size is a key parameter influencing demographic characteristics of fish populations as well as market value of landed catch. Yet in bioeconomic modelling body size is often an overlooked biological and economic parameter. Here we evaluate how size-dependent pricing influences optimal harvest strategies in a model parameterized for two pelagic fisheries, those targeting Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus*) in Norway. In our model, positively size-dependent pricing clearly shifts optimal harvest strategies towards lower harvest rates and higher mean body size of caught fish. The results are relatively insensitive to biological (e.g., natural mortality) and economic details of the model (e.g., discount rate or demand function). These findings show that size-dependent pricing influences optimal harvest strategies aiming at maximum economic yield, and hence, require more attention in resource economics and in fisheries management.

Keywords: Bioeconomic modelling, fisheries management, optimal harvest strategies, size-dependent pricing

Introduction

It is common that price of fish depends on their size; typically, large individuals fetch a higher price per kilogram than small individuals of the same species. When present, such size dependence should be considered when evaluating harvest strategies (Hilborn and Walters 1992). While size-dependent pricing is occasionally included in bioeconomic models, it is very rare that the consequences of size-dependent pricing per se have been studied in any detail. We are aware of only few studies where this question has been touched: Gallagher et al. (2004) and Holland et al. (2005) showed that for Oregon ocean shrimp (*Pandalus jordani*) and rock lobster (*Jasus edwardsii*), respectively, size-related pricing indeed influences management strategies. Similarly, Tahvonen (2009) demonstrated in a generic age-structured model how equilibrium revenue and stock size are affected by size-dependent pricing. More typically, size-dependent pricing has been either overlooked, acknowledged but not analyzed (Anderson 1989), or taken as an extrinsically determined model component that is kept fixed in the analysis (e.g., Thunberg et al. 1998, De Leo and Gatto 2001, Katsukawa 2005). Some studies also acknowledge other biological factors influencing price, e.g., seasonal changes in fish quality (Larkin and Sylvia 1999). Size-dependent pricing is also important in aquaculture (Bjørndal 1988, Asche and Guttormsen 2001). Thus, we have all reasons to expect that the size dependency of the price is widespread and highly relevant for optimal utilization of fish stocks.

Here our aim is to quantify how size-dependent pricing influences optimal harvest strategies. We use Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus*) as case studies. Specifically, we focus on the Norwegian spring spawning herring stock and the Northeast Atlantic mackerel stock, following the stock definitions used in the management (ICES 2010). Herring and mackerel are of major importance for the fisheries of

24 several European countries, with a total catch of respectively about 1.7 and 0.7 million tonnes in

25 2009 (ICES 2010). Moreover, herring and mackerel are key species in the northeast Atlantic

26 pelagic ecosystem (Skjoldal et al. 2004), making their sustainable management even more

27 important.

28   We utilize an age-structured, discrete-time population model with size-dependent

29 harvesting. Price data are based on Norwegian market data for herring and mackerel. For

30 simplicity we assume that the relationship between size and price is linear; this allows us to

31 smoothly vary the strength of size dependency, in contrast to the earlier studies that only

32 considered a limited set of fixed pricing scenarios (Gallagher et al. 2004, Holland et al. 2005)

33 The cost of harvesting is output-regulated and depends on yield. In the optimization the main

34 target is to maximize the net present value over a long time-scale with discount rates on an

35 efficient market level, while high discount factors are used to emulate an open-access situation.

36 We show how optimal fishing mortality and resulting mean individual weight in the catch

37 depends on the size dependency of pricing. We also estimate the shadow cost, i.e., the

38 opportunity costs for applying a suboptimal harvest regime and the lost margin of benefit due to

39 ignoring the size dependency of pricing.

Methods

Biological model

42   The biological model is based on an age-structured population dynamics model with

43 annual time steps. Sexes are combined because male and female life histories are similar in

44 herring and mackerel. The parameters and their values are listed in Table A1 (Appendix).

45   There are n discrete age classes denoted by N_a with $a = 1,2,..,n$, and there is no

46   senescence. The last age class is so-called plus-group representing all fish n years of age or

47   older. Population dynamics is then described by

48

49
$$N_a(t+1) = \begin{cases} r(SSB(t)) & a = 1 \\ s_a N_{a-1}(t) & \text{if} \quad 1 < a < n, \\ s_n(N_{a-1}(t) + N_a(t)) & a = n \end{cases}$$

50

51   where SSB is the spawning stock biomass, $r(SSB)$ the stock-recruitment function and s_a is age-

52   specific survival probability defined below.

53   The connection between age and size is defined through the von Bertalanffy growth

54   model $l(a) = L_\infty \left(1 - e^{-ka}\right)$ where L_∞ is the asymptotic length and k the growth coefficient.

55   Furthermore, we assume an allometric weight-length relationship $w(l) = vl^u$, where v is the

56   length-weight coefficient and u is the allometric exponent.

57   Reaching maturity is based on the age of the individual and defined by the age-maturity

58   ogive $o(a) = \left(1 + e^{-(a - a_{50})/a_{width}}\right)^{-1}$ with a_{50} is the age where 50% of the individuals have reached

59   maturity and a_{width} is the coefficient describing width of the maturity envelope. Mature

60   individuals constitute the spawning stock, and spawning stock biomass is defined as

61      $SSB = \sum_a w_a o_a N_a(t)$. For herring recruitment follows the Beverton-Holt stock-recruitment

62   model as defined by (Fiksen and Slotte 2002), $r(SSB) = \dfrac{b_1 SSB}{b_2 + SSB}$, where b_1 is asymptotic

63   maximum recruitment and b_2 determines how fast the asymptote is approached. For mackerel

64   we use the hockey-stick recruitment model estimated by ICES (2010) implying that below a

65   threshold SSB_{max} recruitment is a linear, increasing function of SSB, $r(SSB) = b_3 SSB$, whereas

66   above the threshold recruitment is assumed to be constant, $r(SSB) = r_{max}$.

67   The fishing mortality is assumed to be length-dependent. Catchability usually increases

68   with size until levelling off at some intermediate size, a relationship usually described by a

69   sigmoid curve. However, in our study stocks, no such levelling-off can be detected between

70   fishing mortality (mean fishing mortality at age from 1984–2009; ICES 2010) and length-at-age

71   (from the growth model described above): for mackerel, the three-parameter sigmoid model fails

72   to converge, whereas for herring the inflection point in the resulting fit is far outside the range of

73   observed lengths. Within the range of observed lengths, a two-parameter power function and the

74   sigmoid function predict similar fishing mortalities for mackerel, but the power function gives a

75   lower AIC (difference 2.0) than the sigmoid function. The relationship between fishing mortality

76   and length is therefore most parsimoniously described as a power function for both stocks. Here

77   we normalize length relative to mean catch length $\bar{l}$, such that

78

79          $F_a = F(l(a)) = F_0 (l / \bar{l})^{\eta}$,   (1)

80

81   where F_0 is fishing mortality at mean catch length and η is a selectivity parameter that

82   determines the strength of length dependency; the function is convex for $\eta > 1$. The equation

83   was fitted to fishing mortality at age data from (ICES 2010), transforming age into length using

84   the von Bertalanffy model described above. Mean catch length $\bar{l}$ used in the normalization was

85   estimated through back calculation of mean catch weight based on weight at age in the ICES

86   catch from 2009 (ICES 2010).

87   The natural mortality M is based on the values used in the stock assessment (ICES

88   2010). The survival probability s is determined by the total mortality Z, which is the sum of

89   fishing mortality F and natural mortality M : $s_a = e^{-Z_a} = e^{-(F_a + M_a)}$

90   The link between the biological and economic part of the model is the catch equation,

91   $H_a = N_a\left(1 - e^{-Z_a}\right)F_a/Z_a$, where H_a is catch numbers at age. Total catch in terms of biomass, or

92   yield, is catch numbers times the mean age-specific individual weight, $Y = \sum_a H_a w_a$.

93   **Economics**

94   We assume that the relationship between size and price can be expressed as a simple

95   linear function of weight, such that we can easily change the strength of size dependence. To

96   make the parameters easily interpretable, we standardize weight relative to the mean observed

97   individual catch weight over all age classes, $\overline{w}$. Furthermore, we standardize the price-weight

98   coefficient   relative   to   the   observed   coefficient, β_0.   The   price   function   is   then

99   $p(w) = p_{\overline{w}} + \beta\beta_0(\dfrac{w - \overline{w}}{\overline{w}})$, where the intercept $p_{\overline{w}}$ is the price per unit biomass for $\overline{w}$, the

100 observed slope β_0 gives the price increase when individual weight is increased by $\overline{w}$, and β is

101 the relative deviation from the observed slope. $\overline{w}$ thus acts as the pivot point in this function.

102 The parameters $p_{\overline{w}}$ and β_0 of the price function (Figure 1) were estimated with linear

103 regression using data provided by the Norwegian Fisheries Directorate (Per Sandberg, personal

104 communication). The data comprise of annual average prices per weight class in 2000–2010. To

105 obtain mean weight for each weight class, we assumed that weight at age in the catch is

106 normally distributed with mean taken from ICES (2010) and coefficient of variation of 30%. We

107 then multiplied the age-specific weight distributions with catch numbers at age (ICES 2010) to

108   obtain total weight distribution in a given year, which allows estimating the mean weight for a

109   certain weight class as well as the overall mean weight $\overline{w}$. Mean price $p_{\overline{w}}$ was derived from

110   the data from the Norwegian Fisheries Directorate.

111   We also considered constraining the influence of size on price. As the minimum price we

112   used the minimum price set by the Norwegian pelagic fish sales organisation, which was 0.60

113   NOK•kg^{-1} for both herring and mackerel in 2010 (Norges Sildesalgslaget 2010). As the

114   maximum we used the highest mean price in 2010, which was 4.16 NOK•kg^{-1} for herring and

115   11.7 NOK•kg^{-1} for mackerel.

116   The total revenue is the sum of the annual yield times the weight-dependent price for

117   each age class, $R_t = \sum_a p(w_a)Y_a$. The cost function is derived from the model of Touzeau et al.

118   (2000). To avoid potential complications due to the nonlinearity of this cost curve, a simplified

119   cost function with a linear relationship between yield and cost based on a linear regression of the

120   cost function of Touzeau et al. (2000), $C_t = C_0 + \upsilon Y_t$, has been used. Here the intercept C_0

121   represents fixed costs and the term υY_t variable costs. The net revenue is then $\Pi_t = R_t - C_t$.

122   With d denoting discount rate, the net present value is the sum of annual discounted net

123   revenues:

124

125          $$NPV = \sum_0^t \frac{\Pi_t}{(1+d)^t}.$$

126

127   We tested a demand function estimated from Norwegian yield and price data in 2000–

128   2009. However, the resulting fit was poor because the lack of information about willingness to

129   pay outside the narrow range of actual production volumes and because of other factors

130   influencing the price. Sensitivity analysis showed no significant influence on the results, and

131   therefore demand effects were not considered further in this study. However, because of this,

132   and the simple cost function used, we emphasize that we do not expect the model to give precise

133   quantitative predictions, even though the results shown are qualitatively robust.

134   **Simulations**

135   The model was run over 1000 years, an essentially infinite time horizon unless discount

136   rate is very low ($d < 0.01$). The first 200 years were used to establish pre-fishing equilibrium.

137   Fishing started from the virgin stock at year 200, causing the stock to decline towards a new

138   equilibrium.. It is assumed that size selectivity of the fisheries is fixed, but that the managers can

139   adjust the overall level of fishing mortality such that net present value (NPV) of the stock is

140   maximized. Harvest strategies in our model are therefore defined through the parameter F_0,

141   fishing mortality at mean catch length. The optimal F_0 was identified using the function

142   "optimize" in R (R Development Core Team 2010).

143   **Results**

144   The effect of size-dependent pricing is to shift harvest maximizing net present value

145   (NPV) towards lower values (Figure 2). Comparing the harvest strategy optimized for size

146   dependency of the current pricing regime and one without any size dependency, the shadow cost

147   of omitting the size dependency in the current pricing regime is found to be about 3.1% for

148   herring and 3.8% for mackerel relative to the optimal NPV (discount rate $d = 0.05$). Shadow

149   costs define here the difference in NPV between the optimal harvest strategy with the current,

150   size-dependent price regime and the one that would be optimal when we assume no size-

151   dependent pricing, i.e., the opportunity cost of ignoring size dependency in price.

152   With increasing effect of size on price (increasing β), the mean fishing mortality that

153   maximizes NPV decreases and the corresponding mean individual size increases (Figure 3); for

154   herring the effect is almost linear within the considered range whereas for mackerel the effect is

155   levelling off for strong size dependence. Mean fishing mortalities (age groups 4-8 for mackerel

156   and 5-14 weighted by stock numbers for herring) yielding maximum NPV (with discount rate

157    $d = 0.05$) are 0.146 year^{-1} in the current pricing regime ($\beta = 1$) compared to 0.189 year^{-1}

158   without size-dependent pricing for herring and 0.242 year^{-1} compared to 0.357 year^{-1} for

159   mackerel. For reference, the latest stock assessments estimated fishing mortalities at 0.154 year^{-1}

160   for herring and 0.233 year^{-1} for mackerel (ICES 2010). In our model, the decrease in mean

161   fishing mortality between no size dependency and a realistic size-dependent pricing is about

162   23% for herring and 32% for mackerel, and the mean catch weight increases by about 6% and

163   8%, respectively. The patterns remain similar if the initial stock states are changed from the

164   pristine levels to lower population abundances estimated in the latest stock assessments (ICES

165   2010).

166   The discount rate has no influence on the qualitative effect that size-dependent pricing

167   has on optimal fishing mortality and the corresponding mean size (Figure 3), even when very

168   high discount rates emulating an open-access situation are considered (Figure 4). Nevertheless,

169   the discount rate has a considerable quantitative effect on the optimal fishing mortality: the

170   optimal value increases almost threefold between the extreme cases of no discounting and a very

171   high discount rate of one, mimicking an open-access situation. As theory suggests, the biggest

172   effect on optimal fishing mortality is found on low to intermediate discounting levels.

173   Because natural mortality is an important parameter in age-structured models, we

174   investigate its influence further. For both species, changing natural mortality results in changes

175   in optimal fishing mortality and, to somewhat lesser extent, in the resulting mean catch weight

176   (Figure 5). These changes are opposite for the two species: higher natural mortality leads to

177   higher optimal fishing mortality for mackerel but lower optimal fishing mortality for herring;

178   these effects are slightly more pronounced for low β: an increasing β tends to dampen the

179   influence of changing natural mortality. The qualitative difference between the species is caused

180   by the age-dependent natural mortality in herring: assuming a constant natural mortality for

181   herring leads to mackerel-like results. For catch weights, the influence of changing natural

182   mortality is qualitatively the same for both species: mean catch weight is increased (decreased)

183   by higher (lower) natural mortality.

184   Comparing the continuous price function with the empirical step functions either in 2009

185   or 2010 given in Figure 1 shows that the differences are negligible: optimization with discrete

186   price classes displays the same shift between constant price and size dependency and similar

187   quantitative results. The same applies when applying minimum and/or maximum price caps.

188   Additionally, optimal fishing mortality depends on the selectivity parameter η, but the effect is

189   negligible (mackerel) or does not influence the qualitative pattern (herring) (Figure 6).

190   **Discussion**

191   The size of fish is a key parameter from biological as well as technical and economic

192   perspectives. In terms of biology, size is closely linked with growth, maturation, reproductive

193   output and survival. Avoidance of growth overfishing — catching fish too small, before a cohort

194   has realized its growth potential — has been a crucial part of fisheries management since

195   Beverton and Holt (1957). Using minimum size restrictions and mesh size regulations as

196   management tools to protect the productivity of a fish stock reflects this idea. Likewise, the

197   fishing industry has a strong interest in fish size both to optimize the industrial utilization and to

198 serve consumer preferences. Ultimately, these market incentives are a key driver for size-

199 dependent pricing. Yet the connection between price and body size is an understudied issue in

200 fisheries economics. This is surprising given that size-dependent pricing is ubiquitous and that

201 its role in rational harvest management has in theory been acknowledged for a long time

202 (Hilborn and Walters 1992). While a number of studies on capture fisheries have included size-

203 dependent pricing, the majority of these have only considered a single scenario, without

204 studying the effects of size-dependent pricing per se (e.g., Helser et al. 1996, Thunberg et al

205 1998, Katsukawa 2005). A few studies have included a small number of alternative size-

206 dependent pricing scenarios when analysing specific fisheries (Gallagher et al. 2005, Holland et

207 al. 2005). There are also a few generic models that have included size-dependent pricing

208 (Anderson 1989, Tahvonen 2009). While Anderson (1989) did not elaborate on the importance

209 of size-dependent pricing, Tahvonen (2009) showed with a concrete example how positively (or

210 negatively) size-dependent pricing leads to equilibrium revenues to be maximized at a higher

211 (respectively lower) stock biomass level. The topic has also been discussed outside fisheries

212 economics. For example, price of fish produced in aquaculture is size-dependent, and this has

213 consequences for optimizing the production cycle (Bjørndal 1988, Asche and Guttormsen 2001).

214   Our goal here was to demonstrate the importance of size-dependent pricing for

215 economically optimal harvest strategies using simple age-structured models parameterized for

216 two important pelagic fish stocks. The results confirm our expectations: fishing pressure

217 maximizing economic yield in terms of revenue and net present value depends on the applied

218 size-based pricing regime, with implications for mean size of fish in the catches and equilibrium

219 stock abundance. The results reveal potential for overestimation of future profits and rent

220 dissipation due to the application of suboptimal harvest strategies when ignoring size-dependent

221 pricing; the effect in the examples studied here is nevertheless quantitatively modest. However,

222 the effect on the resultant harvest strategy is appreciable. Considering that in most commercially

223 important fish stocks the price is size-dependent, the insights presented here call for broader

224 utilization of size-dependent pricing in economic modelling.

225 When the size-price relationship is monotonic and positive, maximum economic yields

226 are obtained through higher stock sizes and smaller catches than when such size dependence is

227 absent. In other words, positive size–price relationships imply that lower fishing mortalities

228 optimize the net present value. It is acknowledged that catches below MSY typically maximize

229 the resource rent (Clark 2006, Grafton et al. 2007, Tietenberg and Lewis 2008). Our results

230 suggest that this effect might even be stronger than MEY estimates ignoring size-dependent

231 pricing would suggest. Therefore, taking positively size-dependent pricing into account would

232 result in lower harvest rates, which would not only ultimately increase society's direct economic

233 benefits from fisheries, but also reduce the negative effects fisheries might have on the

234 ecosystems. This is in accord with the precautionary approach to fisheries management, calling

235 for more conservative harvest policies that lead to an increased overall stock abundance. This

236 would enhance population resilience, harvest productivity and efficiency.

237 Our results resonate with the calls to save the big fish for the sake of improved biological

238 sustainability (Birkeland and Dayton 2005, Francis et al. 2007, Diekert et al. 2010). This

239 statement may seem counterintuitive since we emphasize the high market value of large-sized

240 fish. However, we have focused on a single-owner fishery where the manager adopts a long time

241 perspective, avoiding the short-sighted temptation of targeting the large fish. In our model the

242 opportunity cost of choosing a suboptimal harvest strategy can only be mitigated by reducing the

243 overall fishing mortality, therefore allowing more fish to reach large sizes, and ultimately,

244 leaving more big fish in the sea.

245   We emphasize that in general, mesh size regulations and other means of modifying size-

246   dependent catchability can be important levers of optimizing the harvest, even though we did not

247   consider them here. Our model applies to pelagic fisheries where effective regulation of size-

248   dependent catchability is difficult; gears like purse seines are weakly size-selective, and pelagic

249   fish have low survival after slipping through meshes or being strangled in a net. However,

250   demersal fish are often more robust and have better chances of surviving if slipping through

251   meshes or sorting grids, or discarded after the capture. Mesh size regulations can therefore be a

252   means to ensure that enough fish have chance to grow to most valuable size classes. In such

253   cases, economic implications of considering size-dependent pricing are likely larger than what

254   we have found for herring and mackerel here.

255   We have used the simplest possible price function, a linear relationship between price

256   and weight, as the default price function. While this is a good approximation for herring and

257   mackerel, more complex relationships occur in some fisheries (Thunberg et al. 1998). There is

258   also some evidence that the price premium for larger size disappears for very large mackerel

259   (Fig. 1), a situation which may not be uncommon if very large fish have lower flesh quality,

260   higher concentrations of contaminants, or are less suited for industrial processing. Similarly, if

261   small-sized fish are destined to fish meal production instead of human consumption, their

262   precise size may become unimportant. We therefore also tried constraining the price between

263   certain minimum and/or maximum levels, but this did not change the results in any essential

264   way (the bulk of the harvest comes from medium-sized fish). Additionally, our price function

265   implies continuously increasing effect of size on price, whereas real markets commonly operate

266   with discrete weight classes. While using the real weight classes should give more precise

267   results, our simulations suggest that a linear function is a good approximation. Moreover, market

268 weight classes often vary over time and space. For these reasons we consider a linear

269 approximation as justified here.

270   Our study has several general limitations. We rely on a single species approach and focus

271 in the steady state scenario without environmental oscillations. Size structure in the model is

272 determined by the age structure using a static age-length relationship. In reality, size structure of

273 the harvestable stock is determined by intra- and inter-specific interactions (availability of

274 resources, and presence of predators). In particular, density-dependent body growth (e.g.,

275 Lorenzen and Enberg 2002) might counter the increase in average size that is expected to occur

276 when fishing is reduced and therefore influence management strategies (Helser and Brodziak

277 1998). A significant source of uncertainty is natural mortality. This is modelled as constant

278 (mackerel) or age-dependent (herring); both assumptions are crude approximations of reality but

279 unfortunately data for more realistic choices are not available. Also our economic model is

280 rather simplistic, apart from inclusion of size-dependent price. We assume a simple yield-

281 determined cost function, and absence of market feedbacks on price. Our initial explorations

282 suggested that considering effort-dependent costs or demand curves is not important for the

283 questions addressed here. Moreover, developing a more detailed bioeconomic model for

284 mackerel would have been a major task on its own, whereas for herring, more detailed

285 information exists (e.g., Touzeau et al. 2000, Sandberg 2006). Finally, the model does not

286 account for practical challenges in balancing stakeholder interests nor policy implementation

287 and enforcement; in reality, suboptimal management due to political and social pressures and

288 illegal fishing are more a rule than an exception (Beddington et al. 2007, Agnew et al. 2009,

289 Mora et al. 2009).

290   Another angle worth discussing is that of fisheries-induced adaptive changes. Statistical,

291 experimental and modelling approaches are giving increasing support to the hypothesis that

292 fishing causes evolutionary shifts in life-history traits (Jørgensen et al. 2007, Dunlop et al. 2009,

293 Sharpe and Hendry 2009). Because these changes typically involve reduced adult body size

294 (Heino 1998, Enberg et al. 2011), size-dependent pricing is relevant also when trying to estimate

295 the possible economic impacts of fisheries-induced evolution.

296   To conclude, this study has highlighted that size-dependent pricing has important

297 implications for fisheries management. Because markets usually value large fish more than

298 small fish, harvest strategies should consider how the harvest influences size structure of the

299 catch: the higher the harvest pressure, the lower the mean size of fish. Therefore, harvest

300 policies that aim at maintaining harvest of large-sized fish lead to lower harvest levels than those

301 that ignore the quality of the catch; ultimately, this might lead to more sustainable harvest and

302 increased economic benefits from the fisheries. We encourage further explorations into

303 consequences of size-dependent pricing on fisheries management, both in the direction of further

304 generalizations and towards more detailed studies on specific fish stocks and fisheries.

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Appendix

Table A1: List of parameters and their values.

Parameters	Definition	Units	Values	
			Herring	**Mackerel**
n	maximum age class[2]	year	15	12
M_a	natural mortality[2]	year^{-1}	$\begin{cases} 0.9 \\ 0.15 \text{ for } a = \begin{cases} a \le 2 \\ 2 < a < \\ n \end{cases} \\ 0.5 \end{cases}$	0.15
b_1	asymptotic recruitment[1]	-	$1.9 \bullet 10^{11}$	

b_2	steepness of recruitment function[1]	kg	$5.1 \cdot 10^9$	
b_3	initial slope of recruitment function[2]	kg^{-1}		1.811
r_{max}	maximum recruitment[2]	-		$4.252 \cdot 10^9$
L_∞	asymptotic length[3]	mm	370	418
k	von Bertalanffy growth parameter[3]	$year^{-1}$	0.26	0.43
v	length-weight coefficient[3]	$kg \bullet mm^{-u}$	$2.32 \cdot 10^{-5}$	$3.4 \cdot 10^{-3}$
u	length-weigh exponent	-	2.81	3.24
a_{50}	age at 50% maturity[2]	year	4	3
a_{width}	width of maturity envelope	year	0.2	0.2
η	selectivity parameter[2]	-	4.3	3.3
β_0	price function slope[4]	$NOK \bullet kg^{-1}$	2.47	8.65
$\overline{w}$	mean catch weight[2, 4]	kg	0.295	0.462
C_0	fixed costs[5]	NOK	$3.4 \cdot 10^5$	$3.4 \cdot 10^5$
υ	cost function slope[6]	$NOK \bullet kg^{-1}$	0.7	0.83

[1](Fiksen and Slotte 2002)

[2](ICES 2010)

[3](Jennings and Beverton 1991)

[4](Norwegian Directorate of Fisheries, direct communication)

[5](Touzeau et al. 2000)

[6](Froese and Pauly 2009)

Figure 1: Linear weight-price functions (solid lines) estimated from real price data (dots) and step functions based on price per weight categories for herring (a, c) and mackerel (b, d). The actual price slopes β_0 are 2.43 (herring) and 8.97 NOK•kg^{-1} (mackerel). For reference, also the case with constant price ($\beta = 0$; grey line) is shown. The pivot point of these lines corresponds to the observed mean individual catch weight, $\overline{w}$ (dotted line), and price per kilogram for this weight, $p_{\overline{w}}$. The price data are annual mean prices per weight class from Norwegian spring-spawning herring and Northeast Atlantic mackerel in 2000–2010 provided by the Norwegian Fisheries Directorate (Per Sandberg, personal communication). We use annual catch weight distributions (ICES 2010) to transform weight classes into mean weight of each weight class (a, b). Step functions (c, d) represent prices per weight class in 2009 (dashed line) and 2010 (solid line).

Figure 2: Net present value (NPV) for herring (a) and mackerel (b) fisheries as a function of harvest proportion under the current pricing regime (solid line), no size-dependent pricing ($\beta = 0$; short dashed line) and a twofold price slope ($\beta = 2$; long dashed line). The distance between vertical grey lines illustrates the difference in the NPV-maximizing harvest strategies in the presence and absence of size-dependent pricing. Discount rate $d = 0.05$. Harvest proportion is calculated from the mean fishing mortality over reference ages as defined by ICES (ages 5–14 years for herring, 4–8 years for mackerel; ICES 2010).

Figure 3: The influence of relative price slope β on optimal fishing mortality (black) and the resulting mean individual weight (grey) in the catch of herring (a) and mackerel (b) with respect to different discount rates d. Discount rate takes values $d = 0.05 \pm 0.05$ ($d = 0$ dashed, $d = 0.1$ dotted line). Optimal strategy is the one maximizing the net present value of a pristine stock. Strength of size dependence of price is expressed as the relative price slope

β, with $\beta = 1$ corresponding to the current price dependence shown in Figure 1 and $\beta = 0$ to no price dependence. Fishing mortality is the mean fishing mortality over reference ages as defined by ICES (ages 5–14 years weighted by stock numbers for herring, 4–8 years for mackerel; ICES 2010).

Figure 4: Mean fishing mortality optimized for net present value in herring (a) and mackerel (b) fisheries under the assumptions of discount rates between 0 and 1. The continuous line shows results for the real size dependence of pricing. The envelope with dashed lines shows the case of no size dependency (short dashed) and doubled slope (long dashed). Optimal strategy is the one maximizing the net present value of a pristine stock. Fishing mortality is the mean fishing mortality over reference ages as defined by ICES (ages 5–14 years weighted by stock numbers for herring, 4–8 years for mackerel; ICES 2010).

Figure 5: Mean fishing mortality (black) that maximizes NPV in herring (a) and mackerel (b) fisheries and the corresponding mean catch weight (grey) as functions of the relative price slope. The lines represent the default natural mortality M_a (solid) and M_a decreased (long dashed) or increased (short dashed) by 20%. The discount rate is $d = 0.05$. Optimal strategy is the one maximizing the net present value of a pristine stock. Strength of size dependence of price is expressed as the relative price slope β, with $\beta = 1$ corresponding to the current price dependence shown in Figure 1 and $\beta = 0$ to no price dependence. Fishing mortality is the mean fishing mortality over reference ages as defined by ICES (ages 5–14 years weighted by stock numbers for herring, 4–8 years for mackerel; ICES 2010).

Figure 6: Mean fishing mortality (black) optimized for NPV in herring (a) and mackerel (b) fisheries and the corresponding mean catch weight (grey) as functions of the relative price slope. The lines represent the default selectivity parameter η (solid line) and η decreased

(long dashed line) or increased (short dashed line) by 20%. The discount rate is $d = 0.05$.

Optimal strategy is the one maximizing the net present value of a pristine stock. Strength of

size dependence of price is expressed as the relative price slope β, with $\beta = 1$

corresponding to the current price dependence shown in Figure 1 and $\beta = 0$ to no price

dependence. Fishing mortality is the mean fishing mortality over reference ages as defined

by ICES (ages 5–14 years weighted by stock numbers for herring, 4–8 years for mackerel;
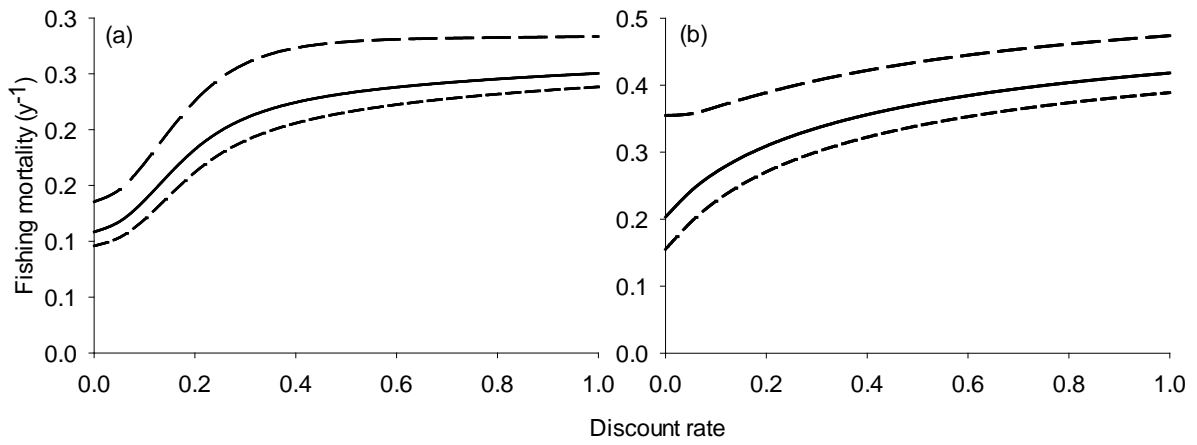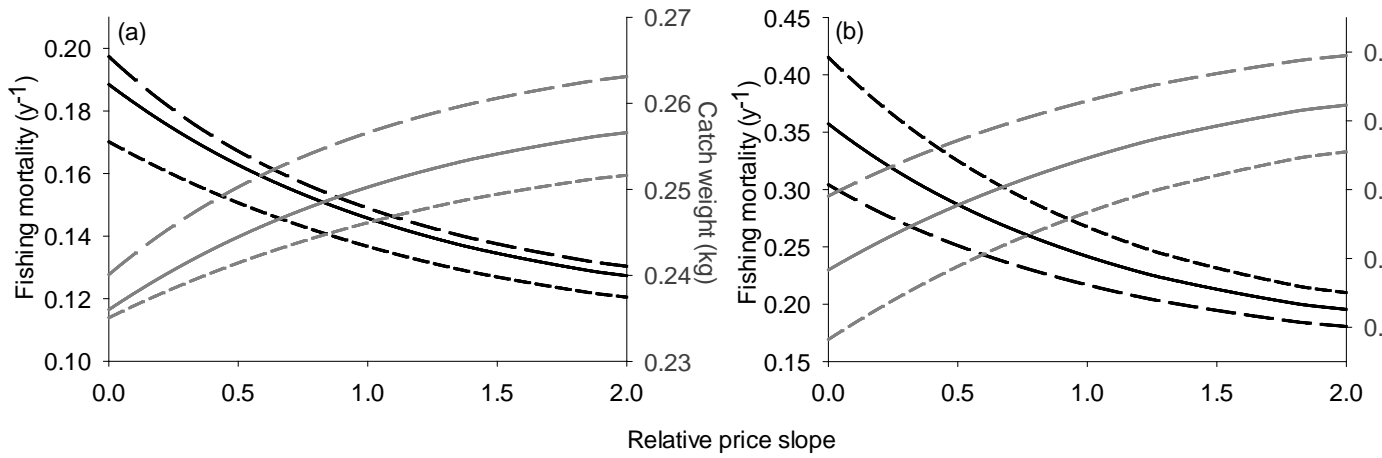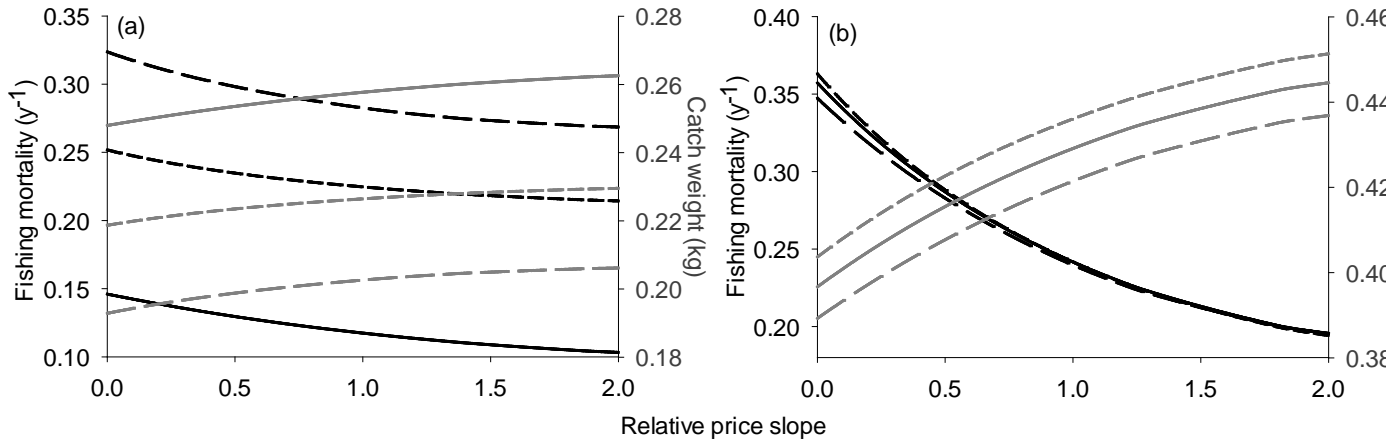
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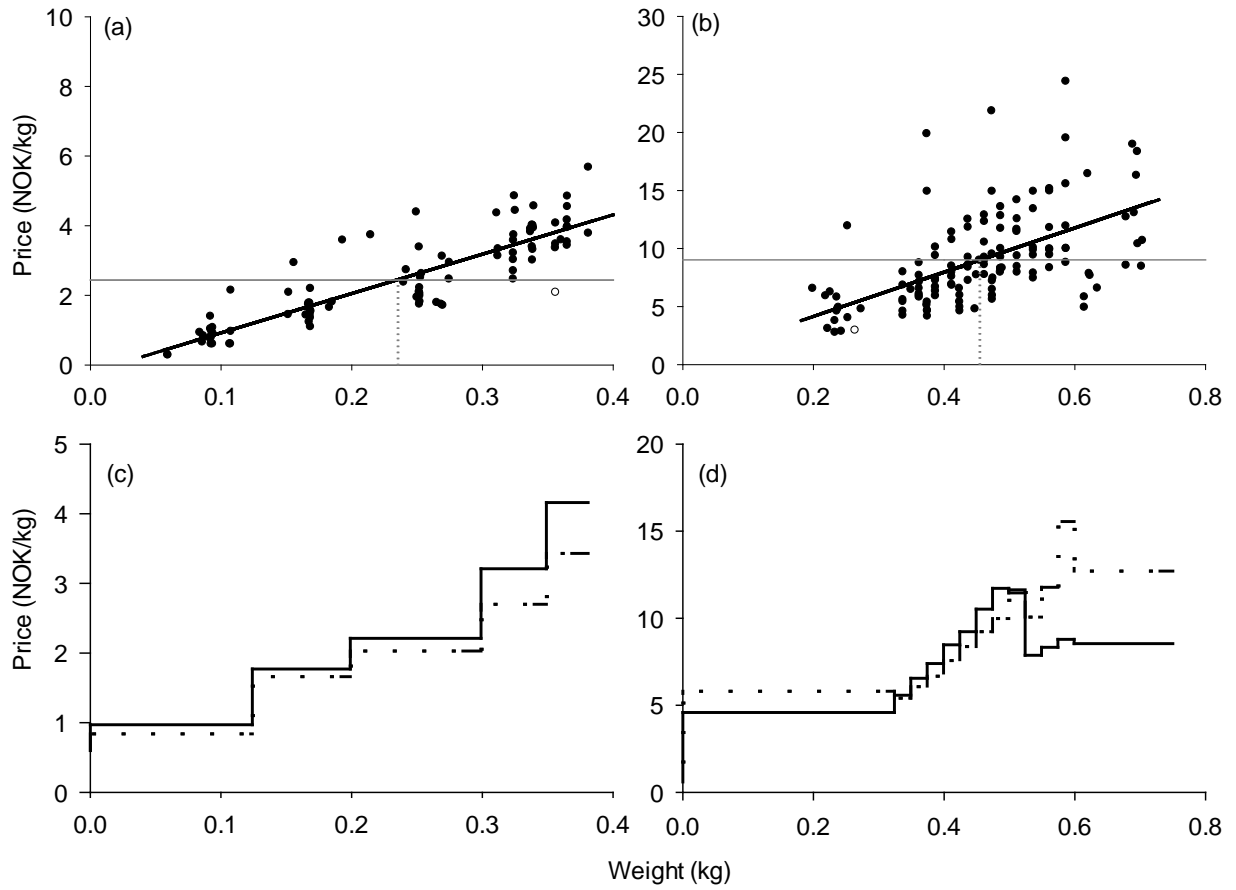
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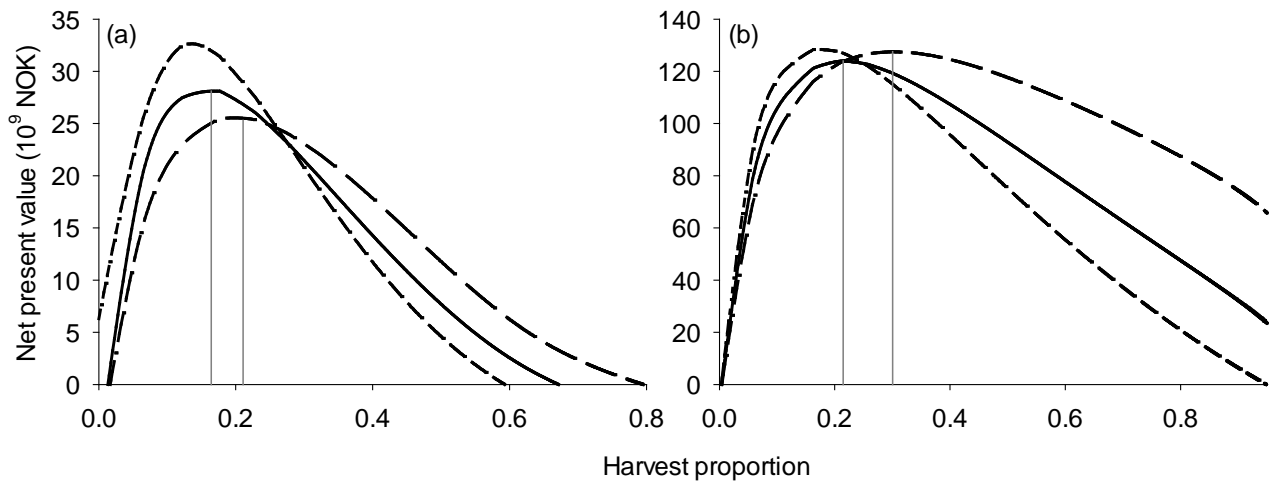
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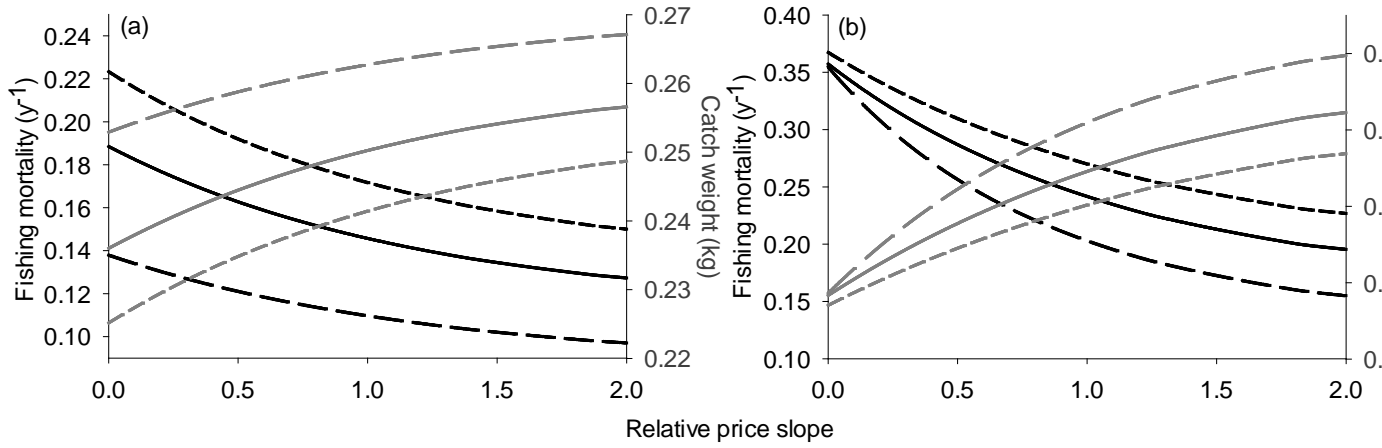
Figure 3

Figure 4

Figure 5

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Figure 6