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## Ecological and economic consequences of different recovery scenarios of depleted stocks

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### Abstract

There is an increasing trend in the percentage of fish stocks throughout the world that are overexploited, depleted or recovering and for which effective recovery plans are required. This paper develops an ecological-economic evaluation tool to explore the impact of the choice of a recovery scenario on the time needed to recover the stock and on the net benefit generated by the fishery during the recovery period and beyond. This is done by merging a classical age-structured model for a single-species population with an economic cost-evaluation framework. Recovery scenarios for two stocks with a large and a small asymptotic body size are evaluated and compared. The economic results indicate that the difference between choosing one recovery scenario over the other is limited. It has been shown that the largest and oldest females of a stock (the big-old fish) have a higher reproductive success than smaller and younger females, and therefore a recovery plan may have to pay particular attention to these big-old individuals. The big-old fish does not matter much neither from an economic nor from an ecological perspective. Only if there is a high fishing pressure during the recovery period can a saving of the big-old fish reduce recovery time significantly.

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The United Nations Food and Agriculture Organization (FAO), which monitors the state of the world fisheries, has estimated that in 2008 more than one-quarter of marine fish stocks were either overexploited, depleted or recovering from depletion (28 %, 3 % and 1 % respectively). This is the lowest percentage recorded since the mid-1970s. While reviews of a range of worldwide recovery plans (Caddy and Agnew, 2004; Wiedenmann and Mangel, 2006) show examples of stocks recovery from overfishing (Richards and Rago,

1999; Pipitone et al., 2000; Terceiro, 2002; Hart, 2003), there are many other examples of slow or unsuccessful stock recovery, even with substantial reductions in fishing mortality (Polachek, 1990; Hutchings and Myers, 1994; Tegner et al., 1996; Shelton and Healey, 1999). Given the declining condition of fish stocks, there is no doubt that the current state of world fisheries gives cause for concern, therefore, effective recovery plans are required (Worm et al., 2009; Murawski, 2010).

Seen from a production perspective, the goal of fish-

eries management is to exploit the fished stock in a manner that maximizes the yield. In terms of fisheries reference points, this means that the fishing mortality should be the one that generates the maximum sustainable yield  $F_{MSY}$ . If a stock is in a depleted state ( $F > F_{MSY}$ ), then the question for management is to draw a plan which will achieve  $F_{MSY}$ . However, the success of a fishery management plan depends (at least) on two different requirements: achieving the economic objectives of the fishery and achieving the fisheries reference point. The successful recovery of a species depends on a multitude of different conditions: fishing effort, climatic conditions, changes in the ecosystem, bycatch from other fisheries, and changes in recruitment dynamics. The effect that can most readily be quantified is the direct effects of fishing on stock structure and recruitment. Calculations of the effect of a recovery plan only taking fishing into account therefore represents the most optimistic estimate of the impact of a recovery plan. Such a calculations should be used as a baseline for considerations of the other potential effects that may affect the recovery of a particular stock. The goal in this paper is to examine how different fishing patterns and pressures affect the recovery of a depleted fish stock to levels that can produce the maximum sustainable yield ( $MSY$ ) in the ecologically and economically most attractive fashion.

The time it takes to recover a depleted stock depends on two factors: the time to reach maturation and the speed at which the spawning stock biomass ( $SSB$ ) can be recovered to a level where recruitment is limited mainly by density-dependent effects. For a large and long-lived species (large asymptotic body size) the age at maturation is higher than for a small and short-lived species. Considering this effect only, the large species is expected to recover slower than a small species. On the other hand, a large species has a larger reproductive potential than a small species, even when the longer time to reach maturation is taken into account (Andersen et al., 2008; Andersen and Beyer, 2011). Considering reproduction only, it is therefore expected that a large species will recover its reproductive potential faster than the small species. These two effects (time to reach maturation and reproductive capacity) therefore vary in opposite directions for species with large and small asymptotic body size. An evaluation of the ecological consequences of a recovery plan therefore requires a quantitative analysis that weights the time to reach maturation against the reproductive potential of the mature individuals. The evaluation of a recov-

ery plan should take other factors than pure ecological factors into account. In particular the economical consequences may be assessed by a cost-benefit analysis. As a large species typically have a higher value per weight than a smaller species, the economical consequences will also depend on the body size of the stock in a systematic fashion. Hence, the question addressed here is: what are the ecological and economic consequences of different recovery plans for small and large species?

A stock that is exploited at high rates for a sufficient duration of time may enter a collapsed state in which its recruitment is limited by the biomass of spawners and their production of eggs. There have been several examples of collapsed states where the stocks have not rebuilt even in a complete closure of the fishery due to Allee effects (Hutchings and Reynolds, 2004). However, the case we are addressing here is a stock whose spawner biomass has been lowered such that it produces a lower yield from the fishery than it potentially could, but whose recruitment is not necessarily substantially limited by spawner biomass. We are therefore addressing a "recovery" of a "depleted" stock ( $SSB < 10\% SSB_{unfished}$ ) to produce maximal yield, in contrast to the "rebuilding" of a "collapsed" stock ( $SSB < 1\% SSB_{unfished}$ ) whose recruitment is limited by spawner biomass or egg production.

Several studies on fish stocks indicate that the big-old fish (the *Boff*) produce higher quantity of eggs and of higher quality in terms of survival than smaller and younger females (Hislop, 1988; Kjesbu et al., 1996; Trippel, 1998; Berkeley et al., 2004). Therefore, one would expect a lower recruitment per spawning stock biomass when the age structure of the spawners is skewed towards younger individuals. Age-structure and big-old fish appears, thus, to play a key role on both the recruitment success and sustainability of exploited fish populations. Moreover, the selective removal of the big-old fish probably contributes to the difficulty that some populations experience in recovery from overfishing (Birkeland and Dayton, 2005; Field et al., 2008). However, even though the big-old fish may produce better eggs, there are also much fewer of the big-old fish in the stock. There is therefore a need to make quantitative analyses which weight the higher quantity of the eggs of the big-old fish against the larger quantity of the small-younger fish to determine the importance of the big-old for the whole stock (Calduch-Verdiell et al., 2011). The issue that we would like to emphasize in this paper is the contribution of the big-old fish in a recovery plan.

To explore the impact of the choice of a recovery plan we use a size-based life history model for describing the demography of the fish stock (Calduch-Verdiell et al., 2011), and an economical cost-benefit analysis (CBA) to describe the long-term economic consequences of recovery. The ecological impact of the recovery plan is described by the time needed to recover the stock size to levels that can produce the  $MSY$ , and the economic impact is described by the net benefits generated by the fishery ( $NPV$ ) during the recovery period and beyond. We analyse three different recovery plans: (1) Fishery closure (i.e. instantaneous fishing mortality rate is zero); (2) Lowering fishing mortality ( $F \leq F_{MSY}$ ) but fishing only on intermediate sizes (i.e. saving the big-old fish); (3) Lowering fishing mortality ( $F \leq F_{MSY}$ ), but fishing all size groups. The model is general and uses life-history invariants to calculate stock structure and recruitment solely based on a characterization of a fish stock by the asymptotic size of individuals, which is available for most stocks. The analysis of this paper is on two theoretical stocks with life history traits typical of a large and long-lived species ( $W_\infty=20$  kg) and of a small and short-lived species ( $W_\infty=0.5$  kg).

## Model formulation

The ecological model used to evaluate the time to recover under different scenarios is a classical age-structured population model with a Beverton-Holt stock-recruitment relationship. The effective number of parameters in the model have been reduced using size-based scaling relationships and life-history invariants, such that the main parameter describing a certain stock is the asymptotic (maximum) body size  $W_\infty$ . The principles of the model is described in Calduch-Verdiell et al. (2011) and Andersen and Beyer (2011), so here the main principles are provided briefly, and the model equations and parameters are given in Table 1.

Growth is modeled by the von Bertalanffy growth equation relating weight  $w$  to age  $x$  (Fig. 1a). The spawning stock biomass, the total biomass of all sexually mature fish in the population, is  $\sum N_t(x)w(x)m(x)$ , where  $N_t(x)$  is the number of fish of age  $x$  at time  $t$ . Maturation at age  $m(x)$  is described by a sigmoid function with 50 % maturation at  $\eta_M W_\infty$ . Recruitment is assumed to take place once annually and supplies the first age class with recruits. Fig. 1b shows the yearly surviving eggs production as a function of asymptotic size. The natural mortality for an individual is a de-

clining function of size,  $\mu(w) \propto w^{-1/3}$ , which can be described in terms of the ratio between adult mortality  $M$  and the von Bertalanffy growth constant  $M/K$  as Andersen et al. (2009). The mortality for an individual because of fishing is described by a sigmoid function with inflection point at  $\eta_F W_\infty$ . The effect of reducing the fishing mortality on big-old fish is examined by lowering the fishing mortality to zero for  $w > \eta_{Boff} W_\infty$  (Fig. 1c,d). Fishery yield is determined by Baranov's catch equation (Baranov, 1918).

The ecological model is first iterated until the unfished population reaches a stable age distribution. Then, a depleted fishery is established by fishing until the spawning stock biomass is only 10 % of the  $SSB_{unfished}$ . Now, the depleted population under different scenarios has to return to safe biological levels (i.e. the  $SSB$  that can produce 95 %  $MSY$ ). We estimate the time to recover ( $TTR$ ) a depleted population, the changes in the  $SSB$  and the changes in the yield for 25-years period within three different recovery scenarios: (1) fishery closure, (2) lowering fishing mortality ( $F \leq F_{MSY}$ ); fishing only on intermediate sizes, (3) lowering fishing mortality ( $F \leq F_{MSY}$ ); fishing all size groups. Thereafter, the economic desirability of the recovery plan is evaluated by a Cost Benefit Analysis (CBA). The analysis quantifies the costs and benefits accumulated at different points in time by translating them into a common unit: the Net Present Value ( $NPV$ ) which is the net benefit generated by the fishery. The  $NPV$  for 25-years period is evaluated for the three recovery scenarios.

$$NPV = \sum_{t=1}^T \left( \frac{1}{1+\delta} \right)^t (Y(\rho - C_v(SSB_t)) - C_f), \quad (1)$$

where  $T=25$  years,  $\delta$  is the discount rate,  $\rho$  is the price per kg fish landed,  $C_v$  is the variable unit cost and  $C_f$  is the fixed cost.

We find the  $NPV$  by applying a discount rate ( $\delta$ ) of 2 % as recommended by Weitzman (2001) for projects with medium future life (e.g. 25 years). The price ( $\rho$ ) is size specific as larger fish receive a higher price. Here, we define two different prices, a low price for small fish ( $w < w_{Boff}$ ) and a double price for big-old fish ( $w \geq w_{Boff}$ ).

The variable unit cost ( $C_v$ ) is the cost of fishing and it is inversely related to the  $SSB$ . The strength of the stock size effect is different between species of schooling and non-schooling fish. For example, it is generally assumed that there is only a weak relationship

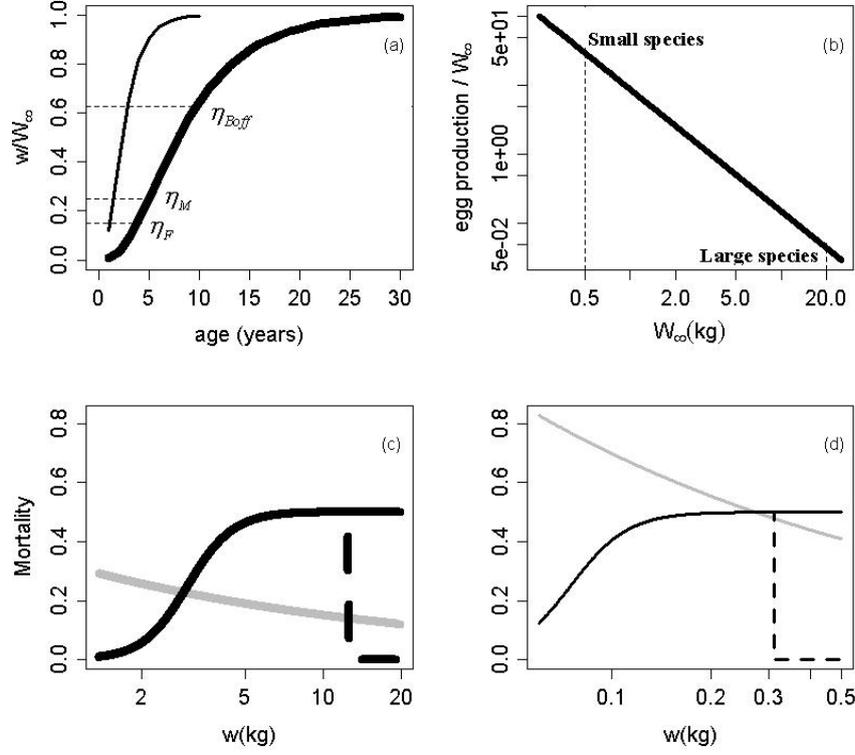


Figure 1: (a) von Bertalanffy growth curve, large and long-lived species ( $W_\infty=20$  kg ; thick lines) and small and short-lived species ( $W_\infty=0.5$  kg ; thin lines). (b) Production of eggs as a function of asymptotic size. The vertical lines are drawn at small and large species asymptotic sizes. (c) Mortality as a function of size for large and long-lived species and (d) mortality as a function of size for small and short-lived species. Grey lines are natural mortality, black lines are fishing mortality of  $0.5 \text{ yr}^{-1}$ , and dashed lines are the fishing mortality when big-old fish are not fished.

between  $SSB$  and variable unit cost in fisheries targeting schooling fish (Bjørndal, 1987, 1988). The reasoning behind this assumption is that because schooling fish concentrates in schools they are not uniformly distributed over an area. Once a fishing vessel has targeted a school, the catch during the harvest operation may be unaffected by the size of the fish stock. On the other hand, in non-schooling fishery the variable unit cost is assumed to be sensitive to the size of the exploited stock (Schaefer, 1957). Non-schooling fish are distributed over a wider area, if the stock size effect is present, vessels will spend less time to fill their nets when there is abundance of fish, or will return half empty in case of scarcity of fish. On the other hand, the variable unit cost does not depend on the  $SSB$  but on the stock that the fishing gear is seeing, that which

we call the potential  $SSB$  ( $SSB_{pot}$ ). When fishing is on all sizes  $SSB_{pot}=SSB$  but when introducing a selectivity in the upper end  $SSB_{pot} = \sum_{w=W_F}^{W_{Boff}} SSB(w)$ . The cost of fishing with the selective gear (i.e. saving the big-old fish) will therefore be larger.

$$C_v(SSB_{pot}) = aSSB_{pot}^{-b}, \quad (2)$$

where  $b=1$  for non-schooling, large and long-lived species and  $b=0.2$  for schooling, small and short-lived species. The unit variable cost will be the maximum when the  $SSB$  is the minimum, here we assume that  $C_v=0.9$  when the stock is depleted.

The annual fixed cost associated with all capital used in the fishery is assumed to be proportional to the fishery variable costs:

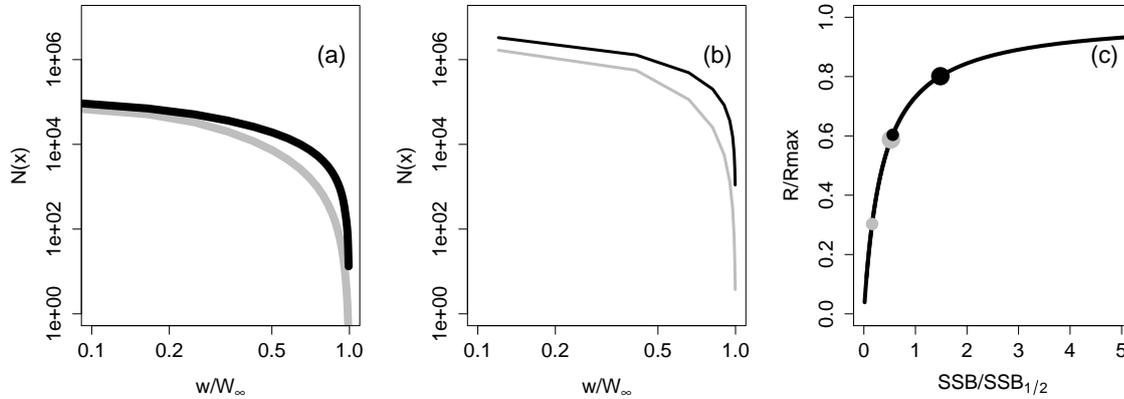


Figure 2: Stock structure for large and long-lived species ( $W_\infty=20$  kg; panel a) and for small and short-lived species ( $W_\infty=0.5$  kg; panel b). The spawning stock-recruit curve scaled by the maximum recruitment ( $R_{max}$ ) and by the value of the  $SSB$  where recruitment is half of the maximum ( $SSB_{1/2}$ ) to show the stable point for the large and long-lived species (big circles) and small and short-lived species (small circles) (c). The recovered situation where  $SSB = 95\%SSB_{MSY}$  is shown in black, and the depleted situation where the  $SSB$  is reduced to 10 %  $SSB_{unfished}$  is in grey.

$$C_f = \gamma \cdot C_v(SSB_{10}) \cdot Y_{10} \quad (3)$$

where  $\gamma$  is the annual fixed proportion of the capital to amortize, the chosen value is based on Danish accounting statistics (Andersen et al., 2009).  $C_v(SSB_{10})$  is the unit variable cost when the  $SSB$  is 10 %  $SSB_{unfished}$  and  $Y_{10}$  is the corresponding yield.

## Results

The depleted situation is created by fishing the  $SSB$  down to 10 % of the  $SSB_{unfished}$ , resulting in a depletion of the big-old fish in the stock relative to the recovery situation where fishing is at  $F_{MSY}$  (Fig. 2a,b). The fishing mortality that leads to a depleted situation is  $0.35 \text{ year}^{-1}$  for the large species and  $1.05 \text{ year}^{-1}$  for the small species. Due to this difference in fishing mortality, the stock structure is fairly similar for both the stocks with both small and the large body size. The recruitment of the large species is higher than for the small species, both in the depleted and the recovery situations (Fig. 2c). This means that density dependent effects are stronger on the larger species. The relative increase in recruitment required to recover the depleted

population is larger for the small species (roughly a factor two) than for the larger species (a factor of 1.3), and therefore the small species has to make a relatively larger recovery of recruitment than the large species.

The time to recover ( $TTR$ ) a depleted population increases as a function of the asymptotic size (Fig. 3a,d). Recovery from a depleted state always takes longer for a large than for a small species. However, the difference in time is modest (6 years vs. 5 years). This is because of the lower impact that depletion has on the recruitment of large species than on a small species. If the recruitment is strongly affected, which would happen in a rebuilding from a collapsed state (1 % of  $SSB_{unfished}$ ), the difference between  $TTR$  for large and small species becomes more pronounced (Fig. 4).

For both large and small species, the shortest recovery time occurs with fishery closure during the whole recovery period. Reducing fishing pressure to  $F_{MSY}$  and removing fishing mortality on big-old fish will allow the stock to recover at a faster rate than fishing all age groups ( $TTR$  fishing only intermediate sizes is 14 years for large species and 9 years for small species;  $TTR$  fishing all sizes is 23 years for large species and 14 years for small species). However, when the level of fishing pressure is 50 %  $F_{MSY}$  the difference in recovery time for both fishing all age groups and fishing only on

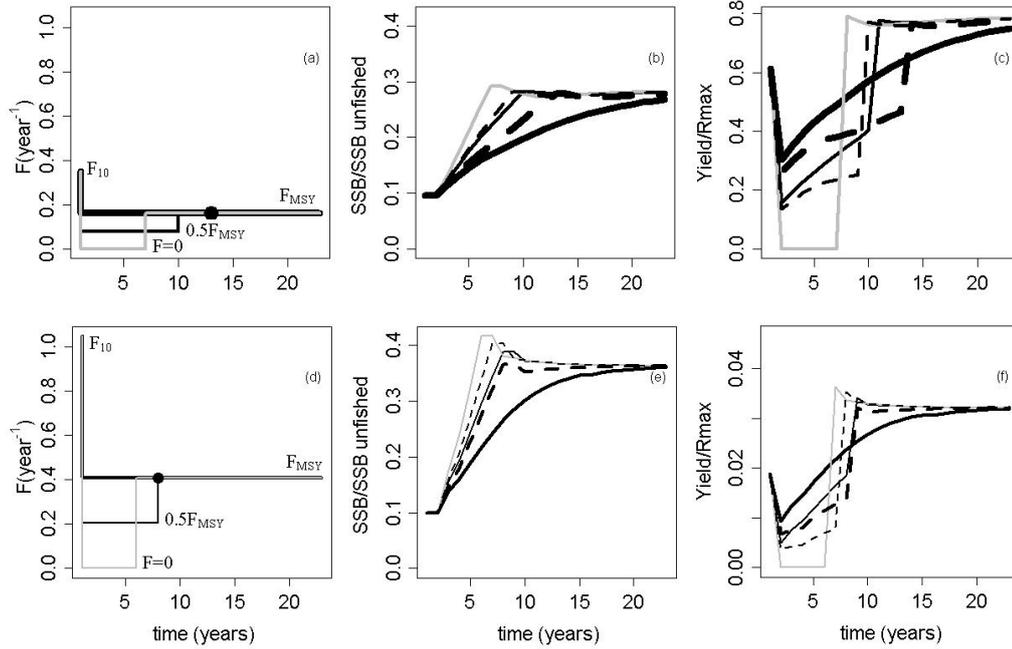


Figure 3: Fishing strategies (a-d), proportion of *SSB* (b-e) and Yield for 25 years period (c-f). Fishery closure during the recovery period (grey) and fishing mortality rate decreases to different fishing levels until the *SSB* catch up the 95 %  $SSB_{MSY}$  (black lines, thick lines for  $F_{MSY}$ , and thin lines for 0.5 %  $F_{MSY}$ ). Fishing on intermediate sizes until  $SSB > 95\%SSB_{MSY}$  (dashed lines), fishing all age groups (solid lines). Panel (a-b-c) large and long-lived species and panel (d-e-f) small and short-lived species.

intermediate sizes is modest (for large species, 9 years for both scenarios, fishing all age groups and fishing on intermediate sizes. For small species, 7 and 6 years). In general, recovery scenarios that substantially restrict catches (e.g.  $F=0$  or  $F < 50\%F_{MSY}$ ) during the recovery period recover populations more rapidly than those that allow higher catches during the recovery period.

The *SSB* increases constantly during the recovery phase to the desired stock size, which indicates that both large and small species are able to recover under the three recovery scenarios (Fig. 3b,e). Small species increase a bit more the *SSB* than large species for a given decrease of  $F$  (when  $F=0$ , *SSB* for small species reach 40 % of the  $SSB_{unfished}$ , *SSB* for large species reach 30 %). Removing fishing mortality on big-old fish during the recovery period only help to increase the *SSB* when fishing mortality rates are high (e.g.  $F_{MSY}$ ).

A greater reduction in  $F$  results in an expected large loss in yield in the short-term, before an increase starts

at the end or after the recovery period (Fig. 3c,f). Thus, while more severe reductions in fishing certainly recover the *SSB* faster it happens at the expense of the short-term yield. When the big-old fish are not fished, the yield is distributed among the smaller size classes (from  $0.15W_{\infty}$  to  $0.625W_{\infty}$ ) so a decrease on the yield is to be expected. However, the stock depends on experienced and large bodied spawners to support reproduction as a consequence, the *SSB* increase faster to reach the *SSB* that produce the *MSY* and an improvement of the yield will be balanced with the faster increase in the *SSB*. In the end, the difference between the yield fishing all age groups and fishing intermediate sizes is small for both species.

For both large and small species, all scenarios have reached recovery before or at 23 years (Fig. 5a). Therefore, for a comparison of the economics related with the different scenarios, the present value of the net benefit over the first 25 years is calculated. As a benchmark is

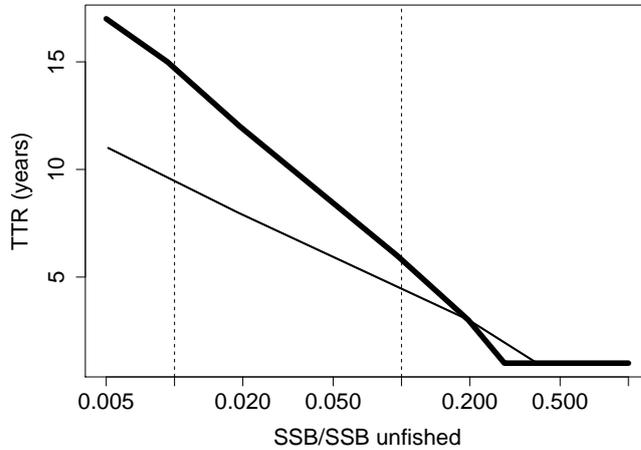


Figure 4: Time to recover to  $SSB_{MSY}$  as a function of depletion and collapse of the  $SSB$  relative to the  $SSB_{unfishied}$  for the large species (thick line) and the small species (thin line). In a depleted situation (0.1), the large species recover faster, while in a collapsed situation (0.01), the small species recover fastest. The vertical dashed lines are drawn at collapsed situation (0.01) and at depleted situation (0.1).

chosen the fishery closure such that all economic data are presented relative to this. Setting fishing mortality to  $F_{MSY}$  will, compared with closing the fishery totally during the recovery period, for large species reduce the net benefit with between 20 and 25 % and for small species between 10 and 20 %. If fishing mortality is set to lower levels than  $F_{MSY}$  (e.g. 50 %  $F_{MSY}$ ) during the recovery period, the reduction in net benefit will be less. Thus, the more restricted catches is during the recovery period ( $F=0$ ,  $F < 0.5F_{MSY}$ ) the more beneficial from an economic perspective (Fig. 5b,c).

A sensitivity analysis of the selection of size at big-old fish parameter ( $\eta_{Boff}$ ) is addressed in Fig. 6. Fishing only on intermediate sizes and defining big-old female to be smaller and younger reduce the recovery time and the reduction is larger for large species (panel a). As expected only the scenario when fishing is on intermediate sizes is affected by a change in the selection parameter where the  $NPV$  decreases (panel b-c).

## Discussion

We have combined a general demographic model of exploited fish stocks with a cost-benefit analysis ( $CBA$ ) to evaluate the ecological and economic consequences of different recovery scenarios. We emphasize that our

recovery context is for moderately reduced fish populations and not those for which  $SSB$  has been reduced seriously to affect recruitment. The demography of fish stock was described by a recent size-based framework which has the advantage that species can be described only by their asymptotic size (Calduch-Verdiell et al., 2011; Andersen and Beyer, 2011). The remaining parameters are species-independent and determined by cross-species analysis of life-history invariant from the literature (Charnov, 1993). This framework makes it possible to make a general assessment of a given management action, in this case a recovery plan. The economical aspects of the recovery plan are assessed by a cost-benefit analysis that calculates the long-term net present value of the recovery plan. The cost-benefit analysis allows a quantification of the favorable and unfavorable impacts of the proposed scenarios and it has been applied to evaluate management scenarios in different fisheries (Herrick et al., 1994; Freese et al., 1995; Brown and Macfadyen, 2007; Kronbak et al., 2009). Combining the two models made it possible to make an impact assessment of both the ecological and economical consequences of choosing one recovery plan over another of fish stocks in general.

The demographic model alone provides an ecological impact assessment of the recovery plans. The model

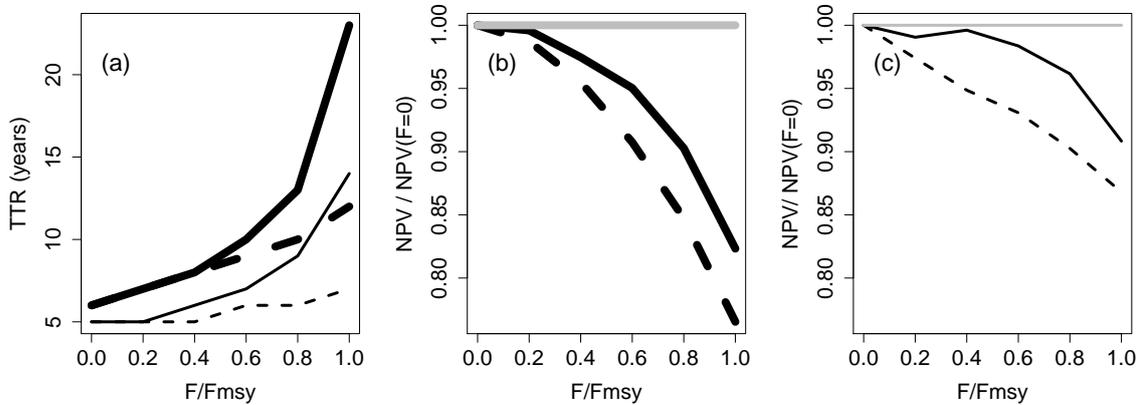


Figure 5: Recovery time ( $TTR$ ) (a) and the net present value ( $NPV$ ) for 25 years (b-c) as a function of fishing mortality relative to the  $F_{MSY}$ . Large and long-lived species (thick lines and panel b) and small and short-lived species (thin lines and panel c). Fishing on intermediate sizes during the recovery period ( $SSB < SSB_{MSY}$ ) (dashed lines), fishing on all sizes (solid black lines) and fishery closure (grey). Big-old fish ( $w \geq w_{Boff}$ ) has double price. Discount rate=2 %. Size of big-old fish is  $0.625W_{\infty}$ .

demonstrates, not surprisingly, that small and short-lived species recover faster due to their shorter generation time (Andersen and Rice, 2010). However, the difference in  $TTR$  is modest if the stock is recovering from a depleted state. Only if the stock is completely collapsed is there a significant difference in time to rebuild. The modest difference in  $TTR$  between large and small species is somewhat counter-intuitive, and is not what is expected from simple metabolic scaling arguments (Savage et al., 2004) which predict that the biological rates, and therefore also  $TTR$ , scales as weight to the power  $-0.25$ . The reason why the metabolic scaling prediction fail is because there are two competing processes going on in a fish population: the time to reach maturation and the recruitment (Andersen and Beyer, 2011), which pull  $TTR$  in opposite directions. When both processes are accounted for, the result that large species are expected to recover relatively fast from a depleted state is because their recruitment is expected to be less influenced by a 90 % reduction in  $SSB$  than a small species. Only if the stock is collapsed such that recruitment is significantly impaired, will the metabolic scaling predictions hold.

The fishing strategy that leads to the fastest recovery is the fisheries closure. However a modest fishing during the recovery does not delay the recovery significantly, in particular not for small species. Another is-

sue that we emphasized in this paper is the contribution of big-old fish in the recovery plan. Fishing only on the intermediately sized fish, i.e. saving the big-old fish, during the recovery period did not lead to a significantly faster recovery. The importance of the big-old fish was larger for large species than for small species. The saving of the big-old fish only decreased the recovery time if the fishing mortality was high during the recovery period. The economical analysis also showed that the best option was to close the fishery completely during the recovery. However, the long-term losses due a partial closure are relatively modest, and were never higher than 20 %. Saving big-old fish further reduces the  $NPV$  but the reduction is again modest, at most 25 %. In summary our results show that from narrow economic considerations based on the  $NPV$  are of minor importance in the selection of an appropriate recovery plan.

The question is then which recovery plan is the optimal seen from both an ecological and an economical perspective. The analysis clearly demonstrates that a complete closure is optimal from both perspectives. This option may, however, have other detrimental consequences not covered by the quantitative analysis performed here, e.g. socio-cultural consequences (Pollnac and Littlefielda, 1983). One immediate consequence of a fishery closure is a loss of income to fishermen which

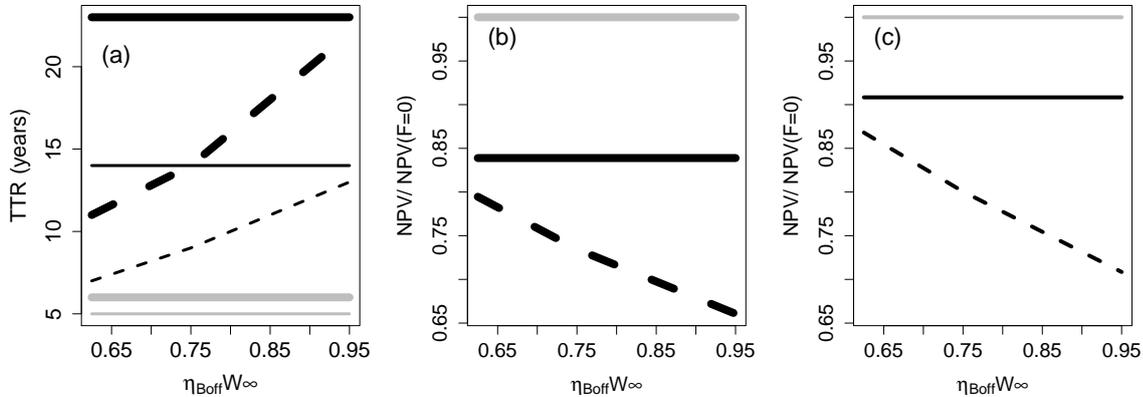


Figure 6: Recovery time ( $TTR$ ) (a) and the net present value ( $NPV$ ) for 25 years (b-c) as a function of the size of big-old fish relative to the asymptotic size. Large and long-lived species (thick lines and panel b) and small and short-lived species (thin lines and panel c). Fishing on intermediate sizes during the recovery period ( $SSB < SSB_{MSY}$ ) (dashed lines), fishing on all sizes (solid black lines) and fishery closure (grey). Big-old fish ( $w \geq w_{Boff}$ ) has double price. Discount rate=2 %. Fishing mortality rate  $F_{MSY}$ .

need to seek other sources of income or state welfare. Alternatively they need to will seek alternative fisheries which has other implications, e.g. it may require vessels to travel further to fish and put a higher fishing impact on other parts of the fish community. Further, industries downstream (supplier, yards) and upstream (fishing processing) can, if the referred fishery is a main supplier for the industry, be severely affected, which have additional consequences for local communities. So, even if optimal from a narrow ecological and economical perspective, there may be reasons for not recommend a complete closure of the fishery.

As the differences in  $NPV$  between the different recovery scenarios considered here are modest, the main constraint to consider when selecting a recovery strategy is the time to recover. As Safina et al. (2005) noted, a 10 years recovery requirement is a reasonable and beneficial deadline. Our analysis demonstrated that recover within 10 years can be achieved even with a fishing mortality as high as  $0.8 F_{MSY} \text{ yr}^{-1}$  for large species and  $0.9 F_{MSY} \text{ yr}^{-1}$  for small species. Saving the big-old fish from fishing does not make an appreciable improvement in the time to recover. It been argued that due to the inherent uncertainties in the recovery of fish stocks, delaying recovery puts the recover of the focal stock as well as other ecosystem components at risk (Hutchings, 2000; Jackson et al., 2001). On the other hand allowing

a significant fishery during the recovery has many direct socio-economical and cultural benefits.

Although the model framework is a useful tool for making general predictions about the ecological and economical consequences which are relevant in a general evaluation of management strategies (Arrow et al., 1996), it is a simple standard model which only describes the most important mechanisms, and which has several limitations. First of all the model framework is a single-species approach, that does not take multi-species interactions into account. Multi-species interactions affect recovery plans in at least two ways. First the ecological interactions such as competition and predation among species lead to natural variation in recruitment, survivorship, and growth of fish. However simulations with a full multi-species community model have demonstrated that the single-species model provides a good description of the recovery trajectory of that species (Andersen and Rice, 2010). The model will however not provide an assessment of the indirect effect of the recovery on the other species in the community and the potential loss of economic yield from species that are prey of the focal species (Caddy and Agnew, 2004). The other multi-species interaction is that associated with mixed-species fisheries. In some regions, many different species are captured by the same gear (e.g. many bottom trawl fisheries). Continued fishing

for other species in habitats where the depleted species is expected to recover can delay recovery (Caddy and Agnew, 2004; Rijnsdorp et al., 2007; Worm et al., 2009; Murawski, 2010). Consequently a recovery plan for a target depleted species which excludes measures to reduce bycatch of the depleted species (e.g. better gear selectivity, closed areas) due to fisheries for other species will likely underestimate recovery time. Our simulations implicitly assume that the simulations includes all sources of fishing mortality. Finally, the simulations only consider a recovery of the *SSB* and not other effects, like the stock structure, recovery of certain phenotypes or genotypes of the stock. Still, a recovery of the *SSB* is a good proxy for the recovery of other aspects of a stock as well. All taken together, the simulations should be used a rule-of-thumb type of guideline for how different species and recovery plans are expected to affect the recovery of a stock.

In our simulations we have paid particular attention to the big-old fish, but we have disregarded maternal effects, which may increase the importance of the big-old fish. However we have chosen not to include maternal effects explicitly, partly because they are difficult to quantify, and partly because a recent analysis have shown that maternal effect have a limited impact on the reproductive ability of the whole stock (Calduch-Verdiell et al., 2011). The parameters for both the demographic and the economical models have been set at reasonable average values, but there may be large variations between stocks. Therefore the results should be regarded as rules-of-thumbs. If the model is to be applied in for a stock where one aspect of either its ecology, e.g. high natural mortality or significant maternal effects, or economic importance, e.g. exceptionally large price difference between different sizes, a simulation may need to be carried out using specific stock-specific parameter values.

In conclusion, the economic analysis in this paper indicates that the differences between choosing one recovery scenario over the other are limited. There are differences in the recovery time between scenarios, but some fishing mortality may be allowed if the recovery should be completed only in 10 years. The big-old fish does not matter much neither from an economic nor from an ecological perspective. Only if there is a high fishing pressure during the recovery period can saving the big-old fish reduce recovery time significantly.

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Table 1: Model equations and the parameters

Process	Equation	Number
Von Bertalanffy growth equation <sup>a</sup>	$w(x) = W_{\infty} (1 - e^{-Kx})^3$	(1)
Natural mortality <sup>b</sup>	$\mu(w) = \frac{1}{3}\bar{h}\eta^{1/3} \left(\frac{M}{K}\right) w^{-1/3}$	(2)
Fishery Yield <sup>c</sup>	$Y = \sum B(x)F(x) \frac{1 - e^{-(\mu(x)+F(x))\Delta t}}{(\mu(x)+F(x))\Delta t}$	(3)
Population equation	$N_t(x) = N_{t-1}(x-1)e^{-(\mu(x)+F(x))\Delta t}$	(4)
Recruitment equation <sup>c</sup>	$R(SSB_t) = \frac{\alpha SSB_t}{SSB_{1/2} + \alpha SSB_t} R_{\max}$	(5)
Symbol	Parameter	Value
<i>Control parameters:</i>		
$F$	Fishing mortality	free (0, ..., 2)
$W_{\infty}$	Asymptotic (maximum) size	free (20kg, 0.5kg)
<i>Fundamental parameters:</i>		
$\bar{h}$	Growth constant <sup>d</sup>	$0.6 \cdot 27g^{1/3} \text{ yr}^{-1}$
$M/K$	Mortality/growth relation <sup>e</sup>	0.95
$\eta_M$	Ratio between size at maturation and $W_{\infty}$ <sup>f</sup>	0.25
$\eta_F$	Ratio between size at 50 % $F$ and $W_{\infty}$	0.15
$\eta_{\text{Boff}}$	Ratio between size at big-old individuals and $W_{\infty}$	0.625
$SSB_{\max}$	Value of $SSB$ where the recruitment curve is maximum	
$SSB_{1/2}$	Value of $SSB$ where recruitment is half of the maximum recruitment <sup>g</sup>	
$\alpha_0$	Constant in recruitment relation <sup>g</sup>	
$\gamma$	Annual fixed proportion of the capital to amortize <sup>h</sup>	1/8
<i>Derived parameters:</i>		
$K$	von Bertalanffy growth constant	$\bar{h}W_{\infty}^{-1/3} / 3$
$\alpha$	The yearly egg production per body mass <sup>i</sup>	$\alpha_0 W_{\infty}^{-1/3}$

<sup>a</sup> Bertalanffy (1938)<sup>b</sup> Andersen et al. (2009)<sup>c</sup> Baranov (1918)<sup>c</sup> Beverton and Holt (1957)<sup>d</sup> At 10° (Andersen et al., 2008)<sup>e</sup> Andersen et al. (2009)<sup>f</sup> Beverton (1992)<sup>g</sup> Value unimportant for the calculation as the parameter is normalized out in the graphs.<sup>h</sup> Andersen et al. (2009)<sup>i</sup> Gunderson (1997); Andersen et al. (2008)