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Generic Harvest Control Rules for European Fisheries

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Abstract

In European fisheries, most stocks are overfished and many are below safe biological limits, resulting in a call from the European Commission for new long-term fisheries management plans. Here we propose a set of intuitive harvest control rules that are economically sound, compliant with international fishery agreements, based on relevant international experiences, supportive of ecosystem-based fisheries management, and compatible with the biology of European stocks. The rules are based on the concept of maximum sustainable yield (*MSY*), with a precautionary target biomass that is 30% larger than the one that can produce *MSY*, and with annual catches of 91% *MSY*. Allowable catches decline steeply when stocks fall below *MSY* levels, and are set to zero when stocks fall below half of *MSY* levels. We show that the proposed rules would have prevented the collapse of the North Sea herring in the 1970s and that they can deal with strong cyclic variations in recruitment such as known for blue whiting. Compared to the current system, these rules would lead to higher long-term catches from larger stocks at lower cost and with less adverse environmental impact.

Keywords European fisheries, harvest control rules, maximum sustainable yield, overfishing, precautionary principle

Introduction

European fisheries are in deep trouble, with 88% of the stocks officially declared overfished and 30% outside of safe biological limits (EC 2009). In addressing this problem, the European Commission has started a discussion process asking for input on 'how to make the most' of future European fisheries, once they are brought back from the brink, and more specifically, how long-term management plans for all European fisheries can be developed (EC 2009). Here we propose a set of harvest control rules based on six pillars: (1) The rules are compatible with economic optimization of fisheries management (Scott 1955, Pindyck 1984, Bjørndal 1988, Clark 1990); (2) the rules are firmly rooted in international fishery agreements and instruments (UNCLOS 1982, UNFSA 1995, FAO 1995, JPOI 2002) to which the European countries are parties; (3) the rules adhere to the precautionary principle, which is a binding principle of European Union law (FEU 2009); (4) the rules build on relevant experiences with harvest control rules in other regions, such as Australia, New Zealand and the USA; (5) the rules take into account species interactions and support the move towards ecosystem-based fisheries management (Pikitch et al. 2004); and (6) the rules account for the known biological properties of European stocks. We explore whether the rules would have prevented the collapse of the North Sea Herring in the 1970s and how they would have rebuilt the stock if applied after the collapse. We also explore whether the rules can deal with species characterized by cyclic phases of low and high recruitment. We compare the rules with an alternative system that is currently discussed in Europe. And finally, we compare the actual landings in 2007 with the landings that would be allowed under the proposed new rules.

The central reference point for fisheries referred to in international agreements and instruments (UNCLOS 1982, UNFSA 1995, FAO 1995, JPOI 2002) is the biomass (B_{msy}) that can produce the maximum sustainable yield (*MSY*). The international agreements make it clear that allowable catches can differ from *MSY* due to environmental and economic factors, special requirements of developing countries, fishing patterns, the interdependence of stocks, and international minimum standards. However, catches above *MSY* may result in biomass declining below B_{msy} and lower catches in the long term. Low biomass and low catches have negative impacts with regard to environmental, economic, social and political goals. Thus, any meaningful application of these *MSY*-qualifiers can only result in catches smaller than *MSY* and target biomasses bigger than B_{msy}. This is made explicit in Annex II of the UN Fish Stocks Agreement (UNFSA 1995) which specifies that the fishing mortality which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points.

MSY-management has been formally implemented in the USA (MSA 2006), New Zealand (MFNZ 2008) and Australia (DAFF 2007), and should be implemented in Europe by 2015 (EC 2009). Typically B_{msy} acts as a trigger-reference point below which catches are systematically reduced to reach zero at a limit biomass B_{lim}, the point below which the reproductive capacity of the stock is endangered. In healthy stocks, catches that are lower than *MSY* result in long-term biomasses that are larger than B_{msy}, and two corresponding target reference points have been defined: one is the biomass B_{mey} that can produce the maximum economic yield (*MEY*), used in Australia, and the other is the biomass B_{oy} that can produce the optimum yield *OY* as determined by economic or ecological factors, used in the USA. It should be noted that the harvest control rules proposed in this study can refer to the biomass of reproductively active females (e.g. USA) or of all spawners (e.g. spawning stock biomass *SSB*, as used in Europe).

There is increasing evidence that fishing such as currently exercised in Europe does more damage to the stocks than needed to obtain the respective catches (Froese et al. 2008).

Especially the combination of excessive fishing pressure and fishing of juveniles has led to unnatural selection for small size, early maturation, and reduced fecundity (Conover and Munich 2002, Froese 2004, Edline et al. 2007, Jørgensen et al. 2007, Darimont et al. 2009). In the following, we account for these experiences and insights in deriving a set of generic harvest control rules for Europe.

Proposed harvest control rules

The following are our suggestions for harvest control rules (Figure 1):

1. **Reference and Trigger Biomass**: The reference biomass B_{msy} for the subsequent rules and reference points is the biomass that can produce the maximum sustainable yield. This biomass also acts as a trigger when stocks fall below this level, see Rule 5.
2. **Target Biomass**: The target biomass, to be achieved on average over approximately 5 years, is 1.3 B_{msy}. The target biomass can be increased as required by economic, ecosystem or other considerations.
3. **Limit Biomass**: The limit biomass B_{lim}, which is to be avoided with a high probability, is 0.5 B_{msy}. A higher biomass limit may be set for species with low resilience to exploitation.
4. **Total Allowable Catch**: Fisheries are managed by a total allowable catch (TAC). A maximum TAC is set for each stock so that the respective target biomass is maintained on average. This maximum TAC may be taken as long as biomass fluctuations remain above B_{msy}.
5. **TAC Reductions**: If the biomass falls below B_{msy}, then the TAC is linearly reduced, as a function of biomass, to reach zero catch at B_{lim}.
6. **Mixed Fisheries**: In fisheries where several target species are caught with the same gear, the maximum TACs for the respective stocks will be set such that the most sensitive stocks do not fall below B_{msy} on average over five years, with a high probability of not falling below B_{lim}.
7. **Discard**: No discard of commercially exploited species will be allowed, except for species with a demonstrated high discard survival rate.
8. **Bycatch**: Ecological risk assessment will be conducted on bycatch species and to assess potential damage to the environment caused by fishing, with respective measures to be taken to minimize risk.
9. **Size structure**: The mean size and age in the catch will be adjusted to minimize changes in age structure caused by fishing, and to reduce the effects of fisheries-induced unnatural selection.

Note that we expect the estimates for *MSY* and B_{msy} to be reviewed in regular intervals of, e.g., 5 years.

Justification of the rules

Re Rule 1. Reference and Trigger Biomass: Rule 1 follows directly from the United Nations Convention on the Law of the Sea (UNCLOS 1982) and the subsequent international fisheries instruments and agreements. The United Nations Fish Stocks Agreement (UNFSA 1995) explicitly identifies B_{msy} as a target during the rebuilding of stocks and F_{msy}, the fishing mortality giving B_{msy} on average, as a limit reference point, i.e., after the rebuilding phase B_{msy} is no longer a target but a reference point that triggers management action. Note that while some of the international instruments are voluntary (FAO 1995) or non-binding declarations of political will (JPOI 2002), UNCLOS (1982) and UNFSA (1995) contain binding obligations which ought to be implemented at the national level. The EU and all of its member states, as well as Iceland, Norway and Russia are parties to UNCLOS and UNFSA.

Furthermore, in February 2009, the United Nations General Assembly called upon *all* States to apply stock-specific precautionary reference points as described in Annex II UNFSA (1995), i.e. F_{msy} and B_{msy}, and to use these reference points for triggering conservation and management action.

Re Rule 2. Target Biomass: The precautionary principle of European law (FEU 2009) basically demands that in the presence of uncertainty EU policymakers should implement policies that reduce the probability of harm being done to resources or society. Applied to fisheries, the precautionary principle demands that the target biomass should be chosen such that the probability of falling below B_{msy} is low. Here we suggest 1.3 B_{msy} as default target biomass. In a previous analysis (Froese and Proelß 2010) two of us determined approximate upper 95% confidence limits of B_{msy} for 54 European stocks, where B_{msy} was taken as the mean of estimates from two different methods. These limits were on average 1.29 B_{msy} (n = 54, mean = 1.287, 95% CL 1.251 – 1.323). The proposed default target biomass of 1.3 B_{msy} thus accounts for the uncertainty in estimating B_{msy}, though not yet for the additional uncertainty in the estimation of current biomass. Also, the proposed default allows the biomass to fluctuate by 23% below the target before B_{msy} is reached. Average negative annual fluctuations for 54 European stocks were 13% (median = -0.13, n = 54), with 90% of the fluctuations being smaller than 23% (90th percentiles = -0.23, n = 54). A similar result is obtained if negative amplitudes (sequences of annual decline in biomass) are analyzed: 90% of such amplitudes were smaller than 48% of the biomass at the beginning of the sequence (median of 90th percentiles = -0.48, n = 54) (see Table S1 in the online Supplement). Assuming that such amplitudes fluctuate around the mean target biomass would mean that the negative section was about half of the observed amplitude, i.e., 24%. In summary, the proposed target of 1.3 B_{msy} accounts for the observed uncertainty in the estimation of B_{msy} and for the observed biomass fluctuations in 54 European stocks and thus is in line with the precautionary principle.

The biomass that can produce the maximum economic yield *MEY*, i.e., the biomass that gives maximum net returns or profit from the fishery as a whole when the value of the catch and the cost of fishing are considered, is larger than B_{msy}, because a larger stock reduces the harvesting costs per ton of fish. Thus, conservative fishing provides both larger fish stocks and higher profits (Grafton et al. 2007). However, *MEY* is a function of fish prices, exchange rates, input costs (fuel, gear, capital rents, salaries), recruitment to the stock, and other factors such as changes in fishing technology (DAFF 2007). This makes *MEY* a moving target that is difficult and costly to predict for the next fishing season with a reasonable degree of confidence. Estimates of B_{mey}/B_{msy} ratios for several Australian stocks ranged from 1.03 to 1.47 (DAFF 2007), i.e., they vary around the default target biomass proposed by us and will probably in most cases not be significantly different from it. Nevertheless, Rule 2 gives the option of using B_{mey} as target biomass if it is larger than 1.3 B_{msy}.

A default target biomass for the maximum economic yield has been implemented by Australia as B_{mey} = 1.2 B_{msy}, which would allow biomass fluctuations of -17% before stock size falls below B_{msy} (DAFF 2007). A default target biomass avoids the situation where uncertainty or disagreement about optimum yields could lead to B_{msy} being used as a target instead of a limit. Also, the default target biomass, when chosen, has the advantage of avoiding the additional cost and effort associated with annual estimation of the maximum economic yield (DAFF 2007).

The long-term yield associated with a target biomass of 1.3 B_{msy} is 0.91 *MSY* in the context of a Schaefer model (Schaefer 1954, Walters et al. 2008), confirming the observation that 'pretty good yields' can be obtained over a wide range of stock sizes (Mace 2001, Hilborn 2009). The target biomass corresponds to 65% of the unexploited biomass, which is probably near the lower size limit for stocks to be able to fulfil their natural ecosystem roles as predator, prey or competitor (Walters et al. 2005). For forage species it may be necessary to set a higher biomass target (Hilborn and Walters 1992), such as 1.5 B_{msy}, which represents 75% of unexploited biomass and still provides long-term yields of 75% of *MSY*. Appendix S1 shows corresponding calculations for the Fox (1970) model and presents the relationship between the proposed harvest control rules and the Fox and Schaefer models, respectively. It also discusses the suitability of other stock assessment methods.

A target biomass larger than B_{msy} is supported by the developing understanding of the effect of food-web dynamics in marine ecosystems. For many ecosystems, fishing a wide range of species at F_{msy} results in depletion of predators through the combination of both fishing and loss of prey (Walters et al. 2005). Other simulations have found that many species were depleted and some even collapsed when a multispecies *MSY* was taken from an ecosystem (Worm et al. 2009). A target biomass larger than B_{msy} also results from economic optimization when social discounting, uncertainty of biomass development, and stock-dependent harvesting cost are considered (see Appendix S3).

Finally, we want to point out that the proposed target biomass of 1.3 B_{msy} results in yields which are close to the "optimal conservative level of harvest" (Jensen 2005), where the biomass is as close as possible to the unexploited level while at the same time the yield is as close as possible to *MSY*. These optimal yields are 0.91 *MSY* under the Fox and 0.94 *MSY* under the Schaefer model, respectively (Jensen 2005).

Re Rule 3. Limit Biomass: We propose 0.5 B_{msy} as the default limit biomass where targeted fishing is halted and a rescue plan with additional measures, such as minimizing bycatch in other fisheries, is to be activated. A comparison of lower stock limits used in Europe (B_{pa}) relative to B_{msy} gives a median value of 0.34 with an upper 95% confidence limit of 0.44 (Froese and Proelß 2010). Thus, the proposed threshold of 0.5 B_{msy} provides an adequate biomass limit for most European stocks.

A default 0.5 B_{msy} biomass limit with zero catch below it is already used in Australia (DAFF 2007). In New Zealand the default limit is 0.5 B_{msy} or 20% of the unfished biomass, whichever is the higher, because 0.5 B_{msy} can be very small for some stocks (MFNZ 2008). Nine of the European stocks analyzed in Froese and Proelß (2010) had B_{pa} estimates larger than 0.5 B_{msy}, thus requiring the adoption of a more conservative Limit Biomass.

Re Rule 4. Total Allowable Catch: We propose that European fisheries continue to be managed by total allowable catch, because exclusive input-management such as only limiting days at sea has not produced the desired results (Branch et al. 2006a) and has been abandoned, e.g., in the USA, where the 2006 Amendment to the Magnuson-Stevens Act introduced Annual Catch Limits as main management tool (MSA 2006). From an economic perspective, the problem of overfishing is best addressed by regulating the catch, as this is the quantity that links economic decision-making with the ecosystem. Alternative management approaches that propose to regulate fishing effort require additional information on harvesting technology, prices, or ecosystem functioning in order to implement optimal fishing, and thus are more costly to implement. We agree with the assessment of the New Zealand Ministry of Fisheries that TACs are "generally thought to be the most effective management method worldwide" (MFNZ 2009), and such output controls are the strongly preferred management framework in Australia (DAFF 2007). Experience in both countries indicates the continued need for some input restrictions in addition to TACs, such as closed seasons and areas and upper limits to boats and gears, and we support this. Also, our proposed rules do not prescribe how the TAC is allocated among individual fishers. Several options are possible, including individual transferable quotas such as implemented in New Zealand, Australia and Iceland.

A fixed TAC for biomasses above B_{msy} simplifies management and facilitates planning by fishers and industry. Predictable catches are one of the goals expressed by the European Commission (EC 2009). It could be argued that with fixed maximum TAC fishers forego catches when the stock rises above the target biomass, but this is compensated by the constant catch when the biomass is below target between 1.3 B_{msy} and B_{msy}. A respective maximum TAC would apply to all stocks of a species. This would prevent the current situation where exceptionally good year classes and catches in one stock may flood the European market and may strongly reduce ex-vessel prices in other stocks of the same species, with the result that much of the excess harvest may end up as fish meal. Under the proposed system, such exceptional year classes would build up the stock, improve age structure, and provide a buffer against future years with low recruitment (see simulations for herring and blue whiting below).

No upper bound on catches would mean that fishers and processing industry have to maintain the capacity to process exceptional catches, i.e., a harvest control system based on fixed maximum fishing mortality rate rather than on fixed maximum TAC provides an incentive for overcapacity (see Appendix S4, Figure A2). From the perspective of ecosystem-based fisheries management, a harvest control system with no upper bound on catches does more damage to the stocks and the ecosystem than needed to maintain long-term yields close to *MSY*.

We believe that a harvest control rule expressed in biomass and catch is much easier to communicate than a system based on biomass and fishing mortality. Because of the transparency resulting from the known maximum TAC and the simple calculation of TACs at biomasses below B_{msy}, we expect a much stronger support from stakeholders for rebuilding, maintaining and protecting spawning stock biomass.

Re Rule 5. TAC Reductions: The simple and relatively steep linear reduction in catch if stock biomass falls below B_{msy} aims to quickly prevent further decline in biomass, as demanded by the precautionary principle. This accounts for the European experience where past reductions in TACs can best be described as 'too little too late,' with the result that most stocks are now below the proposed biomass limit and most catches are far below *MSY*. Figure 2 shows recent biomass and catch data for 54 European stocks relative to the proposed harvest control rules. Nine of these stocks have biomasses that are larger than B_{msy} and after modest adjustment of their respective TACs they would easily fall into the new system. Twelve stocks have biomass levels between B_{msy} and 0.5 B_{msy}, and most of these will be able to rebuild beyond B_{msy} within a few years (Froese and Proelß 2010) if their TACs are adjusted as proposed by the new system. The remaining stocks are below the 0.5 B_{msy} threshold. Under the proposed rules, these fisheries would be closed to bring the stocks out of the danger zone and into the profitable range as quickly as possible. Alternatively, fishing mortality could be reduced to F_{msy} in 4 equal annual steps, as was recently proposed by the European Commission (EC 2010). For most stocks, this should result in biomass increasing beyond 0.5 B_{msy}, at which point the new rules could be applied. For B_{lim} = 0.5 B_{msy}, the reduced TAC can be easily calculated as TAC(%) = 2 B(%) -100, e.g., if the maximum TAC for a given stock is 100,000 t and the predicted biomass is 80% of B_{msy}, the total allowed catches for the coming fishing season will be 2 * 80 – 100 = 60% = 60,000 t.

From an economic perspective, a linear increase towards maximum TAC is the optimal strategy under plausible assumptions on market demand for fish and harvesting cost, as formally shown in Appendix S3. The economic rationale is that, beyond B_{lim}, the stock is within safe biological limits, and as it becomes more and more productive, it is able to supply the market to an increasing extent. A linear reduction in fishing mortality has been implemented in Australia (DAFF 2007) and is common in the USA. The differences between a linear decline in fishing mortality and a linear decline in TAC are small, see Figure A2 in Appendix S4.

Re Rule 6. Mixed Fisheries: Rule 6 is a more direct, simpler and unambiguous application of the *MSY* concept than the Australian implementation, where a sensitive species in a mixed fishery may fall below B_{msy} on average, but must not fall below B_{lim}, with a number of additional rules to be observed (DAFF 2007). The simpler rule better fits the European situation because the number of target species in mixed fisheries is relatively low, and reducing the catch of sensitive species such as sharks and rays seems technically feasible.

Re Rule 7. Discard: There is wide consensus in Europe that the standing order to discard commercially exploited species at sea if they are undersized or if the respective vessel's quota for this species is exhausted, has to be abandoned and replaced by a system where these species are landed and counted against the national quota (EC 2009). Discard of commercially exploited species is strongly discouraged in several countries outside the European Community, e.g., recorded and accounted for in stock assessments in Australia (DAFF 2007) or recorded and paid for by fishers at a deemed price in New Zealand (Peacey 2002). In the British Columbia groundfish fishery with 100% observer coverage, all discards of commercial size are recorded and appropriate deductions made from the quota of the respective boat (Branch et al. 2006b). Norway has completely banned the discard of fish for which a total allowable catch (TAC) has been set, so that all catch of these species must be retained and landed (NMF 2009). Exceptions may apply to, e.g., unintentional catch of commercially exploited sharks and rays if these species show a high survival rate after discard.

Re Rule 8. Bycatch: Unintended catch of non-commercial species and destruction of habitat by fishing gears represent a considerable negative impact on the ecosystem. The precautionary principle and the goal of ecosystem-based fisheries management require that such impact is assessed and subsequently minimized. In Australia, Ecological Risk Assessments are performed on bycatch species, such as sea turtles or dolphins, and the fishery has to adopt appropriate risk management measures to reduce any high risk (DAFF 2007).

Re Rule 9. Size structure: The precautionary principle and the ecosystem-approach to fisheries management request that negative impacts of a given TAC on the target species are minimized. The distorted size and age structure and the effects of unnatural selection (Conover and Munich 2002, Edline et al. 2007, Jørgensen et al. 2007, Darimont et al. 2009) visible in several European stocks are not unavoidable, but result primarily from overfishing and catches consisting mostly of juveniles (EC 2009). These negative impacts can be reduced if fishing targets the size and age class where individuals have reached the peak of cohort biomass and have concluded the natural mean duration of their reproductive phase (Mace 2001, Froese 2004, Froese et al. 2008). This can be implemented, for example, by mesh sizes in nets and traps that allow smaller fish to escape, and by targeting seasons and areas where undersized fish are rare. Because the relative number of fish killed is minimized, such fishing results in high survival of older fish (Froese et al. 2008). Note also that our fixed maximum TAC (Rule 4) means that fishing mortality decreases as biomass increases beyond B_{msy} (see Appendix S4, Figure A3), thus assisting in rebuilding and maintaining an age structure similar to the unfished one.

Discussion

Asking the right question

To date, European fisheries managers have asked the question: "What is the *smallest* stock size that can still deliver sustainable catches?" This is evidenced by a formal request of the European Commission asking the International Council for the Exploration of the Seas (ICES), its principal scientific advisory body with regards to fishing, to provide reference points for spawning biomass and fishing mortality that carry "a low probability of stock collapse" (ICES 1998). These reference points (B_{pa} and F_{pa}) were called 'precautionary' and were *de-facto* used as target for European fisheries management. We submit that this constitutes a clear violation of the Law of the Sea Convention (UNCLOS 1982) and other international instruments (FAO 1995, UNFSA 1995), because B_{pa} as estimated by ICES represented on average only 34% of the biomass that can produce *MSY* (Froese and Proelß 2010) and F_{pa} is by definition larger than F_{msy}. Clearly, B_{pa} and F_{pa} were not precautionary but excessive compared to the internationally agreed *MSY* concept, leaving European stocks at only 14% (Fox) to 19% (Schaefer) of the unexploited biomass, on average (Froese and Proelß 2010), i.e., well below the limit biomass as defined in this study (see Fig. 2). With the advent (FAO 2001, Pikitch et al. 2004) and acceptance (EC 2009, MFNZ 2008, DAFF 2007, NMF 2009) of ecosystem-based fisheries management, a new conservative zone of consensus has emerged (Hilborn 2007, Worm et al. 2009) and the right question to ask now is: "What is the *largest* stock size that can still deliver good catches?" We believe the proposed harvest control rules provide a suitable answer.

Application of the rules to herring and blue whiting

It can be asked whether our proposed fixed TAC is conservative enough to maintain stocks in the face of highly unpredictable and sometimes cyclic recruitment. Assuming the same recruitment and similar age-specific distribution of mortality, body weight, and maturity, we modelled the biomass that would have resulted from the proposed harvest control rules for two stocks. Figure 3 shows data for the North Sea herring (*Clupea harengus*, Clupeidae) from the beginning of the time series in 1960 to 1978, when the stock had collapsed and the fishery had been closed (ICES 2009a). The open circles in Figure 3 show biomass and landings resulting from the proposed harvest control rules, see Methods in Appendix S2. As can be seen, a maximum TAC of 0.91 *MSY* = 428,109 t would have maintained the herring stock at much higher biomass mostly beyond 1.3 B_{msy}. The stock would not have collapsed, and there would have been no need to close the fishery. In only two years, 1962 and 1978, would the landings have been below 0.91 *MSY*.

Figure 4 shows the recovery of the herring stock from 1979 to 2008. Under the proposed harvest control rules, the fishery would have reopened in 1983, landing 0.91 *MSY* from 1985 onward, and maintaining spawning stock biomass beyond 1.3 B_{msy} from 1987 onward. This is in contrast to the actual fishery, where the biomass was outside of safe biological limits in 26 out of 30 years ($B < B_{pa}$ = 1.3 mio. t), and where landings in 2008 stood at only 0.49 *MSY*.

Figure 5 shows data (ICES 2009b) from 1981 to 2008 for the blue whiting (*Micromesistius poutassou*, Gadidae), a species known for its alternating cycles of low and high recruitment. Under the proposed harvest control rules, the stock would have contracted to the lowest value in 1983, but it would still be above B_{lim} and fishing would be allowed. Subsequently the stock would have increased beyond B_{msy} in 1999, and increased further to very high biomasses in 2006 and 2008, despite reduced recruitment since 2006. Because of the high biomass, the stock was unlikely to fall below B_{msy}, even if the current low recruitment phase would last for a few more years. Thus, the proposed harvest control rule would have managed the stock better than the actual fishery, where spawning stock biomass was near B_{msy} in 2008 and predicted to fall below it in 2009 (ICES 2009b).

Note that economic results are implicit in these simulations, as revenue is expected to increase with landings and relative cost of fishing are expected to decline with increasing biomass. Note also that our comparisons are not a fair judgement of past herring and blue-whiting management, as managers at the time had to base their assessments and advice on much shorter time series of data.

Reality check

Our proposed harvest control rules may appear obvious, however, they are in stark contrast to the current level of discussion in Europe: a recent proposal (ICES 2010) aims for continued fishing even if the stock is outside of safe biological limits, and for catches above *MSY* as soon as the stock is above B_{msy}. International agreements, the precautionary principle, ecosystem-based management, and resource economics have apparently not been considered. In Appendix S4 we compare the two proposals in more detail and show that such management would not have prevented the demise of the North Sea Herring.

Climate, genes and protected areas

Recent publications (Cheung et al. 2009a,b) suggest that climate change will lead to increased stress and potential large scale re-distribution of fish stocks within the next 50 years. Stocks may be able to adapt to a certain extent to these changes through natural selection, but only if the gene pool is large enough for suitable genotypes to persist and if natural selection is not largely replaced by unnatural selection such as may result from overfishing (Edline et al. 2007, Darimont et al. 2009).

We are aware that overcapacity of the European fleet is a driving force behind unsustainable management (EC 2009, Villasante and Sumaila 2009, Villasante 2010) and that the marine ecosystem would benefit from marine protected areas where no fishing is allowed (Beattie et al. 2002). Both issues have to be addressed by the future management regime. Here we have focused only on the aspect of responsible fishing, because the extraction of fish is the strongest and most direct impact on the resource and no other measure is likely to rebuild the stock and the ecosystem if fishing itself is not done in a responsible manner. Even so, the proposed maximum TAC will facilitate planning by fishers and the fish-processing industry and remove incentives for overcapacity. The expected high biomass of stocks will benefit the marine ecosystem and allow fishers to easily fish out their quota, even if some areas were closed to fishing.

Less becomes more

There is a widespread perception that society has to tame its appetite for seafood in order to sustain healthy fisheries. The good news is that while it is true that in the current European situation catches have to be reduced, it should only take a few years until catches first regain and then exceed current levels, because healthy large stocks sustain larger catches than currently obtained. The actual catches of the stocks shown in Figure 2 for the year 2007 amount to 7.6 million t (Froese and Proelß 2010). If these stocks were rebuilt, the total catch under the proposed harvest rules would be 12.4 million t, i.e., an increase of 63% in landings at lower cost of fishing and with less adverse impact on the marine ecosystem.

Quality of data and appropriateness of rules

Our proposed harvest control rules rely on reasonable estimates of *MSY* and B_{msy} and reliable estimates of annual stock biomass and landings. We want to use this opportunity to acknowledge the tremendous work done by ICES stock assessment working groups in this respect and to stress the need for continuation of that work and expansion to the many European stocks for which insufficient data are available. Our arguments here were almost entirely 'single species' arguments, while there is growing recognition and methods to allow consideration of multispecies *MSY* (Worm et al. 2009). While these considerations may need to be included in future development of the harvest rules suggested here, we believe that the proposed rules reflect current good fisheries practice (Sainsbury 2008) consistent with international agreements, that they have been shown to be feasible in practical fishery applications, and that they should form the basis of the revised Common Fisheries Policy of the European Union.

Addressing the main failures

We believe that the main causes for the failure of fisheries management in Europe were aiming for the wrong target (~0.34 B_{msy} instead of 1.3 B_{msy}) and the prevalence of short-term considerations over long-term goals. At the annual negotiations within the Council of Ministers, scientific advice was followed for only 8% of the stocks and TACs were regularly set even beyond the level that would secure stocks, exceeding the scientific advice by 50% on average (Piet et al. 2010). The proposed harvest control rules replace these TAC negotiations altogether: the TAC becomes a politically decided rule-based consequence of the estimated biomass.

In summary, the proposed rules have the potential of rebuilding and sustaining European fisheries and the seafood supply for European consumers. They provide a biomass target that is precautionary and in line with international agreements and the goals of ecosystem-based fisheries management, while still providing good catches close to *MSY*. Their implementation would turn Europe from an international laggard into a leader with respect to responsible and smart fisheries management.

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Figure Legends:

Figure 1. Proposed generic harvest control rules for European fisheries, where B/B_{msy} is the biomass relative to the biomass that can produce the maximum sustainable yield *MSY*, and *Y*/*MSY* is the yield relative to *MSY*, indicated by the red lines. The leftmost dotted vertical line indicates the biomass 0.5 B_{msy} below which recruitment tends to be impaired and the stock is in danger of collapsing. The dotted line at 1.3 B_{msy} indicates the default target biomass around which stocks are expected to fluctuate. The dotted line at 1.5 B_{msy} is a possible conservative target for forage fish and sensitive species. The continuous red line indicates the maximum yield allowed under this harvest control framework, resulting in a biomass of 1.3 B_{msy} with a yield of 0.91 *MSY* in the context of a Schaefer model. A more conservative exploitation level of 0.75 *MSY* is indicated by the broken red line and would result in a biomass of 1.5 B_{msy}.

Figure 2. Relative catch and biomass data for 54 European stocks shown in the framework of the proposed harvest control framework (data for 2007). Stocks with biomass levels beyond 0.5 B_{msy} and catches above 0.91 *MSY* can be brought into the new system by reducing their catch levels towards the red line; the few stocks below the red line are forage fish which may be candidates for reduced exploitation levels. The many stocks left of the 0.5 B_{msy} threshold need zero catches to bring them out of the danger zone and into the new system as soon as possible. Note that most stocks have current catches below the long-term allowable catch.

Figure 3. Time series data of North Sea Herring spawning stock biomass and reported landings, from 1960 to 1978. Management according to the proposed harvest control rules (red line) would have resulted in stock biomass and landings indicated by the open circles.

Figure 4. Time series data of North Sea Herring spawning stock biomass and reported landings, from 1979 to 2008. Management according to the proposed harvest control rules (red line) would have resulted in stock biomass and landings indicated by the open circles.

Figure 5. Time series data of Blue Whiting biomass and reported landings, for 1981 to 2008. Cycles of low and high recruitment are indicated. Management according to the proposed harvest control rule (red line) would have resulted in stock biomass and landings indicated by the open circles, with much higher biomasses during the recent phase of low recruitment.

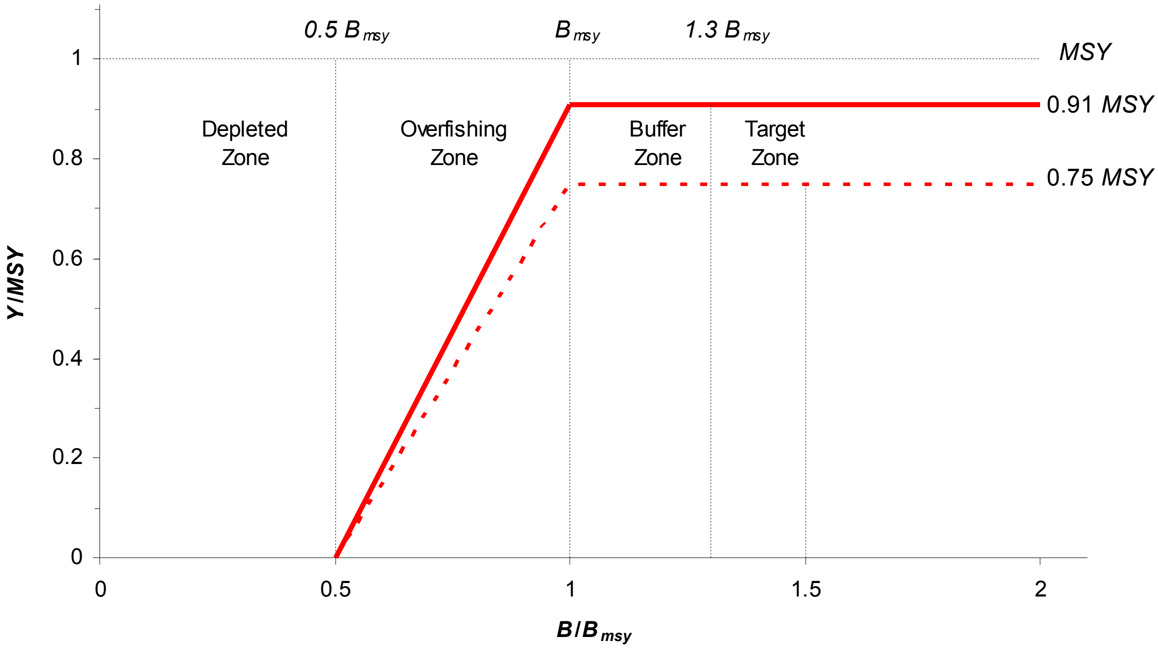

Figure 5. [HCR1_Graph.xls]

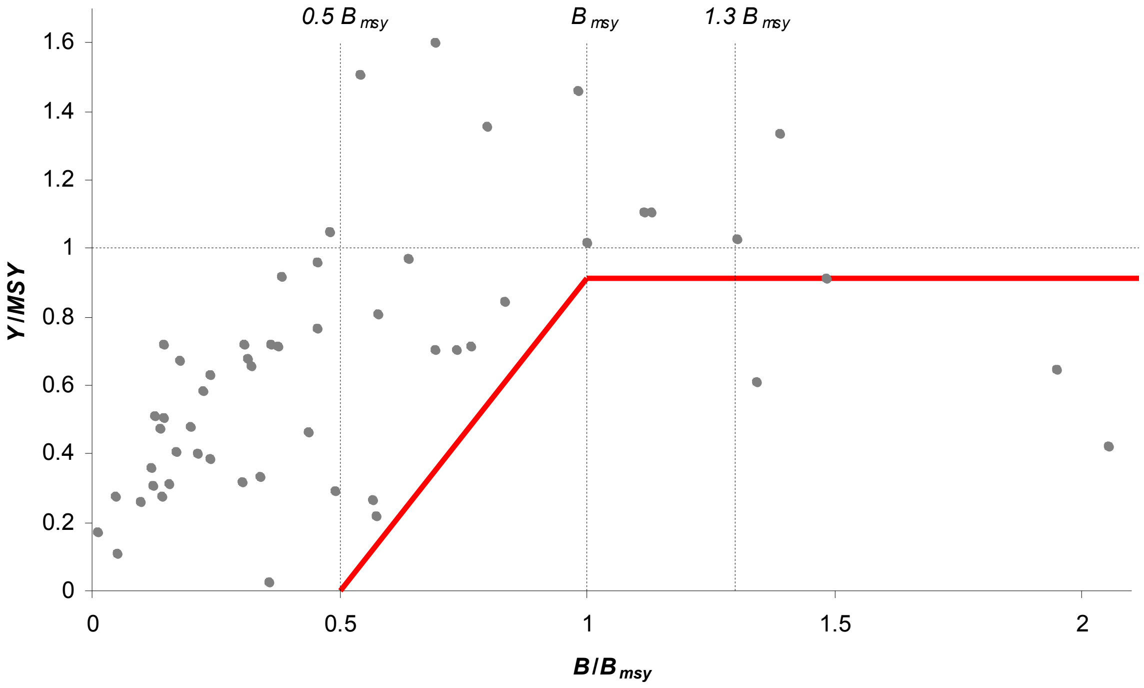

Figure 6. [HCR1_Graph.xls]

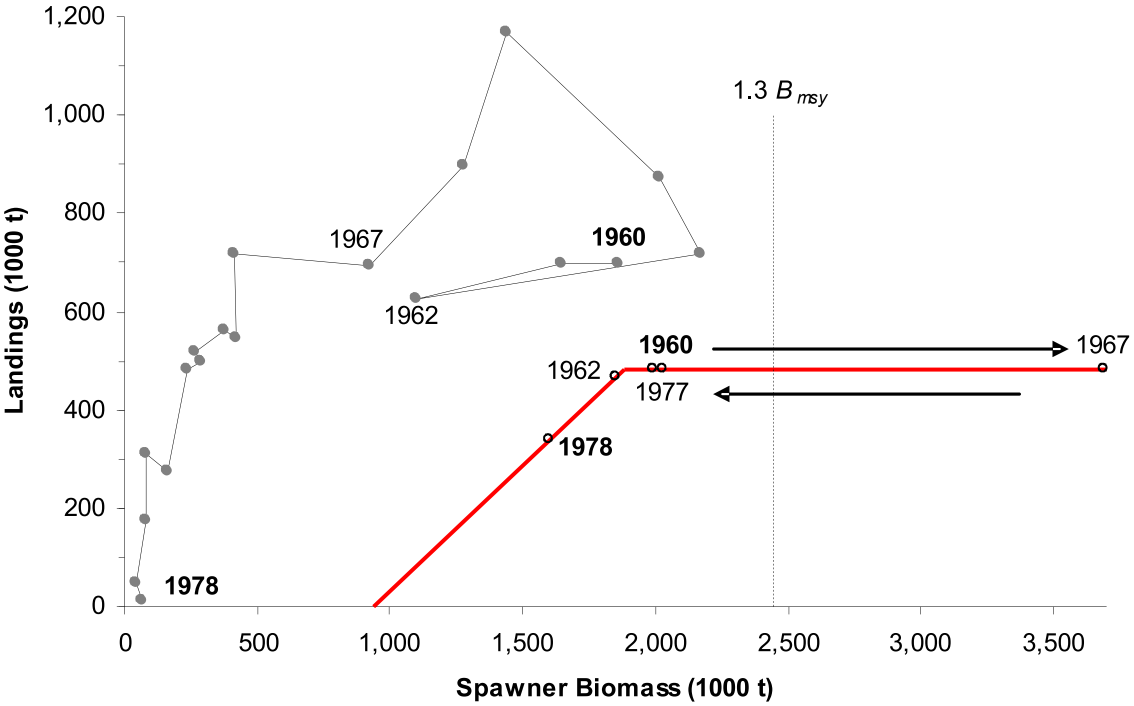

Figure 7. Time series data of North Sea Herring spawning stock biomass and reported landings, from 1960 to 1978. Management according to the proposed harvest control rules (red line) would have resulted in stock biomass and landings indicated by the open circles [her-47d3SIM.xls].

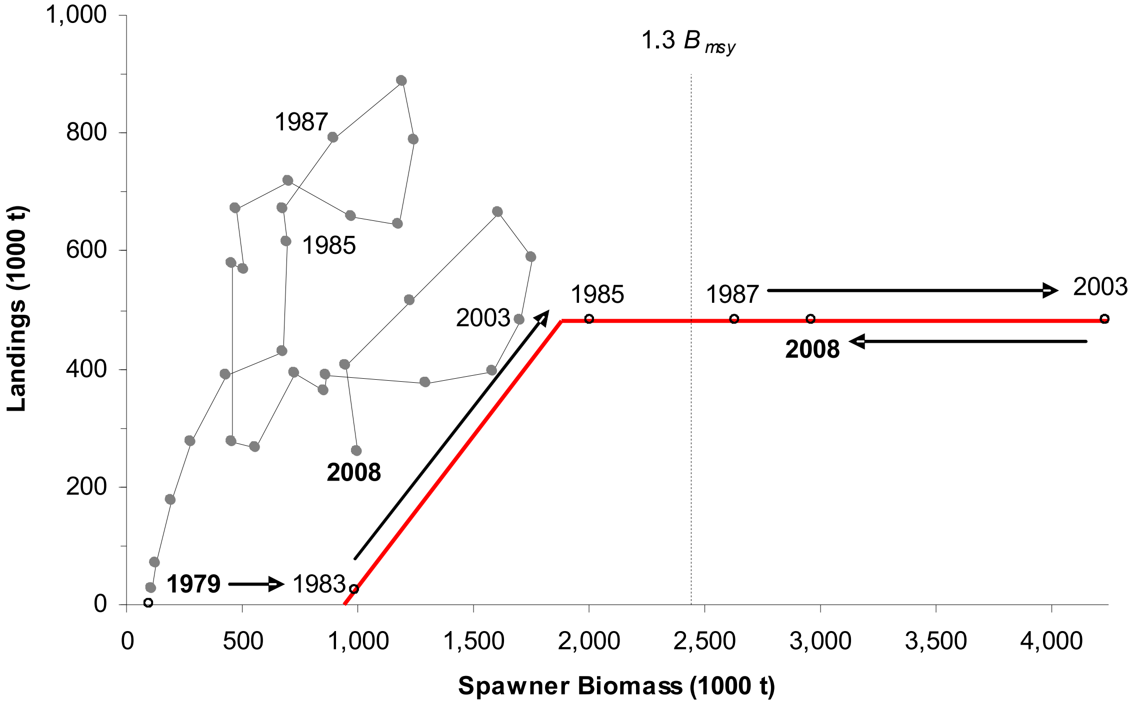

Figure 8. [her-47d3SIM_II.xls].

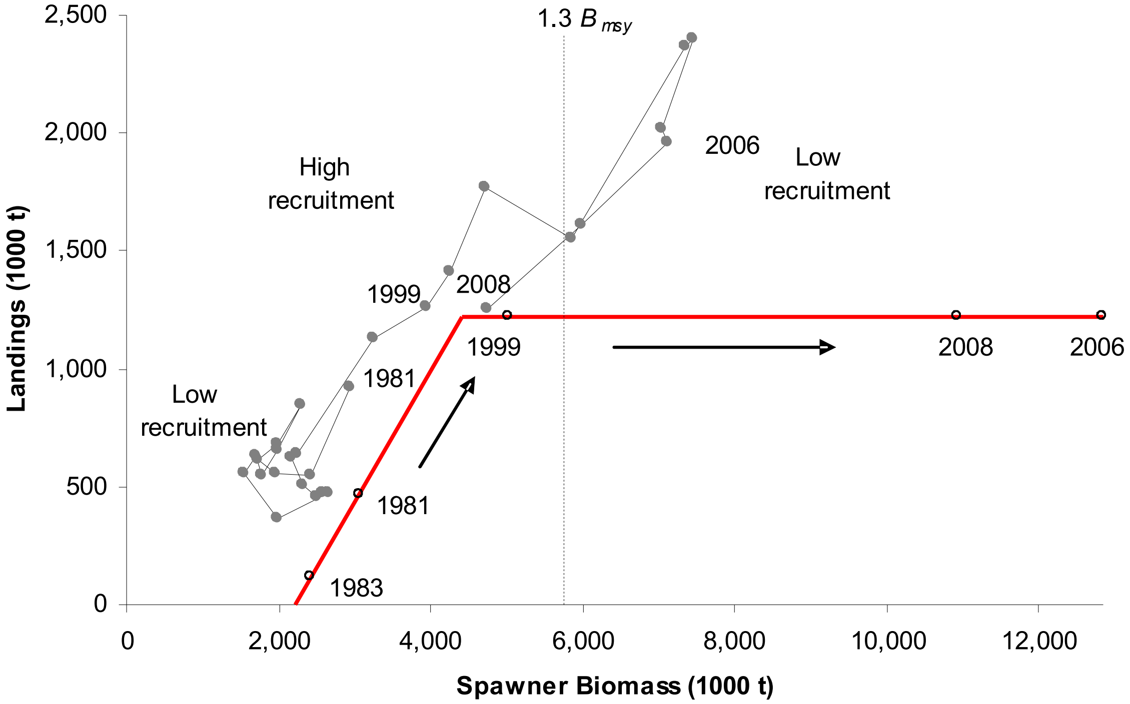

Figure 5. [whb-combSim.xls].

Appendix S1: Harvest control rules and Schaefer and Fox models

The equilibrium yield of the Fox model is given by

(1) $$Y_e = k_{\max} B(\ln(B_\infty) - \ln(B))$$

where Y_e is the equilibrium yield, k_{max} is the maximum rate of population increase, B is the biomass and B_∞ is the unexploited biomass. In the context of the Fox model, $MSY = k_{max}\, B_\infty/e$ and $B_\infty = e\, B_{msy}$. Dividing both sides of Equation 1 by MSY and expressing biomass relative to B_{msy} gives

(2) $$\frac{Y_e}{MSY} = \frac{B}{B_{msy}}(1 - \ln(\frac{B}{B_{msy}}))$$

Equation 2 was used for the generic Fox model curve in Figure A1.

The equilibrium yield for the Schaefer model is given by

(3) $$Y_e = r_{\max} B - \frac{r_{\max}}{B_\infty} B^2$$

where r_{max} is the maximum intrinsic rate of population increase. In the context of the Schaefer model $MSY = r_{max}\, B_\infty/4$ and $B_\infty = 2\, B_{msy}$. Dividing both sides of Equation 3 by MSY and expressing biomass relative to B_{msy} gives

(4) $$\frac{Y_e}{MSY} = 2\frac{B}{B_{msy}} - (\frac{B}{B_{msy}})^2$$

Equation 4 was used for the generic Schaefer model parabola in Figure A1.

We realize that more surplus production models are in use and would result in different estimates of parameters and relationships between them. However, while these models may differ substantially in their estimates of unexploited biomass, all models pass through the origin of the yield-biomass diagram and try to capture the peak in the available data, and thus their estimates for MSY and B_{msy} are rather similar (Fox 1970, Jensen 2005). An analysis of 54 European stocks showed that estimates of MSY and B_{msy} derived with different models and assumptions, such as surplus production, yield-per-recruit, and spawning-biomass-per-recruit analysis, were mostly not significantly different from each other (Froese and Proelß 2010). This means that a variety of standard stock assessment models can be used to estimate MSY and B_{msy} for the purpose of applying the proposed harvest control rules.

For many European stocks, no time series of biomass or recruitment data are available and the application of the standard methods for estimation of MSY and B_{msy} is therefore impossible. However, a number of traditional, simple stock assessment tools such as analysis of trends in fishing effort or mean size in catch show promise to provide suitable proxies. Note that currently no TAC is set for most of these data-deficient stocks, i.e., the introduction of the *MSY*-concept is expected to increase rather than reduce the number of stocks for which advice can be given.

Appendix S2: Simulated landings under the proposed harvest control rules

For simulation of landings under the proposed harvest control rules for North Sea Herring (Figures 3 and 4) we used data given by ICES (2009a) and estimates of *MSY* and B_{msy} from Froese and Proelß (2010). We took age-specific stock numbers, natural mortality, fishing mortality, weight in the stock, weight in the catch, and proportion mature as indicated by ICES. For 1960 to 1978 we only used the traits given for 1960, to avoid distortion by extreme values during the collapse of the stock. For 1979 to 2008 we took mean values over these years. For every age class, we calculated the number of fish dying from fishing N_{Ft} as

$$(5) \qquad N_{Ft} = N_t e^{-0.5M_t} - N_t e^{-0.5M_t} e^{-F_t}$$

where N_t is the number of individuals at the beginning of the year, M_t is the age-specific natural mortality and F_t is the age-specific fishing mortality. We calculated the number surviving to the beginning of the next year as

$$(6) \qquad N_{t+1} = N_t e^{-(M_t + F_t)}$$

We calculated the spawning stock biomass *SSB* for a given year as

$$(7) \qquad SSB = \sum_t^{t_{\max}} N_t e^{-0.67M_t - 0.67F_t} W_t P_t$$

where t_{max} is the maximum age considered, W_t is the age-specific body weight in the stock and P_t is the proportion of individuals that are mature at age t, where—following ICES—the factor 0.67 accounts for the fact that not all fish will survive from the beginning of the year to the beginning of the spawning season.

The TAC corresponding to a certain *SSB* was calculated as indicated under the justification of Rule 5 in the main text. The fishing mortality that would generate such TAC was determined iteratively by applying a multiplier to the age-specific distribution of F given by ICES.

For simulation of landings under the proposed harvest control rules for blue whiting (Figure 5) we used data given by ICES (2009b) and estimates of *MSY* and B_{msy} from Froese and Proelß (2010). We used mean values for natural mortality, fishing mortality, weight in the stock, and proportion mature, for 1981 to 2008. For every age class, we calculated the number dying from fishing N_{Ft} as

$$(8) \qquad N_{Ft} = N_t e^{-F_t}$$

We calculated the number surviving to the beginning of the next year as indicated for the herring. We calculated the spawning stock biomass *SSB* for a given year as

$$(9) \qquad SSB = \sum_t^{t_{\max}} N_t W_t P_t$$

The TAC corresponding to a certain *SSB* was calculated as indicated under the justification of Rule 5. The fishing mortality that would generate such TAC was determined iteratively by applying a multiplier to the age-specific distribution of F given by ICES.

Appendix S3: Harvest control rules from economic optimization

We use $Y(B)$ to denote the harvest-control-rule. Using a stochastic version of the Schaefer model in continuous time, biomass growth is governed by the stochastic differential equation

$$dB = \left[r_{\max} \left(1 - \frac{B}{B_{\infty}} \right) - Y(B) \right] dt + \sigma B \, dz \tag{10}$$

where dz is the increment of a Wiener process, i.e., the last term represents the increment of a geometric Brownian motion with standard deviation σ.

We assume stock-independent harvesting cost, as is the case for the North Sea herring (Bjørndal 1988). With an isoelastic inverse demand function $p(Y) = bY^{-\eta}$ with elasticity $\eta = 2$ and a social discount rate δ, the Hamilton-Jacobi-Bellman equation that determines optimal management of the fish stock is

$$\delta V(B) = -bV'(B)^{-\frac{1}{2}} + \left[r_{\max} \left(1 - \frac{B}{B_{\infty}} \right) - V'(B)^{-\frac{1}{2}} \right] V'(B) + \frac{1}{2} \sigma^2 B^2 V''(B) \tag{11}$$

Here we have used $V(B)$ to denote the value function, i.e., the present value of the fish stock under optimal management. The solution to this second-order differential equation is

$$V(B) = -\left(\frac{r_{\max} + \delta - \sigma^2}{2} \right)^{-2} \frac{1}{B} + const \tag{12}$$

The corresponding harvest-control-rule is

$$Y(B) = V'(B)^{-\frac{1}{2}} = \frac{r_{\max} + \delta - \sigma^2}{2} B \tag{13}$$

As proposed, the optimal harvest control rule is linear relative to the biomass. For most European fisheries, the variance of annual growth rates, expressed as percent of current stock sizes, exceeds reasonable values for the social discount rate, i.e., $\sigma^2 > \delta$. With this, the optimal expected long-term biomass is larger than B_{MSY}, it is

$$B^{\mathring{a}} = B_{\mathrm{MSY}} \left[1 + \frac{\sigma^2 - \delta}{r_{\max}} \right] \tag{14}$$

Stock-dependent harvesting cost would reduce optimal harvest even more and thus lead to an even larger optimal expected long-run biomass (Pindyck 1984).

Appendix S4: Evaluation of an *F*-based Harvest Control Rule

An ICES workshop in December 2009 on the transition towards *MSY*-Management (ICES 2010) suggested an *F*-based harvest control system, where B_{pa} would act as trigger reference point, with $F = F_{msy}$ for higher biomass and a linear reduction of fishing mortality towards zero at zero biomass. Figure A2 shows the two systems. The harvest control rules proposed in this study are more precautionary than the *F*-based system, suggesting lower landings for a given biomass, never exceeding 0.91 *MSY*, and halting fishing once the stock is outside of safe biological limits. In contrast, the *F*-based system exceeds *MSY* by far once $B > B_{msy}$ and—as presented—continues fishing until the stock is extinct.

Figure A3 shows an application of both systems to the North Sea Herring for 1960 to 1978. For the *F*-based system, the TAC was calculated from the *F* corresponding to a certain biomass. The ICES estimate of 1.3 million t biomass was used for B_{pa}. Otherwise the same procedure as described above for the herring was applied.

In comparison with the *F*-based system, the proposed harvest control rules would have built up a much higher biomass, kept the stock above B_{msy} for 17 out of 19 years, and avoided the observed collapse with a final biomass close to B_{msy} and only a 30% reduction in TAC. The *F*-based system would have kept the stock above B_{msy} for 10 out of 19 years, with a final biomass outside of safe biological limits and fluctuations in TAC ranging from 0.3 to 1.4 *MSY*.

Figure Legends Appendix

Figure A1. Representation of the proposed harvest control rule in the context of common surplus-production models, with the green parabola representing the Schaefer model and the blue curve representing the Fox model, assuming similar (here: identical) estimates for *MSY* and B_{msy}. Note that the Schaefer model is more conservative, predicting lower sustainable yields for a given biomass.

Figure A2. Comparison of a harvest control system (HCR) based on an upper limit to the rate of fishing mortality *F* (upper bold lines) with the harvest control rules proposed in this study, which are based on an upper limit to catches (lower thin lines). The blue lines represent the fishing mortality and the red lines the corresponding catches. Note that the *F*-based HCR is expected to fluctuate around B_{msy} and *MSY* (left circle) whereas the proposed HCR will fluctuate around 1.3 B_{msy} and 0.91 *MSY* (right circle). The proposed HCR is more precautionary and achieves long-term landings closer to the maximum economic yield, which is obtained at biomasses larger than B_{msy}.

Figure A3. A comparison of an *F*-based system (upper purple line) with the proposed harvest control rules (lower red line), as applied to the North Sea herring for 1960 to 1978. Arrows indicate the predicted development of the stock biomass and landings over time.

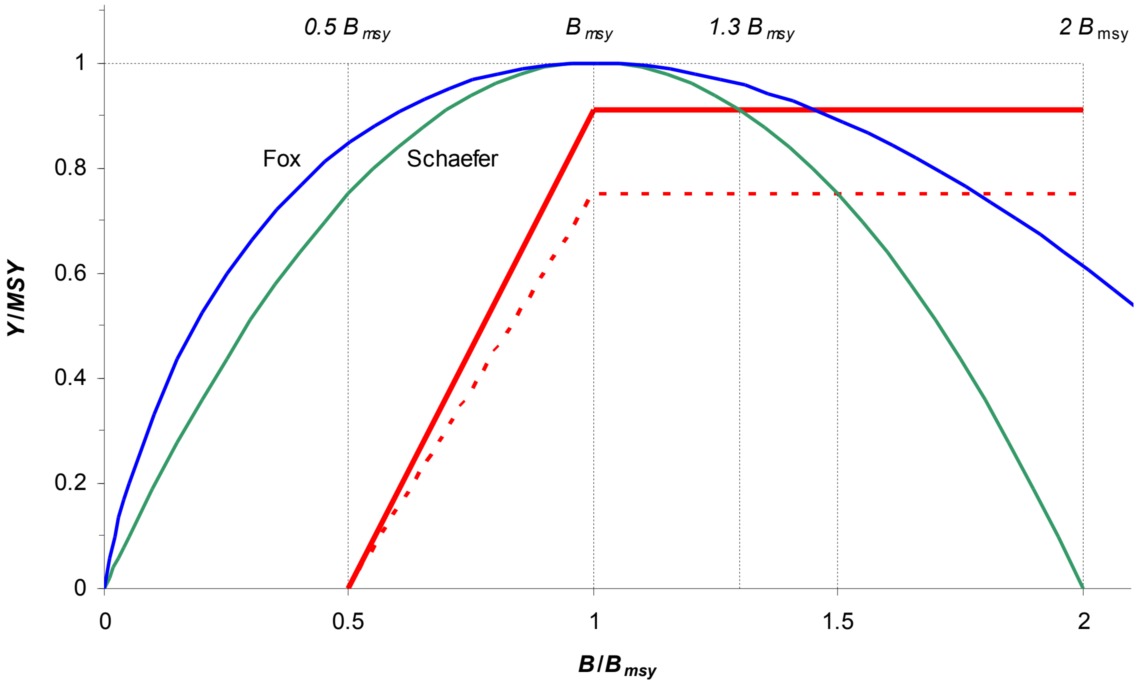

Figure A1. [HCR1_Graph.xls]

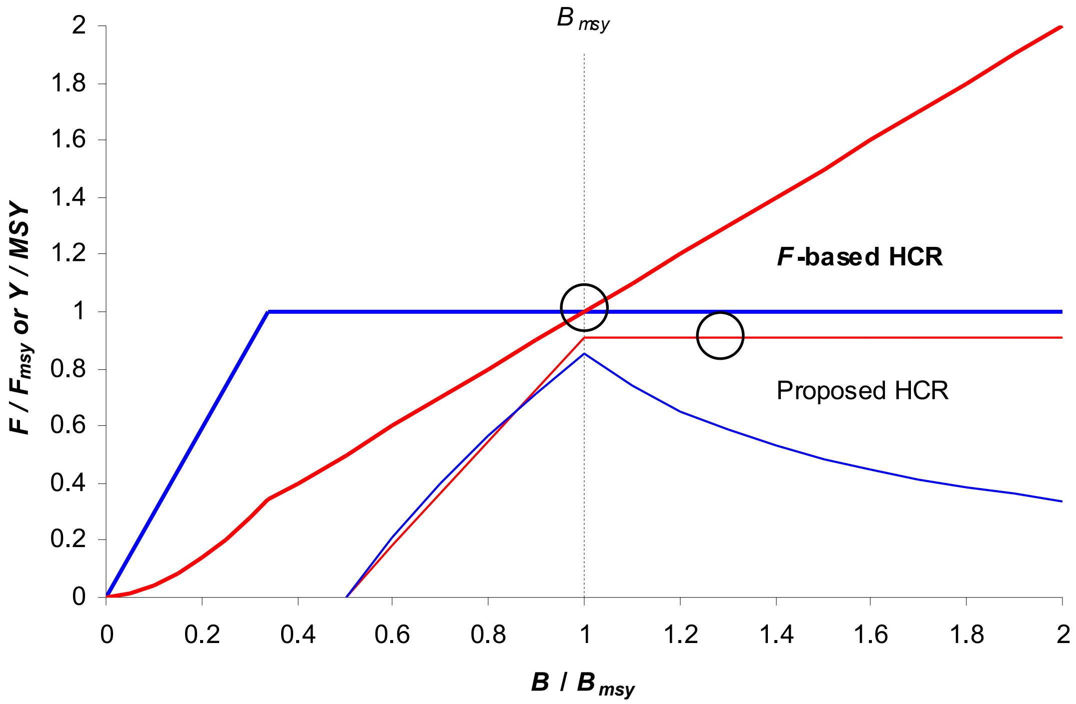

Figure A2. [F-HCR.xls]

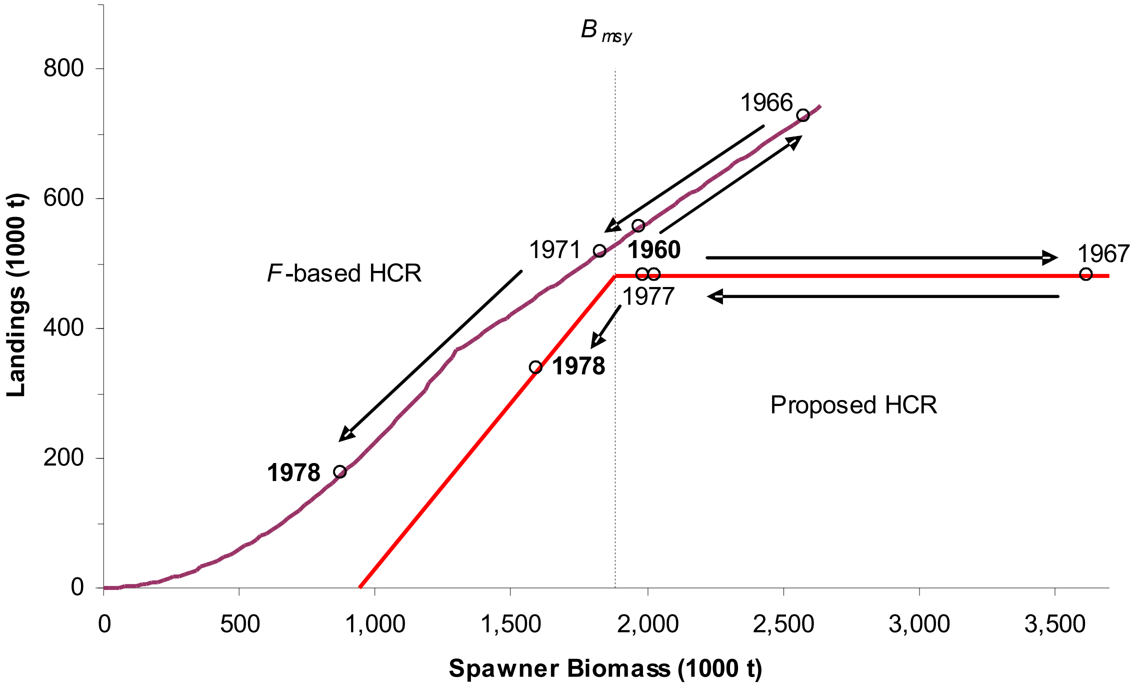

Figure A3. [her-47d3SIM_III.xls]