



Contribution to the Themed Section: 'Balanced harvest and the ecosystem approach to fisheries'

Food for Thought

Balanced harvesting in a variable and uncertain world: a case study from the Barents Sea

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Balanced fishing proposes a considerable change to current fisheries management to increase overall biomass harvested while reducing the ecosystem impacts of large-scale fisheries. However, to date, the work to a large degree has focused on simplified models, which exclude much of the variability in real ecosystems, as well as basing harvesting rates on a perfect, but unrealistic, knowledge on stock productivity. Furthermore, the published studies have avoided examining the practicalities of implementing balanced fishing in a real world. This has resulted in a gap that remains to be overcome before balanced fishing can be considered a viable management strategy for large marine ecosystems. We discuss variability in recruitment, in biology and life history characteristics, in data quality, and in fishing practice and management, and their implications for implementation of balanced fishing, using examples from the Barents Sea. We try to outline the complexities that need to be investigated as a precursor to moving balanced fishing from an academic exercise to a practical management scheme. Given the difficulties in moving to “full” balanced fishing, we highlight the importance of investigating to what extent benefits can be gained by implementing only the most achievable parts of a balanced fishing regime.

Keywords: balanced harvesting, Barents Sea, fisheries management, recruitment dynamics.

Introduction

Unsustainable harvest of marine fisheries resources is perceived to be a problem in many fisheries (Costello *et al.*, 2012). At the same time, projections from the IPCC have suggested that demands for food from the marine ecosystem will increase dramatically over the coming decades (IPCC, 2007). A number of recent papers (e.g. Garcia *et al.*, 2012; Law *et al.*, 2012; Rochet and Benoit, 2012) have promoted “balanced” fishing across all components of an ecosystem as an approach which could give a high yield of biomass with reduced disruption to the ecosystem compared with current fisheries. Here, “balanced” means that the components of the ecosystem are fished with a moderate intensity relative to their level of production (Garcia *et al.*, 2012). At the same time, by explicitly focusing on

productivity, vulnerable low productivity species are clearly highlighted and should receive protection. Variations on balanced fishing have been investigated within a variety of modelling studies, and have been often found to, in theory at least, give high yields with low impacts on ecosystem stability (Garcia *et al.*, 2012; Jacobsen *et al.*, 2014; Law *et al.*, 2015). In addition to these theoretical studies, examples of successful real-world fisheries which approximate to balanced or non-selective harvesting have been identified for small-scaled largely subsistence fisheries in lake ecosystems (e.g. Jul-Larsen *et al.*, 2003), although not for any large-scale economic fisheries. This approach is in contrast to traditional fisheries management which has focused on protecting early life stages, and targeting large commercially valuable life stages. The highly

size-selective regimes practiced by many fisheries both allow individuals to reach larger size (believed to be more productive spawners, [Trippel, 1998](#)) and approximate to the maximum yield-per-recruit predicted for each stock (potentially in a multispecies context). Although there are multiple conflicting objectives in the current fisheries management (e.g. [Hilborn, 2007](#)), a key goal of modern fisheries management is to have fisheries which are both economically and biologically sustainable.

These are also the main concepts of an ecosystem-based approach to fisheries (EAF). Norway has committed to implement ecosystem-based fisheries management (EBFM) in the North Sea, Norwegian Sea, and Barents Sea (e.g. [Anon, 2006, 2009, 2011](#)), but as is true in many other countries ([Pitcher et al., 2009](#)), it is still unclear how exactly this will be done. In particular, it is not clear where the balance between “exploiting” and “protecting” an ecosystem will be drawn. As a starting point, implementing ecosystem-based management in Norway should, according to [Pitcher et al. \(2009\)](#), be relatively straightforward as it scores high on ecosystem-based principles already. Also, the existing fisheries management already includes a number of “ecosystem components”.

Northeast Arctic cod and Barents Sea capelin are currently managed with ecosystem-based considerations taken into account, where the importance of capelin as food for cod has been considered in the capelin fishery since 1991 ([Gjosæter et al., 2012](#)), and similar harvest control rules (HCRs) for cod that take into account capelin biomass are under consideration ([Anon, 2015](#)). However, this principle is not currently applied across all managed stocks. There are also additional management measures (e.g. prohibiting bottom trawling in the region of cold water corals) which are aimed at protecting ecosystem components. One possible approach to implementing EBFM is therefore to continue adding ecosystem considerations to the existing management regime. An alternative approach would be to overhaul the management regime.

In part, the delay in implementing EBFM is due to uncertainties to what is considered as EBFM, and to what degree the principles should be followed ([Pitcher et al., 2009](#)). The gap between the single-species assessment models and the complex multispecies/ecosystem models is part of the challenge that needs to be overcome. Balanced harvesting (BH) proposes a possible approach to EBFM, where simulations so far have proved that the ecological effects of fishing balanced are less than current fisheries management ([Garcia et al., 2012](#)).

Serious consideration is currently being given to how a BH approach could function in commercial fisheries (e.g. [European Parliament Report, 2012](#)). Consequently, it becomes imperative to assess the possible impacts on these fisheries. The proponents of the balanced approach have used an ecosystem analysis perspective to identify ecosystem impacts at different harvesting levels, mostly with simplified dynamics in the stocks and fisheries (e.g. [Law et al., 2015](#)). The question then is to what degree the results can be useful for the stake-holders, researchers, and managers when it comes to a discussion of whether and how balanced fishing should (or could) be implemented in the real world. The current modelling approach has, to a certain degree, tended to underemphasize the variability (in life history characteristics, recruitment, and fishing). Factors such as variable recruitment, spawning mortality, recruitment overfishing, etc. are generally omitted (especially in size spectra models). These may be of greater or lesser importance in different ecosystems, and the match between a model and the

actual ecosystem dynamics needs to be investigated on a case-by-case basis. At the same time, the models have relied on perfect knowledge of stock productions when setting fishing pressure, whereas the typical fisheries management technique of a management strategy evaluation (MSE) would require investigating the effects of known uncertainties on the stock development.

Obviously, all models are simplifications; the unaddressed question in BH is to what extent the simplifications’ impact on the models ability to capture the real-world dynamics that would be critical for fisheries management. [Garcia et al. \(2012\)](#) based their study on Ecopath and Atlantis ecosystem models that are able to capture a wider range of the variability inherent in the ecosystems, increased structural uncertainty follows such increased complexity. In [Garcia et al. \(2012\)](#), the ecosystem models used were all documented and representative for their respective ecosystems, including variability in life histories, recruitment, and also with realistic commercial fisheries. On the other hand, the productivity in the models is easy to calculate for both stocks and size groups at any time and fisheries removal can easily be adjusted accordingly. This is a daunting task for a real-world fisheries management (as discussed below), especially when targeting as many components as possible. Hence, in some studies, BH has often been presented as a variant of the “constant F” strategy. Where a “variable F” strategy has been used ([Law et al., 2015](#)), this is based on known information on modelled productivity. For many stocks, a “constant F” is a reasonable fishing strategy if combined with protection against recruitment overfishing at low stock levels. For others (see the capelin example and the juvenile productivity discussed below), a more flexible harvesting strategy is required. In contrast to existing management strategies, the fishing pressure in BH is set based on the productivity of the species, and can vary with age/size. This has so far been done within a modelling context where productivity is known, in the move to actual fisheries management, it is less clear how BH will deal with the uncertainties in the data and implementation issues. Furthermore, the variation in fishing pressure may need to be implemented based on factors other than productivity, for example, during recovery of a collapsed stock, where an ideal fishing pressure would be as low as possible to rapidly escape the region of recruitment overfishing.

In contrast, successful modern fisheries management is heavily focused on dealing with the consequences of the variability in stock dynamics. There is especial focus on variable recruitment and the implications for the stock, which has so far been absent from the studies on BH. In contrast, traditional management has not well accounted for trophic interactions or whole ecosystem effects. In theory, BH has an appealing simplicity, and may indeed represent a potential EAF. However, in a variable and uncertain world, there is a range of issues to be addressed before BH could move into practical fisheries management.

This paper attempts to highlight some of the areas in which the variability in real large-scale fisheries has not, as yet, been included in the major balanced fishing studies, and to discuss the potential for each area to impact on the practicality of balanced fishing as a viable management strategy for large-scale fisheries. A famous quote about fisheries data comes from John Shepherd of the University of Southampton: “Counting fish is just like counting trees—except that they are invisible and keep moving”. Any attempt to move from the current “perfect knowledge” of current modelling studies to practical management for BH must address the issues arising from the uncertainties in the fisheries data, as well as the detailed biology of the stocks to be managed. We do not attempt to solve the issues raised, rather we hope to present a “road map”

of the kinds of challenges that would need to be addressed before balanced fishing could move from an academic exercise to a real-world management strategy. Nor do we assess the validity of the existing modelling studies; rather we focus on the steps between the existing modelling studies and possible implementation.

The paper uses examples from the Barents Sea ecosystem to illustrate the potential challenges, in an attempt to give a concrete aspect to this discussion. We also give examples of how these issues are currently addressed. This ecosystem represents a good test bed for BH for several reasons. First, the ecosystem is well studied, with time-series for some stocks going back up to 100 years, as well as over a decade of dedicated ecosystem surveys (e.g. [Jakobsen and Ozhigin, 2011](#); [ICES, 2014](#)). Second, this is an ecosystem which is currently mostly well managed under a traditional fisheries management approach, with a range of measures aimed at specific ecosystem considerations already included. A series of measures (quota reductions, removal of subsidies, implementation of HCRs, closed areas, gear regulations, discard bans) beginning in the early 1990s have, together with favourable climatic conditions, led to current sustainable harvests typically ~40% higher than the long-term average for the major stocks ([Gullestad et al., 2015](#)). For cod (*Gadus morhua*, Linnaeus, 1758), the top trophic, commercially dominant species in the Barents Sea, this has also meant that the age structure of the stock is approaching that of the unfished state ([Kjesbu et al., 2014](#)). As a consequence, this area represents an example of how traditional management can work, and thus what BH needs to improve on to be worth considering. Most of the large fish stocks in the Barents Sea are harvested commercially. The main demersal fish stocks [cod, haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes* spp.)] are all harvested at a rate close to MSY. Since MSY is related to the carrying capacity, and hence productivity, of each stock, this has had the unintended effect that within demersal stocks as a group, the fisheries are fairly balanced by species. However, capelin is lightly harvested, as the current harvest strategy implies that securing enough capelin as food for cod is the main priority. Herring (*Clupea harengus*) and blue whiting (*Micromesistius poutassou*), which are found in the Barents Sea as juveniles, are not fished in the Barents Sea but are harvested outside the Barents Sea as adults. Deep-sea shrimp (*Pandalus borealis*) are at present harvested at a low rate, due to market conditions. Several relatively abundant stocks which are not (or negligibly) harvested, notably long rough dab (*Hippoglossoides platessoides*) and polar cod (*Boreogadus saida*). All of this implies that fishing intensity is not balanced between all of the key species. For all fisheries, minimum catch size restrictions apply (generally the minimum size is somewhat below the average size at first maturation). Thus, harvesting within species is not balanced; rather a strong “traditional” size selectivity applies.

It should be stressed that different ecosystems and fisheries around the world are governed by very divergent dynamics. Therefore, any examination of only one ecosystem can, at best, only give overall indications of the main general issues, whereas practical management studies should be grounded in the specific dynamics of the ecosystem in question.

We first discuss the implications of the metric of success for any study on fisheries management, before highlighting these various areas of variability and their interactions. Finally, we attempt to separate the different components of balanced fishing (fish over a large part of the ecosystem, balance fishing by productivity within a species, and balance fishing between species) which form part of a

natural whole in a modelling context, but which require separate consideration when considered in a practical management context.

What metric of success?

In analysing any approach to fisheries management, consideration needs to be given to the metric used to assess the success of different approaches. In an EAF, a minimum of two such metrics are required, one for the catches (yields) and one for the impact on the ecosystem. Current BH studies typically use overall catch in tonnes for the yield metric and impact on the ecosystem size spectra slope to measure impact on the ecosystem (e.g. [Garcia et al., 2015](#)). Other metrics are also used if the realism of the modelling supports this, for instance, a requirement that no stock drops below critical limits (e.g. [Garcia et al., 2012](#)).

Maximizing biomass yield as a metric of success is problematic in the context of multispecies fishing. BH does not attempt to “maximize” yields (which would be achieved by harvesting the lowest practical trophic level and fishing out high trophic levels, e.g. [Jakobsen et al., 2014](#)), rather it presents a strategy which could give higher biomass yield than current fisheries practice, while reducing the ecosystem impact ([Garcia et al., 2012](#)). However, it should be noted that increasing biomass yield may not increase revenue or profits, much of the increased yield under BH comes from small individuals and species, which may have low value. Given the current situation in the Barents Sea with higher prices for many high trophic level species, and for larger individuals within a species, there is no guarantee that BH will increase the value of the catch ([Jakobsen et al., 2014](#)). This price-size structure is found in many economic fisheries, but there are examples in non-western markets where the lower-trophic level biomass is more extensively utilized ([Law et al., 2015](#)). In general, one would expect high-value species to occur at a variety of sizes (e.g. crabs, gadoids, molluscs), with both high- and low-value species at similar sizes. The choice of outcome to optimize (such as biomass yield) for a given ecosystem is a political question rather than a scientific one, although, as discussed later, it also raises issues with management and enforcement, and these issues may vary between ecosystems and markets.

Balanced fishing studies have highlighted that BH preserves the size spectrum of an ecosystem, in contrast to over-exploitation under a traditional selectivity regime which selectively depletes both the largest species and the largest individuals of a given species ([Garcia et al., 2012](#); [Law et al., 2015](#)), and may consequently not be a good solution for resilience in the system ([Law et al., 2015](#)). This imbalance caused by selective fisheries both changes the structure and dynamics of the ecosystem as trophodynamic processes in aquatic ecosystems are often more linked to body size than taxonomic identity ([Jennings et al., 2001](#); [Zhou et al., 2010](#); [Garcia et al., 2012](#)). Also, such imbalance can impose evolutionary pressures for early maturation and faster individual growth (e.g. [Engelhard and Heino, 2004](#); [Guénette and Gascuel, 2012](#)). It therefore seems clear that a change in the size spectra implies a change in the underlying ecosystem. However, the converse, that an unchanged size spectrum reflects an unchanged ecosystem, is not obvious. Within any given ecosystem, there will be multiple species with different life histories of approximately the same size. Ignoring the variable life histories between species raises two possible risks. The first is that some species (so-called “vulnerable” species) could have their populations reduced (or even replaced) by similar sized higher productivity species without this being identifiable from the size spectrum. A similar outcome unrelated to productivity could occur within an economic fishery where a high-value species may be partially

replaced by a lower value species if fisheries are not constrained at the species level. Beyond the loss or reduction in species, one may also change the functioning of the ecosystem if the two species perform different ecosystem functions, for example, a pelagic fish compared with a benthic feeder. Such issues can of course arise under any fishing regime; they demonstrate the need to look beyond simple size spectra to examine ecosystem functioning. An approach to avoid this limitation is to examine the detailed species balance using ecosystem models which resolve the relevant species for the system, and which has proven to be able to reconstruct historical time-series, as, for example, some of the models used in Garcia *et al.* (2012).

The challenge then for BH is to identify, for a given ecosystem, how much additional detail is required, and on which species, to simulate and monitor the fisheries impacts. While the current fisheries impact relatively few stocks, and hence a limited number of vulnerable species, a balanced fishery targeting as many stocks as possible in the ecosystem would likely require wider research and monitoring to identify the vulnerable species impacted by fisheries and to track the responses of these vulnerable species to the new harvesting regimes.

It should be noted that the very concept of “unchanged” ecosystem functioning is problematic. One would expect non-stationarity in ecosystem structure, even without considering long-term drivers such as climate change. If the goal of BH, and EAF in general, is to reduce impacts on ecosystem functioning, and ecosystem functioning is a moving target, then it is not entirely clear how the success of such a goal can be assessed. This is not currently a goal that is well addressed by any potential management and monitoring scheme.

Balanced over which components and trophic levels?

If we are to “balance over the ecosystem”, the question inevitably arises as to which parts should be harvested, and (separately) which parts need to be included in any modelling studies. In addition to fish, there is currently a harvest of zooplankton, whales, as well as small-scale harvest of seabird eggs (Jo Anders Auran, pers. comm.) in the Barents Sea and Norwegian Sea. All of these are exploited at a level below what might be considered MSY, but they are harvested. Other important ecosystem components (e.g. Eriksen *et al.*, 2012) are currently not harvested. If some parts of the system are to be excluded from the harvesting (for example, on ethical, social, or market considerations) then this needs to be specified, and if they are significant components of the ecosystem, the consequences of leaving them out should be thoroughly evaluated. There will likely always exist species and groups that to a certain degree will remain unexploited, but it is then important to be aware of their role in the ecosystem, and if possible include them in modelling studies. For example, marine mammals (significant consumers of biomass in the Barents Sea) tend to selectively feed on smaller fish, and are often able to move large distances to exploit food sources (e.g. Lindström *et al.*, 2009). A management regime that led to a higher biomass of small fish might be expected to result in a higher biomass of marine mammals (and seabirds), which in turn could reduce the expected increase in the biomass of small fish. Zooplankton can also be expected to respond to changes in the stock structure of the fish population, and in turn influence those changes. BH in general needs to specify over which parts of the ecosystem (from plankton through fish to marine mammals and seabirds), the harvesting should occur, and evaluate

the effects of only balancing over part of that system. In practice, any attempt at balancing the harvest in the large marine ecosystems is likely to be imperfect. Thus, the challenge here is of resolving the question regarding how balanced is balanced enough to reach the desired management objectives should be given high priority in modelling studies.

Measuring and predicting productivity

Whereas in traditional fisheries management, fishing pressure is typically defined in terms of catch per unit of biomass, in BH fishing pressure becomes catch per unit of overall stock productivity. In principle, individual productivity is simple to calculate from knowledge of growth and natural mortality, data on both of which are available from surveys on many stocks, and overall stock productivity is then a function of the computed individual productivities and stock biomass. Note that this stock level productivity is inherently more uncertain than stock size, since it requires stock size to be combined with additional estimates on growth and mortality. In practice, estimating productivity is far from straightforward, largely because of the noise associated with survey data. Reasonably accurate growth estimates can be obtained from survey data where age reading of the fish is possible. Where this is not possible, tagging experiments can give growth estimates. However, estimating natural mortality is more problematic. Partly, this is because BH advocates fishing over more species within the ecosystem, thus requiring data on a wider range of species than at present, and partly it relates to uncertainties in the available data. Survey data are mostly used as abundance indices, not as absolute estimates, and are inherently noisy as fish are usually patchily distributed. Spatial (both horizontal and vertical) and temporal coverage of the stock often vary between years. Thus, tracking the numbers of fish from one year to the next can be difficult, and mortality is often not easy to estimate reliably, even for data-rich stocks. This problem is exacerbated when disaggregating by age, and becomes especially problematic for the young fish, which have more variable survey catchability (i.e. relationship between survey indices and actual abundance) than the older fish. In addition, the productivity of the youngest fish is typically the most variable. Whereas older fish have a rather stable productivity in the absence of strong environmental stressors or when the stock is approaching carrying capacity, younger fish can show strong variability in both natural mortality and growth. This variability at the youngest stages is included in most current stock assessment models as variability in recruitment, and is a central part of stock assessment.

Bogstad *et al.* (2016) calculated the variability in abundance for Northeast Arctic cod at different stages for the period 1983–2009. They found that the ratio between the maximum and minimum assessed cohort abundance ranged from 285 at the 0-group stage to 7 at age 3, based on results from 27 cohorts. Most of this difference in abundance is caused by variable mortality; only a minor part is caused by initial cohort abundance (egg production). Thus, modelling productivity on early life stages is essentially equivalent to modelling recruitment at some older age. When other, longer, time-series and other stocks are considered, the difference between cohorts is even bigger—at age 3 the max/min ratio of cohort abundance is ~20 for Northeast Arctic cod and 150 for Northeast Arctic haddock (ICES, 2015). This variation in recruitment success is difficult to monitor and simulate (Helle *et al.*, 2000; Mukhina *et al.*, 2003; Ottersen *et al.*, 2013), and these difficulties can induce major uncertainties on the behaviour of the modelled stocks (e.g. Howell *et al.*, 2013). Furthermore, the variability is typically not in

the form of purely random white noise, but instead may consist of a run of poor years interspersed with one or more good years of recruitment (e.g. Eriksen *et al.*, 2011). This places challenges on both monitoring and producing realistic models of how stocks will respond to fishing pressure.

The selectivity of most traditional fisheries means that the youngest fish (the most variable and the hardest to measure) are excluded from the fishery. This selectivity means that several years of data have been collected on each cohort, giving more data to estimate the variability in the strength of the incoming year class before it enters the fishery. BH in contrast would likely set the highest fishing pressure on the youngest fish, as they typically have the highest mortalities and growth rates. Within the context of management, it is not sufficient to estimate current values, short-term predictions are required to regulate the fishery. There is a lag (typically of at least 1 year) between data being collected, that data being analysed and fisheries advice given, and that advice being implemented in the form of quotas or effort regulation. If the fishery is to target the youngest individuals (as BH does) then this implies not only predicting the coming year's productivity, but also the forthcoming year's recruitment. Directing fisheries at the younger fish would involve giving advice on the acceptable catch of, for example, next year's population of 1-year-old fish. Although most stocks show a strong relationship between spawning-stock biomass (SSB) and recruitment at very low stock levels, this does not apply for large SSBs, where recruitment is generally considered very variable and impossible to predict (Szuwalski *et al.*, 2014). Again, this is of particular concern to BH, which would target these highly productive newly recruiting fish. Finally, BH advocates including the widest possible range of stocks within the harvest, which poses questions about the availability of data on many of the previously unfished species. In moving from a modelling context, where productivity is perfectly known, to practical application, BH therefore faces a significant challenge. The productivity of the fractions of the stock which BH would target are the hardest to measure and to predict, as well as being the most variable. The fact that BH proposes extending the fisheries to more species in an ecosystem only exacerbates this problem. In current fisheries management, an MSE would be able to assess the impacts of perceived uncertainty in key characteristics on the effects of different management regimes (e.g. Punt, 2006). A similar approach would be possible for BH to assess the impacts of imperfect knowledge on the performance of a balanced management regime. We therefore recommend that any BH regime that would include fishing on the youngest individuals should be subject to an MSE-style evaluation of how the variability and uncertainty would impact on the fishery and the ecosystem.

Recruitment overfishing

Recruitment overfishing occurs when the adult population is reduced to such an extent that recruitment is also affected (e.g. Rouyer *et al.*, 2011). In the natural system, a fishing level that avoids harming recruitment in one year may have a notable impact on recruitment in a different year. Due to the high natural variability of some stocks, this impact can occur at relatively low fishing levels. One example of this is the Norwegian Spring-spawning herring in the Barents and Norwegian Seas. Improved fishing technology in the 1960s coincided with a period of good recruitment, and the stock was able to sustain very high catches. However, a subsequent period of poor recruitment meant that the stock was unable to sustain such high catches, management was insufficient to adapt to this change, and the schooling nature of the fish meant that

catch rates remained high even as the spawning stock dropped to 0.1% of its previous level (Røttingen, 2004). Modern fisheries management has a number of approaches to deal with this. One is a “hockey stick” HCR; below a certain level of the SSB, the fishing pressure is reduced (ICES, 2014). A second approach is “escapement fishing” used for short-lived species, ensuring that a certain fixed number of fish escape the fishing to spawn, and allowing (highly variable) fishing on the remaining part of the stock (ICES, 2014). In a BH, the variability in production over time in all harvested stocks (i.e. all harvested ecosystem components) should ideally be tracked to adjust fisheries to stock productivity. However, as this may not be realistic, a more precautionary approach must be adopted, with reduced harvest rates relative to stock production. How reduced remains to be tested in models mimicking different patterns of variability in recruitment and difficulties in estimating productivity.

An extreme example can be seen in the Barents Sea capelin (Figure 1). This stock has highly variable recruitment, a short life-span (~3–4 years), and a near 100% spawning mortality (Gjøsæter, 1998). The fishery is focused on the spawning migration (when the fish are at their fattest and their most concentrated). This combination means that in some years, a very large catch can be taken without harming the stock, whereas in other years, the stock is already naturally below the level at which recruitment overfishing occurs, and any catch will impair recruitment. A fishing pressure related simply to the productivity of the existing fish would miss large amounts of catch in good years, while impairing recruitment in poor years, despite providing a small catch. Thus, the fishing pressure should follow the overall development of the stock (and its relation to recruitment overfishing and the spawning mortality) rather than simply the productivity or biomass of the existing fish. In the current fishery, an escapement strategy is used, ensuring that there is a specified (95%) chance to avoid recruitment overfishing in any year (Gjøsæter *et al.*, 2002). It is unlikely that any fishing regime that does not account for these life history and ecosystem effects will be able to efficiently harvest this stock.

A second example from the Barents Sea comes from two species of redfish, *Sebastes mentella* (Travin, 1951) and *Sebastes norvegicus* (Ascanius, 1772). These are both long-lived, low productivity species that in theory could sustain similar catch rates. However, both species have experienced overfishing in the past, and both have shown alternating extended periods with good and poor recruitment. Thus, the *S. mentella* stock current has a relatively high SSB, but is currently in a period of ~10 years in which very poor

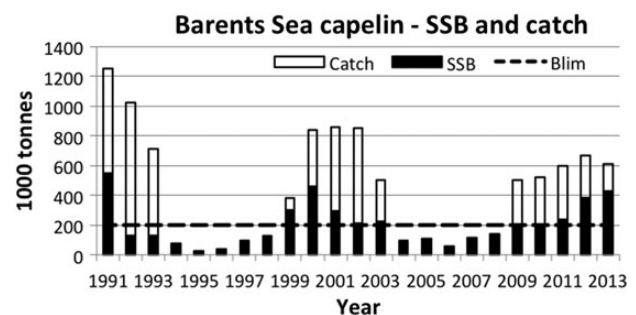


Figure 1. Biomass and catch of Barents Sea capelin at the end of the spawning migration estimated from the assessment model (Gjøsæter *et al.*, 2015, Table 1). The approximate level of biomass required to ensure optimal recruitment (B_{lim}) is shown as a dotted line.

past recruitment means that there will be few fish maturing into the spawning stock (ICES, 2014). Fishing levels are therefore currently set lower than would be the case considering only the SSB or the productivity to avoid recruitment overfishing in this period. Conversely, *S. norvegicus* has been through an extended period of poor recruitment and is currently in need of rebuilding. Again, recommended fishing levels are well below what would be expected from the current productivity. These two species represent fish of similar size and overall productivity, but their recent stock and recruitment histories dictate that they require different management. The challenge here is for BH strategies to be adapted beyond using the productivity of the targeted fish (either at a given time or averaged over time) to take account of the historical variability and so avoid the recruitment overfishing which would reduce long-term yields.

Variable fishing

Oceanic commercial fishing typically consists of a number of different fleet sectors, with different vessel and gear types, operating from multiple ports, targeting different stocks over different areas. Each sector can be expected to organize their fishing in such a way as to attempt to maximize their profitability within the management constraints placed upon them. At a minimum, the fishers must achieve break even (possibly with the aid of subsidies) to continue fishing. The task for management is then to ensure that these constraints (quotas, effort restrictions, gear regulations, discard bans, etc.) combine to achieve the desired management outcome. There is inevitably a tension between the short-term economic interests of each individual fishing vessel and the long-term management goals, which any management scheme (including BH) needs to address. To ensure that fishing would be “balanced” in some way over species and size categories within each species, management would have to ensure that the catch of each size category of each species approximates the “desired” balanced catch.

It should be stressed that in large-scale commercial fisheries, fishing is not a uniform activity. Fishers choose the vessel and gear they use, and the times and locations of their fishing, and will aim to maximize some outcome (typically profitability). There is also a variable relation between effort and catch as stock size varies. For some species, there can be an almost linear relation between stock size and catch per unit effort, while for schooling species such as herring, the catch rates can be almost unaffected by stock size (Brierley and Cox, 2015). These variabilities combine to give the possibility to “fine tune” fishing patterns to achieve given management objectives, and to minimize the difficulties of fishing stocks of different productivities, life histories, and recent recruitment patterns. However, it also means that such fine tuning is an ongoing, and potentially highly complex, process.

Where the catch per unit effort is closely related to stock size, effort-based fisheries management can, to some extent, avoid these difficulties (although the stocks should still be monitored to ensure that recruitment overfishing is avoided). However, while effort-based management can work well for single-species fisheries, it is more difficult for ecosystem-based mixed fisheries, where fishers are able to switch their targeting between species and size categories. These difficulties are particularly acute where (as is generally the case) there are price differentials involved in mixed species fisheries. The fishers have an obvious incentive to target the most valuable portion of the stock, and in the absence of species-based quotas, there is no restriction on them doing so.

There is obviously a challenge to management (BH or otherwise) that species of different productivities can be caught in the same

hauls, and this could be expected to increase as the range of the stocks targeted increases. As described above, there is an additional issue that a stock with a recent period of poor recruitment can be more vulnerable to fishing than its productivity might suggest. Finally, some species may have different value and/or catching costs if caught at different times of the year (especially spawning migration fisheries), which impacts on the size caught, the profitability of the fishery, and the mix of “bycatch”.

The quality of scientific knowledge is generally highly variable between and within stocks. These variabilities in data quality make giving advice on harvesting some “data-poor” stocks difficult under current management. Under a precautionary approach and a maximum allowed catch, reduced data quality should imply reduced catch. It is not so clear how reduced data quality should be handled under the target (“neither too high nor too low”) fishery needed to achieve a balanced harvest.

The challenges here for BH are to move from a theoretical model in which fishing is directly specified to an implementable management scheme.

Within a theoretical approach, or in a size-spectra model, there is little difference between balancing fishing effort between species and balancing over the different length classes within each species. However, in management, the challenges raised by the two approaches are very different. Balancing between species is something that can be done under the current management system of setting quotas (in either biomass or effort) for individual species. There remain the challenges described above in assessing what the appropriate level is for each stock, as well as mixed fisheries interactions, making some combinations of fishing level problematic to achieve, but in principle this simply requires varying the quotas within current management systems. Balancing over size categories within a species becomes much more problematic. As noted above, assessing the youngest part of the stock is a challenge, so even calculating how much to take of each size category is difficult. There are also often practical challenges in catching the smallest individuals, and it is rare that a given gear would be appropriate for all sizes of a given species. It may be that for many species, one could balance over some range of sizes, but not over the smallest individuals. It is not currently clear how much of the proposed benefits of balanced fishing would be lost if the smallest, most productive, size categories for each species were to be excluded. Coupled to these practical difficulties is the fact of price differentials, where large fish of a given species are often worth more than small fish of the same species, which gives fishers an incentive to concentrate on the more profitable size categories. A management scheme which relies on the goodwill of fishers is likely to fail in face of such incentives. The challenge then for BH is to identify the practical management measures needed to ensure that the catch in a given ecosystem will approximate to a balanced harvest.

As discussed above, fisheries target a number of species and size classes in the Barents Sea, e.g. the fishery on NEA cod is almost exclusively on fish age 3 and above. They also include, in addition to harvest of shrimps, small pelagic fish, and large demersal fish, several trophic levels, including a harvest for small copepods was initiated (Broms, 2015), and there is some harvest of bird eggs and whales. Kolding *et al.* (2012) used the parameterizing of the Ecopath ecosystem models to investigate how harvest was associated with stock productivity in marine ecosystems around the world. Their results demonstrate that the harvesting of the Norwegian and Barents Seas (combined in the relevant Ecopath model, parameterized to reflect the ecosystem state and harvesting in 2000) is

harvested more balanced than most marine systems, in terms of harvesting many of the targeted stocks proportionally to their productivity (Figure 2). Nevertheless, there is no balance within species (most fisheries have a minimum catch size) and many components and size classes of the ecosystem are still not harvested. The question remains, has this inadvertent partial balanced harvest contributed to the positive development of the fish stocks and ecosystem resilience in these systems? In practice, any attempt at balancing the harvest in this, or any, large marine ecosystems is likely to be imperfect. Thus, resolving the question regarding “how balanced is balanced enough” to reach the desired results of the management regime is of importance for evaluating if a particular management regime can achieve those objectives.

Summary

Balanced fishing is a proposed regime which has the potential to achieve an EBFM. Balanced fishing has been shown to be effective in giving a high yield in kilogrammes (though not necessarily in value) with low impacts to the ecosystem size spectra in a few small-scale fisheries and in various model studies where stock production is easily available and harvest easily adjusted to production (Jul-Larsen *et al.*, 2003; Garcia *et al.*, 2012; Jacobsen *et al.*, 2014; Law *et al.*, 2015). However, it is not clear that these results translate to

large-scale commercial ocean fisheries. There are a number of challenges in moving from a model, with simplified dynamics and perfect knowledge, to practical fisheries management. Fish productivity in the real world is so far difficult to estimate, with estimates especially uncertain for the youngest individuals, and especially within a management time frame where short-term (1–2 years) predictions are typically required. In addition, models are only to a certain degree able to capture the variability in the real-world system. This mismatch is the main challenge to current fisheries management, and would probably continue under a balanced fishing regime. Variability in life history between species, in temporal recruitment patterns, and in fishing patterns all need to be considered with greater degrees of realism before any generalizations can be drawn about the practical implementation of balanced fishing in real large-scale fisheries. The ongoing attempt to include greater realism in modelling studies of BH (Garcia *et al.*, 2012; Law *et al.*, 2015) is therefore critical to being able to model more the possible outcomes of any change in harvesting regime, and needs to be developed further. The issue of how to move from a “perfect knowledge” modelling environment to an “imperfect knowledge” management regime remain to be addressed. It is often not clear from the current literature how much of the predicted gain in catches and in maintaining ecosystem structure is due to just expanding

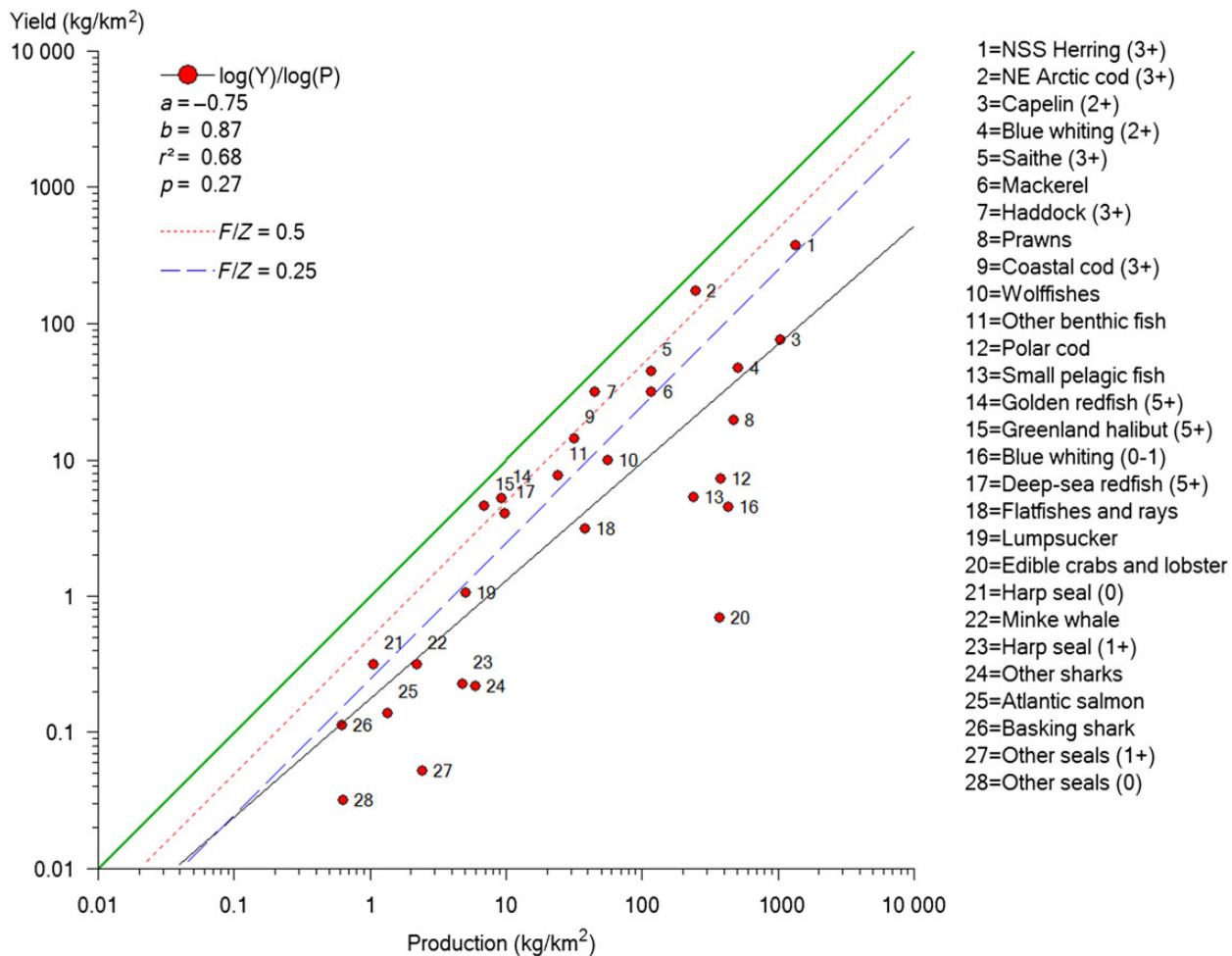


Figure 2. Harvest relative to production for the 28 stocks or groups harvested in the Norwegian/Barents Sea extracted from an Ecopath model for the two seas (Kolding *et al.*, 2012) parameterized to reflect ecosystem state and fisheries in year 2000. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

the species diversity caught (which is already occurring as species become economically viable to harvest), how much is due to balancing the harvest between harvested species (which is also practical under current management techniques) and how much is due to the specific balanced exploitation pattern over size categories of “all” ecosystem components (which is more difficult to implement and enforce). This is addressed in a theoretical context in Law *et al.* (2015); we would argue that this should become a more general practice, as the results are likely to be ecosystem-specific. Ecosystem models such as Atlantis or Ecopath with Ecosim give the possibilities of studying the effects on a more detailed level, including the socio-economic effects. The practice of utilizing different model classes (as in Garcia *et al.*, 2012) is critical in being able to incorporate as wide a range of variability as possible in the modelling studies. Equally, the ability to vary fishing pressure within the model (as in Law *et al.*, 2015) is an important step forwards that should be more widely adopted, and should be further investigated in the context of uncertain data. To date, no management structures have been proposed that could implement “full” balanced fishing in a large marine ecosystem. Although some of the previously mentioned studies have begun to increase the biological realism, the studies have remained confined to simulations with highly simplified removals, where the productivities have been known. We applaud the efforts to increase the biological realism, and would encourage focus on the effects of the uncertainties in fisheries and scientific survey data on the modelling of fish stocks in specific ecosystems. Furthermore, the focus has largely (though again not entirely) been the total biomass, and not the effect of the individual ecosystem or fisheries components. In addition, greater realism is required on the economic aspects of any change in fisheries management, given the high variability in price between different species within any ecosystem. There are thus several key questions that have not yet been fully addressed:

- (i) Do we actually want to evaluate a management framework on biomass caught rather than value caught (or some other socio-economic measure)?
- (ii) Do the modelling studies conducted so far remain robust when the components/stocks are studied at an individual level?
- (iii) How can BH deal with the uncertainty in the estimates of the production of each species/trophic level for management, especially for the youngest individuals, and how should the mismatch between the variability in the models and the real world be taken into consideration?
- (iv) Are there viable management structures that could be used to implement balanced fishing in large marine ecosystems?

Finally, given the complexities of attempting to implement a complete paradigm shift in fisheries management, one further question becomes of interest if balanced fishing is to move beyond the realms of an academic exercise: how much of the benefits of balanced fishing would be achieved by only implementing the “easiest” parts of BH? For example, what would be the outcome of balancing only between a limited number of species (but not by size category within those species), or of balancing only over those size ranges for which accurate data are available for each stock?

We do not intend to argue that balanced fishing is impossible to implement in the real world, but rather to point out that it needs more research, and with that research focused on bridging the gap between modelling and management, incorporating the effects of

the uncertainties inherent in fisheries management data. This is not a criticism of BH, rather it is an inevitable step in the development of the theoretical approach. For some of the issues raised here (e.g. protecting and monitoring vulnerable species), BH studies have begun to address the issues, and the challenge is to apply the techniques to particular ecosystems. In other cases (e.g. how to handle uncertain data), more research is needed. In particular, it is critical to investigate whether it is possible to construct a viable management structure for balanced fisheries. To date, this has not been done. Without some concrete proposals on potential management regimes, balanced fishing remains very much an academic exercise with less real-world applicability.

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