A combined Gadget/FLR model for management strategy evaluations of the Barents Sea fisheries

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A biologically sensible age–length structured multispecies Gadget model (incorporating minke whales, cod, herring, and capelin) for the Barents Sea—acting as the operating model—has been linked to Fisheries Library in R—acting as the management procedure—to perform management strategy evaluations. Assessments may be run using either XSA, survey-based methods, or by taking modelled stock numbers directly. Total allowable catches are based on the assessment and harvest control rules (HCRs). The tool can be used for assessing a wide variety of sources of uncertainties within the assessment process. Model structure and linkages are described and a fit to the historical data is presented. A base case of future dynamic (non-steady state) stock trends, based on the existing HCRs, is compared with alternative management and environmental scenarios. The relative differences for each scenario in terms of stock size and catches highlight a number of uncertainties within the biological and fisheries system. The results indicate that the current management rules are robust to the range of scenarios examined so far.

Keywords: Barents Sea, capelin, FLR, management strategy evaluation, minke whales, multispecies modelling, northeast Arctic cod, Norwegian spring-spawning herring, operating model.

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Introduction

The management of the commercially important Barents Sea stocks is based on agreed harvest control rules (HCRs) and annual stock assessments. Although species interactions in the area are strong, management is mostly based on single-species models. One notable exception is the capelin (*Mallotus villosus*), where predation by cod (*Gadus morhua*) is taken into account (Gjøsæter *et al.*, 2002; ICES, 2009b). Therefore, a tool is needed that models the fish populations, their interactions, and the assessments, to evaluate the performance of the different HCRs and to predict how environmental change might interact with management regulations. When making predictions, the uncertainties involved must also be considered. These uncertainties may arise not only from random sampling error in the data, but also from model formulation, bias in data collection, misreporting of catches, deviations from the agreed HCRs, and environmental change. We present a single tool that can assess a wide range of different uncertainties, to identify their relative contribution to the overall uncertainty. We also present a range of scenarios that highlight key results for the Barents Sea ecosystem and illustrate the overall utility of the tool.

The tool links a multispecies Gadget operating model (Begley and Howell, 2004) to assessment models available from Fisheries Libraries in R (FLR, an extension of the R programming language; Kell *et al.*, 2007) and management rules to allow a full forward simulation of the interacting stocks in the Barents Sea. This integrated Gadget/FLR model is used to produce medium-term projections under the current management and environmental conditions and to assess the likely impacts of a range of different fishing and management scenarios. The combination of a process-driven, biologically sensible operating model with an explicit assessment and management model allows the uncertainties in our knowledge of the different parts of the system to be examined in more detail than has previously been possible. The two submodels are structurally different. We consider that this is a critical advantage, because it allows for model misspecification as one source of possible error (Kell *et al.*, 2007) and therefore provides a more realistic mirror image of the actual situation than if they had the same structure. The system also accounts for the lag between data collection (information from modelled surveys and catches) and the implementation of the TAC based on the assessment.

The operating model describing the interactions through predation (Figure 1) includes cod, capelin, herring (*Clupea harengus*), and minke whales (*Balaenoptera acutorostrata*), but the scenarios presented here focus mainly on the fish component. In addition to predation by cod and minke whales on adult and juvenile fish, predation by herring on capelin larvae is also included.

The multispecies interactions in the Barents Sea have been studied extensively. The capelin stock has collapsed three times during the past 25 years (1986–1989, 1993–1997, and 2003–2006). The first collapse in the 1980s appears to have had both clear causes and clear effects (Hamre, 1994; Gjøsæter *et al.*, 2009). The abundance of young herring in the Barents Sea preying on capelin larvae (Huse and Toresen, 2000) resulted in a capelin recruitment failure (Gjøsæter and Bogstad, 1998). Predators were affected in various ways. Cod experienced

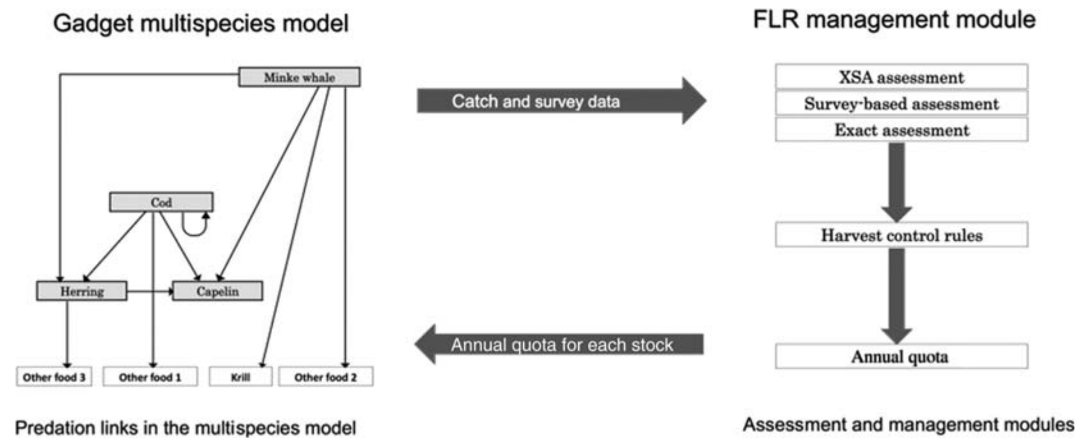

Figure 1. Structure of Gadget/FLR multispecies model, indicating modelled species and interactions (left-hand side), assessment model (right-hand side), and data flows (arrows). Predefined non-modelled "other food" boxes are also indicated. All thick arrows may be represented with associated errors.

increased cannibalism, growth was reduced, and maturation was delayed (Mehl and Sunnanå, 1991). These interactions between cod, capelin, and herring have been crucial elements in most multispecies models set up for the area (Bogstad *et al.*, 1997; Schweder *et al.*, 1998, 2000; Hamre, 2003; Tjelmeland, 2005; Lindstrøm *et al.*, 2009). However, the later capelin collapses provided additional knowledge (Gjøsæter *et al.*, 2009; Hjermann *et al.*, 2010), indicating that these species interactions are less straightforward than they appeared to be a decade ago. Recent analyses (Hallfredsson and Pedersen, 2009; Pedersen *et al.*, 2009) indicate that an abundance of juvenile herring in the Barents Sea is a necessary, but not sufficient, condition for a capelin collapse (Hjermann *et al.*, 2010). 0-group cod (Hallfredsson and Pedersen, 2007) and sandeel *Ammodytes marinus* (Godiksen *et al.*, 2006) have been observed to prey heavily on capelin larvae, and the analysis by Hjermann *et al.* (2010) indicates that predation by 0-group and older cod may also affect capelin recruitment substantially.

Results from the Gadget/FLR model are presented from 1990 on. Therefore, the model covers the period of the second and third capelin collapses in the Barents Sea, where the impacts on the predators have been relatively minor. Moreover, Norwegian spring-spawning herring have gone through a period of stock recovery in the 1980s and 1990s, and it is currently considered to have recovered to a level not far from the historical maximum (ICES, 2009c). Consequently, the time-series of data from a fully recovered stock available for tuning the model is limited; this implies that the prediction of future recruitment of herring may be more uncertain than for cod and capelin.

Methods

Operating model using FLR

FLR is a generic toolkit for management strategy evaluation (Kell *et al.*, 2007), capable of running various combinations of management procedures (incorporating different assessment models) and operating models. In our application, cod is assessed using XSA (Shepherd, 1999) with cannibalism included (ICES, 2009a), whereas capelin is assessed assuming the acoustic estimate in September to be an absolute estimate of age 1 and older fish (Gjøsæter *et al.*, 2002). Both assessments are consistent with the standard stock assessments done by ICES (2009a). The resulting cod assessment is used as an input to a simplified version of the agreed HCR (ICES, 2009a) to produce a TAC for the following year. This TAC is used as an input into the Gadget simulation model as the cod catch for the following year. For herring, the assessment is assumed exact. Whales are harvested at a constant level of 600 animals per year, which is closer to the recent average. Table 1 describes the (approximations of) current HCRs for the different species.

Table 1. HCRs used in the simulations for the base case.

		Control rule	
Stock	**Trigger**	**SSB > trigger**	**SSB < trigger**
Cod[a]	SSB $= B_{pa} =$ 460 kt	$F = 0.4$	F linearly reduced to $F = 0$ at SSB $= 0$
Capelin	SSB = 500 kt	$C = 0.8$ (SSB − 500 kt)	Zero catch
Herring[b]	SSB $= B_{pa} =$ 5 million t	$F = 0.125$	F linearly reduced to $F = 0.05$ at SSB = 2.5 million t; $F = 0.05$ below SSB = 2.5 million t.
Minke whale	None		$C = 600$ individuals year^{-1}

[a]F refers to mean for age groups 5–10.
[b]F refers to mean for age groups 5–14.

Extensions have been written to link the existing suite of assessment models implemented in FLR to Gadget, which acts as the operating model (Figure 1). The combined model can also simulate management rules based on effort control, but all stocks examined here are managed using catch controls. In principle, each data flow (indicated by thick arrows) has associated errors. The system can therefore handle data-collection errors, assessment errors, mis-implementation of HCRs, and poor enforcement. However, no errors have so far been included. This means that the currently derived results are relevant to identifying and comparing factors influencing stock responses to existing HCRs and environmental scenarios, but incorporation of stochastic elements would be required to run risk assessments or management strategy evaluations.

Gadget multispecies model

Gadget (Begley and Howell, 2004; Begley, 2005) is a software tool that has been developed to model multispecies systems, including the impact of both predation among species and harvesting by fisheries, simultaneously allowing for spatial disaggregation by species and disaggregation by fleets. Gadget simulates these processes in a biologically plausible manner, and uses built-in optimization routines to fit the modelled ecosystem to the available data in a statistically rigorous manner. The software and full documentation is available online at http://www.hafro.is/gadget. It provides a toolkit for building a flexible multispecies operating model that can be coupled with assessment models for evaluating fishery management systems and for examining potential effects of a range of natural (e.g. inflow, predation, . . .) or anthropogenic (e.g. climate change, pollution, . . .) forcing factors on a simulated system (Plagányi, 2007).

The multispecies model employed is based on Lindstrøm *et al.* (2009), but several important extensions have been added. Specifically, herring predation on capelin larvae has been incorporated as one of the main factors believed to control capelin recruitment success. The inclusion of predation on early life stages allows examination of impacts at different phases during the life cycle. Another extension is the inclusion of predation by cod on juvenile herring, because this source of mortality may be substantial (Johansen *et al.*, 2004). Links have also been built to transfer information between Gadget and FLR. The model is tuned to data from 1985 to 2008, with the first five years being treated as a "burn-in" period, to avoid focusing on transient behaviour at the start of a model run. Of course, the model must produce realistic variations in stock size and structure, both during the historical period and in the forecasts. Typically, all fish stocks are characterized by sporadic years of good recruitment and stock sizes vary accordingly. For cod and in particular herring, this results in populations dominated by a few cohorts, for the short-lived capelin to large variations in stock size. These variations in the different stocks drive the interactions characterizing the multispecies system. Modelling recruitment as constant or only dependent on spawning-stock biomass would fail to capture stock dynamics, so the utility of such a model would be questionable. Cod, capelin, and herring are modelled as having a closed life cycle, with a Beverton–Holt equation describing the relationship between spawning-stock biomass and recruitment. An annual parameter is then applied to allow recruitment to vary such that it matches the historical reality. This parameter has been applied as a larval mortality, but it represents a year factor determining recruitment, rather than having a specific biological meaning. For forecast runs, the same stock–recruitment relationship is applied and the year factors for the past 20 years are sequentially applied to the next 20 years. This assumes that the historical recruitment pattern will be largely repeated, but the absolute magnitude will depend on the simulated stock sizes. This approach has obvious limitations, because the potential of the appearance of good and bad year classes is not randomized. However, it allows for incorporating a realistic autocorrelation within species and realistic correlations between species.

Previous multispecies age–length-structured model studies in the Barents Sea have been carried out both with minke whales (Bogstad *et al.*, 1997; Schweder *et al.*, 1998, 2000) and without whales (Hamre, 2003; Tjelmeland, 2005), but only some parameters related to predation and food selection were formally estimated. The main advantage of the approach developed by Lindstrøm *et al.* (2009) and followed here is that most parameters are estimated using a formal goodness-of-fit criterion. The linkage of the multispecies operating model to the different single-species assessment models is new.

Results

Base case

The base case represents the model fitted to the historical data (Figure 2) and projected forward for 20 years under the agreed HCRs (Table 1). For the historical period, the reported herring and capelin landings have been assumed to represent the total catch taken. For cod, an adjustment has been made to account for unreported landings following the procedure used by ICES (2009a), whereas unreported landings were assumed negligible in the forecast runs. The agreed cod management plan states that the quota should not change by more than 10% from 1 year to the next (ICES, 2009a). In practice, the 10% limit was exceeded in 2009, when the stock was increasing by more than 10%. It is equally possible that in the event of a rapid stock decline, the limit will also be exceeded, to protect the stock. In

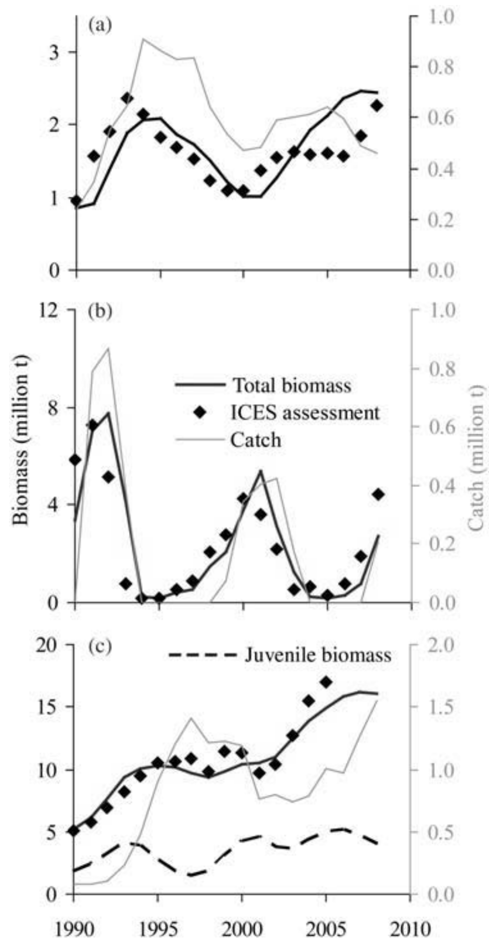

Figure 2. The historical development of the modelled stock biomass for (a) cod (age 3+); (b) capelin (age 1+); and (c) herring (total: age 1+; Barents Sea: juveniles). The total catches for each species (right-hand scale) and the biomass estimates from ICES (2009a, c) assessments are also illustrated.

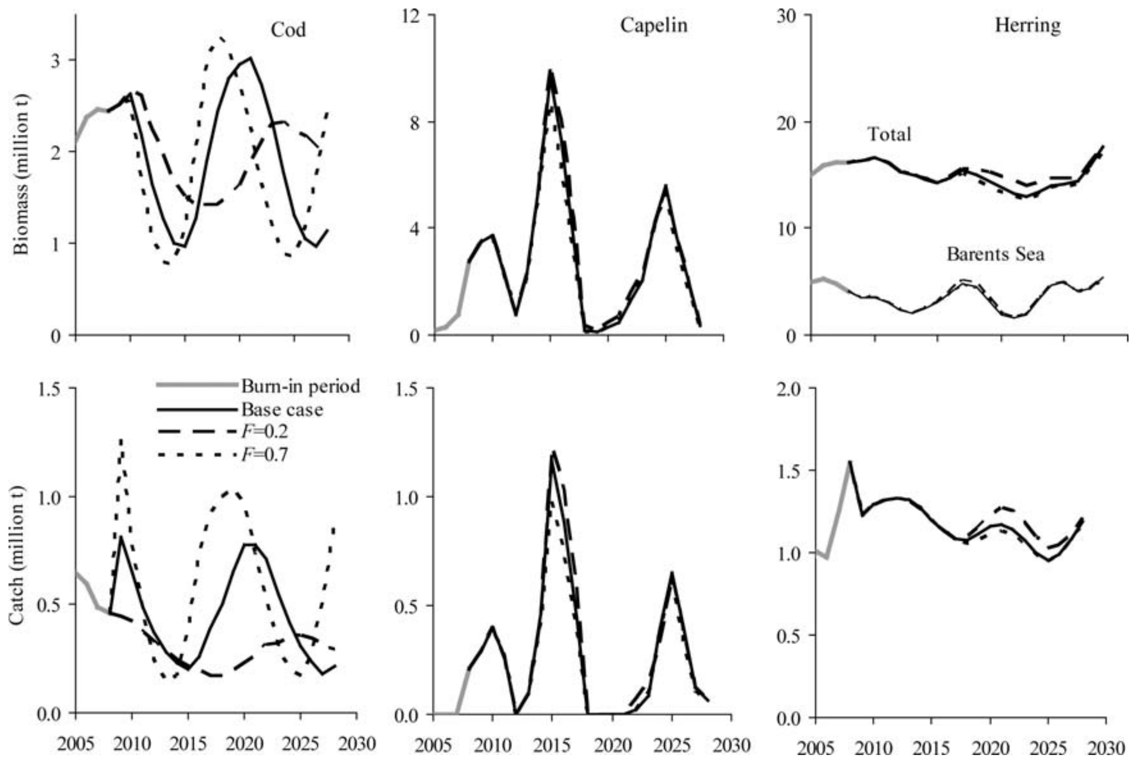

Figure 3. Projected stock biomass (upper panels) for cod (age 3+), capelin (age 1+), and herring (upper line: age 1+ and lower line: juveniles in Barents Sea), and (lower panels) projected total catch for each species, under three different cod HCRs: the base case with $F = 0.4$ when SSB $> B_{pa}$, and for $F = 0.2$ or $F = 0.7$, when SSB $> B_{pa}$, respectively. The last years of the "burn-in period" preceding the forecast are also illustrated.

both cases, scientific judgement and intervention by politicians would determine the precise outcome of the annual decision-making process, and this cannot be readily modelled. Therefore, we chose to exclude any constraint on the rate at which quotas can change between years.

Recruitment forecasts depend on the stock size and structure in the most recent years of the hindcast model, where the uncertainty is highest, and on the recurrent annual pattern imposed, without allowing for effects of environmental factors. Therefore, it should be emphasized that the forecast part just serves for comparison with other scenarios, rather than representing an actual prediction of stock sizes and catches.

Forward simulation scenarios

As examples of the type of issues that can be investigated, we focus on three different sources of uncertainty. The first relates to the agreed HCR. During a period stretching 20 years into the future, the agreed rules are likely to be reviewed at some time and possibly revised. In addition, the actual management could deviate from the agreed rule because of political pressure to set the quota higher or lower than the rule would prescribe. Therefore, a first suite of scenarios examines variations in projected stock levels and catches of all species (relative to the base case) because of changes in the cod HCR. A second source of uncertainty concerns the likely level of herring recruitment after the recent recovery of the stock, because the time-series is still too short to evaluate its effects. Although herring only spend their first 3–5 years of their life in the Barents Sea, they interact with other species, representing a relatively minor prey item for minke whales and cod, but they are highly effective predators of capelin larvae. Therefore, we present the effect of varying the recruitment level of herring. Finally, there is also uncertainty about future changes in environmental driving factors. Although there is broad agreement that temperatures in the Arctic are likely to rise over the coming decades (IPCC, 2007), the potential effects of this on the fish stocks of the Barents Sea are unknown. Therefore, a third suite of scenarios examines the uncertainties about the level of cod recruitment in response to possible environmental changes and the effects of the current management rule in the presence of varying cod recruitment.

Fishing mortality on cod

Two scenarios were investigated based on changing the target fishing mortality (F) in the HCR for cod, keeping the precautionary biomass reference point (B_{pa}) below which fishing pressure is reduced constant. In one scenario, the target F for stock sizes above B_{pa} was raised from 0.4 to 0.7, and in the other it was reduced to 0.2 (Figure 3). The higher F might be seen either as a more risk-prone HCR or as total allowable catches (TACs) set higher than the agreed rule, or as reflecting a situation where the actual catch is higher than the TAC because of illegal landings (but supposed to be known, because the actual catch is accounted for in the assessment). A higher target F provides for higher catches in the short term, at the expense of greater fluctuations in the cod stock and cod catches, because of reduced age diversity and lower long-term averages.

Reducing F above B_{pa} to 0.2 might represent a case where the stock is actually perceived as being in a collapsed state and

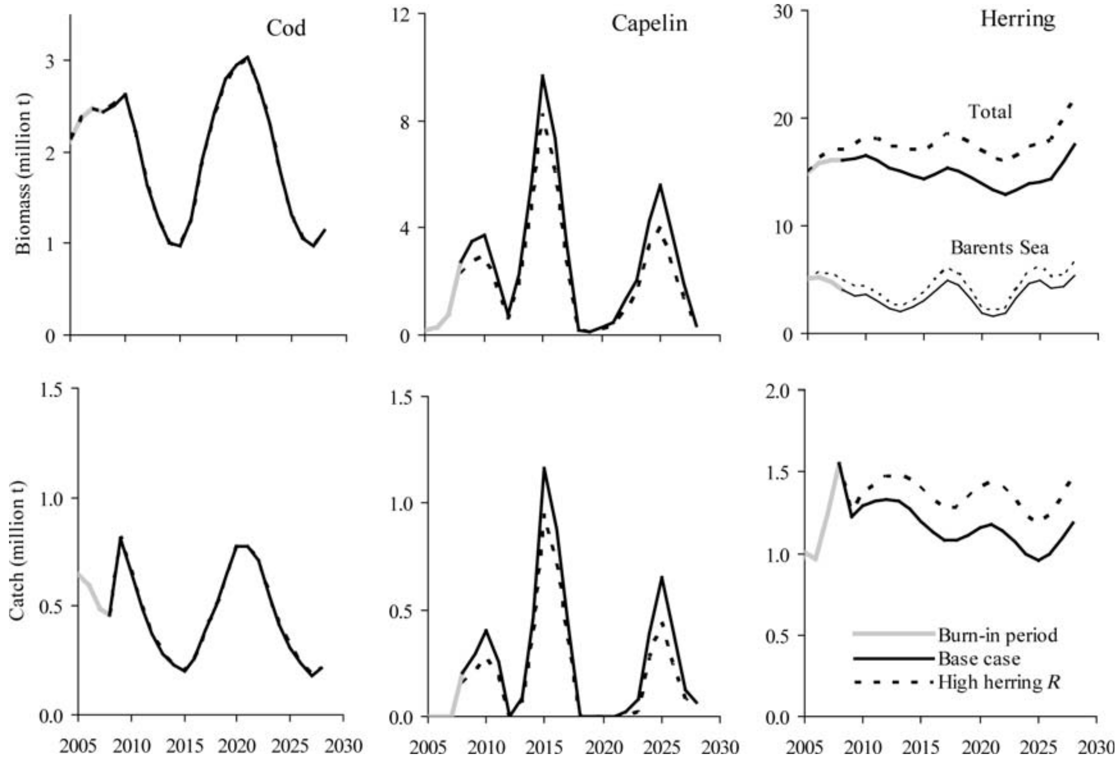

Figure 4. Projected stock biomass (upper panels) for cod (age 3+), capelin (age 1+), and herring (upper line: age 1+ and lower line: juveniles in Barents Sea), and (lower panels) projected total catch for each species, under two different assumptions about future herring recruitment: the base case and if herring recruitment is on average increased by 20%. The last years of the "burn-in period" preceding the forecast are also illustrated.

requiring rebuilding. This produces lower short-term, as well as long-term, catches than in the base case and, in fact, the stock size does not build up to the maxima observed in the base case or with the high *F*. This feature is apparently caused by the feedback mechanism resulting from cannibalism, which limits recruitment to the 3+ biomass. However, the medium-term pattern is much more stable, with longer cycles and higher minimum values, because cohorts persist longer in the stock, resulting in a more diverse age structure. Such low *F* levels will eventually result in high stock sizes, where growth and maturation might become affected, something that the model currently does not take into account. An attempt to model the relationship between stock size, growth, and maturation for cod was made by Kovalev and Bogstad (2005), and that work could be utilized when introducing bottom-up links in Gadget. Because such factors have been ignored, these predictions should be viewed with caution. In addition to changing the dynamics of stock fluctuations, low *F* results in slightly higher average cod stocks and, consequently, slightly fewer herring and capelin.

Herring carrying capacity

After recovering from the collapse in the 1970s, the stock biomass of Norwegian spring-spawning herring is currently not far from the all-time high (ICES, 2009c). Under the base-case assumptions, the stock biomass is predicted to vary around 15 million t in the medium term, slightly below the current level. However, the parameters controlling the herring biomass have been tuned to data collected during the recovery period, and these may not represent future stock dynamics. An alternative scenario is based on a recruitment level that is on average 20% higher, resulting in an average forecast biomass of around 18 million t (Figure 4), compared with 15 million t in the base case. The results indicate that the increase in recruitment should result in somewhat lower peaks in the capelin biomass (and its catches), but it does not change the temporal pattern of collapses, because the timing of these is set to follow the historical pattern. The effects on the cod stock are minimal, with the reduced availability of capelin apparently being offset by the increased availability of herring.

Variation in cod recruitment

Northeast Arctic cod live at the northern extreme of the range of the species in the Northeast Atlantic. Therefore, global warming could—at least in the short term—have a beneficial effect (Eide and Heen, 2002): rising temperatures may result in greater food availability, faster growth, and expanded range to the north, which could be expected to result in higher recruitment. Such a positive relationship between temperature and recruitment of cod and herring was found by Dingsør *et al.* (2007). Conversely, global warming could weaken the Gulf Stream by reducing the amount of sea ice (Cubash *et al.,* 2001), which could make the region colder and also reduce the number of cod larvae being transported from the spawning grounds off the Lofoten islands to the Barents Sea (Eide and Heen, 2002). Therefore, two scenarios were examined, with cod recruitment raised above and lowered below the base case by the same amount, respectively. The change implemented was in the form of a sudden 20% increase or decrease in larval mortality. As expected, the cod biomass increases with higher recruitment and decreases with lower

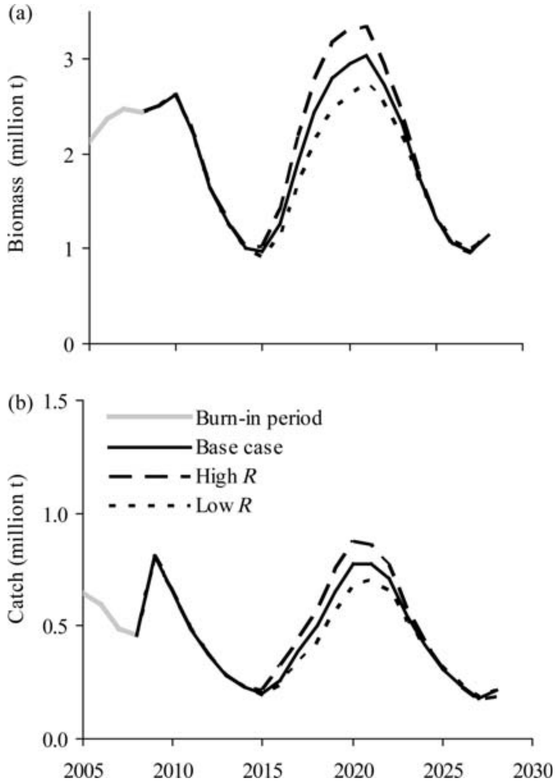

Figure 5. Projected stock biomass (age 3+) and catch of cod under different recruitment assumptions: the base case and for a 20% increase and a 20% decrease in larval survival (high and low recruitment, respectively). The last years of the "burn-in period" preceding the forecast are also illustrated.

recruitment and the catches simply track the stock changes (Figure 5). When the cod stock suffers from increased cannibalism because of reduced capelin abundance, the agreed management rule apparently ensures that the stock reaches a similar low point under all three scenarios, independent of the recruitment level. Hence, greater catches can be taken when recruitment is enhanced, but there is no increased risk of stock collapse.

Discussion

The Gadget model can apparently produce realistic historical stock dynamics and the coupling to FLR-based assessments represents a new tool for investigating the effects of the interactions between, and uncertainties about, the Barents Sea stocks in a multispecies management context. The base case for simulating future stock and catch trends suggests that the currently agreed HCRs function well in keeping the cod and herring stocks viable, whereas the escapement strategy for capelin does not hamper its ability to recover from collapses and to ensure that sufficient food is available during periods of good recruitment of cod. The simulations with different levels of target *F* for cod suggest that if recruitment continues to follow historical patterns, even a higher *F* could be sustained at the cost of catches that are more variable and more frequent stock depletions, whereas the lower *F* would result in greater stability at the cost of a lower medium-term average catch. They also indicate the effectiveness of rapid reductions in *F* below a trigger point in keeping the cod stock biomass at viable levels under a range of different scenarios. The results also indicate that under current fishing pressure, the herring stock is likely to remain large, which in turn means that capelin populations are likely to remain vulnerable to collapse. In fact, none of the management strategies tested was able to prevent such collapses.

The examples presented highlight the importance of interactions within stocks, between stocks, and between stocks and their fisheries, illustrating the utility of a tool that has the potential of dealing with the full range of sources of uncertainty in the fisheries system. However, other possible interactions have not been included in the model. For instance, Lindstrøm *et al.* (2002) hypothesized that during periods of a large herring stock, more minke whales remain in the Atlantic to feed on herring and fewer enter the Barents Sea. In attempting to understand the whole system, all of these interactions should be considered.

There are two obvious areas for further development. The first is to include greater biological realism within the model. This could be within species, for example, including bottom-up effects of food availability on predator condition, but also regarding interactions between species, for example, having minke whale migration dependent on herring abundance or having cod predate on 0-group capelin. A second direction of work would be to exploit the capabilities of the tool for incorporating random variations. This could be in the form of noise on the data or attempting to introduce stochasticity on the recruitment. Although this is difficult to do well in a multispecies context, it would render the tool suitable for conducting full multispecies management strategy evaluations.

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