S. Aanestad, L.K. Sandal and S. Tjelmeland – *"Barents Sea Capelin and Cod Stock Scenarios. Testing biological consequences of economically-based management."*

Chapter 4

Essay III

Abstract

In this article we present a scenario model for the jointly Norwegian and Russian capelin and cod stocks in the Barents Sea. The model basically consists of two sub-models. The first is an autonomous management model which, based on profit functions and growth functions with coefficients calibrated from real data, finds a feedback rule for maximizing the Norwegian share of the fishery rent by using numerical dynamic programming. The second (Bifrost) is a biological multi-species growth model provided by the Institute of Marine Resources in Bergen. This model has higher resolution than the simple top-down growth used in the management model. With this we simulate possible scenarios resulting from employing the management model as a decision-making instrument in the real world. We concentrate on possible future catch and stock sizes rather than on economics. The objective is to find out whether the economical based management strategy is sustainable from a biological perspective.

Scenarios from six different strategies are tested, of which two are purely biological and inspired by existing management. Bifrost is applied direct to measure total allowable catch (TAC) in these strategies, whereas the four economic strategies are found from the management model. These strategies are compared with the biological strategies and the results are promising. The best economic strategies turn out to give higher long-term cod stocks than the biologic strategies.

4.1 Introduction

Scenario modeling in fishery economics is a relatively new topic. Originally it was developed for whaling, but it is now gaining popularity in fisheries (Schweder 2006, Link, Schneider and Tol 2004 and Eide 2007). In this article, for instance, it is used to combine economic optimizing with complex biological bottom-up multi-species modeling in the management of the fisheries of capelin and cod in the Barents Sea. The idea is to account for complex biology when evaluating a management models with purely economic objectives that is based on a quite simple 2D growth model. With a few exceptions (Hagen, Hatlebakk and Schweder 1998, Helstad 2000 and Eide and Flaaten

1998), one typically observes in the literature of fishery economics complex economic perspectives combined with quite simple biology. On the other hand biologists usually ignore the economics. Scenario modeling is a point of attack that makes it easier to deal with both economic optimizing and complex biological modeling at the same time.

Although there has been evolution in the field since Clark and Munro (1975) introduced optimal control theory to fishery management models in the mid-seventies, dynamic programming is never used when the biology is described by a complex multispecies growth model. The reason is that the size of the throughput becomes impossible to handle within reasonable computer time when the variable dimension of the problem arises. Basing the optimizing on a biological growth model with two interacting fish species requires dynamic optimizing in at least two dimensions, and adding in year classes or spatial locations for the fish species increases the dimensions further. Therefore, the management model that is tested in this work consists of a simple two-dimensional predator-prey growth model for cod (Gadus morhua) and capelin (Mallotus Villosus) that is combined with a corresponding simple economic model. The management model is previous presented in Agnarsson et. al. (2008), but is here verified with a new numerical solution.

The novelty in this work is that consequences of the model are tested when a much more complex biologic growth model is assumed to represent the real growth. From a social economic point of view single species economic models are of little value for optimal management of capelin since capelin might be more profitable as prey for cod than as catch for the fishing boats. The question is whether or not the two species management model, which is aware of the double role of capelin, is complex and robust enough to form a basis for sustainable management from a biological point of view.

The Barents Sea is not among the most complex ecosystems. It has an arctic climate with only a few species of importance. Among these are capelin and cod, which have nursery and feeding grounds here. This also applies to herring (*Clupea harengus*) (Dalpadado, Ingvaldsen and Hassel 2003), which plays a major role in the capelin-cod system. Hamre (2003) concludes that capelin and herring are the key prey species at fish level and that cod is their dominant predator. In addition to this, there is strong evidence for herring being one of the main causes of collapse in the capelin stock as it preys heavily on capelin fry. Other species of relevance are sea mammals (Schweder, Hatlebakk and Hagen 1998), sea birds, harp seals and some additional fish species. Harvest is also a major factor in the ecosystem (Hjermann, Ottersen and Stenseth 2004).

Although we cannot say for sure whether the top-down or the bottom-up approach is the best approximation to the true biomass variation for capelin and cod in the Barents Sea, we may be able to say something about the resilience and adaptability of the management model after simulating its consequences through another model, namely the Bifrost model. What are the consequences for the stocks of such management according to a simulation model with higher resolution? This is the main question of interest in this article. Will the capelin stock survive according to the simulations; will the size of the cod stock drop over time? These questions will be answered.

Even though we do not include herring when deciding TACs according to the management model, herring influence is accounted for when we simulate consequences on future biomasses and catches of capelin and cod. Bifrost, the simulation model used for testing consequences of the management model, is a multispecies assessment model involving herring as well as cod and capelin. This is a so-called bottom-up model starting with the small processes that influence the total marine ecosystem. Factors like capelin-cod interaction conditional on other food, herring effects on capelin recruitment and temperature effects on maturation of capelin and cod are all taken care of in this model. As far as herring influence is concerned, concurrent runs between Bifrost and the herring assessment model, SeaStar, are possible. In sec. 4.4.1 and sec. 4.4.2 we present simulations with SeaStar turned "off" and "on" respectively to find out whether a dynamic, more realistic, three-species approach is crucial to the simulations. Interesting differences between constant herring influence (SeaStar "off") and dynamical herring influence (SeaStar "on") are found, and this shows that more research should be carried out on joint management of the capelin and cod stocks in the Barents Sea and the herring stock further south. The findings in this work are rather promising on behalf of the two-dimensional management model tested, as it appears to be just as sustainable as other strategies that are based on existing management.

4.2 The Model

4.2.1 General considerations

The model consists of a set of two interacting fish biomasses $\big(x(t), y(t)\big)$ representing the joint Norwegian and Russian resources of capelin and cod in the Barents Sea. In the scenario model we investigate different management strategies for these stocks. Specifically, we examine an optimal feedback strategy designed to set TAC levels $(u_x(t), u_y(t))$ maximizing the Norwegian share of the economic rent given by the fishery.

As already mentioned, the scenario model consists of two models. It is the simulation model (Bifrost) provided by the Institute of Marine Resources in Bergen and it is the management model. The management model has its own biological growth model, which is quite different from the growth in the simulation model. The procedure is as follows:

1. Find optimal TACs from the management model according to the present stock sizes

2. Set optimal TACs in the simulation model

3. Simulate next year's stock sizes in accordance with the TACs (Bifrost)

4. Start again from point 1 with the new stock sizes as the starting-point.

Now, if we let the biomass growth in the simulation model be our representation of the real-world marine ecosystem, we investigate consequences for the stock sizes of following the feedback policy from the management model. Further, effects from three groups of management strategies (six strategies) are compared. These are

- $\tilde{A}_1$ and $\tilde{A}_2$: The management model with two different levels of the discount rate, 1% ($\tilde{A}_1$) and 5% ($\tilde{A}_2$). (See sec. 4.3.1).

- $\tilde{B}_1$ (1% discount rate) and $\tilde{B}_2$ (5% discount rate): Strategies revealed from strategy $\tilde{A}$, but capelin catch is more aware. (See sec.4.3.2)

- $\tilde{C}_1$ and $\tilde{C}_2$: two pure biologically based strategies associated with the existing management regime for capelin and cod. (See sec. 4.3.2)

Strategies $\tilde{A}_1$ and $\tilde{A}_2$ are based on finding feedback TAC-levels that are maximizing all discounted future income from the two fisheries, and strategy $\tilde{B}_1$ and $\tilde{B}_2$ are ad hoc strategies intended to improve performance of respectively $\tilde{A}_1$ and $\tilde{A}_2$.

Strategies $\tilde{C}_1$ and $\tilde{C}_2$ are based on the existing multi-species management of capelin and single species management of cod. A target spawning level of capelin and F-value of cod are chosen to maximize long-term catches of the two species. No direct optimizing has been done to find these sizes, but through repeated trials sensible results are reached.

Strategies $\tilde{A}_1$ and $\tilde{A}_2$ use simple relations between stock sizes and profit and between stock sizes and stock growth. Let us have a look at the management model that produces them.

4.2.2 The optimal management model

The management model is the same as that used by Agnarsson et. al. (2008), but the model is resolved with other algorithms. It consists of an economic objective function, which is to be maximized under the constraints of two biological growth functions for the stocks of capelin and cod in the Barents Sea. That is, the principal form of the management model is given by

$$V(x_0, y_0) \equiv \max_{u_x, u_y} \int_0^\infty \Pi\big(x, y, u_x, u_y\big) e^{-\delta t}\, dt, \qquad \text{when} \tag{4.1}$$

$$\dot{x} = f_1(x, y) - u_x \quad \text{and} \quad x(0) = x_0 \tag{4.2}$$

$$\dot{y} = f_2(x, y) - u_y \quad \text{and} \quad y(0) = y_0, \tag{4.3}$$

and δ is the discount rate. In the following we will go further into the economics represented by the flow of profit $\Pi(\cdot)$ and the biological growth represented by $f_1(\cdot)$ and $f_2(\cdot)$.

Economic profit

The Norwegian profit function is of the form

$$\Pi(x, u) = p(u)\, \alpha u - C(x, \alpha u) \tag{4.4}$$

for both the species. Here α is the pre-decided Norwegian share of the TAC, $p(u)$ represents the (inverse) demand function and $C(x, u)$ is the associated cost. Price elasticity and cost dependent on stock size are, however, only assumed for cod. As far as the prices are concerned, the joint Norwegian and Russian catch is large enough to influence the world market, whereas capelin is price-inelastic since it is easily replaced by other species on the market. The specific inverse demand (price) functions for capelin and cod are therefore given by

$$p_x = p_1$$
$$p_y(u_y) = p_2 - p_3\, u_y$$

and with Norwegian catches of $\alpha_1\, u_x$ and $\alpha_2\, u_y$ the cost functions are

$$c_x(\alpha_1 u_x) = c_1\, (\alpha_1 u_x)^{1.4}$$
$$c_y(y, \alpha_2 u_y) = \frac{c_2}{y}\, (\alpha_2 u_y)^{1.1}.$$

The stock dependence of the cost function for cod implies that the cost approaches infinity as the stock approaches zero. This means that cod is economically protected. There is no such protection associated with capelin.

With no economic interspecies interactions in the fish market, total Norwegian profit flow from the fisheries of capelin and cod is given by the sum of profit from each of the fisheries

$$\Pi(x, y, u_x, u_y) = p_1 \alpha_1 u_x - c_1 (\alpha_1 u_x)^{c_2} + (p_2 - p_3 u_y) \alpha_2 u_y - \frac{c_3}{y} (\alpha_2 u_y)^{c_4},$$

where all the coefficients $\alpha_1, \alpha_2, p_1, p_2, p_3, c_1, c_2, c_3 > 0$.

Biological growth

The growth functions describe the dynamics of the capelin-cod system before catch is added. It is set to

$$f_1(x,y) = b_1x^2 + b_2x^3 + b_3xy \tag{4.5}$$
$$f_2(x,y) = b_4y^2 + b_5y^4 + b_6xy, \tag{4.6}$$

where the last term of each function represents predation and other interspecies relationships between the two species. Both the coefficients for the profit functions and the coefficients for the growth functions are found by calibration with real historical data. (see Tables 4.1 and 4.2). For further information about the properties of the biological model, refer to Agnarsson et. al. (2008).

Table 4.1: Coefficients for the (inverse) demand and cost functions.

	Species	Function	Parameters	t-statistic	R^2
Price/ inverse demand	Capelin	$p(h) = 1$			
	Cod	$p(h) = p_2 - p_3\,u_y$	$p_2 = 12.65$	9.7	$R^2 = 0.59$
			$p_3 = 0.00839$	3.94	$F = 15.6$
Cost	Capelin	$C(x,u) = c_1(u)^{1.4}$	$c_1 = 0.07$	32.12	$R^2 = 0.98$
	Cod	$C(y,u) = c_2\,\frac{u^{1.1}}{y}$	$c_2 = 5848.1$	44.7	$R^2 = 0.95$

Table 4.2: Parameter values and statistical properties for the biological functions.

Species	Function	Parameters	t-statistic	R^2
Capelin	$f(x,y) = b_1x^2 - b_2x^3 - b_3xy$	$b_1 = 0.00018$	4.9	$R^2 = 0.59$
		$b_2 = 1.19E - 8$	3.1	
		$b_3 = 0.00021$	3.4	
Cod	$f(x,y) = b_4y^2 - b_5y^4 + b_6xy$	$b_4 = 0.00022$	8.4	$R^2 = 0.5$
		$b_5 = 3.49E - 11$	4.2	
		$b_6 = 1.82E - 5$	2.6	

4.2.3 Solving the management model

As already mentioned, the solution of the problem defined in equation (4.1-4.3) is found in feedback form. That is, the optimal catch of capelin and cod is a function of stock sizes only. Therefore we can write the optimal catch as

$$[u_x^\star, u_y^\star] \equiv [\tilde{u}_x(x,y), \tilde{u}_y(x,y)]. \tag{4.7}$$

The problem is not, however, algebraically solvable. The solution must be derived numerically via the optimal value function, $V(x,y)$. This function can be found in various ways. Letting the discrete dynamics be defined by the time step $0 < h << 1$, the initial value $(x_h(0), y_h(0)) = (x, y)$ and

$$x_h(i+1) = \varphi_1(x,y,u_x) \equiv x_h(i) + h\left(f_1\big(x_h(i), y_h(i)\big) - u_x\right) \tag{4.8}$$

$$y_h(i+1) = \varphi_2(x,y,u_y) \equiv y_h(i) + h\left(f_2\big(x_h(i), y_h(i)\big) - u_y\right), \tag{4.9}$$

we solve the equation

$$V_h(x,y) = \max_{u_x,u_y}\left\{h\Pi(x,y,u_x,u_y) + \beta V_h\big(\varphi_1(x,y,u_x), \varphi_2(x,y,u_y)\big)\right\} \quad \text{with} \tag{4.10}$$

$$\beta \equiv 1 - \delta h \tag{4.11}$$

by fixed-point iteration. This can be done according to the procedure described in Grüne and Semmler (2004).

4.2.4 The simulation model - Bifrost

Bifrost is an assessment tool developed at the Institute of Marine Research in Bergen, Norway. It was originally designed for the Barents Sea capelin, but is now considerably expanded. It has developed into a simulator for experimenting with harvesting control rules in the capelin-cod-herring system of the Barents Sea. In the simulation process it considers cod-capelin interactions conditional on other food, herring effects on capelin recruitment, temperature effects on recruitment of capelin and cod, capelin consumption affecting growth of cod, temperature influence on the maturation of cod and finally predation by harp seal on both capelin and cod.

Concurrent runs between SeaStar, an assessment tool for herring, and Bifrost are possible. In this work simulations are both performed with constant herring influence on the capelin cod system (SeaStar turned "off") and with a dynamical herring stock (SeaStar turned "on"). [1]

4.3 Three/six management strategies

4.3.1 Strategy A: Optimal management with feedback-Policy

In this work the optimal value function represents the discounted sum of all future economic rent from the fishery of capelin and cod in the Barents Sea. Despite this practical interpretation, it is mainly a theoretical size used to find optimal TAC levels for

[1] For more detailed information about the Bifrost simulator, refer to the website *http://www.assessment.imr.no/*.

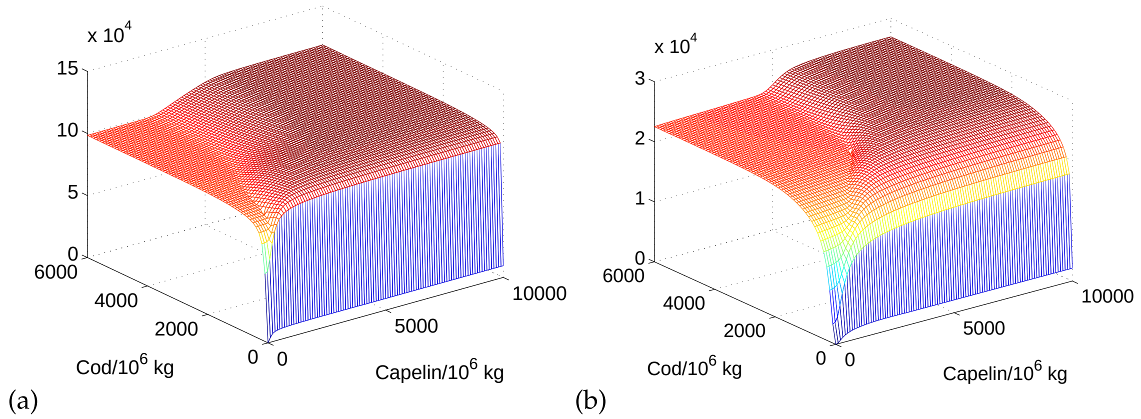


Figure 4.1: The optimal value function when discount rate is respectively (a) $\delta = 0.01$ and (b) $\delta = 0.05$.

capelin and cod. Its shape on the capelin-cod grid, however, (see Figure 4.1(a) and Figure 4.1(b)), is of sufficient interest for a presentation, as it is strongly linked to the optimal TAC levels.

Two discount rates are used in the simulations. The level of these appears to have minor influence on the shape of the optimal value function, but of course the total discounted value is higher with lower discount rate since more future profit is added. Another noticeable difference is that the first plateau expands slightly more to the right (ends at higher capelin stocks) for 5% discount rate. Also, the step up to the next plateau is steeper and shorter than for 1% discount rate. The term *plateau* is somewhat inaccurate, however, since the optimal value function grows with the biomasses of capelin and cod on most of the grid, but with the scaling used this growth is not very visible.

Optimal TACs of capelin show both expected and unexpected behavior on the capelin-cod grid. First of all we observe an expected discontinuity visible as a wall rising up along the capelin axis. This discontinuity is between zero-level of cod, which gives optimal TACs on "bliss-level", the level that maximizes current profit, and the first non-zero level of cod giving considerably lower optimal TACs along the capelin axis. Further on, for low levels of capelin along the cod axis, there is a ridge in the TAC-levels. (See figures 4.2(a) and 4.2(c)). In figures 4.2(b) and 4.2(d) we can see that the corridor to the right of the ridge is wider for low discount rate (1%) than for high discount rate (5%). The stock levels on the curve constituting the verge between the ridge and the zero corridor coincide with the stock levels on the curve constituting the beginning of the step from the first plateau to the second plateau in respectively Figure 4.1(a) and 4.1(b). As far as TAC sizes are concerned, the top of the ridge is below four hundred thousand tons, which is not a very high harvest from a historical perspective.

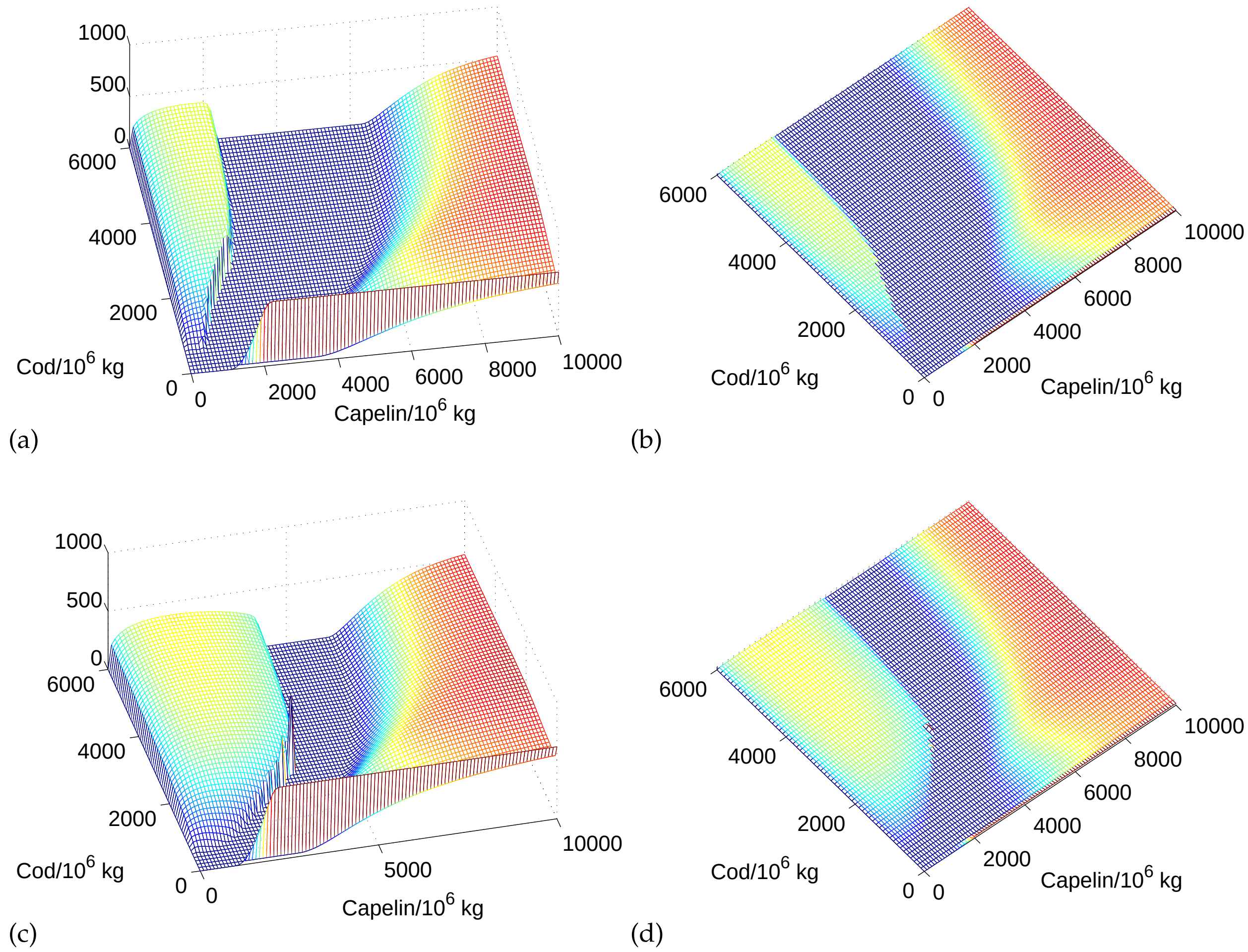


Figure 4.2: Optimal catch of capelin as a function of stock sizes for discount rate $\delta = 0.01$ in (a) and (c) (same figure watched from different angles) and discount rate $\delta = 0.05$ in (b) and (d).

In the optimal harvest of cod surface, the main trend is that TACs rise with rising stock levels and the size of the capelin stock seems to have minor influence. (See Figure 4.3(a) and 4.3(b)). This picture is heavily interrupted, however, for certain combinations of capelin and cod. A peak or a ridge emerges on the area of the capelin-cod plane where zero-harvest of capelin is optimal. This interesting irregularity is a strong expression of multispecies effects in the model.

According to the biological model, the optimal feedback policies are based on stock combinations to the left (lower capelin stocks) of the corridor in Figure 4.2(a)-4.2(c) will result in extinction of capelin as the trajectories end up with an equilibrium level of around 2.5 million tons of cod and the absence of capelin. (See Figure 4.4.) Beyond

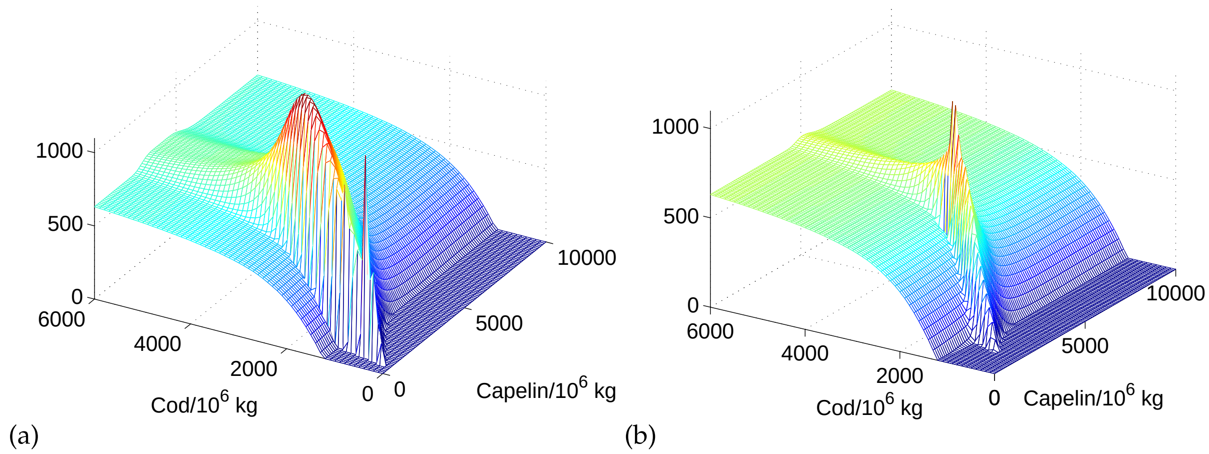


Figure 4.3: Optimal catch of cod as a function of stock size of both capelin and cod when discount rate is (a) $\delta = 0.01$ and (b) $\delta = 0.05$.

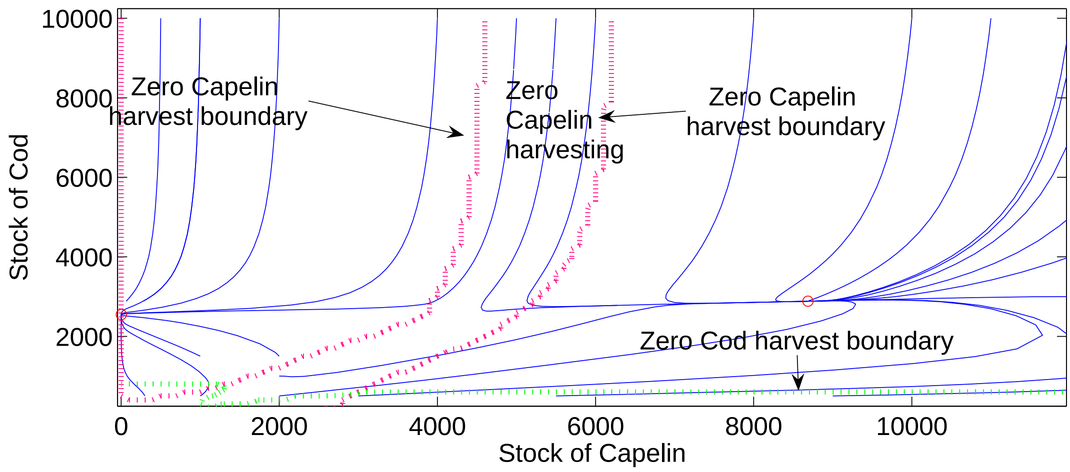
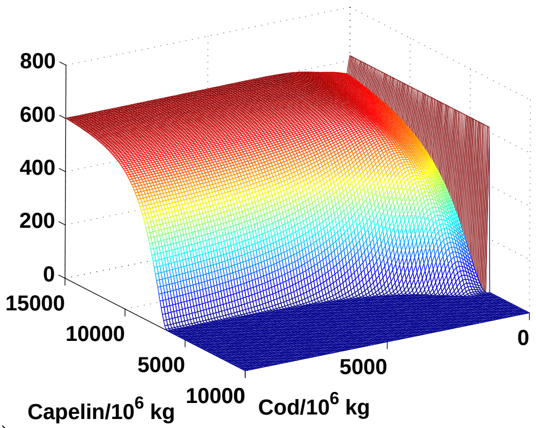


Figure 4.4: Optimal paths and equilibriums from Norwegian feedback policy when discount rate is 5%. These paths are based on the biological sub model used in the management model.

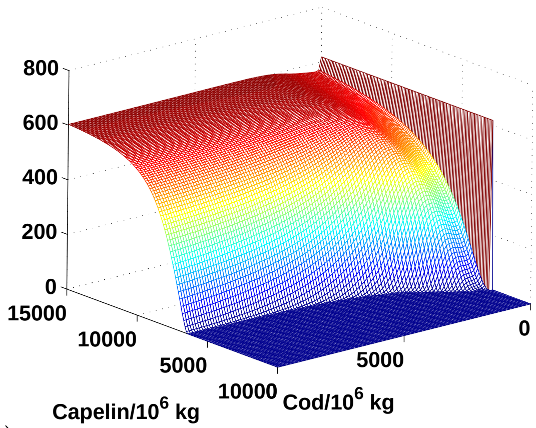
that, we see that there is another equilibrium for about 8.5 million tons of capelin. (Red rings.) When discount rate is lower (1%) the equilibrium stock sizes are slightly lower. (See overview in Figure 4.3.)

Table 4.3: Equilibriums of capelin and cod respectively resulting from optimal harvest according to the biological sub-model used in the management model. (Units in million tons.)

Discount rate	Interior equilibrium	Extinct capelin
$\delta = 0.01$	$(8.727, 2.887)$	$(0, 2.552)$
$\delta = 0.05$	$(8.678, 2, 885)$	$(0, 2.550)$



(a)



(b)

Figure 4.5: A suboptimal extinction-aware catch of capelin.

4.3.2 Alternative sub-optimal strategies

Strategy B: A modified optimal strategy

The second strategy presented is based on the optimal strategy (strategy $\tilde{A}$). TACs of cod are the same, but the TAC of capelin is a more cautious figure. When the capelin stock is high, the TAC of capelin is also the same, but the ridge for low levels of capelin is removed. (See Figure 4.5(a) and 4.5(b)).

There are three aspects behind this modification. From an economic perspective the economic model puts no protection on capelin as the cost function does not depend on the stock size (see Figure 4.5). Although capelin is a schooling species, it may be too optimistic to assume that the fishing costs do not rise with smaller stocks. Second, from a biological point of view, the capelin growth might be under- or over-estimated for low levels of capelin and high levels of cod. Also, influence from the capelin-predator herring is not directly measured in the growth, and both of these aspects of uncertainty suggest a more cautious management of capelin. Finally, there are also ethical aspects concerning a potential planned capelin extinction.

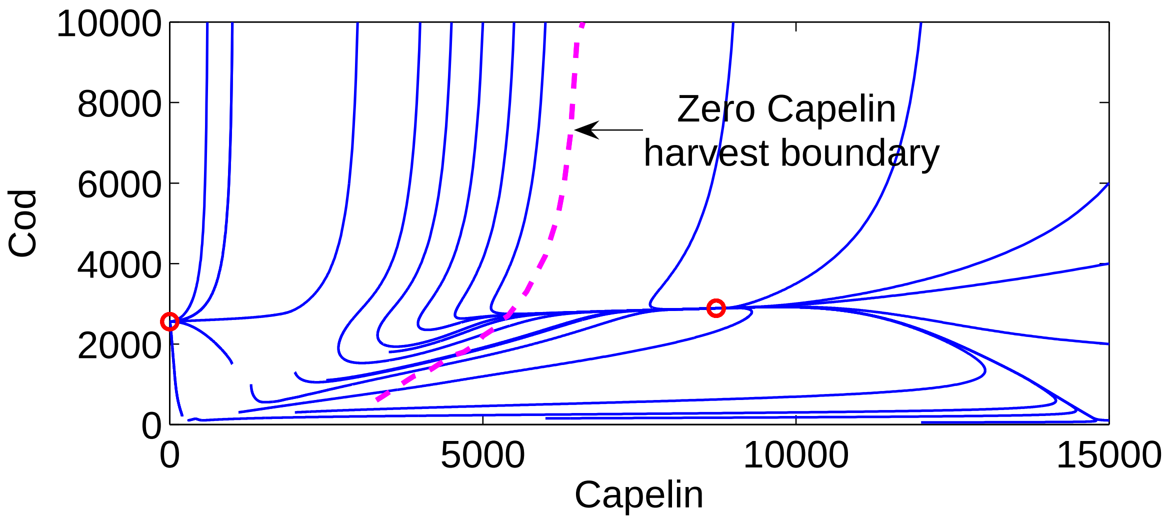


Figure 4.6: Paths and equilibriums when discount rate is 1%. These paths are based on the biological sub-model used in the management model.

Strategy C: A purely biologically based reference strategy

The reference strategies $\tilde{C}_1$ and $\tilde{C}_2$ are both inspired by existing management rules for capelin and cod. Management of capelin has been pioneering because of its multi-species approach. Today it is managed according to a rule allowing a maximum 5% probability for the spawning stock to become smaller than 200 thousand tons. In both strategy $\tilde{C}_1$ and $\tilde{C}_2$ we choose a target spawning level of 500 thousand tons, which should correspond quite well to the existing management rule.

Strategies $\tilde{C}_1$ and $\tilde{C}_2$ differ in the management of cod. Whereas the fully-exploited fishing mortality level of cod, the F-value, is 0.65 in $\tilde{C}_1$, it is 1.0 in $\tilde{C}_2$.

4.4 Simulations with Bifrost

4.4.1 Simulations assuming constant herring influence

In the Bifrost simulations presented below herring influence is assumed constant as it is represented by a biomass of 0.5 million tons throughout the whole simulation period.

We will first present simulations with each of the management strategies, and then we will compare the strengths and weaknesses of the economic management strategies with those of the biological strategies. Combinations of historic spawning stock biomasses (SSBs) and TACs from 1972 to 2005 and corresponding prognostics for the

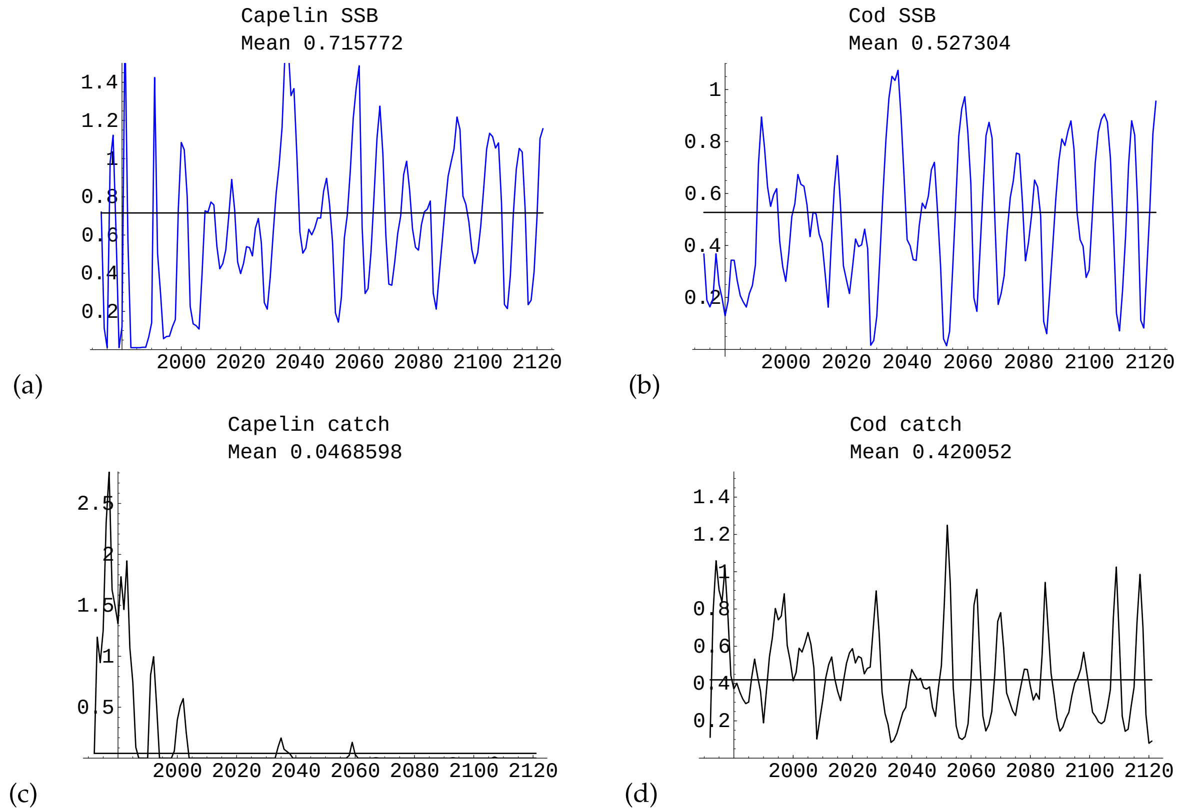


Figure 4.7: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from strategy $\tilde{A}_1$ (1% discount rate).

years 2006 to 2120 may be viewed in figures 4.7 to4.11. In each of these figures a horizontal line indicates the average of the 600-year period from 1972 to 2571. Table 4.4 shows basic statistics as mean and standard deviation (SD) for the 965-year prognosis of total biomasses (TBs) and TACs.

The scenario resulting from strategy $\tilde{A}_1$ can be viewed in Figure 4.7. SSB of capelin turns out to be somewhat lower in the first years (historic results) than for the prognostic period, but the variability is high (see Figure 4.7(a)). Total biomass has a mean of 3.09 million tons and a standard deviation of 0.66 for the prognostic years (see Table 4.4). The total biomass average for cod (1.21 million tons) is much lower than for capelin, as is also the standard deviation (0.17). This might be a little surprising since the SSB numbers as appear to fluctuate just as much for cod in Figure 4.7(b) as for capelin in Figure 4.7(a). These figures, however, only show the first hundred years of the prognostics and there may in addition be differences in the variability of the SSB and TB.

The fishery of capelin (see Figure 4.7(c)) is characterized by total closures interrupted by small positive TACs for a few years when the biomass is high enough. TACs of cod

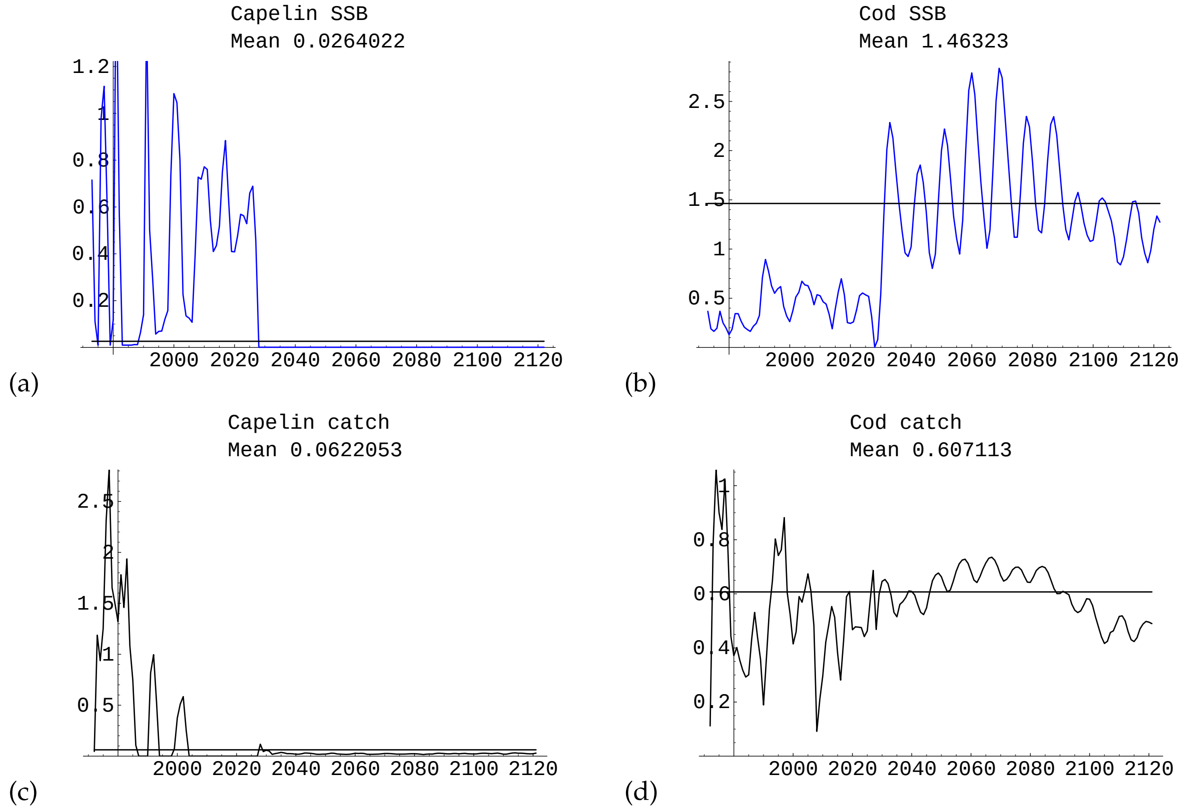


Figure 4.8: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from optimal strategy $\tilde{A}_2$ (5% discount rate) when a constant Barents Sea herring stock of 0.5 million tons is assumed.

(mean of about 415 thousand tons) are a lot higher than for capelin, but the standard deviation is very low for the TACs of both (six thousand tons for capelin and 92 thousand tons for cod).

Though the feedback curves in strategy $\tilde{A}_1$ and strategy $\tilde{A}_2$ are quite similar (see figures 4.2 and 4.3), the simulation results from Bifrost differ very much when discount rate rises from 1% to 5%. With strategy $\tilde{A}_2$ a drastic shift occurs between the year 2025 and the year 2030 (see figures 4.8(a) and 4.8(b)). Then the SSB of cod grows heavily and the capelin stock falls dramatically. At the same time the fishery of capelin opens from a total closure (see Figure 4.8(c)).

Average TACs of both capelin and cod are higher with strategy $\tilde{A}_2$ than with strategy $\tilde{A}_1$, but the standard deviation in the TACs is much lower (see Table 4.4). All this shows that, according to Bifrost, strategy $\tilde{A}_2$ is better than strategy $\tilde{A}_1$.

The simulation with strategy $\tilde{B}_1$ is very similar to the simulation with strategy $\tilde{A}_1$. The only difference is that TACs of capelin are a little lower for a few years. For the

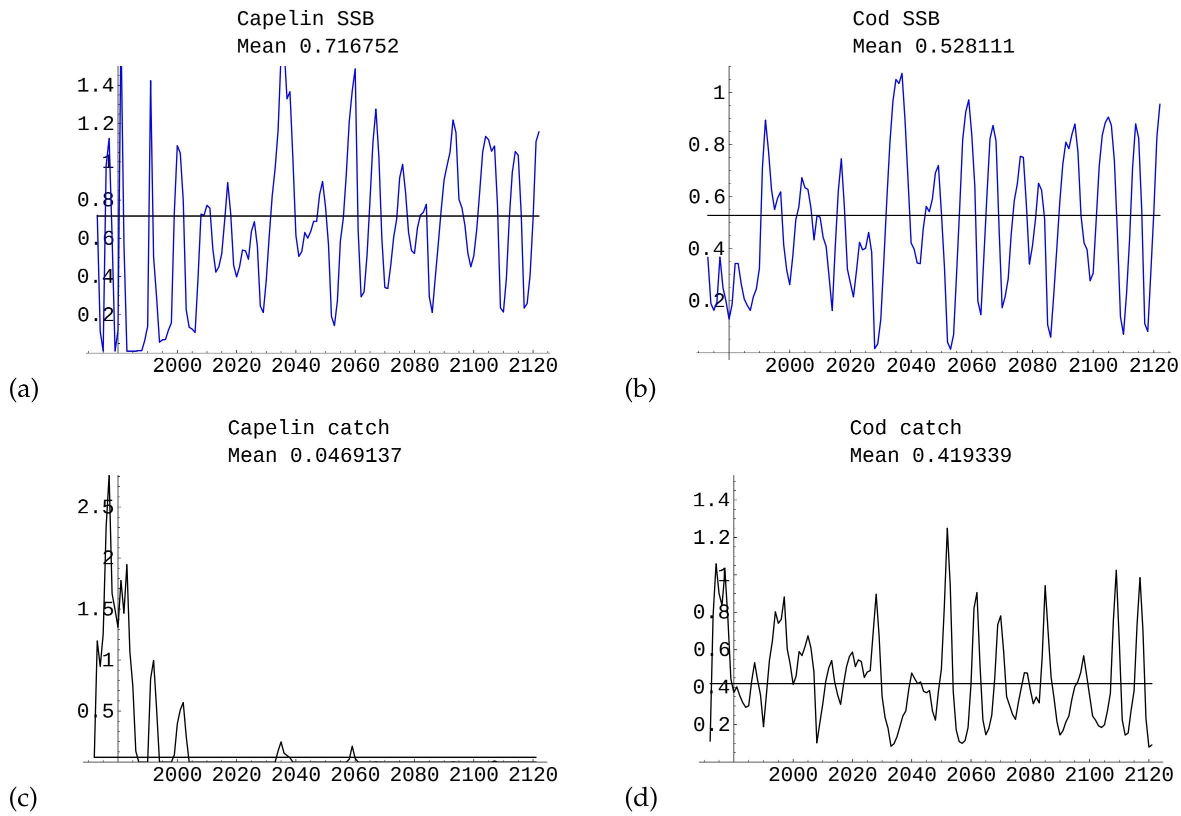
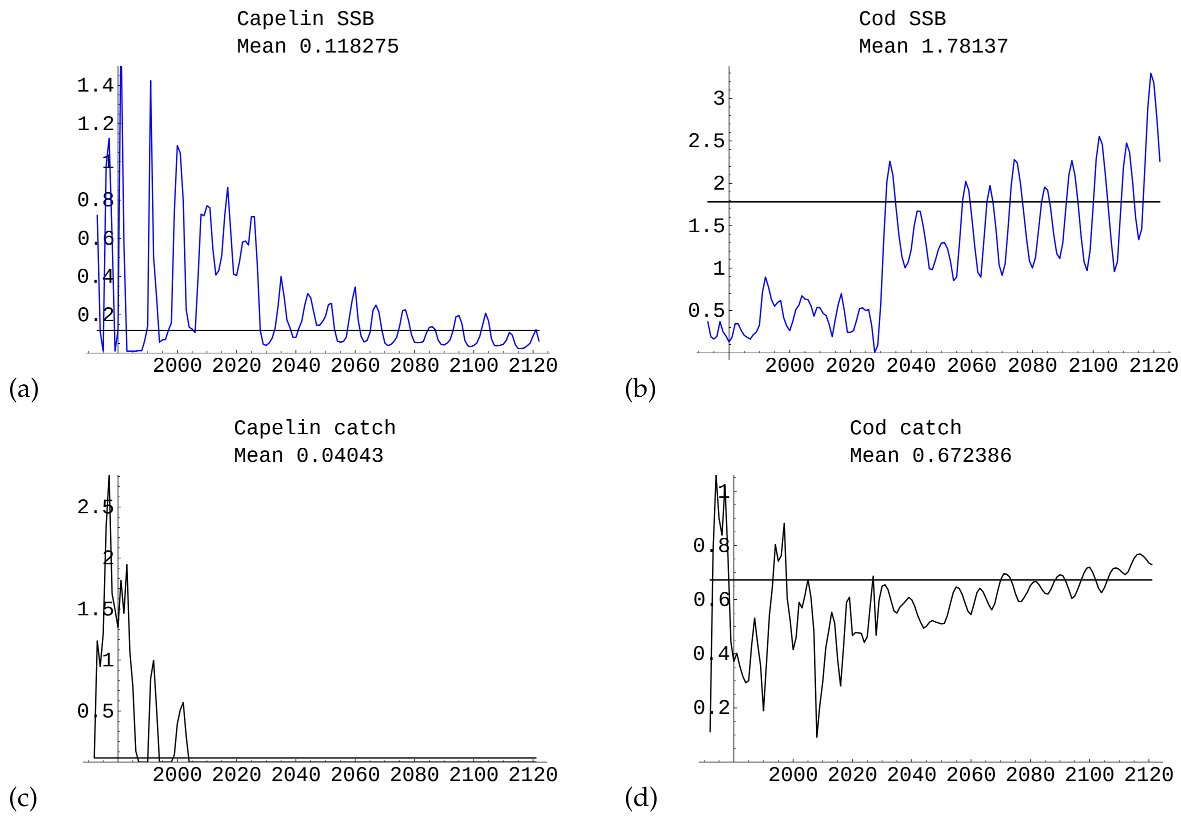


Figure 4.9: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from strategy $\tilde{B}_1$ (1% discount rate) when a constant Barents Sea herring stock of 0.5 million tons is assumed.

years visible in figures 4.7 and 4.9 TACs and SSBs are identical.

In the same way as there are many similarities between the simulation of strategy $\tilde{A}_1$ and $\tilde{B}_1$, the similarities between $\tilde{A}_2$ and $\tilde{B}_2$ are obvious. Both simulations have a sudden rise in the cod stock and a fall in the capelin stock between 2025 and 2030, and both simulations have very high TACs of cod and low TACs of capelin. In strategy $\tilde{B}_2$ the fishery of capelin is completely closed for the whole period of the simulations (see prognostics in Table 4.4). Another characteristic is that TACs of cod are very high, with rather low standard deviation. TACs of cod are on average above 702 thousand tons with a standard deviation of around 77 thousand tons. The very high mean in TB of about 3.38 million tons makes the high TACs possible.

The purely biologically based management strategies $\tilde{C}_1$ and $\tilde{C}_2$ differ from each other only with respect to the fully-exploited fishing mortality level of cod. Nevertheless, the resulting TB mean and TACs differ dramatically both for capelin and cod. The simulation of $\tilde{C}_1$ gives a capelin average of 1.946 million tons and a cod average of 1.967



million tons. This result is different from all the other strategies, which either give high stocks of capelin and low stocks of cod or low stocks of capelin and high stocks of cod. Average TACs with strategy $\tilde{A}_2$ and $\tilde{C}_1$ are, however, rather close. The main difference is that TACs of cod are a little higher and have much lower variation with strategy $\tilde{A}_2$. In both cases TACs on capelin are very low, but the total biomass of capelin is much higher with strategy $\tilde{C}_1$.

The simulations with strategy $\tilde{C}_2$ differ considerably from the rest of the simulations. The main difference is that both the total biomass average (4.104 million tons) and TAC average (0.967 million tons) of capelin is very high, but at the same time both TB and catch of cod is much lower than for all the other strategies. An interesting observation is that it takes some time before the SSB of capelin becomes high and the SSB of cod becomes low with strategy $\tilde{C}_2$. In the first part of the prognostics (the part visible in figures 4.11(a) and 4.11(b)) we see that the SSB is mainly lower than the mean for capelin and higher than the mean for cod).

In the second run with the Bifrost simulator, the biomass of herring is at a constant level of 800 million tons. Under such circumstances both the capelin and cod stock biomasses get lower according to both figures 4.12-4.17 and Table 4.5. Still, capelin does

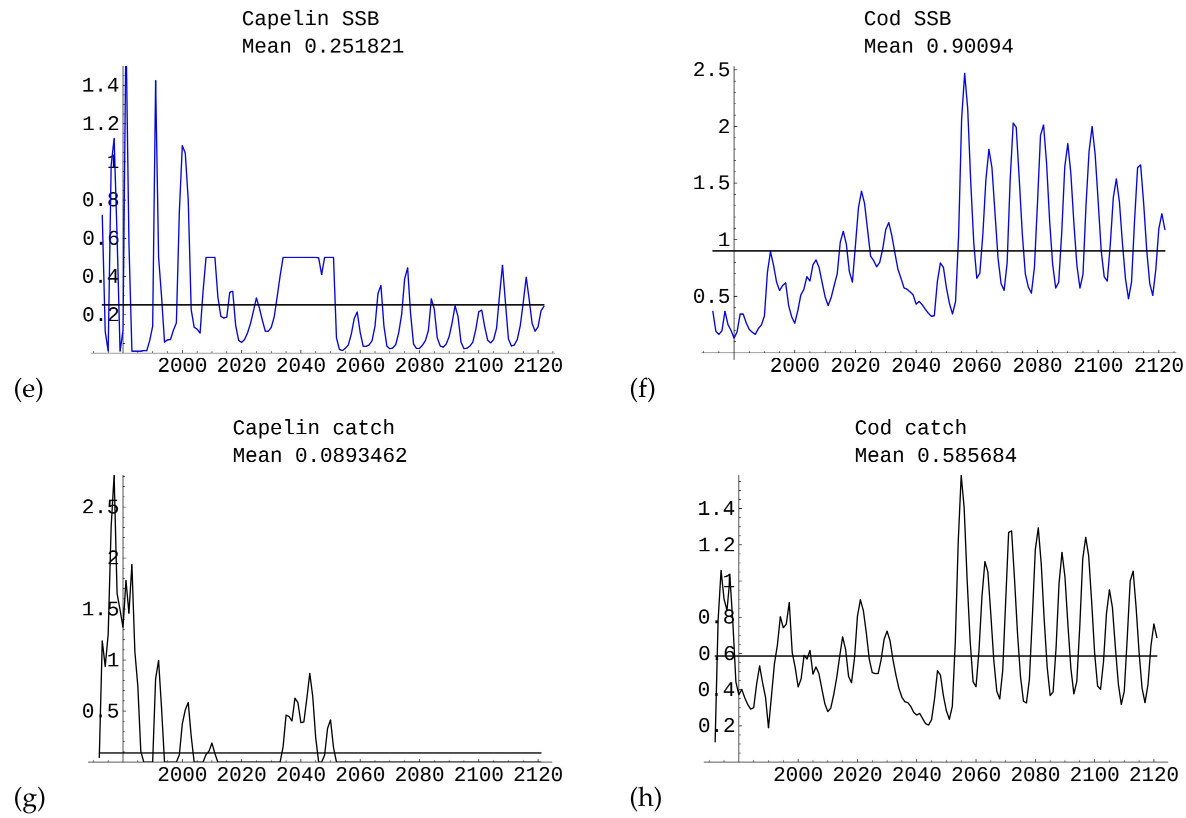


Figure 4.10: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from biologically based strategy $\tilde{C}_1$. Relative F on cod $= 0.65$. Target SSB capelin $= 0.5$. Constant Barents Sea capelin of 0.5 million tons

not get exterminated with any of the strategies even though it is very close with strategy $\tilde{A}_2$.

4.4.2 Simulations with SeaStar integrated in Bifrost

In the simulations presented below a dynamic herring influence is accounted for in Bifrost through the assessment tool SeaStar. Two different herring managements are tested. The first leads to a long-term average Barents Sea fraction of 0.5 million tons (see figures 4.18-4.23 and Table 4.6), and the second gives an average of 0.8 million tons. (See Table 4.7).

It is hard to see any system in the changes taking place when we switch from a constant to a dynamic herring influence. The most dramatic change comes under strategy $\tilde{A}_1$. When constant herring influence from a Barents Sea herring biomass of 0.5 million tons is assumed, the total biomass of capelin has a mean value of about 3.09 million

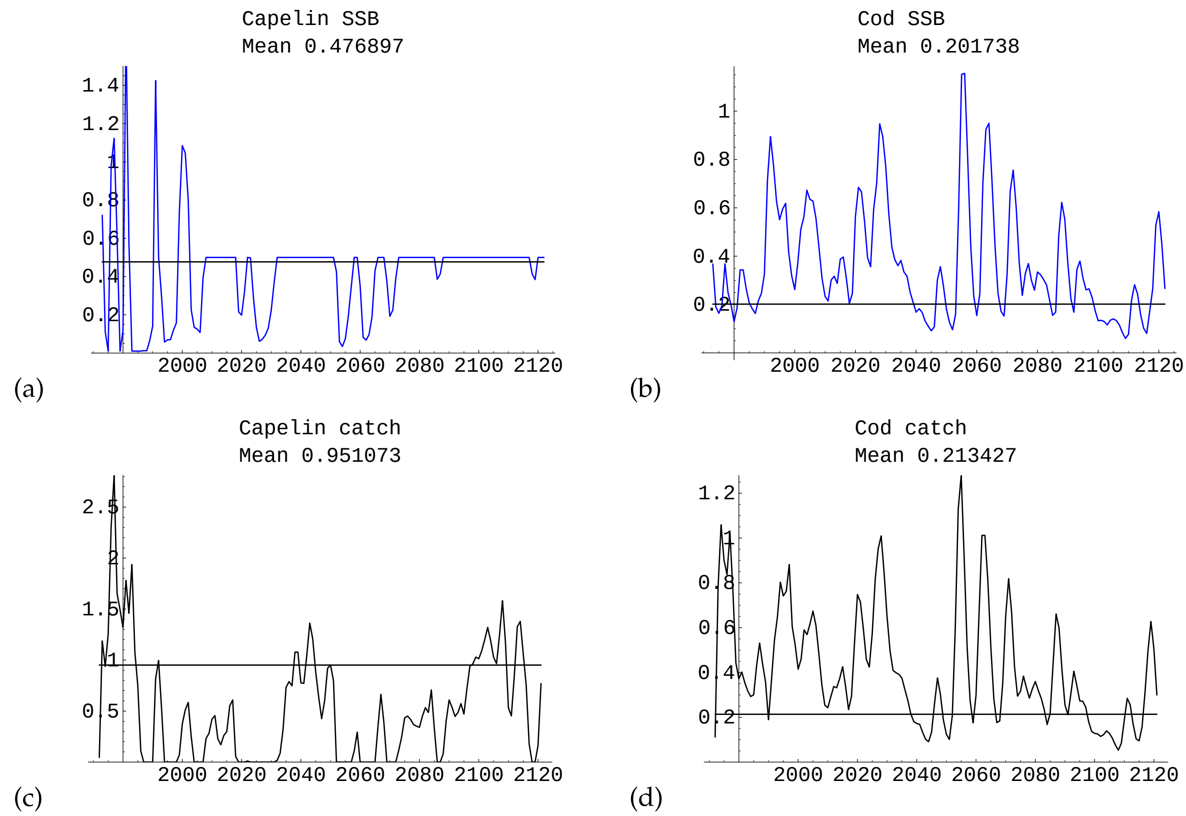


Figure 4.11: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from biologically-based strategy. Relative F on cod $= 1.0$. Target SSB capelin $= 0.5$. Constant Barents Sea herring stock of 0.5 million tons.

tons, but with dynamic herring this mean value falls to about 0.10 million tons. Similarly, with a stronger herring influence (0.8 million tons), the mean TB of capelin falls from 2.21 million tons under constant herring influence to 0.21 million tons when the herring stock is dynamical. Conversely, the TB of cod grows considerably from about 1.21 million tons to about 2.6 million tons when the long-term mean of herring is 0.5 million tons and from 0.892 million tons to 2.63 million tons when the mean of herring is 0.8 million tons.

With a mean of 0.8 million tons of herring in the system, simulations with dynamical herring give more desirable results than the simulations with a constant herring influence. When the mean biomass of herring is lower (0.5 million tons), the picture is more complex. In addition to strategy $\tilde{A}_1$, Strategy $\tilde{B}_1$ also appears better when herring influence is dynamical. Even though the mean TB of the capelin stock falls slightly, both TACs of capelin and TACs of cod grow. For the rest of the strategies, constant herring gives better results than dynamical herring of mean 0.5 million tons, since stocks and

Table 4.4: Mean and standard deviation (SD) for prognostics of total biomass and TACs of capelin (autumn stock) and cod (january) when a constant Barents Sea herring stock of 0.5 million tons each year is assumed. Each run covers a 965 years period with 2006 as the starting year.

Strategy	Capelin stock		Cod stock	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	3.091630272	0.662100941	1.20874704	0.174171855
A, $\delta = 0.05$	0.143890648	0.407358485	2.615785602	0.540907652
B, $\delta = 0.01$	3.090494807	0.662041799	1.208038903	0.174585102
B, $\delta = 0.05$	1.150288865	0.451976511	3.378947033	0.729517508
C_1	1.945762907	0.756340991	1.966642941	0,646805015
C_2	4.104687943	0.899346301	0.496878953	0.446232054
Strategy	**Capelin TAC**		**Cod TAC**	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	0.005443101	0.024460816	0.410329623	0.24766933
A, $\delta = 0.05$	0.023567972	0.00623093	0.601002962	0.092304818
B, $\delta = 0.01$	0.005071674	0.023421135	0,411132836	0.248686928
B, $\delta = 0.05$	0.0	0.0	0.702030157	0.076879613
C_1	0.051854613	0.158286673	0.587451550	0.248665038
C_2	0.965346285	0.474029877	0,192500381	0.184195318

TACs of cod are higher in the first case. With strategy $\tilde{B}_2$ particularly the difference is significant, as mean TACs are respectively about 0.702 and 0.637 million tons. Yet strategy $\tilde{B}_2$ is still the strategy giving the highest mean TACs of cod.

Looking at long-term maximum sustainable TACs of cod, we see that the simulations with constant herring influence (0.5 million tons and 0.8 million tons) give the following ranking of the strategies: 1.$\tilde{B}_2$, 2.$\tilde{A}_2$, 3.$\tilde{C}_1$, 4.$\tilde{A}_1$, 5.$\tilde{B}_1$ and 6.$\tilde{C}_2$. With dynamic herring influence strategy the ranking is: 1.$\tilde{B}_2$, 2.$\tilde{A}_1$, 3.$\tilde{A}_2$, 4.$\tilde{C}_1$, 5.$\tilde{B}_1$ and 6.$\tilde{C}_2$.

4.5 Discussions

4.5.1 The characteristics of the management model

When looking at the optimal value function in Figure 4.1(a) we should be more concerned about the shape of the surface than the specific values on it. Whereas the values are of little relevance to practical perspectives, the shape of the surface may help us to better understand the properties of both the biological and economic parts of the man-

Table 4.5: Mean and standard deviation (SD) for prognostics of total biomass and TACs of capelin and cod when a constant Barents Sea herring stock of 0.8 million tons each year is assumed. Each run with the Bifrost-simulator covered a 565-year period with 2006 as the starting year. Biomass estimates of capelin and cod respectively correspond to total autumn stock and total stock on January 1.

Strategy	Capelin stock		Cod stock	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	2.214898711	0.42006007	0.891694836	0.147040637
A, $\delta = 0.05$	0.085405304	0.234210912	2.490765284	0.458312948
B, $\delta = 0.01$	2.219912272	0.42183278	0.892104416	0.147830299
B, $\delta = 0.05$	0.867700142	0.272603932	2.997248327	0.635147445
C_1	1.509473215	0.570326057	1.629396401	0.66140552
C_2	2.593762349	0.571576056	0.484616247	0.426159468
Strategy	**Capelin TAC**		**Cod TAC**	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	0	0	0.318495806	0.220373323
A, $\delta = 0.05$	0.018942894	0.015747563	0.575867007	0.090659615
B, $\delta = 0.01$	0	0	0.317066717	0.223027975
B, $\delta = 0.05$	0	0	0.658436597	0.08312256
C_1	0.044380072	0.121733895	0.487169386	0.23482143
C_2	0.423687288	0.277196976	0,187882981	0.176577218

agement model.

First of all we observe that the surface goes through the origin. This is intuitively understandable since an extinction of both capelin and cod would give no future surplus from the fishery of these stocks. Second, with some capelin and no cod present, the biological model gives good growth conditions for capelin and absence of cod for the future. Since cod is more valuable than capelin in the economic model, future profit from such a scenario is considerably lower than with some cod present. This is obviously because of the discontinuity creating a steep wall rising up from the edge of the surface along the capelin axis.

If we have a closer look at the surface edges leading out of the origin along the capelin and cod axis, we see that they rise for small values of the stocks and flatten out for large values. The reason is two-fold: according to the biological growth model extreme stock sizes are not sustainable, and according to the concave nature of the economic model, higher catches would lead to lower prices, and therefore give limited profit.

From an economic perspective, the purpose of capelin is more or less to feed the cod

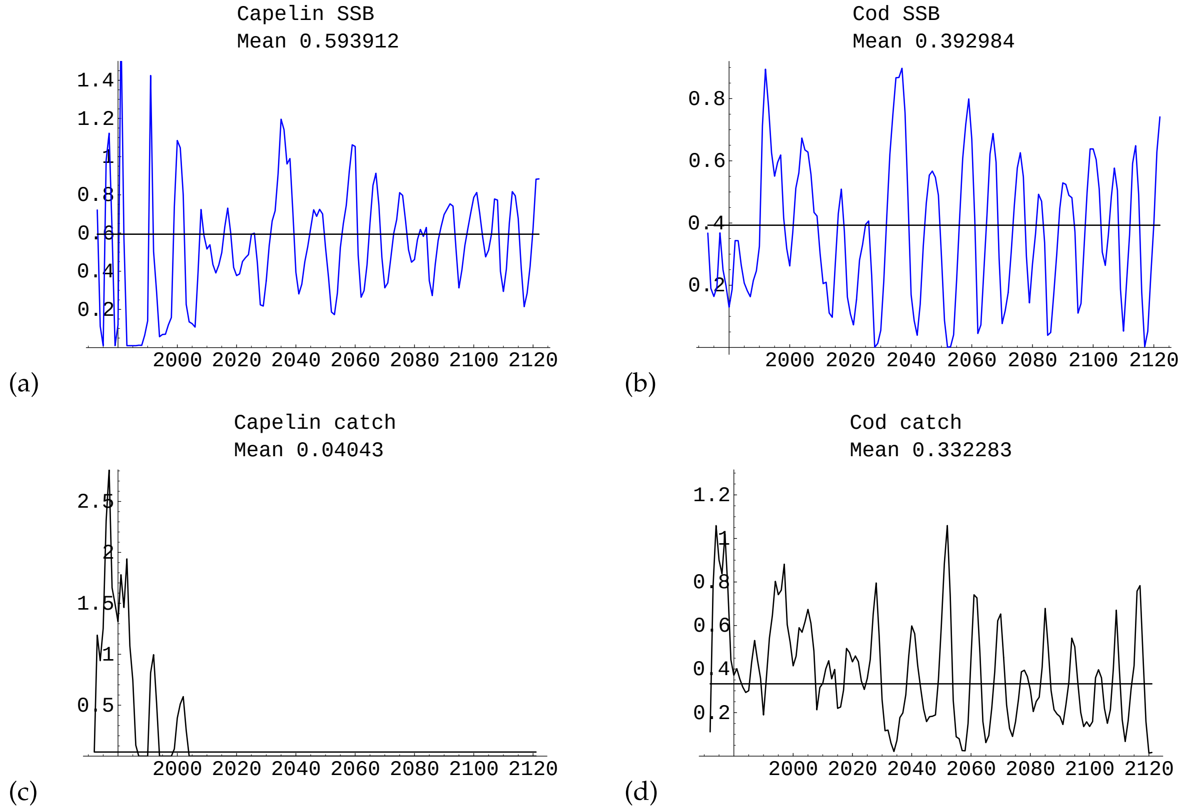


Figure 4.12: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from strategy $\tilde{A}_1$ (1% discount rate) when a Barents Sea herring stock of 0.8 million tons is assumed.

stock, which is the most profitable species, but a small harvest of capelin may in some years add profit without harming the growth of cod too much. Specifically, if the cod stock were totally depleted, optimal harvest would mean much heavier exploitation of the capelin stock since its main predator would have been absent for all future. This is the reason for the wall rising up from the capelin axis of Figure 4.2(a) and 4.2(c).

The pattern of the optimal catch of capelin is rather surprising. (See figures 4.2(a)-4.2(d)). The surprising part is the ridge parallel to the cod axis. Zero-level of capelin means of course absence of capelin harvest, but why do small levels of capelin give higher TACs of capelin than fairly high levels of the stock?

This is not easy to explain, but according to the biological management model capelin will contribute little to further cod growth when there are high levels of cod (roughly two million tons and more) and little capelin. At the same time, capelin is in a situation where it will become totally depleted by predation from cod. In such a situation it might be profitable to catch the capelin and get some immediate surplus. With a lot

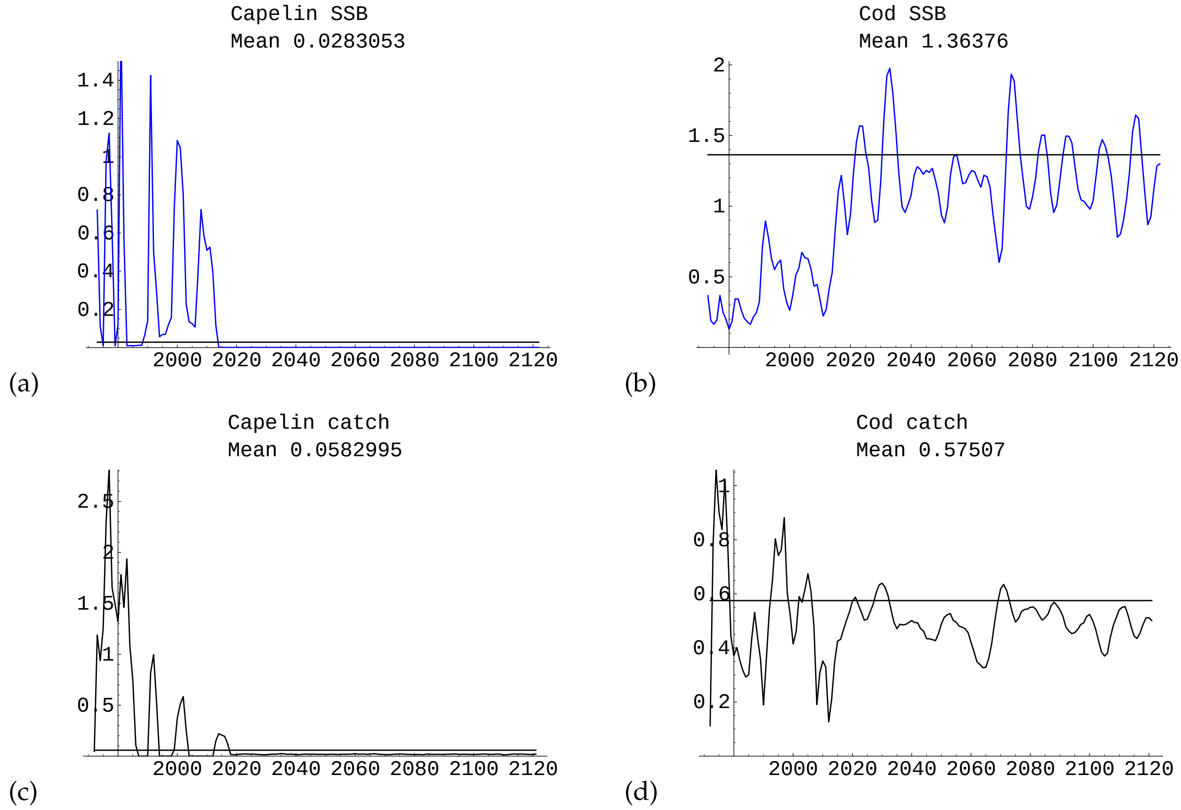


Figure 4.13: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from optimal strategy $\tilde{A}_2$ (5% discount rate) when a constant Barents Sea herring stock of 0.8 million tons is assumed.

more capelin present, the capelin stock may still be under pressure from cod, but will not become depleted. Then no catch of capelin and heavy catch of cod is the best harvest policy. Figures 4.3(a) and 4.3(b) show that cod should be heavily exploited on the area of the capelin-cod plane where zero harvest of capelin is optimal. Specifically, there is a peak in the cod TACs on the borderline between the ridge in the capelin TAC and the zero corridor. This leads us to conclude that heavy exploitation of cod is a rescue operation to secure future stocks of capelin. The ridge in the TACs of capelin covers an area where optimal management leads to extinction of capelin. One could ask, however, whether the simple biological model underestimates the survival ability of the capelin stock. If that is the case, the ridge close to the cod axis in Figure 4.2(a) and 4.2(c) should be replaced with zero levels as optimal harvest of capelin. This is a strong argument for the introduction of strategy $\tilde{B}_1$ and $\tilde{B}_1$.

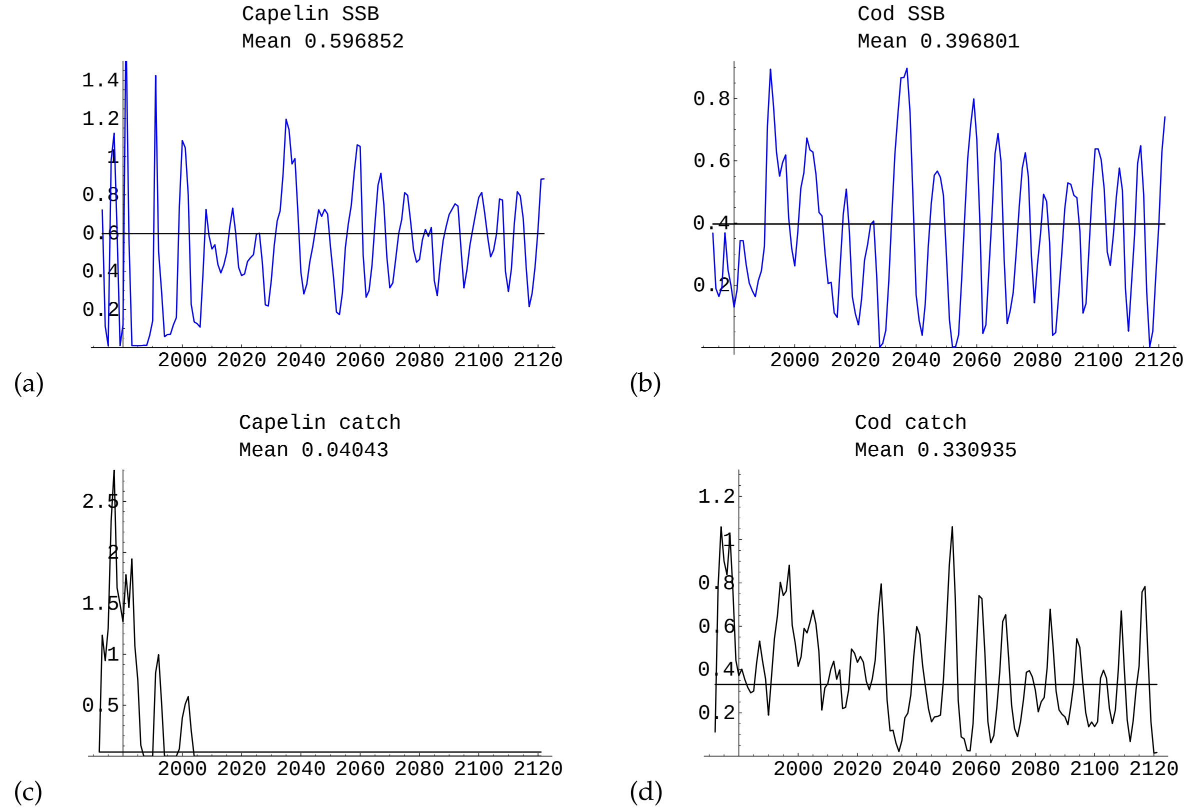


Figure 4.14: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from strategy $\tilde{B}_1$ (1% discount rate) when a constant Barents Sea herring stock of 0.8 million tons is assumed.

4.5.2 Simulations with Bifrost

The two-species nature of the biology in the management model is a simplification of real nature, but it should be superior to a one-species model. In the same way a three-species model would have been a simplification, but less so than a two-species model. In the two-species herring growth influence is indirectly reflected through the parameters of the growth function since the regression analysis performed to find these parameters is based on data/calculations found from survey data and assessment calculations regarding, among other factors, influence from herring. With the uncertainty about the sufficiency of a two-species model in mind, however, we believe that it is a good strategy to test the two-species management model when SeaStar is turned both "on" and "off" in the Bifrost simulations. When SeaStar is "off", herring is set to a constant level, as in sec. 4.4.1, and when SeaStar is on, herring varies according to this assessment tool, as in the simulations of sec. 4.4.2.

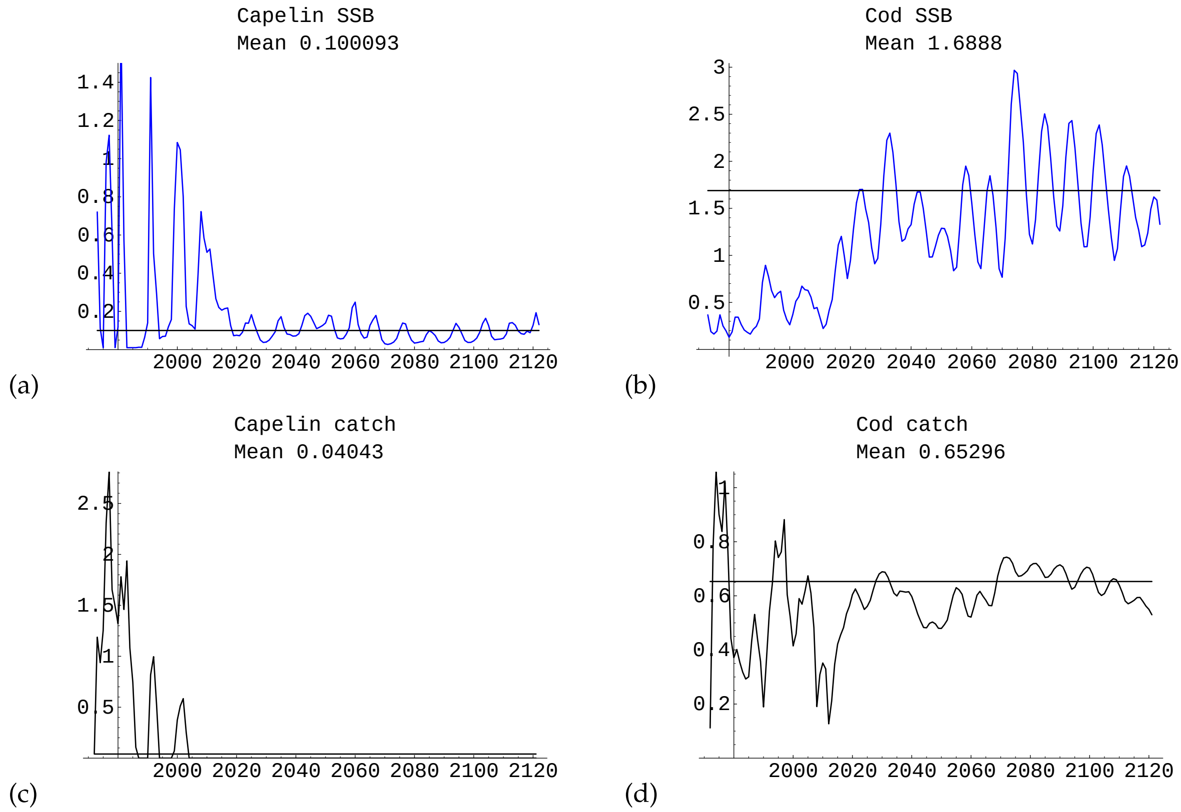


Figure 4.15: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from optimal strategy $\tilde{B}_2$ (5% discount rate) when a constant Barents Sea herring stock of 0.8 million tons is assumed.

With SeaStar turned "off" the strategies with low discount rate ($\tilde{A}_1$) and ($\tilde{B}_1$) result in a much lower average biomass of cod than those with high discount rate. At the same time the biomass average of capelin is higher, actually almost three times higher, than it is with strategy $\tilde{A}_2$ and the capelin extinction-aware strategy $\tilde{B}_2$ (see table 4.4). These findings may be explained by the feedback management. When the discount rate is low, cod harvest is close to bliss, and even above bliss, in parts of the stock area where the capelin stock is under pressure (see figures 4.3(a) and 4.3(b)). In other words, the capelin rescue operation from the management model also works in the simulations. It even works better there than in the management model itself. Although vanishing low biomasses of capelin are found in simulations with strategy $\tilde{A}_2$, the stock survives in all the simulations, as it does when SeaStar is on. The survival of capelin in all the simulations might seem a little strange since, according to the management model, low biomasses of capelin would result in extinction. It is obvious that the survival ability of the capelin stock must be considered stronger in the simulation model than in the

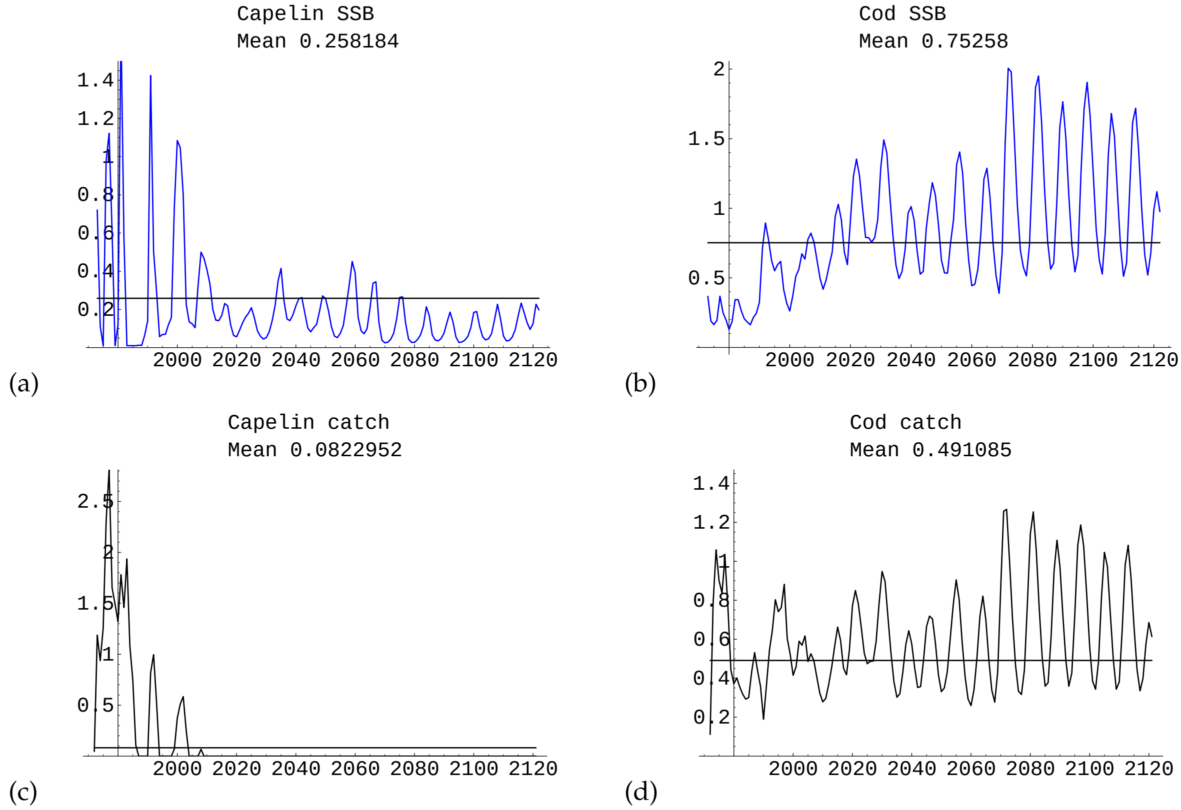


Figure 4.16: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from biologically based strategy $\tilde{C}_1$. Relative F on cod $= 0.65$. Target SSB capelin $= 0.5$. Constant Barents Sea capelin of 0.8 million tons

management model. Yet none of the strategies give capelin levels near the management model equilibriums (see Table 4.3.) Neither the capelin stock, nor the cod stock seems to have the same strong growth potential for high stocks in the simulation model as it does in the management model.

The discount rate seems very important to the results in terms of average catches and standard deviation are concerned. Strategy $\tilde{A}_2$ and $\tilde{B}_2$ (both with 5% discount rate) give higher cod TAC means with much lower standard deviations than all the other strategies when herring influence is constant. (See Table 4.4 and 4.5.) When herring influence is dynamical strategy $\tilde{A}_1$ with low discount rate also gives high TACs of cod with low standard deviation. (See tables 4.6 and 4.7.) The low standard deviation in these strategies is connected with low capelin levels. The capelin levels are, however, acceptable in the simulations with the capelin aware strategies $\tilde{B}_1$ and $\tilde{B}_2$.

Surprisingly, when herring influence is constant (sec. 4.4.1) strategy $\tilde{A}_2$ gives a higher capelin TAC mean than do strategy $\tilde{A}_1$. The reason is that strategy $\tilde{A}_1$ leads

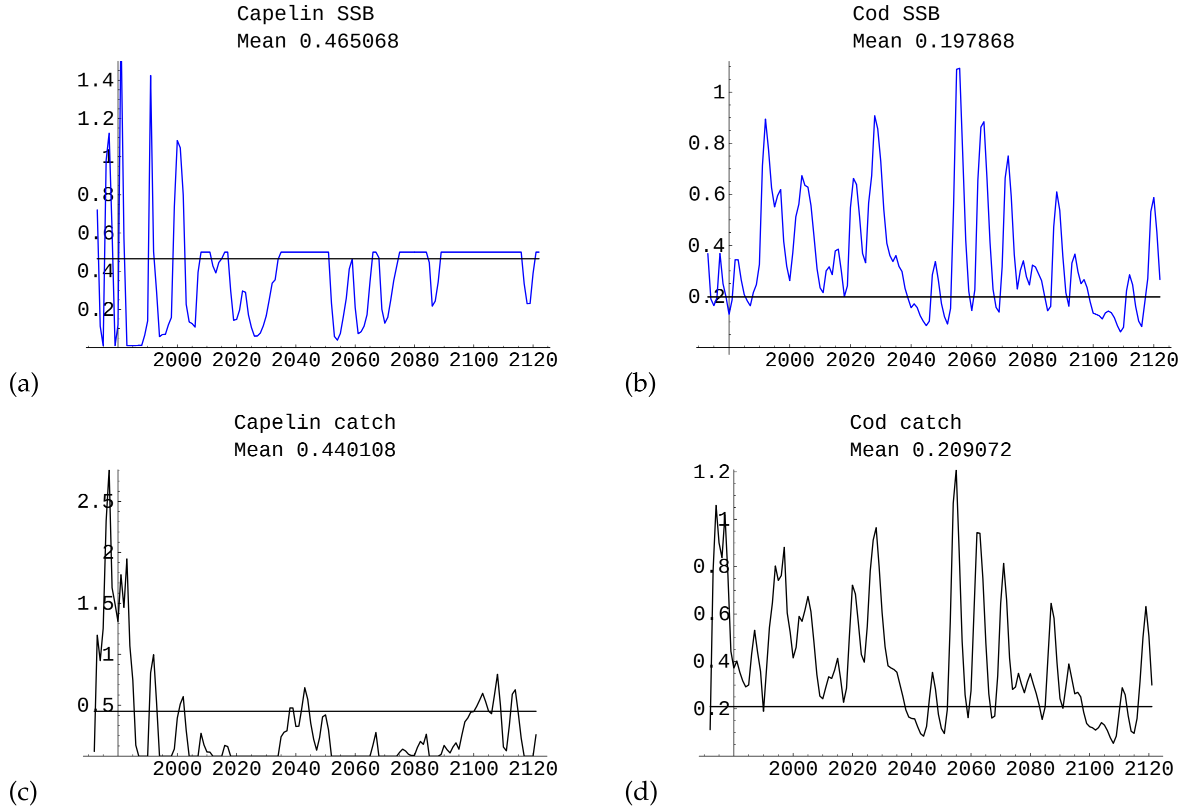


Figure 4.17: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from biologically-based strategy. Relative F on cod $= 1.0$. Target SSB capelin $= 0.5$. Constant Barents Sea herring stock of 0.8 million tons.

to a capelin stock that most of the time is found somewhere in the wide fishing closure tunnel of Figure 4.2(b), whereas under strategy $\tilde{A}_2$ the capelin stock vanishes low and stays there since very high cod stocks are combined with low, but too high, capelin TACs. This means that the misfit between the extremely low growth for small capelin biomasses in the management model and the higher growth in the simulation model leads to a capelin fishery that is probably suboptimal according to the simulations. The cod TACs following from strategy $\tilde{B}_2$ are both higher and more stable than those following strategy $\tilde{A}_2$ (see Table 4.4).

In sec. 4.4.2 we document a dramatic difference between results from simulations with constant herring influence and simulations with a dynamic herring stock when strategy $\tilde{A}_1$ is followed. For the rest of the strategies there is only minor differences, and it is difficult to explain why the mean capelin biomass is so much lower with strategy $\tilde{A}_1$ when SeaStar is on. Of course, heavy predation from a much higher cod stock is an important reason, but why does the cod stock become higher? Probably, variation

Table 4.6: Mean and standard deviation (SD) for prognostics of total biomass and TACs of capelin and cod when a dynamic Barents Sea herring stock with mean 0.5 million tons each year is integrated through SeaStar assessment. Each run with the Bifrost-simulator covered a 565-year period with 2006 as the starting year. Biomass estimates of capelin and cod respectively responds to total autumn stock and total stock on January 1.

Strategy	Capelin stock		Cod stock	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	0.104942418	0.211483267	2.601265362	0.530627246
A, $\delta = 0.05$	0.104653328	1.124502037	2.498446365	0.470974904
B, $\delta = 0.01$	2.709593392	1.952733583	1.639118427	0.9733563
B, $\delta = 0.05$	1.3106663	0.76442343	2.87125168	0.6587045
C_1	2.193543783	1.60508793	1.906429291	0.600704853
C_2	4.570881257	2.817617425	0.484917141	0.426078118
Strategy	**Capelin TAC**		**Cod TAC**	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	0.024383397	0.011183115	0.59004937	0.0976793800
A, $\delta = 0.05$	0.025217851	0.242822457	0,577847113	0.099450130
B, $\delta = 0.01$	0.051455493	0.120846468	0.492555017	0.318010448
B, $\delta = 0.05$	0.0	0.0	0.636517844	0.098382788
C_1	0.1327351	0.363901952	0.569615536	0.231219606
C_2	1.231926845	1.074320779	0.187904156	0.177654534

with a low herring stock in some following years allows the capelin stock to maintain a rather high level (see Figure 4.18(a)), which in turn gives rise to a higher cod stock (Figure 4.18(b)). When such a cod stock interferes with a couple of years with a stronger herring stock, the capelin stock falls below the level where it is sustainable according to the management model. Then continued fishing of capelin prevents a recovery of the stock.

An interesting feature with the Bifrost simulations is the occurrence of sudden changes after a long period with smaller fluctuations. The stocks appear to be fluctuating around an equilibrium, but change to a completely different level within a few years. Such changes are visible in e.g. Figure 4.8, where the SSB of cod has a sudden rise in year 2027 and the capelin stock collapses at the same time. Similar changes can be found in Figure 4.10(b), 4.10(f), 4.13(b), 4.15, 4.18 and 4.19. In addition, traces of such changes occurring after the year 2120, which is the last year plotted in the figs., can be found in figures 4.11, 4.17, 4.20(a) and 4.23. In all these figures the long-term average (marked with a horizontal line) is very different from the average for the whole simulation period. This indicates that there might be similar sudden, but lasting, changes in the stocks

Table 4.7: Mean and standard deviation (SD) for prognostics of total biomass and TACs of capelin and cod when a dynamic Barents Sea herring stock with mean 0.8 million tons each year is integrated through SeaStar assessment. Each run with the Bifrost-simulator covered a 565-year period with 2006 as the starting year. Biomass estimates of capelin and cod respectively correspond to total autumn stock and total stock on January 1.

Strategy	Capelin stock		Cod stock	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	0.104588139	0.211689948	2.630227166	0.534135135
A, $\delta = 0.05$	0.105859949	0.212403585	2.517932311	0.453666864
B, $\delta = 0.01$	2.425595884	1.917156855	1.977312934	1.179767557
B, $\delta = 0.05$	1.114681689	0.683799163	3.195746753	0.640288498
C_1	2.170154644	1.594883362	1.805945447	0.624974832
C_2	4.372569005	2.521841766	0.466860171	0.409037602
Strategy	**Capelin TAC**		**Cod TAC**	
	Mean	SD	Mean	SD
A, $\delta = 0.01$	0.02411249	0.010830534	0.595820109	0.098188791
A, $\delta = 0.05$	0.024825422	0.01275787	0.580031794	0.088291182
B, $\delta = 0.01$	0.041258541	0.108957671	0.53026835	0.320719587
B, $\delta = 0.05$	0	0	0.682807604	0.085331068
C_1	0.150639218	0.407289171	0.539808212	0.232475843
C_2	1.157060003	0.993375262	0.181215568	0.169439547

appearing after the year 2120. To understand these sudden changes in the stock sizes one needs to remember that Bifrost is a year class model. For Example, small recruitment of capelin in some subsequent years contemporaneously with a couple of good year classes of cod reaching maturity may lead to very high biomasses of cod and collapse of the capelin stock. Conversely, a slightly too high catch of cod may bring the cod stock to very low levels and give favorable conditions for capelin, which is the case when strategy $\tilde{C}_2$ is followed. In figures 4.11, 4.17 and 4.23 we can see that the capelin stock is generally much lower than the average and the cod stock is much higher than the average until the year 2120. To shift the average large changes must occur in the next 500 years.

The potential capelin collapse when a large cod stock interferes with strong year classes of herring and over-high capelin fishery suggests that greater attention should be paid to multi-species aspects in the management of capelin and cod. Prognostics of the size of the herring inflow to the Barents Sea basin may become important for future management. Meanwhile, an "aware" management of the capelin stock is the best approach according to the simulations in this work. Strategy $\tilde{B}_2$ gives a higher sustain-

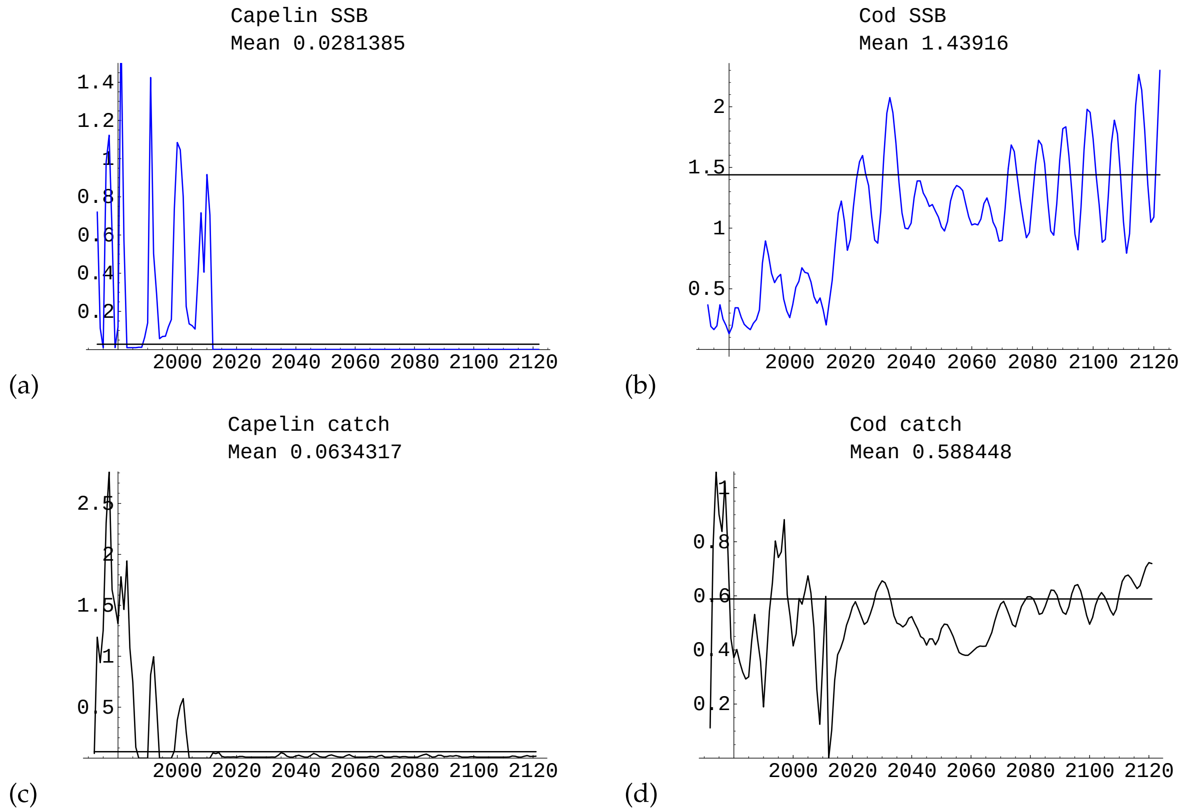


Figure 4.18: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from strategy $\tilde{A}_1$ (1% discount rate) when a dynamic Barents Sea herring stock with mean 0.5 million tons is assumed.

able cod TAC than all the other strategies in all the simulations performed. The best of the purely biologically-based strategies, strategy $\tilde{C}_1$, also gives rather good results with higher capelin TACs than the purely economic strategies. Nevertheless, when the herring stock is dynamical and we focus on mean cod TACs, this strategy is only ranked as number four with regard to the size of the cod TACs.

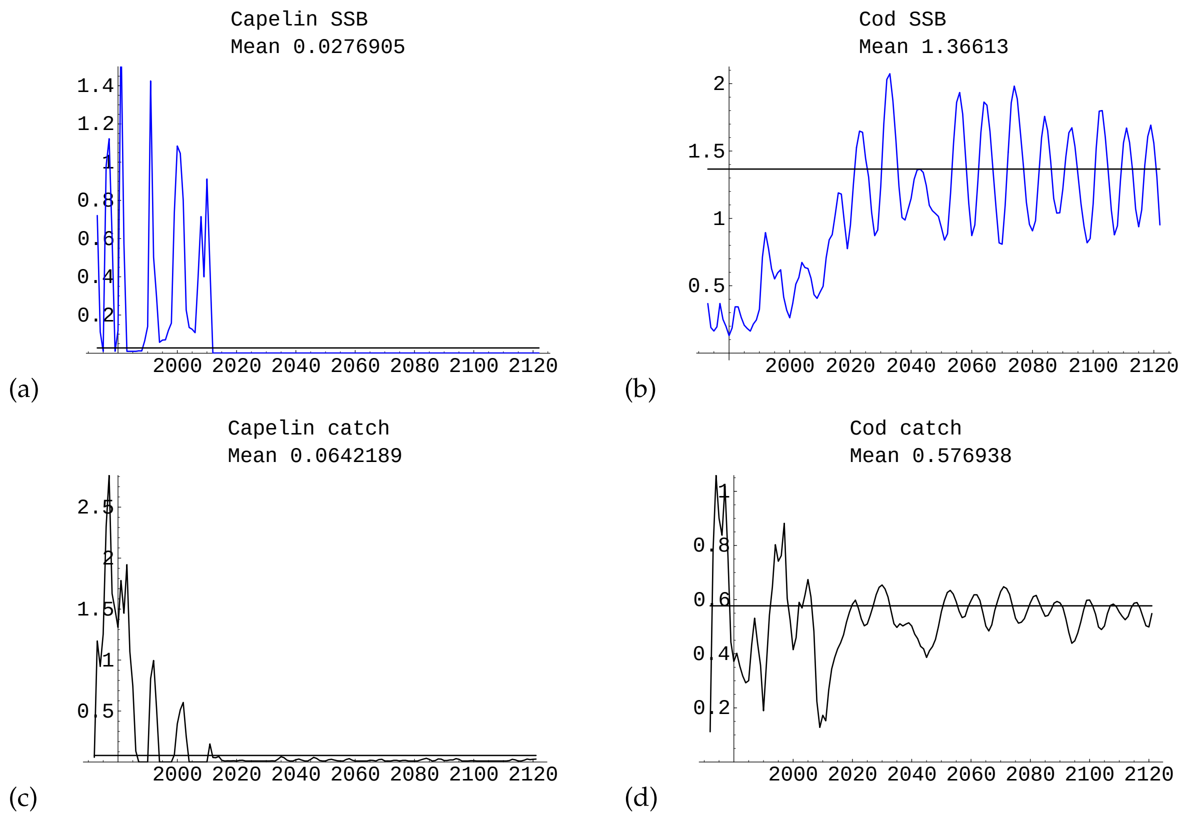


Figure 4.19: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from optimal strategy $\tilde{A}_2$ (5% discount rate) when a dynamic Barents Sea herring stock with mean 0.5 million tons is assumed.

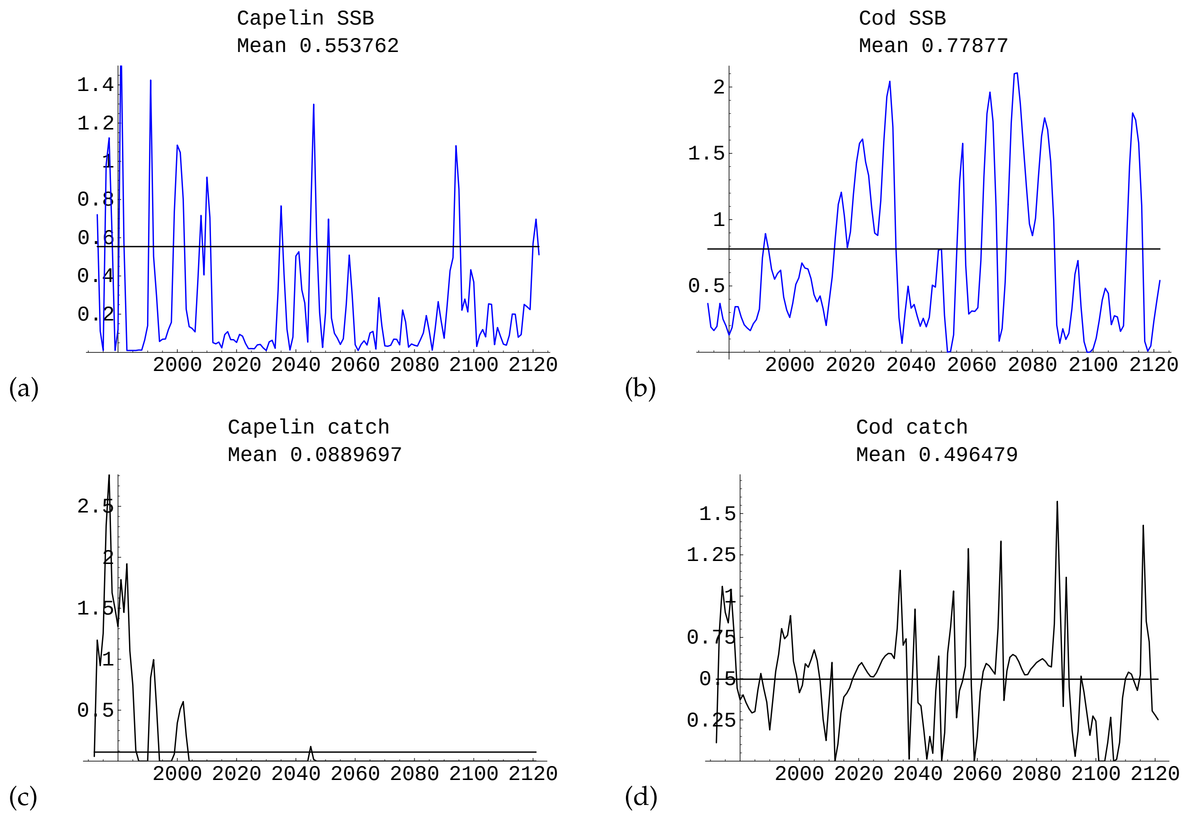


Figure 4.20: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from strategy $\tilde{B}_1$ (1% discount rate) when a dynamic Barents Sea herring stock with mean 0.5 million tons is assumed.

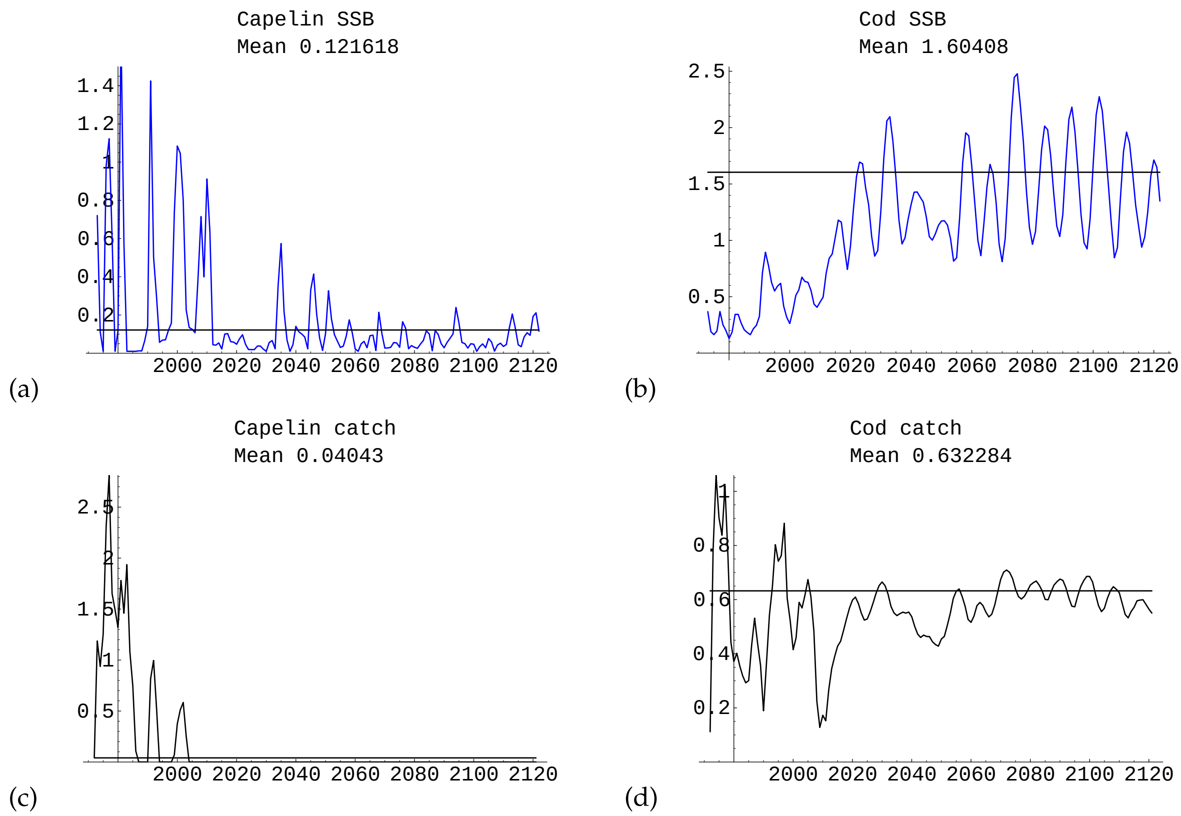


Figure 4.21: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from optimal strategy $\tilde{B}_2$ (5% discount rate) when a dynamic Barents Sea herring stock with mean 0.5 million tons is assumed.

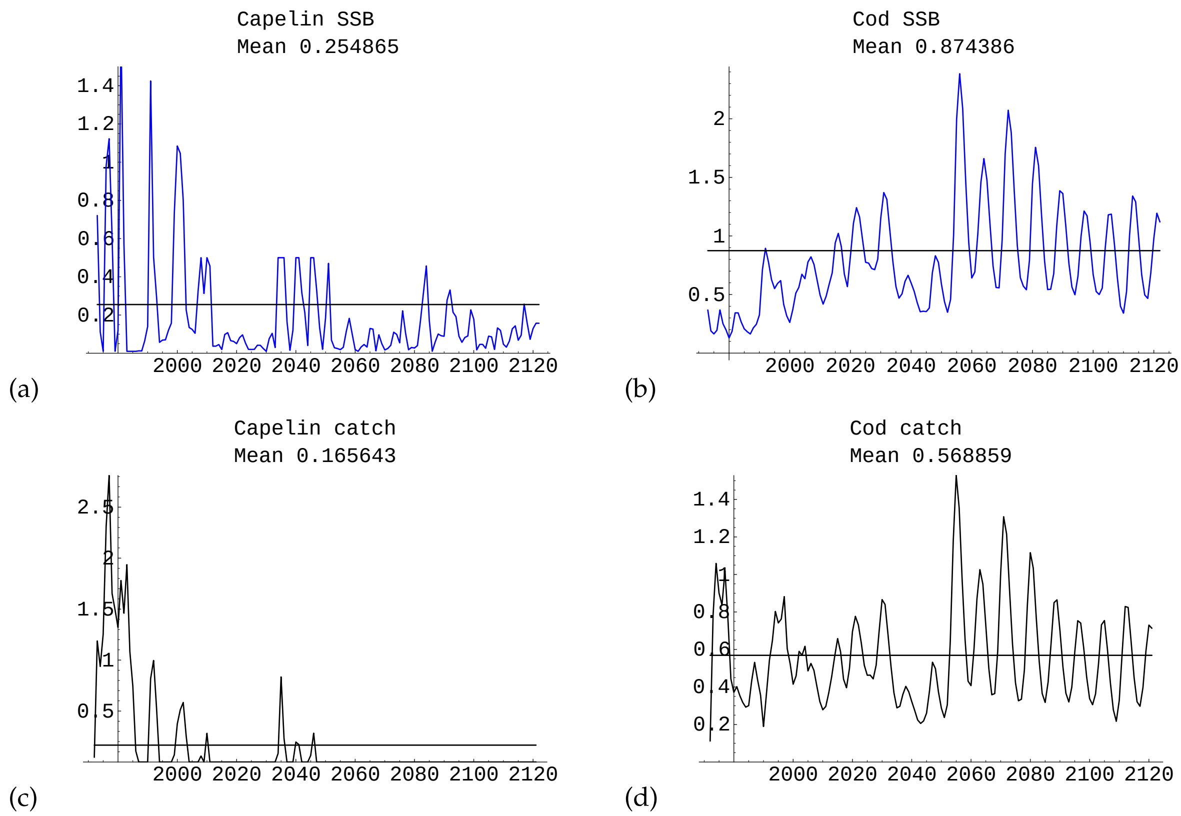


Figure 4.22: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from biologically based strategy $\tilde{C}_1$. Relative F on cod $= 0.65$. Target SSB capelin $= 0.5$. Dynamic Barents Sea capelin stock with mean 0.5 million tons.

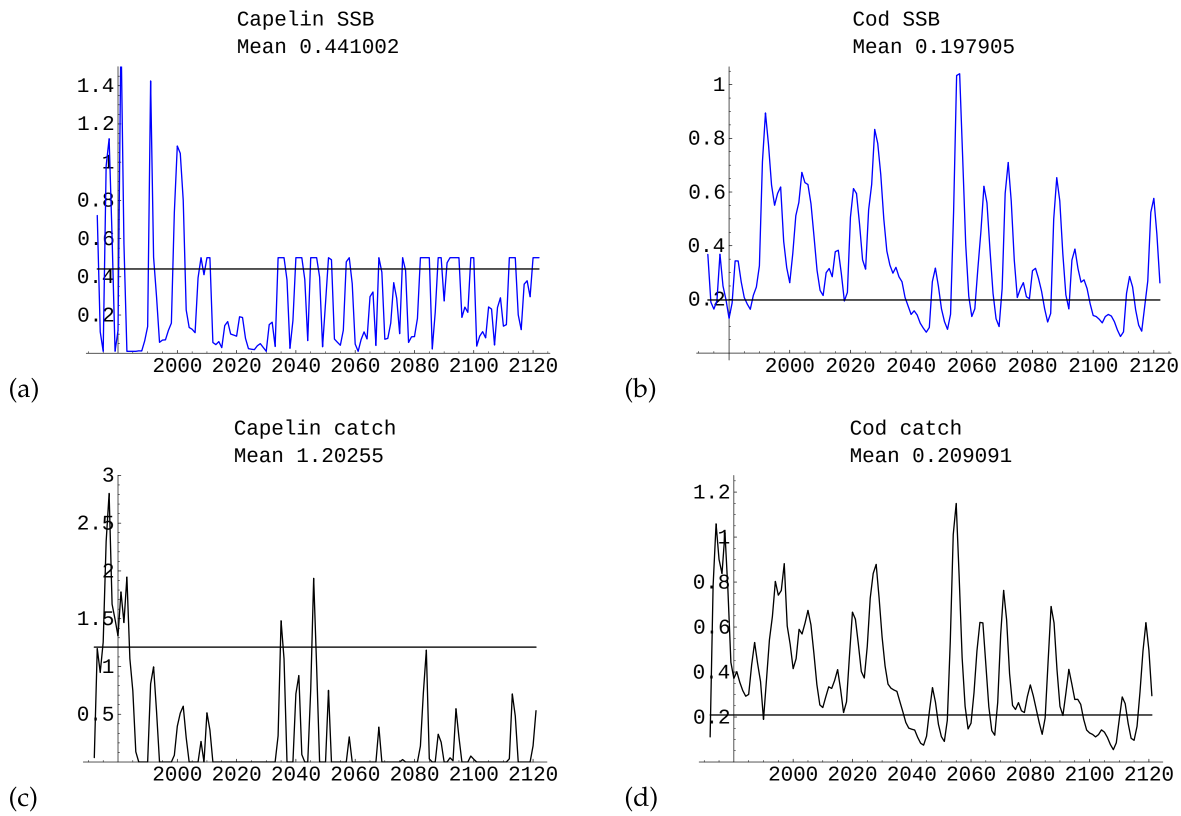


Figure 4.23: Spawning stock biomass (SSB) and catch prognostics for capelin and cod resulting from biologically-based strategy. Relative F on cod $= 1.0$. Target SSB capelin $= 0.5$. Dynamic Barents Sea herring stock with mean 0.5 million tons.

4.6 Conclusions

In this work a feedback model for optimal management of the joint Norwegian resources of capelin and cod in the Barents Sea is presented and tested. The management is based on purely economic objectives, and the simulated scenarios test the biological consequences of adopting the proposed management as prevailing harvest control. The question is whether the management model is sustainable from a biological perspective.

Four feedback strategies are tested and compared with two different reference strategies, both revealed by existing management. The feedback strategies differ in discount rate and capelin-awareness, and the reference strategies differ in the mortality rate of the cod stock. All the strategies are tested under different conditions. Constant herring influence to the capelin-cod system gives other results than a dynamical herring influence simulated from the herring assessment model SeaStar. On both occasions the results from the feedback-management are promising. Larger long-term mean TACs of cod than those resulting from the best reference strategy are found in the best feedback strategies. Because of rather high cod stock biomasses following these strategies, the capelin stock gets a little lower, but does not become extinct. The stocks also tend to have a lower variability (lower standard deviation) in the simulations with the feedback-management.

The simulations assuming a dynamical herring stock give quite different results from those assuming constant herring. This suggests that the three-species perspective (capelin-cod and herring) is important. Further investigations should be carried out concerning multi-species management of capelin and cod, and integrating herring prognostics in the management is a natural extension of the management model tested in this work.

The capelin TAC chosen in the second strategy differs from the first strategy only for low levels of capelin and high levels of cod. Specifically, the difference is that the ridge in the TACs of capelin for low levels of the stock is removed. (See figures 4.5(a) and 4.5(b)). This results in a more aware TAC-setting for capelin. The fishery will only be open for either very high stocks of capelin or for combinations of low cod stocks and rather high capelin stocks. Moreover, the discount rate has little influence on the capelin TACs, but with high discount rate (5%) the fishery is opened for a little lower stocks.

Economical perspectives are not discussed in this work since the purpose is to test biological consequences of economical based management. The conclusions about lower variations in the stocks and a higher cod stock with the economical based strategies suggest, however, that these strategies are superior to the reference strategies as far as economy is concerned. Between capelin and cod, cod is the economically most important species by far. Moreover, in theory and also according to the economical based management model, a higher cod stock increase the efficiency in the cod fishery as it reduce the cost per unit catch.

Nomenclature

Parameters and Variables

x and y	Stock levels of capelin and cod respectively
u and v	Catch levels of capelin and cod respectively
δ	Discount rate
α_1 and α_2	Norwegian shares of TAC for capelin and cod respectively
h	Discrete time jump
β	Parameter in the discrete HJB equation
c_1, c_2, c_3 and c_4	Cost components in the profit function
a_1, a_2 and a_3	Price and income components in the profit function
b_1, b_2, b_3, b_4, b_5 and b_6	Growth functions parameters

Functions

$V(x, y)$	The optimal value function
$\Pi(x, y, u, v)$	Current profit
$f_i(x, y)$	Biological growth function for species i
$CaP(u_1)$	Capelin profit
$CoP(x_2, u_2)$	Cod profit
$P_2(u)$	Price for a unit of cod

4.7 References

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