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Earth nutation influence on Northeast Arctic cod management

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Northeast Arctic cod in the Barents Sea is the largest stock of *Gadus morhua* cod in the world. The cod biomass seems to have stationary cycles related to the Earth's nutation. The present paper suggests that current management strategy has three aspects that may introduce an instability in the biomass. The first is the 6–7 yr positive feedback of recruitment in combination with a phase-delay in estimating data and getting the next quota of landings. The second is that the biomass has no stationary biomass reference in the control strategy and the third is the change in the rate of landings each year. Simulations demonstrate that the biomass needs a 15–20 year planning perspective and it is suggested that the spawning-stock biomass level is managed by a feedback control and the fluctuations of landings by a feed-forward control.

Key words: Northeast Arctic cod, management, biomass stability, forecasting.

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Introduction

Northeast Arctic cod is the largest stock of *Gadus morhua* cod in the world. The fishery of this stock is located along the northern coast of Norway and in the Barents Sea. For centuries it has been the most important economic biomass for Norwegian fishermen and of vital importance for settlement and economic growth in the western part of Norway. The biomass of Northeast Arctic cod has always fluctuated and there have been several theories on the causes of these fluctuations. One is the relationship between the sea temperature and cod recruitment (Sætersdal and Loeng, 1987; Nakken and Raknes, 1987; Eilertsen *et al*., 1989; Nakken, 1994; Ottersen *et al*., 1996; Yndestad, 1996). Another is the impact of predators like birds, marine animals and cannibalism (Haug *et al*., 1991; Gabrielsen and Rygg, 1992) and a third is the amount of food available in a given year (Ajiad *et al*., 1992). Other explanations can be found in Jacobsen *et al*. (1994), St.meld.nr. 51 (1997–1998) and Pennington (1999).

Figure 1 shows the time series of the total biomass, spawning-stock biomass and landings of Northeast Arctic cod from 1950–1998. In the 25 year period from 1950–1975 the total biomass decreased from about 310 000 tons to about 250 000 tons and the biomass fluctuated about 1 000 000 tons and the landings were about 800 000 tons in 1974. Over the next ten years there was a collapse with the biomass decreasing to about 66 000 tons and the landings to 27 000 tons in 1984. To save the biomass the Norwegian government started quota regulation in 1984–1985 based on scientific advice from ICES. In the period from 1983 there was growth of the biomass and, as a result, a new trawler fleet was built in Norway and the quota increased to 520 000 tons in 1987. However the increase in biomass and quota was temporary and in 1990 the quota was down to 210 000 tons. In the period 1990–1993 the biomass again grew to about 2 300 000 tons and the landings to about 770 000 tons in 1994. A quota of 770 000 tons was too much and in 1998 there were indications of a serious reduction of the biomass. Again the quota of landing was reduced to 480 000 tons and as a first step of further quota reductions.

This paper focuses on how current management policies influence the Northeast Arctic cod resource. The Earth's nutation is introducing a stationary temperature cycle in the Barents Sea (Yndestad, 1999a) causing cycles of varying recruitment and growth of Northeast Arctic cod (Wyatt *et al*., 1994; Yndestad, 1996; Yndestad, 1999b). The current management method does not take account of these fluctuations and introduces an instability in the biomass dynamics. It is suggested that the spawning-stock biomass should be stabilised by a feedback control and the landings dynamics by a feed-forward control.

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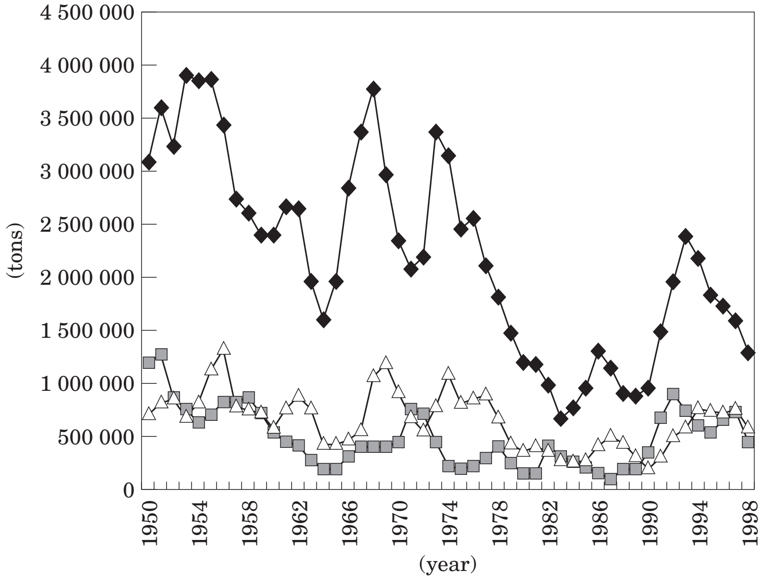

Figure 1. History (1950–1998) of total biomass stock, spawning stock biomass and the official "quota" of landings. —◆—, total stock; —■—, spawning stock; —△—, official quota.

Materials and methods

All history time-series on Northeast Arctic Cod are based on the ICES Report of Arctic Fisheries (ICES, 1999). The biomass time-series from 1999–2020 are forecast by the author and based on a temperature-dependent growth and recruitment model (Yndestad, 1999b).

Systems theory

The biomass of Northeast Arctic cod is related to a complex food chain system. Systems theory is a theory of understanding complex organisations independent of time and space (Lin, 1999). In this case the Barents Sea may have the general system architecture

$$S_B(t) = \{B_B(t), \{S_T(t), S_C(t), S_L(t), S_F(t)\}\} \in bw \tag{1}$$

where $S_T(t)$ is the temperature system, $S_C(t)$ is a cod biomass system, $S_L(t)$ is a landings system, $S_F(t)$ is a food system, $B_B(t)$ is the interaction or the binding between the Barents Sea systems and w is the common purpose. According to Equation (1) general systems are time varying, structurally unstable and mutually state dependent. Management of Northeast Arctic cod must be based on a fundamental understanding of the system dynamic of the biomass system $S_C(t)$ and the influence of bindings to other systems.

A dynamic biomass system is described by a set of first order differential equations

$$\ddot{x}(t) = f(x(t), u(t), v(t), t)$$

$$y(t) = g(x(t), w(t), t) \tag{2}$$

where x(t) represents the biomass-age vector, u(t) a landing-state age vector, v(t) a disturbance-age vector from an unknown source and the w(t) is the error-measurement-age vector. A linear time variant dynamic system of the biomass $S_C(t)$ and landings $S_L(t)$ of Northeast Arctic cod may be modelled by the state space equation

$$\ddot{x}(t) = A(t) \cdot x(t) + v(t)$$

$$y(t) = D \cdot x(t - \tau) + w(t) \tag{3}$$

where D is the measurement matrix and τ is the estimate delay. Comparing statements from people fishing in the Barents Sea and published biomass data (ICES, 1999), it is estimated that the phase delay τ is about 2–3 yr. The disturbance v(t) and the estimate error w(t) are unknown (ICES, 1999). Comparing data from a growth model (Yndestad, 1999b) and published data (ICES, 1999) the author has estimated v(t)+w(t) to be more than ± 30% of the published biomass data y(t). The autonomous system growth matrix $A(t) = A_r(t) + A_g(t) + A_m(t)$ where $A_r(t)$ represents the recruitment matrix, $A_g(t)$ the growth matrix and $A_m(t)$ the mortality matrix.

The system matrix A(t) has a temperature-dependent, stationary disturbance related to the Earth's nutation (Yndestad, 1999a, 1999b) or $A(t) = f(3\omega_n, 3\omega_n, \omega_n/3)$

where $\omega_n = 2\pi/18.6$ (rad/yr) is the Earth nutation angle frequency. The angle frequency of $3\omega_n$ will introduce a biomass fluctuation of 6.2 yr, ω_n will introduce a fluctuation of 18.6 yr and $\omega_n/3$ will introduce a fluctuation of 55.8 yr. The biomass x(t) then is a time-variant, stochastic process that has no stationary state, no stationary mean value, no stationary limit values, no stationary sustainability reference level, no stationary maximum or minimum reference level and no stationary optimum management level. This dynamic property will influence how the biomass has to be managed. The main task of management is to maximise the landings-quota figure whilst, at the same time, keeping a sustainable biomass. Such a policy depends on having good biomass estimates and a fundamental understanding of the biomass dynamics.

Current management

Current management of Northeast Arctic cod is based on the control strategy.

$$u(t) = -F(t) \cdot y(t) \tag{4}$$

where u(t) is the quota of landings vector and F(t) is the continuous landings rate matrix. This control strategy changes the landings rate F(t) each year. Future estimate of the biomass is than only predictable from one year to the next. The biomass shift from one year to the next is computed from equation (3).

$$x(t_1) = e^{A(t_0)T}x(t_0) + \int_{t_0}^{t_1} e^{A(t_0)(t_1-\tau)} \cdot u(t_0)d\tau = A(t_0)^{-1}[e^{A(t_0)} - I]u(t_0)$$

$$x(t_1) \approx [I + A(t_0)]Tx(t_0) + Tu(t_0) \tag{5}$$

where v(t)=0, a one year time interval $T = t_1 - t_0$ and I is an identity matrix. Equation (5) describes how this control strategy influences the biomass dynamics. The control of the biomass is based on choosing a proper quota of landing $u(t_0)$ that moves the biomass to the wanted state $x(t_1)$. There are some fundamental problems related to this control strategy viz.:

(1) The growth matrix A(t) has time-variant, stationary cycles of 6.2 yr, 18.6 yr and 55.8 yr because of the Earth's nutation influence on the Barents Sea temperature. Estimates of the growth matrix will than change each year and biomass dynamics will introduce errors in the estimated data.
(2) The estimate delay τ of 2–3 yr will introduce a phase error in the estimate. A combination of the phase error τ and the stationary cycle of about 6 yr in the growth matrix A(t) will introduce an instability in the biomass.
(3) The quota of landings is changed each year. When the landings rate F(t) is changed faster than the growth rate dynamics of A(t), the future state of the biomass is not predictable.
(4) The control strategy has no long-term strategy that moves the biomass x(t) to a desired level and the biomass will have a low frequency instability.

This means that the current control strategy will introduce three different types of instabilities that sooner or later may lead to a collapse of the biomass.

The same properties may be studied from the system frequency transfer function. A Laplace transform of (3) and (5) gives us.

$$x(t) = [sI - A(t_0)]^{-1} \cdot (x(s) + u(s) + v(s)) \tag{6}$$

$$y(s) = D \cdot e^{-\tau s} \cdot x(s) + w(s)$$

$$u(s) = -F(t_0) \cdot y(s) \tag{7}$$

where $s = j\omega$ (rad/yr). Equation (6) may be reduced to (7)

$$y(s) = \frac{H(s) \cdot v(s)}{[sI + H(s)F(t_0)]} + \frac{w(s)}{[sI + H(s)F(t_0)]} \tag{8}$$

where

$$H(s) = De^{-\tau s}[sI - A(t_0)]^{-1}$$

Equation (8) shows that the estimated biomass dynamic y(s) is only driven by the disturbance v(s) and the error estimate w(s) and the biomass will not be stabilised at any level. In other words there is no long-term reference control and the biomass may collapse. A second observation of equation (8) is that the biomass may be unstable when $|H(s)| = I$ and the phase delay $\perp H(s) = -\pi$.

Constant landings rate

The high frequent instability may be reduced when selecting a stationary landings' rate $F(t) = F(t_0)$. In this case Equations (3) and (5) is reduced to

$$\ddot{x}(t) = [A(t_0) - F(t_0) \cdot D]x(t) \tag{9}$$

when v(t)=0. Equation (9) has the general solution

$$x(t) = e^{[A(t_0) - F(t_0) \cdot D](t - t_0)}x(t_0) \tag{10}$$

and describes how a stationary landings' rate influences the biomass dynamics. In this case the control strategy is based on choosing a proper landings' rate F(t) that in the long run optimises the landings' quota and, at the same time, maintains a sustainable biomass. This control strategy still has some problems. The first is that the

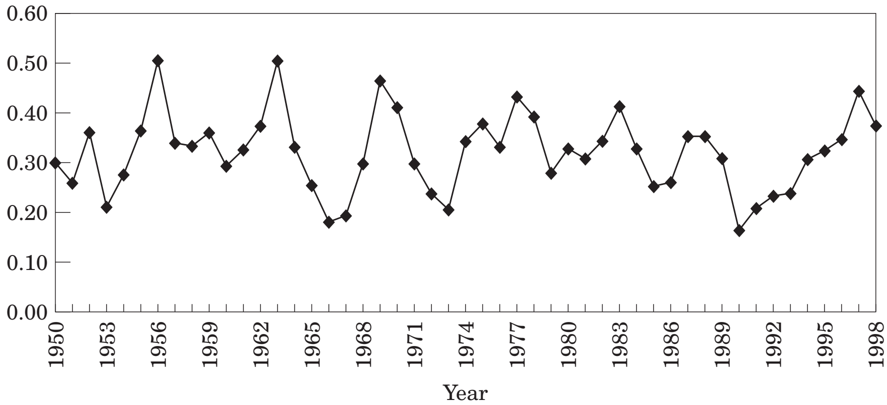

Figure 2. History of the current landings' rate from 1950–1998.

landings' rate $F(t_0)$ influences the total biomass growth rate and the sustainable level. Hence it may take many years to estimate the influence of the landings rate. A second problem is that the growth rate $A(t_0)$ has a stationary low frequency cycle of 18.6 yr. This will influence the growth rate, the sustainable reference level and the optimum management level. The landings' rate $F(t_0)$ will than have to be modified after some years. When the landings' rate $F(t_0)$ is modified to optimise the landings' quota, it is easy to introduce a low frequency instability in the biomass.

Feedback control

The spawning-stock biomass may be controlled by a feedback control strategy

$$\ddot{x}(t)=A\cdot x(t)+u(t)+v(t)$$

$$y(t)=D\cdot x(t)+w(t) \tag{11}$$

$$u(t)=H_R[r(t)-y_s(t)]$$

where r(t) is the required spawning-stock biomass level, $y_s(t)$ the estimated spawning stock and H_R is a control parameter and u(t) is the quota of landings. According to this control strategy, the biomass is controlled by the difference between the reference level r(t) and the estimated spawning-stock biomass $y_s(t)$. The Laplace transformation of a dynamic system has information on the frequency property when $s=j\omega$ (rad/yr). In this case the Laplace transform of Equation (11) is

$$x(s)=[sI-A(t_0)]^{-1}u(s)+[sI-A(t_0)]^{-1}v(s)$$

$$y(s)=D\cdot x(s)+w(s) \tag{12}$$

$$u(s)=H_R[r(s)-y_s(s)]$$

from (12) we have the frequency response.

$$y_s(s)=(sI+DH(s)H_R)^{-1}\,DH(s)H_R r(s)$$

$$+(sI+DH(s)H_R)^{-1}\,DH(s)v(s)+(sI+DH(s)H_R)^{-1}\,w(s) \tag{13}$$

that may be reduced to

$$y_s(s)\approx r(s)+(I+DH(s)H_R)^{-1}$$
$$DH(s)v(s)+(I+DH(s)H_R)^{-1}\,w(s) \tag{14}$$

According to Equation (14) the estimated state $y_s(s)$ will converge to the reference level r(s) and the influence from the disturbance spectrum v(s) and measurement spectrum w(s) is reduced.

Results

During the past 50 years the biomass has varied between 1×10^6 and 4×10^6 tons. In this biomass interval the growth rate is changing between 1.5 and 1.2 and the mean discrete growth rate is estimated to be about 1.3. This means that the sustainable level of the biomass is dependent on the present biomass level but in the long run the biomass has been sustainable when the discrete landing rate $F(nT)<0.3$.

Figure 2 shows the history of the current landings rate

$$F(nT)=\frac{u(nT)}{y_{3+}(nT)} \tag{15}$$

from 1950–1998 where u(nT) is the quota of landings at the year n and $y_{3+}(nT)$ is the ICES estimated total biomass at the year n. In this time series the discrete landings' rate F(nT) has the range from 0.18–0.49 and the mean landings rate $E[F(nT)]=0.3$. The F(nT) time-series demonstrates the low frequency and high instability of the biomass dynamics. The landings' rate has been

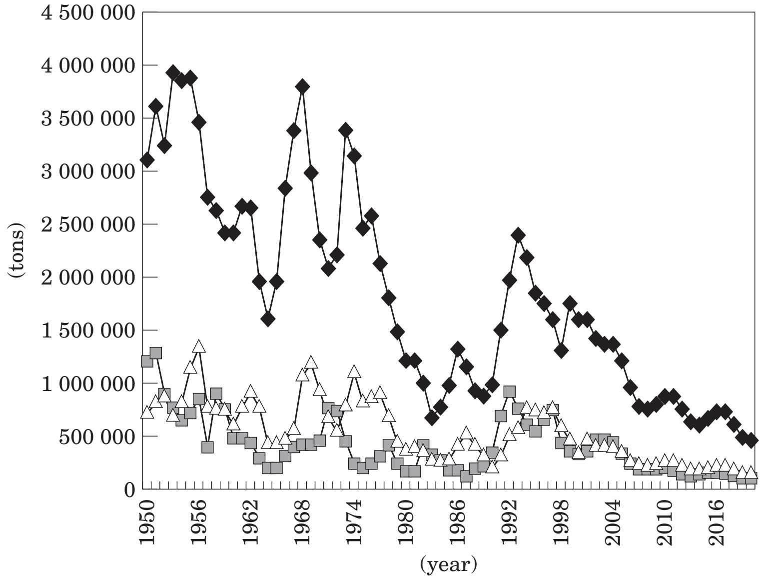

Figure 3. History (1950–1998) and forecast (1999–2020) total biomass stock, spawning-stock biomass and landings when landings' rate constant F(nT)=0.25. —◆—, total stock biomass; —■—, spawning stock biomass; —△—, official quota.

growing over a period of 40 years. Most of this time the landing quotas were too high to maintain a sustainable biomass and in 1987 and in 1996 the landing rate was about 0.5 and caused a collapse in the biomass. A spectrum analysis of the time-series shows that the landings rate F(nT) has a cycle of about 6 yr. This indicates both a low and a high frequency instability in the biomass dynamics.

Constant landings' rate

Figure 3 shows the time-series of historical records of total biomass, spawning-stock biomass and landings in millions of tons over the period 1950–1998. The time-series from 1999–2020 is a modelled forecast based on a constant landings' rate F(nT)=0.25, a discrete mortality rate M(nT)=0.22 and a temperature-dependent, discrete growth rate A(nT). The temperature-dependent recruitment $x_1(t)$ is estimated by the recruitment model (Yndestad, 1999b).

$$x_1(nT)=p_m+p \cdot y_{8+}(nT) \cdot \exp\{k_0+k_1\sin(6.28n/6.2+\varphi_1)+k_2\sin(6.28n/18.6+\varphi_2)\} \quad (16)$$

where the year number n=1950–2020, the minimum recruitment p_m=20 000 cod, the mean linear recruitment rate p=4000 number of cod/spawn biomass, the nutation amplitude relations $k_0=-0.7$, $k_1=0.60$, $k_2=0.3$, the nutation phase relation $\varphi_1=-3.5$, $\varphi_1=1.0$ (Yndestad, 1999b). The spawning-stock biomass is estimated by the proportion mature vector [0,00 0,00 0,00 0,02 0,07 0,23 0,48 0,92 0,98 1,00 1,00 1,00 1,00 1,00] (ICES, 1999).

Figure 3 shows that the biomass is reduced exponentially as expected by Equation (10). In a period of about 20 years the total biomass will converge at about 500 000 tons, the spawning stock biomass at about 100 000 tons and the landings at about 90 000 tons. In this case the 6.2 yr cycle in the growth and recruitment will introduce some small fluctuations in the total biomass. If the landings' rate F(nT) is changed each year forecasting cannot be made on a realistic basis. If the landings' rate F(nT)=0.25 the biomass will grow exponentially to about 1 500 000 tons, the spawning-stock biomass to 400 000 tons and the landings to 400 000 tons.

Feedback control

An FAO white paper (FAO, 1993) suggests that the minimum spawning-stock biomass should be more than 500 000 tons. Figure 4 shows the time series of historical records of total biomass, spawning biomass and landings over the period 1950–1998. The time-series from 1999–2020 is forecast from the model. The forecast biomass is estimated assuming feedback control strategy, the control parameter $H_R=1$ and the spawning stock biomass reference level r(nT)= 600 000 tons. In this forecast the biomass will converge to about 2 700 000 tons and the spawning biomass to about 600 000 tons as expected.

The fundamental approach on the feedback control strategy is that the spawning stock biomass has a fixed reference level r(nT) and landings quota u(nT) is the difference between the reference level and the estimated spawning stock biomass of the measured spawning stock biomass $y_{8+}(nT)$.

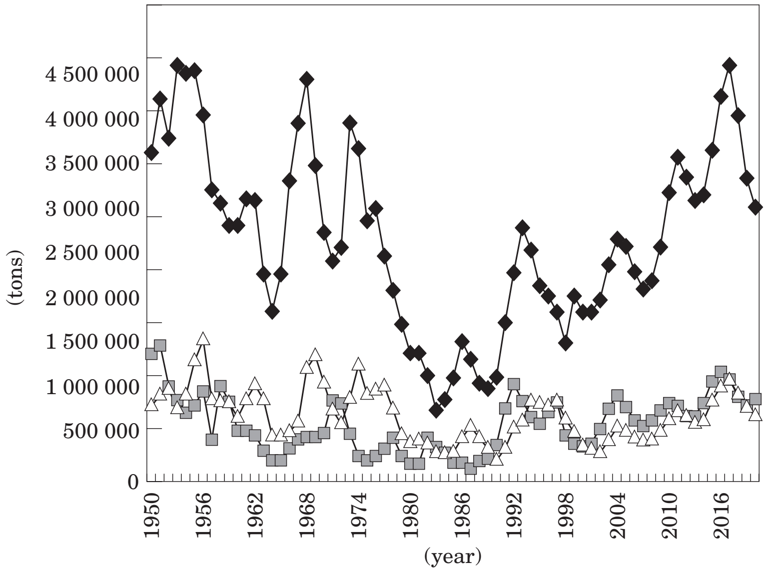

Figure 4. History (1950–1998) and forecast (1999–2020) total biomass, spawning-stock biomass and landings by feedback control. —◆—, total stock biomass; —■—, spawning stock biomass; —△—, official quota.

The forecast illustrates the sensitivity of the biomass to the quota strategy. The control strategy will force the spawning stock biomass to remain at a level of about 600 000 tons and the total biomass will grow to about 3 000 000 tons over the next 20 years. The biomass has a disturbance cycle of 18.6 yr and the time to reach a maximum level is about 20 years. This means that the total planning time of the total biomass should be about 15–20 years. The stochastic resonance at 6–7 yr will still introduce fluctuations in the biomass. This fluctuation is balanced by fluctuations in quota of landings. In this forecast the landings will converge to about 500 000 tons and fluctuate ± 100 000 tons at a cycle of 6.2 yr.

People dependent on fishing for their living need stability and predictability. There are methods to reduce the fluctuations of landings. One method is to introduce an integration $H_R(s)=k/(s+a)$ in the control law of Equation (12). This introduces a phase delay between fluctuations in the biomass and fluctuation in the landings. A second method is to introduce feed-forward control (Phillips *et al.*, 1989). This method will not introduce phase errors. On the other hand, it requires a good future estimate of the biomass. A third method is to optimise landings and the biomass by the object function

$$J = \int_0^t (x(t)Px(t) + u(t)Qu(t) + \dot{u}(t)R\dot{u}(t)dt \quad (17)$$

where P, Q and R are chosen cost indexes. By this method the biomass is managed by a chosen compromise between biomass size, the landings' quota and changes in that quota.

Discussion

The fluctuations of Northeast Arctic cod seem to be influenced by a more fundamental source than temperature, predators, cannibalism, quota estimates and assessment methods. The biomass fluctuation is correlated to stationary fluctuations of 6–7 yr, 18.6 yr and 55.8 yr. This fluctuation is a deterministic and time varying dynamic process that changes the stochastic biomass properties each year. The fluctuations of the biomass have influenced the landing's quota and during the last 50 years the landings have varied between 20% and 50% of the biomass.

Current management strategy has three aspects that may introduce instability in the biomass. The first is the 6–7 yr positive feedback of recruitment in combination with a phase delay in estimating data and getting the next landings' quota. This will introduce a high frequency instability of about 6–7 yr. The second is the biomass which has no stationary reference in the control strategy. This will introduce a low frequency instability in the biomass. The third source of instability is the change of landings' rate each year. This will lead to unpredictability of the biomass dynamics.

To control the biomass dynamics, a long-term strategy for mananging the spawning-stock biomass is needed. In this paper the forecasted biomass indicates that management of the total biomass needs to take into account a period of 15–20 years. Dynamic systems are controlled by the feedback concept. Such a concept will stabilise the spawning-stock biomass, reduce the long-term, temperature-dependent fluctuations and reduce uncertainty in expensive stock assessment exercises. This paper demonstrates that the feedback concept can maintain the spawning-stock biomass level at 600 000 tons. The feedback control is too slow to control the more higher frequency 6.2 yr cycle. This cycle is then reflected in the landing's quota and may be suppressed by introducing a feed-forward control from the forecasted biomass.

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Author Queries

Page	Query
7	Bogstad *et al.* (1996) reference—Please provide citation in text or delete from references.
7	Lunze (1992) reference—Please provide citation in text or delete from references.
7	Nakken *et al.* (1996) reference—Please provide citation in text or delete from references.
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