CLIMATE CHANGE AND PRODUCTIVITY IN THE AQUACULTURE INDUSTRY

Torbjørn Lorentzen, Institute for Research in Economics and Business Administration, Centre of Fishery Economics, torbjorn.lorentzen@snf.no

ABSTRACT

Global warming is expected to affect the ecosystem in the Northeast Atlantic, and sufficient changes will also affect the aquaculture industry. Farming of salmon and trout is the biggest aquaculture industry in Norway. The export value was about 2 billon US dollars in 2005. The objective of the paper is to analyse the potential economic effect a general increase in sea temperature can have on the Norwegian salmon aquaculture industry. The assessment of the economic impact of global warming is made possible by estimating a growth function which explicitly includes sea water temperature. The analysis compares the economic effect of a climate change on fish farming plants in the south and north of Norway. The scenarios are based on a model with monthly seasonal variation in temperature.

Keywords: climate change, temperature, growth rate, salmon farming industry

INTRODUCTION

It is anticipated that global warming will increase the temperature in the Northeast Atlantic and that the future temperature in the waters off the coast of Norway will be affected [1-4]. This is likely to affect the salmon aquaculture industry in Norway. Cold-blooded animals are particularly sensitive to temperature in the environment. Wild species avoid areas where the temperature is outside their natural temperature range, but farmed fish cannot do so, as they are confined to their cages. Environmental conditions in each location determine whether the sea water is suitable for aquaculture production or not. In this paper we will discuss and analyse climate induced changes in sea temperature and their potential effects on the Norwegian salmon and trout farming industry[a].

The paper is structured as follows. In the first section we present the problem to be analyzed. In the next section we describe the natural conditions for production of salmon and trout. Section Three describes the model components used in analysing the influence of temperature change and productivity in the salmon farming industry. Section Four presents the scenario analysis which shows different patterns of temperature changes and possible effects on the farming of salmon in the sea water off Lista and Skrova. Finally, Section five concludes.

NATURAL CONDITIONS FOR PRODUCTION OF SALMON AND TROUT

The typical fish farming company is assumed to maximize the net present value of its profits. To this end, the managers control a number of variables, i.e., feed ratio, type of feed, pattern of feeding, input of labour, number of smolts purchased and the stocking density of the fish, harvest time, etc. On the other hand the firm is exposed to forces and factors that are not under direct control or less easily controlled, i.e., exogenous factors which are both economic and environmental such as fish prices, governmental regulations, feed and other input prices, and site environment (temperature, sea current, wind, waves, salinity, local temperature variation, depth, mortality from disease and algae blooms, number of hours with daylight, etc). The farmers normally have little control over environmental factors once a farm site has been chosen [5].

The quality of the water in a given environment will largely determine which species of fish can survive or can be farmed there. The principal areas of the world in which salmon farming has developed successfully, Norway, Scotland, Ireland, Canada and Chile, all have the kind of environment necessary for this type of aquaculture. Changes in climate could change the production conditions for salmon in the areas where they are now farmed successfully and open up new areas for salmon aquaculture which currently are not suitable.

The quality of the water at any given site determines its production performance and indeed whether or not production is possible at all [6]. What, then, is meant by water quality? The sea temperature is one of the essential parameters for the growth of the fish, because temperature affects all metabolic processes in fish. But for obvious reasons the fish farmer must take the temperature as given. Salmonids favour fairly low temperatures; the normal temperature for salmon farms usually lies within the range 5-20 degrees.[b] Physiological investigations have shown that fast, efficient growth in salmon is best achieved in water temperature of 13-17 degrees [6]. Outside this range, production becomes less efficient, either due to slower growth or to temperature stress problems. The density of oxygen decreases with temperature, and the worst combination of these factors is high sea water temperature and low water flow. As to low temperatures, salmon will die when ice crystals begin to form in the body fluids, which occurs at about -0.5 degrees. Climate change is expected mainly to affect the sea temperature. The relationship between growth and fish weight, including the effect of water temperature, has been examined by Iwane and Tautz [7], Brett, Shelbourn and Shoop [8], Elliott [9], Holmefjord et al [10,11] and Ågard et al [12,13]. Growth and feed ratios has been studied by Austreng, Storebakken and Asgard [14], and Storebakken and Austreng [15].

MODEL SPECIFICATION

Growth pattern and seasonality in the temperature level

In practice the fish farmers in Norway release juvenile salmon and trout mainly twice a year, the so called "spring release" and the "autumn release". The spring release takes place in the period from April to June and the autumn release takes place in the period from August to October. Suppose the fish farmer releases juvenile fish in April. The fish will be ready for the market, i.e. slaughtered and sold, in the period from April to August next year. The fish is therefore slaughtered and sold during a period of 12 to 16 months after the release the previous year.

With an infinite rotation of cohorts, the farmer's objective is to maximize the gross present value (*GPV*) of fish farming with respect to the rotation period *t*, and given an infinitely numbers of identical rotations *n.* We will analyze this problem using the logistic growth function, which seems to provide the best description of the growth of the salmon. With an infinite number of identical rotations with time length $t \in (0, t^M)$ where t^M is the time the fish needs to reach the maximum weight. The objective function can be expressed in the following way:

$$GPV = \sum_{n=1}^{\infty} (p_0 w(t) N_n e^{-M \cdot t}) e^{-r \cdot n \cdot t} \qquad \text{(Eq. 1)}$$

where

p_0	: Price of the fish (constant)
$w(t)$	: Weight of fish at time *t*
N_n	: Released number of juvenile fish in the beginning of rotation *n*
M	: Mortality rate
r	: Real interest rate
n	: Number of rotations
t	: Length of the rotation period (unit of measure: month)

The calculation is based on the following logistic growth function $w(t) = \frac{1}{\alpha + \beta\gamma^t}$, where $1 > \gamma > 0$. The function is nonlinear in the parameters α, β and γ and can be estimated with a nonlinear estimator. The logistic function is an *S*-shaped curve. The benefit of using this function is that it has a convergence property, i.e., the fish grows toward a genetically given maximum weight, and that the function represents a good approximation to actual data. The initial weight of the juvenile fish, given that $t = 0$, can be expressed as $w_0 = \frac{1}{\alpha + \beta_0}$. Based on data from laboratory experiments Lorentzen and Hannesson [16] have estimated α and β, respectively; $\alpha \cong 0.11$ and $\beta_0 \cong 5.32$. The initial weight of the fish is then $w_0 \cong 0.184$ kilogram. The weight of the fish at the end of the first month can be expressed in the following way, given that $\Delta t = 1/12$ of a year

$$w_1 = \frac{1}{\alpha + \beta_0 \gamma_1^{\Delta t}}. \qquad \text{(Eq. 2)}$$

The accumulated weight of the fish at the end of the second month can be expressed as

$$w_2 = \frac{1}{\alpha + \beta_1 \gamma_2^{\Delta t}}, \qquad \text{(Eq. 3)}$$

but $\beta_1 = \frac{1}{w_1} - \alpha$ is equal to $\beta_0 \gamma_1^{\Delta t}$, so the weight w_2 in the second month can be expressed as

$$w_2 = \frac{1}{\alpha + \beta_0 \gamma_1^{\Delta t} \gamma_2^{\Delta t}} \qquad \text{(Eq. 4)}$$

The weight of the fish in the end of month three can be expressed as follows

$$w_3 = \frac{1}{\alpha + \beta_0 \gamma_1^{\Delta t} \gamma_2^{\Delta t} \gamma_3^{\Delta t}} \qquad \text{(Eq. 5)}$$

and the weight of the fish in the end of the year, i.e. after 12 months is

$$w_{12} = \frac{1}{\alpha + \beta_0 \gamma_1^{\Delta t} \gamma_2^{\Delta t} \gamma_3^{\Delta t} \cdots \gamma_{12}^{\Delta t}} \qquad \text{(Eq. 6)}$$

Definitions: Let Π_R^{YS} represents the product of the gammas. Suppose the fish (smolt) is released in month *R*. Let $R \in [1,2,3,....,12]$ and let 1 stands for January, 2 for February, 3 for March etc. The superscript *YS* stands for the time the fish is slaughtered or evaluated at respectively year *Y* in month *S*, where *Y*: number of years after the release (first year, second year etc.) and let *S* stands for the month, i.e. $S \in [1,2,3,....,12]$. *Example*: The weight of the fish after two years and two months in the sea, given that the fish was released in January, can be expressed in the following way. $R = 1$. $Y = 2$ and $S = 2$. Π_R^{YS} for this particular example is as follows

$$\Pi_1^{22} = (\gamma_1^{\Delta t} \gamma_2^{\Delta t} \gamma_3^{\Delta t} \cdots \gamma_{12}^{\Delta t})(\gamma_1^{\Delta t} \gamma_2^{\Delta t} \gamma_3^{\Delta t} \cdots \gamma_{12}^{\Delta t})(\gamma_1^{\Delta t} \gamma_2^{\Delta t}) \qquad \text{(Eq. 7)}$$

and the weight of the fish after two years and two months is

$$w_1^{22} = \frac{1}{\alpha + \beta_0 (\gamma_1^{\Delta t} \gamma_2^{\Delta t} \gamma_3^{\Delta t} \cdots \gamma_{12}^{\Delta t})(\gamma_1^{\Delta t} \gamma_2^{\Delta t} \gamma_3^{\Delta t} \cdots \gamma_{12}^{\Delta t})(\gamma_1^{\Delta t} \gamma_2^{\Delta t})} \qquad \text{(Eq. 8)}$$

The weight of the fish can in general terms be expressed as follows

$$w_R^{YS} = \frac{1}{\alpha + \beta_0 \Pi_R^{YS}} \qquad \text{(Eq. 9)}$$

The fact that $0 < \gamma < 1$, the product of the gammas converges to zero with increased number of months (years) in the sea, i.e. $\lim_{Y \to \infty} \Pi_R^{YS} = 0$, and the fish reaches the maximum weight

$$w_\infty = \lim_{Y \to \infty} \frac{1}{\alpha + \beta_0 \Pi_R^{YS}} = \frac{1}{\alpha}. \qquad \text{(Eq. 10)}$$

The maximum weight is $w_\infty = \frac{1}{0.11} \approx 9.0$ kilogram. Lorentzen and Hannesson [16] show that the value of γ depends on temperature. Varying γ will result in different growth trajectories. Lorentzen and Hannesson 2006 estimated 18 separate logistic growth function for 18 temperature regimes, i.e. for 1 to 18 centigrade. From these functions we estimated the temperature dependent γ as; $\gamma = e^{-0.388z + 0.733D_1 + 1.700D_2}$, where z is temperature (z = 1,2,3,….,16) and D_1 = 1 for 17 degrees and D_2 = 1 for 18 degrees. In remaining part of the article γ is approximated by the following function $\gamma_S = e^{-0.388z_S}$ where the variable z_S is the temperature level in all relevant months $S \in [1,2,3,....,12]$ after the release. As mentioned, the weight level is updated for each month, so the exponent time-variable for gamma is Δt = 1/12. The following condition must be satisfied [17] if there exists an optimal rotation period:

$$\frac{\dot{w}(t^*)}{w(t^*)} = r + M + \frac{r}{(e^{rt^*} - 1)} \qquad \text{(Eq. 11)}$$

The first order condition requires that the relative growth rate of the fish is equal to sum of the marginal alternative cost of waiting, i.e. the sum of the real interest rate, the mortality rate and the last term which expresses the alternative cost of keeping the fish in cages and not substituting it with younger, faster growing fish. For the seasonal logistic growth function, the relative growth rate can be expressed in the following way, and evaluated at time *YS* after the release:

$$\frac{\dot{w}_R^{YS}}{w_R^{YS}} = -\frac{\beta_0 \Pi_R^{YS} \ln \gamma_S}{\alpha + \beta_0 \Pi_R^{YS}} \qquad \text{(Eq. 12)}$$

THE SCENARIO ANALYSIS

What is the economic effect if the temperature increases in the coastal waters off Norway? A scenario can be illustrated by comparing the environment in the north and southwest of Norway. We shall compare the sea water temperature off Lista in Vest-Agder and Skrova in Nordland county. Figure 1 shows where Lista and Skrova are located in Norway. Skrova is located about 1180 km north of Lista.

Figure 1. Location of Lista and Skrova

Source: Senior Research Engineer Kjell Helge Sjøstrøm, Institute of Geography, University of Bergen

The seasonality in temperature can be reproduced by calibrating trigonometric functions. The following functions reproduce the seasonality in temperature for respectively Skrova z_{SK} and Lista z_L :

$$z_{SK} = \psi_{SK} + \lambda_{SK} \sin \frac{2\pi}{T}(t - t_0)$$
$$z_L = \psi_L + \lambda_L \sin \frac{2\pi}{T}(t - t_0) \qquad \text{(Eq. 13)}$$

where ψ is the average sea temperature, λ is the amplitude, T is the length of the period and π is a constant, measured 3.14, t is time and t_0 is the adjustment factor for the phase of the oscillations, i.e. $t_0 \in [1,2,3,....,12]$. Table I shows the status quo situation in the sea water off respectively Lista and Skrova.

Table I: Amplitude and average temperature forLista and Skrova

	AVERAGE TEMPERATURE (ψ)	AMPLITUDE (λ)
Lista	8.70	4.74
Skrova	6.69	3.71
Difference	2.01	1.03

In the following we will present scenarios which show different patterns of temperature changes and possible effects on the farming of salmon in the sea water off Lista and Skrova. The scenario analysis covers the infinite time horizon with identical rotations. We let Lista represent the farmers in the southernmost counties in Norway and analyse what will happen if the temperature continues to increase in the warmest part of the coast of Norway. The scenario is organized in the following three parts: (I) the seasonal amplitude of the temperature increases and the average is constant, (II) the average temperature increases and the amplitude is constant, and finally (III) a simultaneous change in amplitude and average temperature. In the simulations we assume that the juveniles are released into cages in July. The scenarios do not cover temperatures below 1 degree. Personal contact with experts on farming of salmon at the Norwegian Directorate for Fisheries and Institute of Marine Research (IMR) in Bergen indicates that dysfunction is initiated when the temperature surpasses 16 degrees or is lower than 1-2 centigrade. The negative effect of high temperature on growth is caused by *i. a.* less density of oxygen in the water and higher density of bacteria and algae. The negative effect is not linear. It follows from this that the mortality rate *M* is a U-shaped function of temperature, i.e. too low (below 2 degrees) and too high (above 16 degrees) temperature increases the mortality rate. In the scenario analysis we treat the mortality rate as a constant independent of temperature. In the simulation model we assume respectively that temperature between 16 and 17 degrees gives the same growth rate as 12 degrees, between 17 and 18 is equal to 10 degrees, between 18 and 19 equal to 3 degrees, temperature between 19 and 20 is similar to 1 degrees, and finally temperature over 20 degrees or below 1 degree is equal to a physiological breakdown. We have no scientific documentation for these assumptions, except that people in the business indicate a significant, negative change in the growth process when the temperature exceeds 17-18 degrees or creeps below 1 or 2 degrees. It follows from the assumption that critical temperature levels have negative effect on the output from the model.

Scenario I: Change in amplitude

The first scenario focuses on a change in amplitude by respectively (See right illustration in Figure 2. Tick line is benchmark) ± 0.5, ± 1, ± 1.5, ± 2 and ± 2.5, and the change is compared to benchmark or status quo. We apply the presented deterministic trigonometric function which is calibrated for mapping the temperature structure in the sea water off Lista and Skrova.

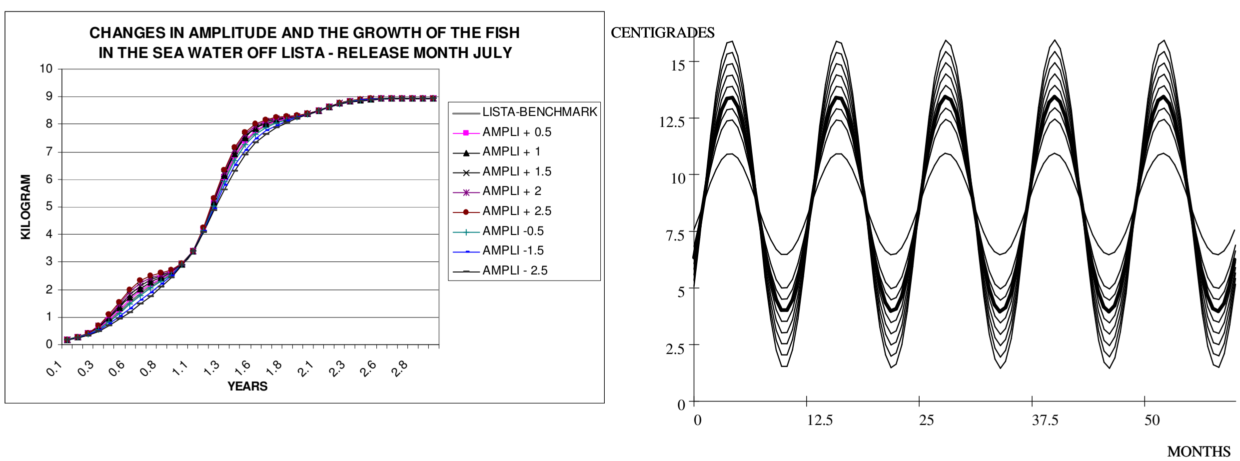


Figure 2. Change in amplitude and the effect on the growth process for fish off Lista

Figure 2 shows the effect on the growth path if the amplitude increases as mentioned. Increased amplitude results in higher maximum and minimum temperature levels, which significantly affects growth. If the temperature is lower than 1 degree, the fish will not grow at all and die, if the temperature becomes so low that ice crystals are formed in the water. If the amplitude increases by 3.1 degrees, the growth will be close to zero in some months because the temperature is about 1 degree. The next scenario analyses how a change in average temperature will affect the growth path.

Scenario II: Change in average temperature

This scenario is based on the assumption that the average temperature is changed by 0.5, 1, 1.5, 2, 2.5, 3 etc. degrees (See right illustration in Figure 3. Tick line is benchmark) compared to the status quo case. These scenarios assume that the amplitude is not affected. The average temperature is increased by 11.5% if the temperature increases by 1 degree compared to the status quo. We have assumed that a too high temperature will reduce dramatically the growth of the fish. In this scenario the average temperature was increased stepwise for testing at what temperature level the growth is about the same as in the status quo situation. The juvenile fish is released into the cages during July. Figure 3 shows that an increase in the average sea temperature accelerates the growth of the fish, and the maximum weight is reached in a shorter time than with lower average temperature. The increase in the average temperature appears to smooth the seasonal variation in the growth path, which are more marked in the benchmark growth path.

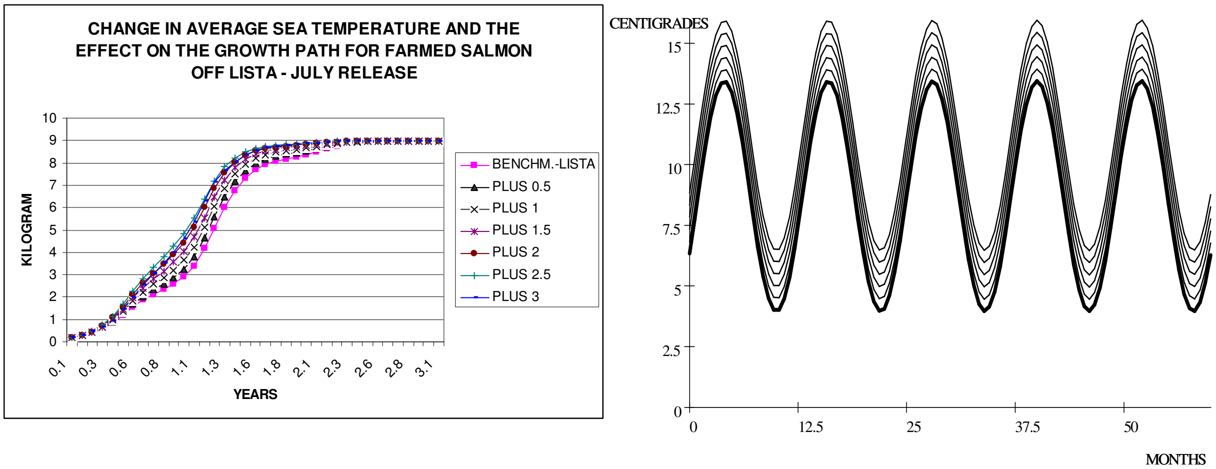


Figure 3. Weight function for farmed fish at Lista for different average temperatures compared to status quo

Clearly, fish farming in both geographical areas can bear an increase in average temperature which is beyond the temperature increase due to climate change which is predicted by IPCC [1]. The sensitivity analysis shows that change in average temperature will not necessarily cause problems. It is rather changes in amplitude which can cause a breakdown. If the amplitude of the temperature in the seawater off Skrova increases by 2-2.5 degrees critical temperatures occur, and farming is close to a breakdown. If the amplitude increases by 3-3.5 degrees in the water off Lista, farming will be extreme risky. In general, as long as the temperature fluctuates inside biologically sustainable limits it does not cause any serious damages. On the other hand, if the temperature is close to the extreme values, it induces devastating effects.

Scenario III: Simultaneous change in amplitude and average temperature

In the last scenario we assume simultaneous changes in amplitude and average temperature. While IPCC [1] has predicted that the average temperature will increase in the future, it has not made any predictions about the future variation of the amplitude. Therefore we analyse both decreasing and increasing amplitude, *given* increasing average temperature.

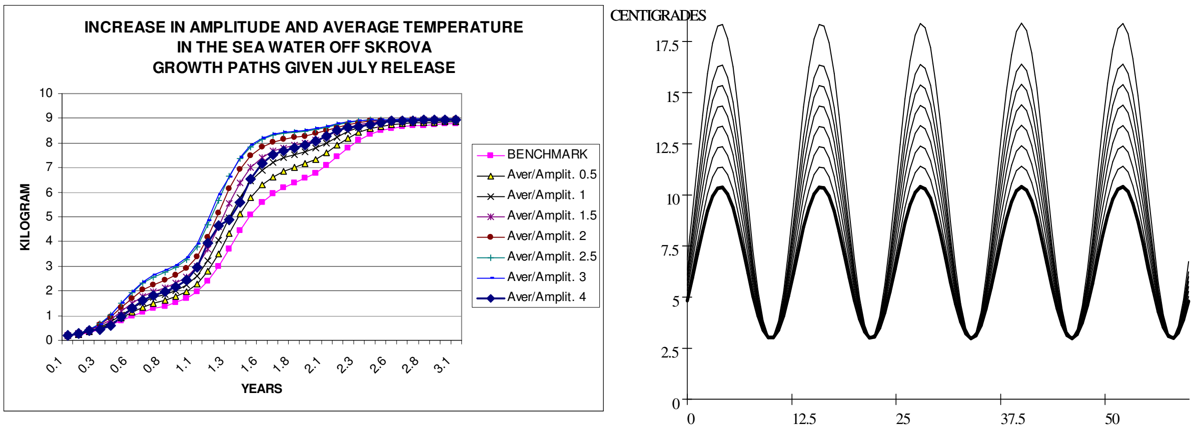


Figure 4. Increase in amplitude and average temperature and the effect on growth

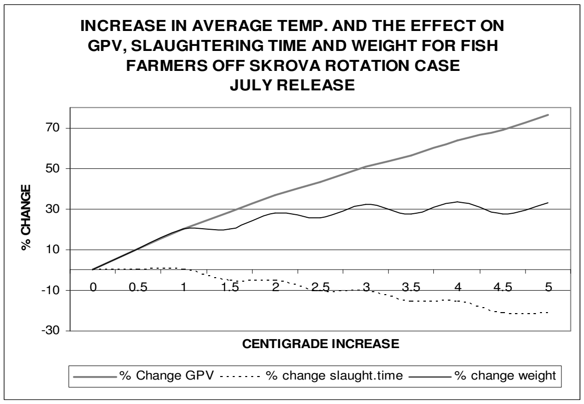
Figure 4 shows what the growth path will look like if the amplitude and average temperature increase simultaneously in the sea water of Skrova (See right illustration in Figure 4. Tick line is benchmark). The growth process for the fish accelerates 3-4 months after the release. If the amplitude and average temperature simultaneously increases more than 3-4 degrees, the increase results in an environment which is similar to a 1 degree increase. Again we see that too high temperatures have devastating effects on the growth of the fish.

Climate change and the economic effect in the rotation case

This section extends the analysis by including a set of successive fish releases, with an infinite time horizon. This part of the analysis is built on the rotation principle and the additional assumptions are that the juvenile fish is released in July. The analysis is built on monthly, seasonal variation in temperature as described above. Climate change means (1) changes in average temperature, (2) change in the amplitude of the temperature and (3) a combination of changes in amplitude and average temperature.

Figures 5 and 6 summarize the effect on gross present value (GPV), optimal slaughtering time and optimal slaughtering weight of an increase in the average temperature for fish farmers located off Lista and Skrova.

At Skrova (Figure 5), a higher average temperature increases the gross present value and the slaughtering weight, while the slaughtering time is reduced. Calculation shows that a one percentage increase in temperature increases the gross present value by 1.07%. If the average sea water temperature increases by 1 degree (about 15% increase) due to global warming, the GPV increases by about 16%. The calculation is valid for the average temperature range from status quo (6.69) to 11 centigrade. At Lista (Figure 5) the percentage change in gross present value is bell shaped with increasing average temperature. Calculations show that the value of the fish farming firms increases by 0.75% per percentage increase in average temperature. This relationship is valid in the average temperature interval from 8.70 to about 11 centigrade. If the average temperature increases by 1 centigrade (11.5% increase compared to status quo), GPV increases by about 9% (8.74%).



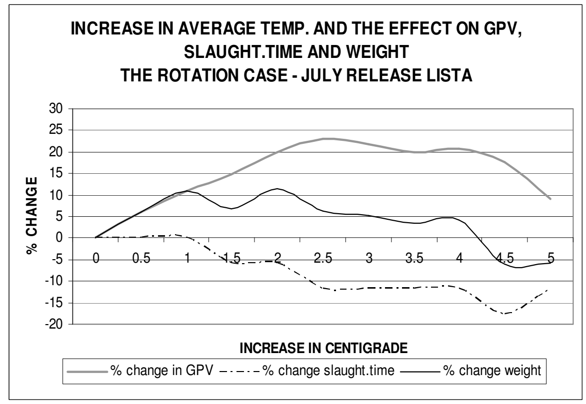
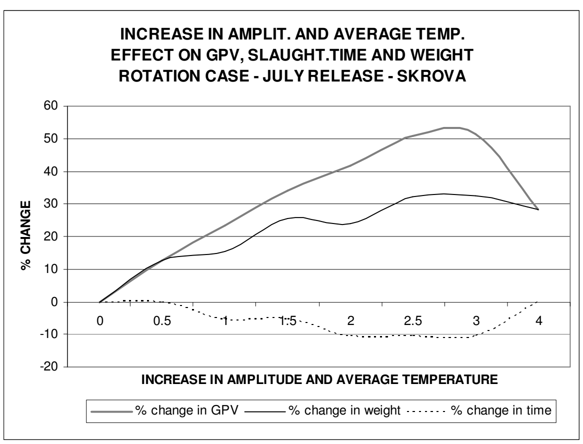


Figure 5. Increase in average temperature and the effect on farming in the sea water off Skrova and Lista

Figures 6 shows how a simultaneous change in amplitude and average temperature affects gross present value, slaughtering time and weight at Skrova and Lista. At Skrova, a simultaneous and equal level of increase in amplitude and average temperature increases significantly the gross present value. Calculation shows that in the temperature range of increase from 0 to 2.5 degrees, GPV increases by 21% per degree of increase. The scenario shows that the optimal slaughtering weight increases and the optimal slaughtering time are reduced. At Lista (Figure 6) the effect of the simultaneous increase in amplitude and average temperature on gross present value and optimal slaughtering weight is bell shaped. A 1 degree simultaneous increase in amplitude and average temperature increases gross present value by 12-13%.



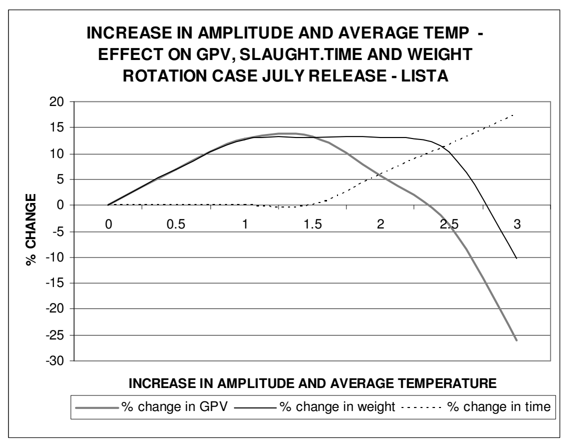


Figure 6. Increase in amplitude and average and the effect on gross present value, slaughtering time and weight for farmers off Skrova and Lista

The scenario shows not only that a small simultaneous increase has a positive economic effect, but also that farming has small safety margins if the temperature increases more than 2 degrees. A climate scenario where the average temperature increases and amplitude decreases (not presented here), results in a higher gross present value, shorter rotation, and a greater slaughtering weight (but bell shaped with reduced amplitude and increased average temperature).

CONCLUDING REMARKS AND DISCUSSION

The background for the analysis is the expected change in temperature in the Northeast Atlantic. The objective of the paper is to analyse the potential economic effects a change in sea temperature can have on the salmon farming industry in Norway. The assessment of the impacts of climate change is made possible by using a logistic growth function which explicitly includes temperature. The most likely scenario is that global warming will increase the sea temperature along the coast of Norway. The sensitivity analyses show that a change in temperature has economic consequences for the aquaculture industry. A general increase in temperature will accelerate the growth process of the fish and increase the productivity in the salmon fish farming industry.

We analysed the following problem for a multiple cohort (rotation) case: If climate changes, what are the expected effects on respectively optimal slaughtering time (rotation period), slaughtering weight and gross present value (GPV) of the fish farming firm? We define ‘climate change’ as a change in amplitude and average temperature. We analysed the problem by changing; (1) the amplitude, (2) the average temperature and (3) simultaneously the amplitude and average temperature. In the calculations of the effects we assume an instantaneous change in temperature. That is not a realistic assumption. The change will last for decades. The implication of the instantaneous change is an over-estimating of the effects.

An *increase* in *average* temperature has a positive effect on gross present value for firms located at Lista and Skrova. The effect is linear for temperature increases up to 5 degrees for Skrova. For additional temperature increase the effect on GPV is positive but diminishing. The effect is also linear at Lista for an increase up to 2.5 degrees. A further increase has a positive but diminishing effect on GPV. If the average temperature off Skrova increases by 1 degree, i.e., from 6.69 to 7.69, the GPV increases by 15-16% for farming off Skrova and about 11% for farming off Lista (from 8.70 to 9.70 degree). The GPV will increase by 1.07% for each percentage increase in average temperature at Skrova. Calculations show that the value of fish farming firms located at Lista increases by 0.75% per percentage increase in average temperature. This relation is valid in the average interval from 8.70 to about 11 centigrade. The analysis shows that an increase in average temperature by 1 degree increases the productivity in fish farming off Skrova and Lista by about 20 and 12-13% respectively.

A simultaneous *increase* in amplitude *and* average temperature induces a bell shaped increase in gross present value (GPV) for farmers located at Skrova and Lista. In the *rotation case* the gross present value (GPV) increases by 20% for farming off Skrova and about 12-13% for farming off Lista if the amplitude and average temperature simultaneously increased by 1 degrees. A simultaneous 1 degree increase in amplitude and average temperature increases the productivity by about 15% for farming off Skrova and about 12% for fish farming located off Lista. A simultaneous *increase* in average temperature and a *decrease* in amplitude increases the gross present value for farmers located off Skrova and Lista. The percentage change is strongest for fish farming located off Skrova.

A general temperature increase in the sea water due to global warming will have a positive effect on productivity and on the value of the fish farming firms located along the coast. The effect is positive but diminishing with increasing temperature. The analysis also shows that farmers located in the southernmost parts of the coast have a narrower safety margin with respect to temperature increase compared to farmers located further north. If amplitude and/or average temperature increase to the level where normal physiology for the fish is put under pressure, the probability for a breakdown is increasing. Global warming is contra productive for the industry if the sea temperature increases too much.

In this paper we apply a constant price which implies that the optimal slaughtering time depends only on the relative growth rate, the real interest rate, and the mortality rate. Clearly, if the price of the fish depends on the weight or dependent on seasonal demand, it will influence the optimal slaughtering time. Feed, insurance, and slaughtering costs have also some influence on optimal slaughtering time. We have chosen to leave these effects aside in order to focus on the temperature change due to global warming.

It should also be mentioned that the temperature structure which is applied in this analysis is based on observation in the water column between 1 and 50 meters. The temperature at the surface is definitely higher, however, than further down. Farming takes place at the surface, so the critical values which are presented in this report actually underestimate the effect temperature changes will have on farming of salmon and trout. We therefore expect that dysfunctions as low growth and higher mortality will show up earlier than these simulations indicate.

REFERENCES

[14] Austreng, E., Storebakken, T. and Asgard, T. (1987): Growth rate estimates for cultured Atlantic salmon and rainbow trout. *Aquaculture*, 60, pp. 157-60.

[3] ACIA (2004): Impacts of a Warming Arctic – Arctic Climate Impact Assessment. Cambridge University Press.

[16] Bjørndal, T., K. Grønhaug, L. Holmefjord and K. Salvanes (1987): *Oppdrettsøkonomi*

(Aquaculture Economics). Cappelen.

[5] Bjørndal, T. and R.S. Uhler (1993): Salmon Sea Management: Basic Economic Concepts and Applications. . Article in Heen. K., R. L. Monahan, F. Utter (1993): *Salmon Aquaculture*. Fishing News Books.

[8] Brett, J.R., Shelbourne, J.E. and Shoop, C.T. (1969): Growth rate and body composition of fingerling sockeye salmon, (Oncorhynchynchus nerka) in relation to temperature and ratio size. *Fish Res. Bed. Can.*, 26, 2363-94.

[9] Elliot, J. (1982): The effects of temperature and ratio size on the growth and energetics of salmonoids in captivity. *Comp. Biochem. Physiol.*, 73B(1), pp. 81-91.

[10] Holmefjord, I., Åsgård,T., Einen, O., Thodesen, J. & Roem, A. (1994): Vekstfaktor, VF3 - eit nytt og betre mål for vekst. Norsk Fiskeoppdrett, 19(12), 42-43. (”Growth factor, VF3 – a new and better measure for growth of salmon”).

[11] Holmefjord,I., Åsgård,T., Einen, O., Thodesen, J.& Roem,A. (1995): Effekt av ulike fôringsnivå på vekst og økonomi i produksjon av laks. *Norsk Fiskeoppdrett*, 20(4),38. (“The effect of different feeding levels on growth and economy in the production of salmon”).

[1] IPCC (2001): Climate Change 2001: *Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel of Climate Change*, Cambridge University Press, New York, USA, 967 p.

[7] Iwama, G.K. and Tautz, A.F. (1981): A simple growth model for salmonoids in hatcheries. *Can. J. Fish. Aquat. Sci.*, 38(6), pp. 649-56.

[16] Lorentzen, T. and R. Hannesson (2006): Climate change and productivity in the aquaculture industry. SNF-Report No. 02/06. Institute for Research in Economic and Business Administration.

[4] Nansen Environmental and Remote Sensing Center (NERSC): *CECA - Climate and Environmental Change in the Arctic*. EU Descartes Laureate 2005.

[2] Stenevik, E.K. and S. Sundby (2004): *Impacts of climate change on commercial fish stocks in Norwegian waters.* Discussion paper no. 76/04. Institute of Marine Research (MIR) and Institute for Research in Economics and Business Administration (SNF). Sundby, S. (2004): Addendum to “*Impacts of climate change on commercial fish stocks in Norwegian waters*” by Stenevik and Sundby (2004).

[15] Storebakken, T. and Austreng, E. (1987): Ration level for salmonids. II, Growth, feed intake, protein digestibility, body composition, and feed conversion in rainbow trout weighing 0.5-1.0 kg. *Aquaculture*, 60, pp. 207-21.

[6] Wallace, J. (1993): Environmental Considerations. Article in Heen. K., R. L. Monahan, F. Utter (1993): *Salmon Aquaculture*. Fishing News Books.

[12] Åsgård,T., Holmefjord, I., Einen, O., Roem, A.& Thodesen, J. (1995): A growt model for improved management in salmonid culture. In: N. Svennevig & Å. Krogdahl (eds): Quality in aquaculture. *Eur .Aq. Soc.*, Spes.publ.,23, pp.173-174.

[13] Åsgård,T., Holmefjord, I. & Giskegjerde, T.A. (1997). Best vekst i nord og sør? *Norsk Fiskeoppdrett*, 22(6), pp. 30-33. (“Best growth in the north or south?”).

ENDNOTES

[a] See also SNF-discussion paper no. 59/05 *Climate Change and Future Expansion Paths for the Norwegian Salmon and Trout Industry* where we analyse more broadly climate change and future expansion paths for the salmon and trout industry in Norway.
[b] All temperatures in this paper are expressed in centigrade (Celsius).