GROWTH, MORTALITY, FEED CONVERSION AND OPTIMAL TEMPERATURE FOR MAXIMUM RATE OF INCREASE IN BIOMASS AND EARNINGS IN COD FISH FARMING

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In the following we will examine the change in growth, mortality and feed conversion for cod as temperature deviates from optimal temperature. Optimal temperature (T_{opt} ^oC) is here defined as optimal temperature for growth i.e. the temperature giving maximum growth rate (g_{max}). We will show that change in growth, mortality and feed conversion can be related to deviation in temperature from optimal temperature, and how this can be used to maximize return from fish farming. It can also be used to estimate yield from fish farming, where temperature conditions are not optimal.

Introduction

Cod represents an important element in the traditional cuisine in many countries. This market requires regular supply that no longer can be harvested from the natural cod stock. Due to market demand and lack of sufficient natural resources, the fish farming industry has identified cod as a new aquaculture species to make commercially available through fish farming. This article addresses important issues of relevance to those wanting to invest in and operate commercial cod farming.

Most fish farming activities are located at fixed sites and thus have fixed temperature profile throughout the year. Few farms will be able to supply the temperature profile for optimal increase in biomass, resulting in suboptimal yield. For the planning of farm activities, market regulation and fish farming valuation[1], the possibility to calculate expected yield given the local temperature profile, may prove to be of great value.

Background

Björnsson et al (2001) established in the article "Optimal temperature for growth and feed conversion of immature cod" [2] that the relationship between specific daily growth rate (g) and temperature in T ^oC could be expressed as a second order polynomial:

Eq. 1 $g\ (t;\ w) = \alpha+\beta T+\gamma T^2 \quad \text{for } 1.0\,^oC \leq T \leq 16.0\,^oC$

for different geometric mean weights of cod. Optimal temperature for growth T_{opt} and maximum growth rate g_{max} for the different weight classes – w – (in gram) was then found from:

Eq. 2 $T_{opt.g}\,(w) = -\beta/2\gamma$ and $g_{max}\,(w) = \alpha - \gamma\, T_{opt}^2$

[1] Olafsen, Tore, Dervå, John Martin, Mulighet og risiko ved oppdrett av torsk, (2002) Norsk Fiskeoppdrett nr 4.
Olafsen, Tore, Dervå, John Martin, Verdifulle torskekonsesjoner, (2002) Norsk Fiskeoppdrett nr 5.

[2] Björnsson, B., Steinarsson, A., Oddgeirsson, M. (2001). Optimal temperature for growth and feed conversion of immature cod. ICES Journal of Marine Science, 58: 29-38.

The relation between optimal temperature and cod weight was estimated as (std. error of the estimate is given in parentheses under the coefficient):

Eq. 3 $T_{opt.g}(w) = 18.28 - 1.43 \ln(w)$ for $1.54g \leq w \leq 2231.1g$

(0.854) (0.176)

and the relation between maximum growth rate g_{max} and cod weight as:

Eq. 4 $g_{max}(w) = 7.74 \; w^{-0.404}$ for $1.54g \leq w \leq 2231.1g$

(1.017) (0.035)

If w_i and w_{i+1} are the weights of the fish at times i and i+1, then:

Eq. 5 $w_{i+1}(g) = w_i e^{g/100}$ for $1.0\ g \leq w \leq$ ca 3000g

Where g is the growth rate and the calculation is performed for the period of one day.

We will use these results to estimate the change in the growth rate (g) as the temperature deviates from T_{opt}.

In the following we will use the data material from this study. For a thorough description of the experimental design and results, we refer the reader to their article "Optimal temperature for growth and feed conversion of immature cod"[2].

The material summarises data from 62 different experiments as described in their study. Of these we have discarded four as they had an extremely high and unexplained mortality rate.

Growth Rate

Obviously the coefficients in Eq. 1, have to be functions of the weight class they are estimated for, so that the growth rate is a function of both weight and temperature.

Let:

Eq. 6 $\Delta T(w) = T - T_{opt.g}(w)$

be the difference between observed temperature and optimal temperature for the specific weight (w), and let:

Eq. 7 $\breve{g}(\Delta T) = g(\Delta T, w) / g_{max}(w)$

be the relative growth rate. Eq. 7 simplifies the estimation of g (ΔT,w), and gives us the opportunity to build directly on the results in Björnsson et al. (2001). We have estimated Eq. 7 as:

Eq. 8 $\breve{g}(\Delta T) = a + b\,\Delta T^2 + c\,\Delta T^3$ for $-11.3\,^{o}C \le \Delta T \le 7.0\,^{o}C$

Where a= 1.0, b=-0.0087 and c= -0.0003 (see Figure 1).
(0.01) (0.006) (0.00005)

We find that this relation explains almost all (more than 90%) of the observed variance in the material[3] and that the standard deviation of the estimated coefficients are small - all coefficients have a significance level of 0.1% or less.

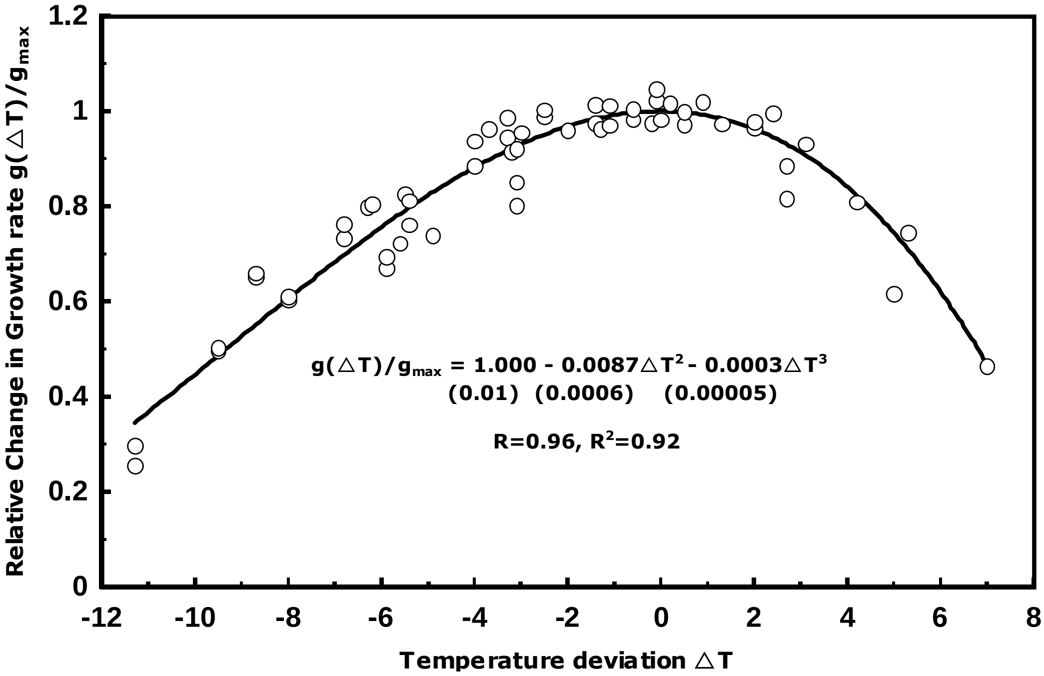

Figure 1 Change in relative growth rate ($g(\Delta T)/g_{max}$) for cod as function of the temperature deviation ($-11.3\,^{o}C \le \Delta T \le 7.0\,^{o}C$). Data from Björnsson et al. (2001), four outliers have been removed.

From Figure 1, we can see that the reduction in the relative growth rate is much slower for negative temperature deviations, than for positive. Since, as we shall see optimum temperature for growth in biomass implies negative temperature deviations. This gives solutions with higher growth rates than would have been the case if the solutions had been with positive deviations.

Mortality

We are again interested in estimating the mortality as a function of △T. Due to the relationship between growth and temperature; it seems appropriate to use the same for mortality. We find that Eq. 9 gives a reasonable explanation of the observed data, see Figure 2.

[3] The first order term was not significant, and Eq. 8 was estimated without that term.

As is seen from the figure the equation explains approximately 50% of the observed variance, which is somewhat lower than expected.

Other more elaborate relations can give a better fit, but we will use the following relation both due to its simplicity and the fact that the standard deviations for the estimated coefficients are small - all with a significance level of 0.1% or less. It is however obvious that Eq. 9 only describes parts of the mechanism, but have in mind that ΔT controls for fish weight by Eq. 6.

Eq. 9 $m(\Delta T) = d + e\,\Delta T + f\,\Delta T^2$ for $-11.3\,^{\circ}C \leq \Delta T \leq 7.0\,^{\circ}C$

Where d= 0.05033, e= 0.01423 and f=0.00146 (see Figure 2).
(0.0061) (0.002) (0.0003)

Minimum mortality occurs when $\Delta T = -c/2d = -0.01424/2*0.00148 \approx -4.8\,^{\circ}C$. At that temperature the mortality is 0.016% pr day.

Since cod weight does not enter the equation, minimum mortality occurs for all weight sizes at that temperature deviation. The temperature where minimum mortality occurs is however a function of fish weights thru Eq. 6.

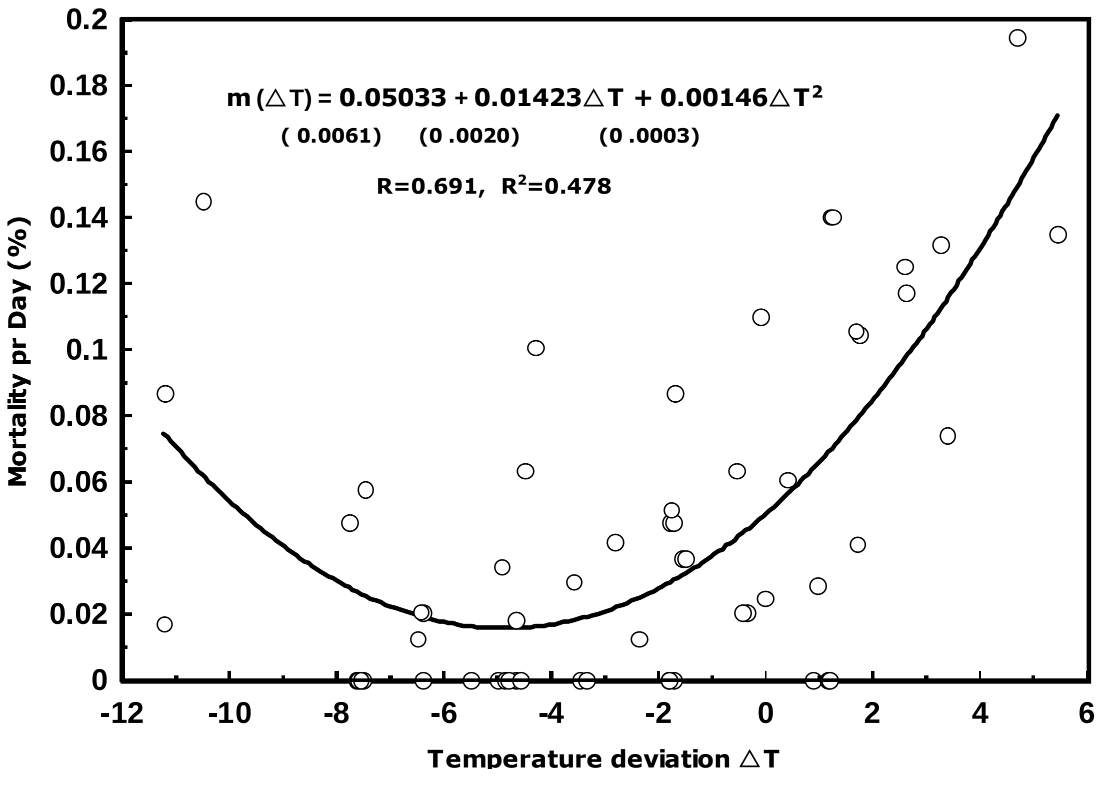

Figure 2 Mortality (% pr day) for cod as function of the temperature deviation (−11.3 °C ≤ΔT≤ 7.0 °C).). Data from Björnsson et al. (2001), four outliers have been removed.

Optimal Temperature for Maximum Rate of Increase in Biomass

From the estimated relations (Eq. 8 and Eq. 9) we can find the optimal temperature for maximum rate of increase in total biomass (△B/B).

We have:

Eq. 10 $G_B(\Delta T; w) = \Delta B/B = (B_{i+1} - B_i)/B_i = (w_{i+1}/w_i)\,(n_{i+1}/n_i) - 1$

Where w_i = expected weight and n_i = expected number of cod at time - i.

From Eq. 5 we have:

Eq. 11 $V(\Delta T; w) = (w_{i+1}/w_i) = \exp\,(g\,(\Delta T; w)/100)$

i.e. the relative growth, and let:

Eq. 12 $S(\Delta T) = (n_{i+1}/n_i) = (1- m\,(\Delta T)/100)$

i.e. the survival rate. The rate of increase in total biomass is then:

Eq. 13 $G_B(\Delta T) = V(\Delta T)\,S(\Delta T)-1$

and the maximum rate will occur when:

Eq. 14 $V'(\Delta T)/V(\Delta T) = - S'(\Delta T)/S(\Delta T)$

We have from Eq. 7 and Eq. 11 that:

Eq. 15 $V'(\Delta T)/V(\Delta T) = g_{max}(w)\,\breve{g}'(\Delta T)/100$

and from Eq. 12 that:

Eq. 16 $- S'(\Delta T)/S(\Delta T) = m'(\Delta T)/(100-m(\Delta T))$

We can then write Eq. 14 as:

Eq. 17 $g_{max}(w)\,\breve{g}'(\Delta T) = 100\,m'(\Delta T)/(100-m(\Delta T))$

For a given weight class, maximum growth rate of biomass occurs at the temperature deviation where the expected reduction in mortality is equal to the expected reduction in growth rate.

Since g_{max} is a function of cod weight (w), the solution[4] - $\Delta T_{opt.B}$ - of Eq. 17 will be a function of cod weight.

In Figure 3 we have plotted the left and right side functions in Eq. 17 for a 1500g cod, in the region $-3.5\,^{o}C \leq \Delta T \leq 0\,^{o}C$.

The intersection of the two curves gives the value of ΔT maximising G_b for 1500g cod. In this case the optimal temperature deviation is approximately $-1.5\,^{o}C$.

Eq. 17 has multiple solutions, however only one is in the region of interest to us: $-10\,^{o}C \leq \Delta T \leq 0\,^{o}C$. There are no solutions with positive ΔT. The optimal temperature profile for maximum increase in biomass will therefore always lie below the profile for optimum growth.

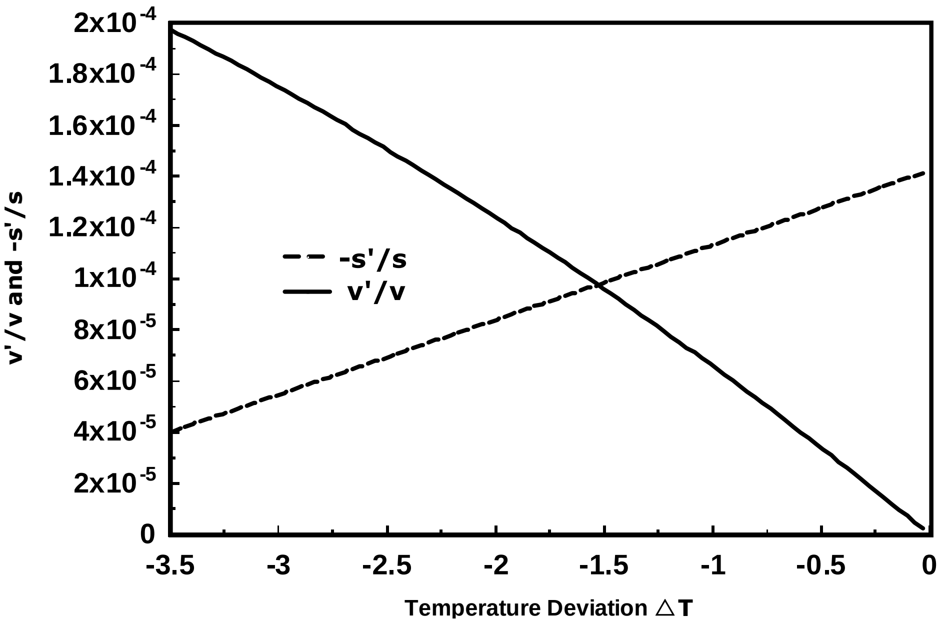

Figure 3 The Relative growth rate (v'/v) and the negative survival rate (-s'/s) for Cod (1500g) as a function of the temperature deviation. ($-11.3\,^{o}C \leq \Delta T \leq 7.0\,^{o}C$).

In Figure 4 we have calculated the growth rate of biomass for three different weights of cod; 1500g, 2000g and 2500g, as function of temperature deviation (ΔT). We see that the maximum of the curves are moving slowly to the left (ΔT at g_{max}; ≈-1.53 ^{o}C, ≈-1.66 ^{o}C and ≈-1.77 ^{o}C), as cod weight increases.

This is due to the fact that when cod weight increases, g_{max} will decline causing a reduction in the left side of Eq. 17 (the maximum value of ğ' (ΔT) is 1.0). The mortality will then have to be reduced for the equation to hold - and this can only happen when the temperature deviation increases.

[4] Eq. 17 is a 4. order equation in Δt.

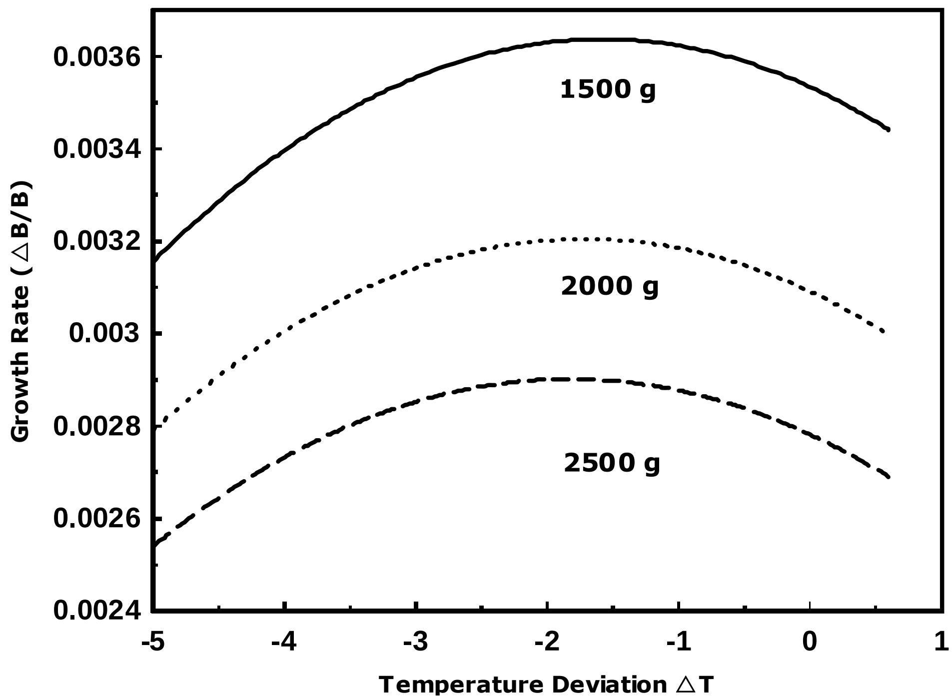

Figure 4 Daily growth rate of biomass (ΔB/B) for cod as function of temperature deviation (−11.3 °C ≤ΔT≤ 7.0 °C), and cod weight (1500g, 2000g, 2500g)

Solving Eq. 17, and plotting $\Delta T_{opt.B}$ for different cod weights will give Figure 5. Here we can see how the absolute value of the optimal temperature deviation is increasing as cod weight increase, starting with $\Delta T_{opt.B} \approx -0.5$ °C for 50g cod increasing to ≈−1.8 °C for 2850g cod.

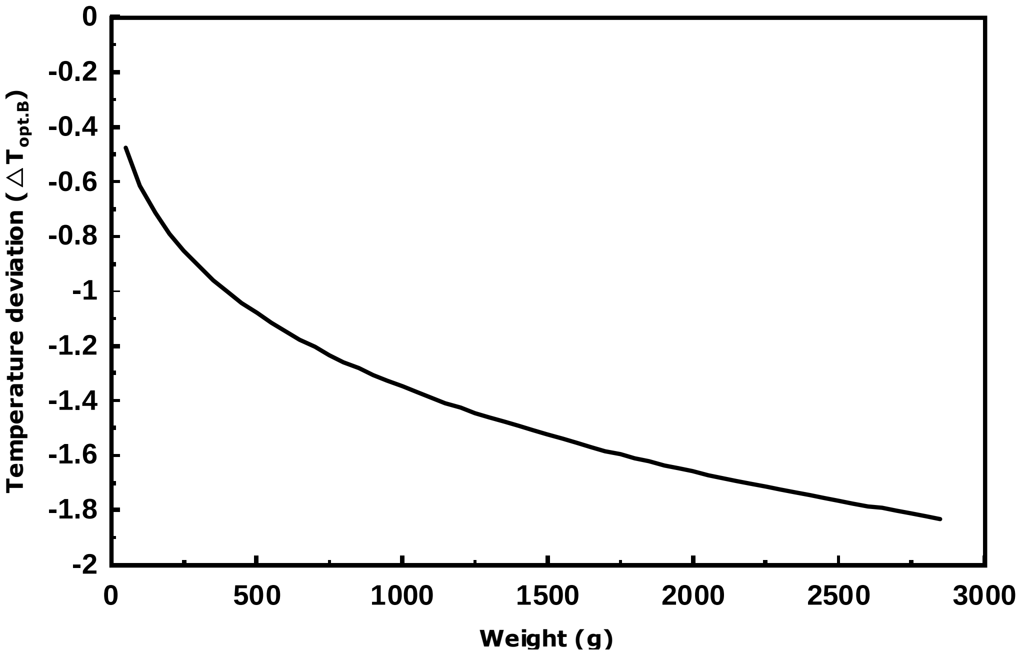

Figure 5 Optimal temperature deviation ($\Delta T_{opt.B}$) for maximum rate of increase in biomass (G_B) for cod as function of weight (1.5g ≤w≤ 2850g).

In Figure 6 we have calculated the optimal temperature for growth of biomass – $T_{opt.B}$ as:

Eq. 18 $T_{opt.\ B}(w) = \Delta T_{opt.B} + T_{opt.g}$

Since $\Delta T_{opt.B}$ always is less than zero, the curve for $T_{opt.B}$ will always be lower than the curve for $T_{opt.g}$ In the figure, $T_{opt.g}$ has been calculated from Eq. 3.

Figure 6 shows that the change in optimal temperature both for growth and increase in biomass is greater for small sized fish than for larger fish, and that temperature reduction is more important for increase in biomass than for growth as fish size increases.

From Figure 4 type of calculation it is easy to estimate the reduction in growth rate of biomass from temperature profiles that are off the optimal profile. The yield from specific sites can then be estimated and forecasted for commercial and regulative purposes.

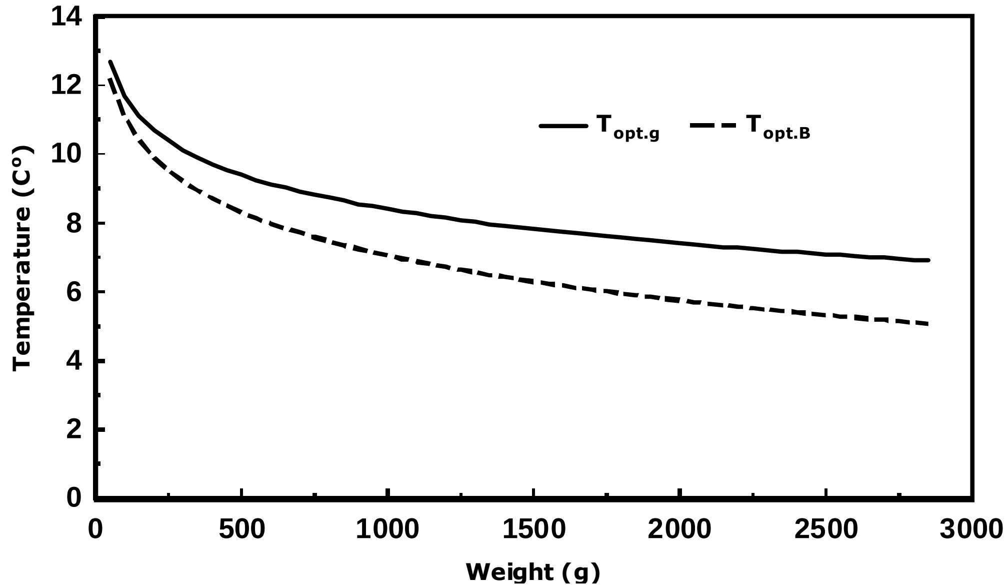

Figure 6 Optimal temperatures for growth of cod ($T_{opt.g}$) and for maximum rate of increase in biomass ($T_{opt.B}$) as function of cod weight (1.5g ≤w≤ 2850g).

For practical purposes $T_{opt.B}$ can be found by regression as:

Eq. 19 $T_{opt.B} = 10.8 - 0.56 \ln (w)$ for $1.5g \leq w \leq 2850g$

Which gives a very good approximation ($R^2 = 0.99$) to the $T_{opt.B}$ curve in Figure 6.

Maximum Rate of Increase in Biomass

From Eq. 13 we can calculate the maximum rate (%) of increase in biomass, as shown in Figure 7:

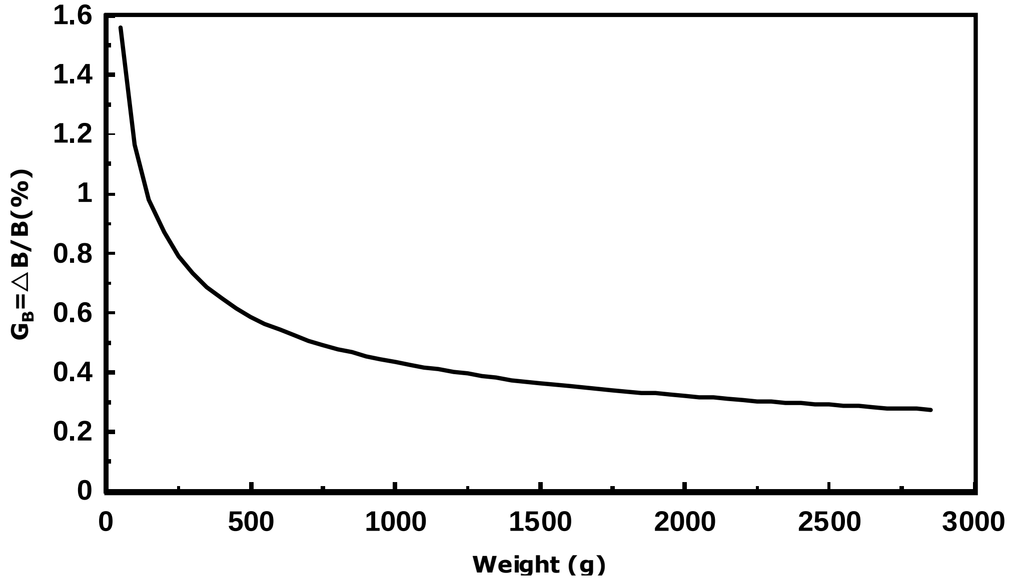

Figure 7 Maximum rate (%) of increase in biomass as function of cod weight (1.5g ≤w≤ 2850g).

The exact formula is (in %):

Eq. 20 $G_B(w) = 8.62\ w^{-0.433}$ for $1.5g \le w \le 2850g$

This gives the maximum obtainable yield from cod farming, if the optimal temperature profile (Figure 6) is followed.

From Eq. 4 and Eq. 20 we can find maximum obtainable yield as percent of maximum growth of cod:

Eq. 21 $100\ G_B/g_{max} = 111.37\ w^{-0.029}$ for $1.5g \le w \le 2850g$

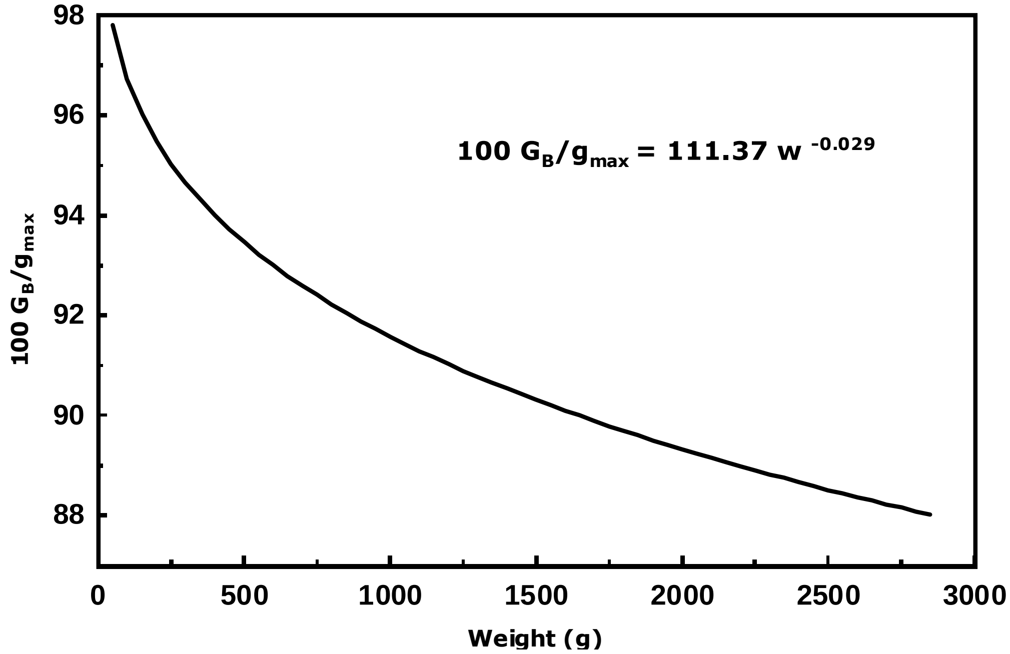

Figure 8 Maximum rate of increase in biomass (G_B) as % of maximum growth rate (g_{max})

As we can see from Figure 8 the yield from cod farming measured with the maximum growth rate of cod as basis is on average approximately 90%, and is decreasing as the cod increases in size.

As we have used g_{max} as basis (benchmark) G_B can be used as benchmark yield curve for cod farming, but cod price and cost of feed will influence the optimal temperature profile.

Optimal temperature for maximum increase in: the ratio of net present value of earnings[5] to the total value of biomass.

If the price of biomass is p (pr gram), cost of feed is q (pr gram) and $f_c(\Delta T)$ the feed conversion ratio, and we assume that all other costs are independent of the temperature profile, the change in net present value of expected earnings (ΔE) from day number i to i+1will be:

Eq. 22 $$\Delta E(\Delta T;w,p,q,r) = [p\ (B_{i+1}(\Delta T;w) - (1+r)\ B_i)/\ (1+r) - q\ f_c\ (\Delta T)\ (B_{i+1}(\Delta T;w) - (n_{i+1}/n_i)\ B_i)]/(1+r)^i$$

[5] Earnings before interest, taxes, depreciation and amortization (EBITDA).

Let $H = \Delta E\,(1+r)/p\,B_i$ and $\omega = q/p$, $(0 < \omega < 1)$ i.e. the feed cost biomass price ratio. Then:

Eq. 23 $\Delta E(\Delta T; w, \omega, r) = H\,B_i/(1+r)^i$ and

Eq. 24 $H(\Delta T; w, \omega, r) = G_B(\Delta T)\,(1/(1+r) - \omega\, f_c\,(\Delta T)) - r/(1+r) - \omega\, f_c\,(\Delta T)\, m(\Delta T)/100)$

Instead of maximising ΔE, we will maximize H to somewhat simplify the calculations. We can immediately see that if ω and r are equal to zero, the optimal temperature profile will be the same as for G_B. It is also of interest to note that for ΔE to be positive, G_B must be greater than r, that is: the rate of increase in biomass must be greater than the weighted cost of capital. For other values we need to maximize Eq. 24.

However to be able to maximise Eq. 24 for ΔT, we have to estimate the feed conversion ratio as a function of the temperature deviation.

Feed Conversion Ratio

In the material, data is also available for the feed conversion ratio observed in the different experiments. We are again interested in estimating the feed conversion ratio as a function of △T. We find that Eq. 25 gives a reasonable explanation of the observed data, see Figure 9. As is seen from the figure the equation explains approximately 50% of the observed variance, which is somewhat lower than expected.

All coefficients have a significance level of 0.1% or less. It is however obvious that Eq. 9 only describes parts of the mechanism, but again have in mind that ΔT controls for fish weight by Eq. 6.

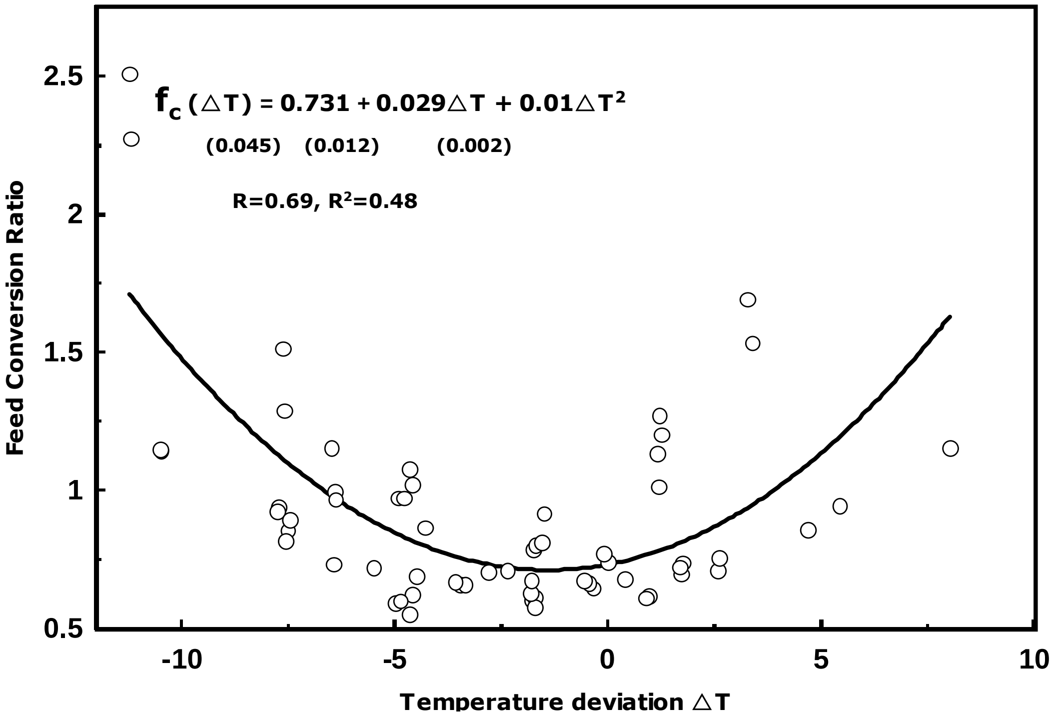

Figure 9 Feed Conversion Ratio as function of the Temperature Deviation (–11.3 °C ≤ΔT≤ 7.0 °C). Data from Björnsson et al. (2001).

Eq. 25 $f_c(\Delta T) = h + k\,\Delta T + s\,\Delta T^2$ for $-11.3\,^{o}C \le \Delta T \le 7.0\,^{o}C$

Where h=0.731, k=0.029 and s=0.01
(0.045) (0.012) (0.02)

Using Eq. 25 we can maximise Eq. 24 for different values of w, ω and r. The values of ΔT for selected values of w and ω (r has been set to 12% pa) are given in Figure 10. As shown the optimal value of ΔT are decreasing with increasing values of w and ω.

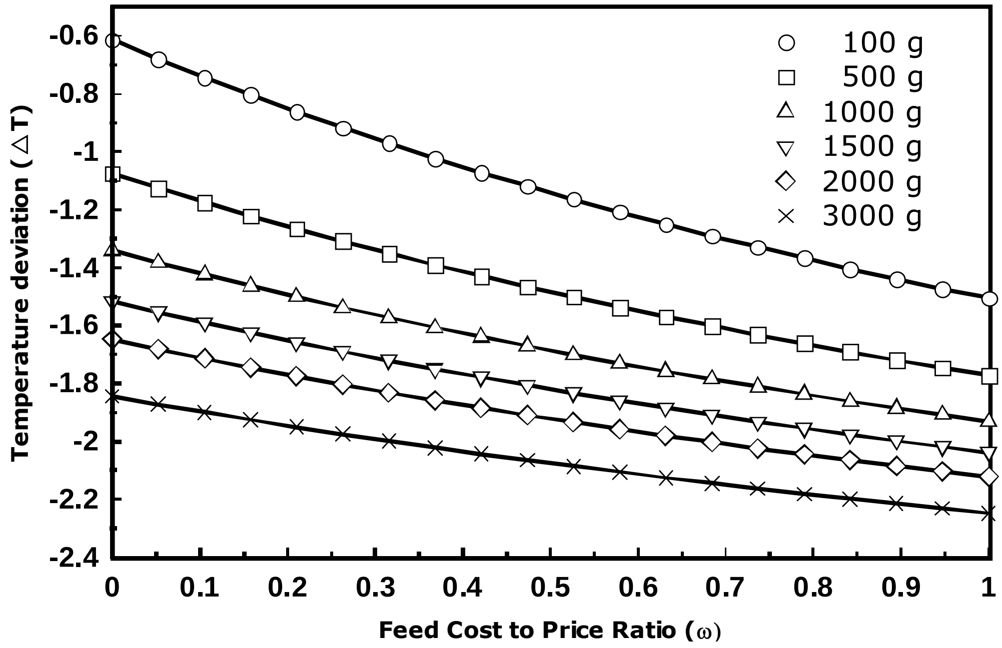

Figure 10 Optimal temperature deviations for maximum increase in the ratio of earnings to value of biomass, for different values of cod Size and the feed cost to price ratio. The weighted average cost of capital is set to 12 % pa.

In Figure 11 we have plotted optimal temperature profiles for different values of ω (ω=0.25, 0.5, 0.75). It is evident that optimal temperatures are lower the higher the feed cost to biomass price. This is not surprising since high feed cost means more invested in biomass, and more to lose from fish death. Low mortality by lowering temperature will therefore increase earnings.

The optimal temperature profile is therefore always lower than optimal temperature for maximum increase in biomass.

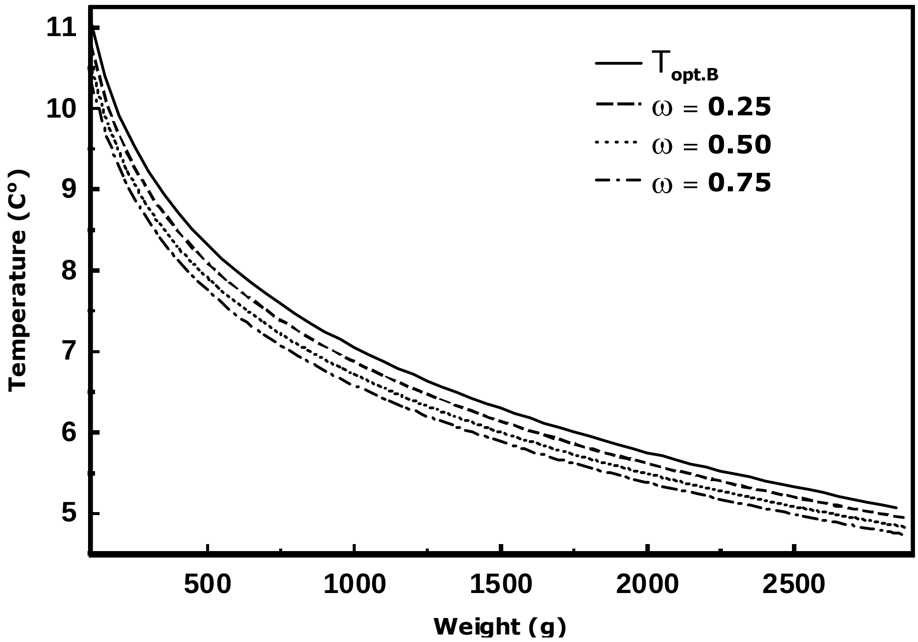

Figure 11 Optimal Temperature for maximum rate of increase in biomass (Topt.B) and maximum increase in the ratio of earnings to value of biomass, for different values of the feed cost to price ratio (ω). The weighted average cost of capital is set to 12 % pa.

If the weighted cost of capital (r) increases, the optimal temperature will be lowered. The reduction in temperature however is much lower than for similar changes in the feed cost to biomass price.

Conclusions

We have found that the optimal temperature for maximum rate of increase in biomass is considerably lower than optimal temperature for growth of cod, and that the difference increases as the cod increases in weight. We have also shown that as the cost of feed increases relatively to the price of biomass, the optimal temperature will decrease.

For fish farming this implies that the water temperature should be lowered considerably throughout the farming process, to be able to achieve the best production result.

Comparing the competitiveness of cod farming in Norway and Iceland, we find yearly mean temperature (and range) of 5°C (0-10°C) and 9°C (5-14°C) in Icelandic and Norwegian fjords, respectively. According to Figure 11, it seems that the temperature profiles in Norway are more suitable for cod farming of juveniles to small cod (<1000 g) whereas the conditions in Iceland may be more suitable for farming large cod (>1000 g).

The low winter temperatures in Iceland may be more critical to the juvenile cod, and may restrict the time they can be put in sea cages. However, the high summer temperatures in Norway, particularly in warm summers, may be critical to the well being of large cod. This may mean that the optimal slaughter size will be much smaller in Norway than in Iceland.

Based on the findings, production yield and value (or profitability) will be significantly different between fish farming sites, depending on their location (temperature profile), the ratio of cost of feed to the price of biomass and on the cost of capital.

For any set of ΔT, *ω and r, some fish farms will have optimal conditions. All other will have suboptimal conditions with lower yield and higher cost.*

The implications for producers of feed are also obvious, the price of feed will determine fish farming profitability, and thereby their own profitability and risk of fish farming bankruptcy.

Governments should take these conclusions into consideration when planning for growth in cod farming. Investors should be aware of the risk involved in terms of expecting significant differences between return from farms in different regions.