Growth curve modeling (GCM) and possible application in fish stock assessment.

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Summary.
A new analytical approach to fish growth dynamics (Growth curve modeling, GCM), has been developed at the Aquaculture Laboratory of the MRI in Iceland. GCM-modeling is based on the analysis of growth trajectory and links larval- to long term growth performance. The method was initially developed for Atlantic cod (*Gadus morhua*) but can arguably be applied to all fish species, creating a new perspective on the underlying growth dynamics of fishes. GCM-modeling shows how the long-term growth potential can be traced back to the initial larval growth performance and how the early larval benchmark sizes are systematically reflected throughout the later juvenile- and adult life stages. GCM-modeling further shows how the life-span is divided into consecutive stages with fixed growth potential and how the potential maximum size of the fish is already fixed at the larval stage. When applied to historical data from the Icelandic cod stock, GCM-modeling reveals a previously overlooked fluctuation pattern in cohort growth rates.

Introduction.
The von Bertalanffy growth equation (VBGE) adequately describes the growth trajectory of most fishes and is widely used in the field of fisheries research (Sparre and Venema 1998). The weight-based VBGE is used as a sub-model in the yield per recruit (Y/R) models commonly used in stock assessment. The weight-based VBGE, with its familiar sigmoid growth trajectory, may actually hold the key to a new perspective on the underlying growth dynamics, as will be presented in this poster. GCM-modeling is a new analytical approach that can be applied in stock assessment to predict cohort growth potential and sustainable yield. Fisheries-induced stock changes have affected the growth of Icelandic cod during the last century (Jakobsdóttir *et al*. 2011) but no discernible patterns in cohort growth performance have been reported. Variations in cohort weight-at-age in the Icelandic cod stock have been attributed primarily to variable prey abundance (Steinarsson and Stefansson 1996).

Material and methods.
The concept of GCM-modeling was constructed from the results from a project run at the MRI Aquaculture Laboratory in 2008-2011 (Steinarsson *et al*. 2012). Atlantic cod juveniles were produced from domestic broodstock using standard hatchery methods but different weaning strategies. The mean larval dry weight of each group was measured weekly during the hatchery stage and live weight at regular intervals thereafter. All fish were PIT tagged and reared communally in tanks until the age of 30 months post-hatch. The fish were fed a dry pellet diet and reared at 8°C after the first year. Growth curve modeling (GCM-modeling) includes a linear regression to the linear part of the mean growth trajectory of each group and backwards forecasting to cross both the *x*- and the *y*-axis. The resulting slope reflects the absolute growth potential (ABS) and the intercepts (X and Y) define the potential maximum size and longevity of the fish. GCM-modeling was further applied to historical weight-at-age data (age range 5-10 years) for the Icelandic cod stock from 1950-2004. The growth potential (ABS) and maximum size (W_{max}) could thus be calculated for each cohort separately to study the temporal variation in the growth performance of the cod stock during this period.

Results and Discussion.
The striking linearity of the long-term growth trajectories from 18 months onwards led to the concept of GCM-modeling (Figure 1). The *x*- and *y*-intercepts of the regression line define the growth dynamics and divide the life-span into distinct growth phases. For this group of farmed cod, X equals

15 months and the linear growth phase ends at 45 months (3X). The maximum weight and potential longevity is reached at the end of the asymptotic growth phase at 120 months (8X). The negative *y*-intercept (-Y=-3.25 kg) reflects the steepness of the regression line and dictates the potential maximum weight as 13 kg (4Y). The slope of the regression line (Y/X) defines the absolute growth potential (ABS = 2.6 kg/year) during the linear phase.

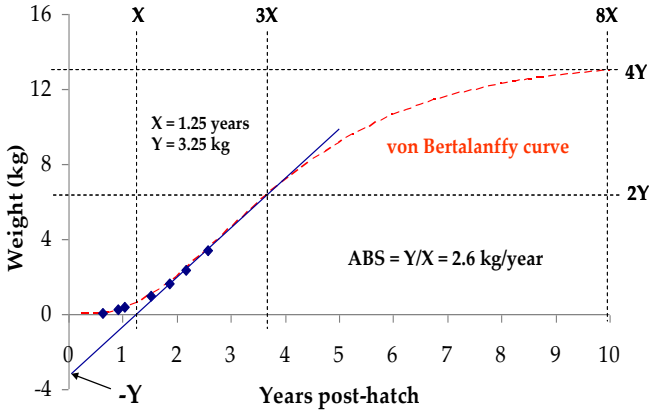

Figure 1. Growth curve modeling (GCM) of a 30 month growth trajectory of farmed hatchery cod. The sigmoid line shows the weight-based VBGE fit. The GCM-parameters are explained in the text.

The Y-parameter is highly variable between farmed groups and consequently, so is their growth potential and maximum size. The results (not shown) suggest that long-term growth potential is in effect a reflection of the larval growth performance during the first 45 days after first feeding (dpff). Amazingly, the benchmark weight at 45 dpff (0.325 g) is reflected in the Y-parameter (3.25 kg) and also in the X-benchmark weight at 450 dpff (325 g).

GCM-modeling was applied to historical weight-at-age data (age range 5-10 years) for the Icelandic cod stock from 1950-2004. The absolute growth potential (ABS) of each cohort was remarkably stable over the 5-year period ($R^2 > 0.97$ for all cohorts), indicating a relatively minor long-term influence of external factors, such as prey abundance. Figure 2 reveals a twofold variation in cohort-ABS, which appears to follow a relatively smooth 10-year fluctuation pattern up into the 1990's. This cohort growth pattern is closely correlated with the mature spawner (10 year+) mean weight (not shown), indicating a link between spawner size and offspring growth performance. The disrupted pattern after 1990 may be explained by the virtual exclusion of large spawners from the stock during that period. The observed increase after the millennium may suggest a recovery of the growth pattern, due to the ongoing recovery of the cod stock.

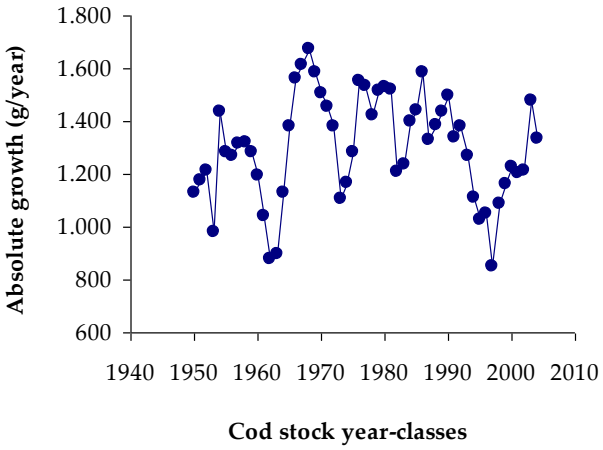

Figure 2. Absolute growth potential during ages 5-10 years for successive cohorts of the Icelandic cod stock, based on GCM-modeling of historical data.

References.

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