Fishery management as exact science

Johannes Hamre[1], Kristin Hamre[2*], Espen Johnsen[1]

[1]Institute of Marine Research

PO Box 1870 Nordnes

NO-5817 Bergen

Norway

Phone: +47 55 23 53 55

E-mail: johannes.hamre@imr.no, espen.johnsen@imr.no

[2]National Institute of Nutrition and Seafood Research (NIFES)

PO Box 2019

5017 Bergen

Norway

Phone: +47 48185034

E-mail: kha@nifes.no

[*]Corresponding author

Abstract

The main objective in research on sustainable fishery management is to understand the effects of fisheries on the resources and predict the Maximal Sustainable Yield. The von Bertalanffy growth model, commonly used in stock assessment, is suboptimal for the calculation of yield, because it cannot be integrated to omit time from the equation. Here, we present a new model to be used as the scientific basis to calculate yield and provide advices for optimal ecological harvesting strategies. The model builds on the principle of exact science and utilizes population measurements from scientific acoustic trawl surveys as input in a real population dynamical model. The model expands the theory of relativity to include the transition of biomass into energy and will improve simulation models used in fisheries science.

Introduction

A main objective in fisheries management is to track the impact of fisheries on the fish stocks and predict the Maximum Sustainable Yield (MSY)[1]. In the classical Beverton & Holt model (1957)[2], the yield by recruit is estimated by assuming that growth and mortality are functions of age. The instantaneous mortality can be expressed as a simple differential equation, whereas the von Bertalanffy asymptotic growth model (1938) [3] used by Beverton and Holt, presupposes constant growth of different year classes and is a function of age, e.g. accumulated time. This growth model is also used in modern dynamic models which make summations of each year class instead of integrating over all ages[1]. It usually fits length–age data well [4] and any seasonal pattern of growth and mortality can be included in these modern models [1]. However, growth is highly dynamic and changes with variations in temperature and food availability. The von Bertalanffy's growth model cannot be integrated, which in mathematical terms prevents the stock models to truly be defined as dynamical models and

thereby fishery management to be defined as exact science. When including the presented dynamic growth model in population models, fishery management can be characterized as exact science.

What do we mean with exact science?

After Vilhelm Bjerknes [5] laid the theoretical foundation for the study of motions in the atmosphere and the oceans with the baroclinic density distributions, he argued that the weather prognosis should be considered as an initial value problem of mathematical physics, and carried out by integrating the governing equations forward in time, starting from the observed atmospheric state. He formulated the principle which is referred to as the numerical weather prediction which can be separated into two:

A sufficiently accurate description of the atmospheric condition at one moment in time

A sufficiently accurate description of the physical laws which cause the transition from one atmospheric state to another.

Bjerknes divided the input data in the model in three different subjects:

Diagnosis of the atmospheric state based on observations at a moment in time

Prognoses of the future atmospheric state calculated from the physical laws

Variables: wind, temperature, air pressure, humidity, clouds

In quantitative biology terms, the Bjerknes principles can be structured as exact dynamical science and expressed as:

Diagnosis: The state of the stocks based on observations at a moment in time

Prognosis: The future states of the stocks based on population dynamical models

Variables: Population size in numbers and weight, recruitment, growth and mortality

Diagnosis

The capelin (*Mallotus villosus*) stock in the Barents Sea was the first example of a quota regulated fishery where the advice was based on 1) hydroacoustic measurements and 2) an estimation of the spawning stock size which provided an optimal harvest of the stock [6] [7]. The acoustic methods have improved tremendously, and today, acoustic survey is a standard method to assess pelagic fish stocks [8].

The experiences made during the project indicated that the abundance estimates resulting from the hydroacoustic trawl surveys had to be structured in length-age matrices (Table 1) to be able to calculate the mortality and increment of growth by cohort (year class) independent of accumulated time. The distribution of fish in number to the different age groups was achieved by reading shells and otholits in fish from trawl samples and the transition to biomass by calculation of a standard Fulton's condition factor from weight and length measurements of the sample [9].

Table 1 represents the diagnoses of the capelin population in time steps, and a time series of annual measurements in the autumn made it possible to predict the state of the stock based on previous acoustic measurements. For this prediction, a model was established to give scientific advices on the capelin fishery in the Barents Sea [7]. The model can simulate different harvesting strategies but has received little attention among fishery scientists despite the long period it has been in use in quota regulation for the capelin fishery. We suggest that this model structure is used generally as diagnosis for fish stocks.

Prognosis

A real dynamic population model calculates changes in biomass independent of time. Such a model is often formulated with differential equations where the change is initially measured as a function of time. Since no quantitative definition of time exists, the time factor is traditionally removed by integration. However, the differential models describing increment in biomass of fish cannot be integrated [10] [11] [12] [2].

Another way to quantify changes in mass than using differential equations was introduced by Albert Einstein in1905. He assumed that the change in particle velocity is a result of adding energy to the particle independent of time ($E=mc^2$), where the change per unit added energy is largest when the velocity of the particle is small, and decreases towards a maximum value; the speed of light [13]. Here, energy and mass are equivalent and transmutable and independent of time. Einstein's postulate met considerable skepticism amongst the mathematicians, but was effectively proven by the testing of the nuclear bombs.

In a similar way, we have established a simple equation of growth increment by postulating that the length increment (dL) is proportional with the length (Ls) and that dL is reduced towards a maximum length (Lmax):

$$dL = k \cdot (Lmax - Ls) \qquad\qquad 1$$

k is a variable determined by food availability, temperature and other environmental factors, e.g. it describes the transformation of biomass into energy. Eq. 1 includes only measurable factors so that dL can be summed arithmetically by year classes using modern computer

techniques. The simple equation provides the new essential basis in our model, and expands the theory of relativity to include biomass. It postulates that biomass, similarly to other physical mass, is equivalent with energy. In other words, the dynamics we are observing are based on a common natural law formulated mathematically by Albert Einstein in 1905.

The similarity between an asymptotic von Bertalanffy model and the instantaneous model of growth increment is illustrated in Figure 1 where the 1983 year class of herring is given as example. Figure 1a illustrates the calculated increase in body length as a function of body length using Eq. 1, which is the basis for calculation of yield. The corresponding growth curve by age is calculated from Figure 1a and visualized in Figure 1b. The points are observed values. The lower observed growth rate of 2-3 year old herring compared to the older fish corresponds with the migration of the year class from the Barents Sea to the warmer Norwegian Sea, e.g. it is caused by a change in k, probably due to the increase in the sea water temperature.

Parameters, variables and simulation

Our growth model contains only one parameter, Lmax. The model presupposes that a fish stock is made up by a group of individuals with different Lmax at hatching. The individual Lmax is genetically determined, does not change during life and is not affected by exploitation. It is different from L∞, which per definition is connected to time and has no individual variation.

Clearly, there are a considerable number of variables that determine the value of k, and the parameterization will demand expertise within oceanography and in biological fields such as genetics and nutrition.

In future simulation models, we suggest to calculate yield from instantaneous growth increment (Eq. 1, Fig 1a) and instantaneous total mortality stepwise for each length group (Table 1).

In an ecological and harvesting perspective

The instantaneous growth function enables us to calculate the differences in yield by harvesting fish of different lengths. For herring, 80% of the potential somatic growth is reached before first spawning which occurs at a length of about 30 cm (Figure 1a). It is thus clear that from a yield perspective it is beneficial to harvest immature fish. This is also the principle of production of most of our farm animals, including farmed fish. Size limitations in fishery may therefore defeat its own end, and prevent a maximum utilizion of the marine resource. A similar perspective is presented by Borrell (2013) [14].

The growth function also enables us to understand the efficiency with which energy is transported upwards in the nutrient chain. For herring, the somatic growth per unit added energy is about 5 to 10 times higher for 0-group fish (<15 cm) than for fish above 15 cm (Figur 1a). This is in accordance with the fact that seabirds along the Norwegian coast mainly feed on 0-group fish [15], which represents an efficient utilization of zooplankton biomass and energy.

The hypothesis that individual Lmax is determined genetically, and follows the animal throughout life, may explain the many reports that exploitation of fish stocks and especially size limited fisheries, leads to a decrease in length and age at which the fish become sexually mature [14] [16] [17] [18]. Selecting the large fish will cause relatively higher mortality of fish with a high individual Lmax than in the smaller fish, and the genetic makeup of the next generation will change accordingly.

The question as to whether the decrease in fish size at first maturity is a genetic or plastic response is still open [14], but this effect of fisheries points to the need for balanced harvesting of body sizes within a stock, and of species within an ecosystem, to diminish fishing induced ecological changes. The need for balanced harvesting has led to the concept of dynamic size spectra [19], where productivity on different trophic levels is calculated, still based on the von Bertalanffy growth function, and used to predict yield in the whole system. Our growth model gives an improved estimation of yield, dependent on the environment and taking into account the transfer of energy between trophic levels. It can be used in different models, including the simulation model, Systmod [20], which is already developed for multiple species.

References

1   Pitcher, T. J. & Hart, P. J. B. *Fisheries Ecology*. (Chapman and Hall, 1982).
2   Beverton, R. J. H. & Holt, S. J. On the dynamics of exploited fish populations. *Fisheries Investigation, London, Series 2* **19**, 1-533 (1957).
3   Bertalanffy, L. v. A quantitative theory of organic growth. *Human Biology* **10**, 181-213 (1938).
4   Allen, R. L. Method for comparing fish growth curves. *New Zealand J. Mar. Freshw. Res.* **10**, 687-692 (1976).
5   Bjerknes, V. Das problem der Wetterforhersage, betractet vom Standpunkte der Mekanik und der Physik. *Meterologische Zeitschrift, Wien* **21**, 1-7 (1904).
6   Nakken, O. & Dommasnes, A. The application of echo-integration systems in investigations on the stock strength of the Barents Sea capelin. (*Mallotus villosus*, Muller) 1971-1974. *ICES C.M. 1975* **B:25** (1975).
7   Hamre, J. & Tjelmeland, S. Sustainable yield estimates of the Barents Sea capelin stock. *ICES C.M. 1982* **H:45**, 47-49 (1982).
8   Simmonds, J. & MacLennan, D. *Fisheries Acoustics: Theory and Practice*. 2nd edn, Vol. 10 (Blackwell Science Ltd, 2005).
9   Fulton, T. W. The rate of growth in fishes. *Fish. Board Scotland, Ann. Rep.* **22**, 141-241 (1904).
10   Lotka, A. J. *Elements of Physical Biology*. (Williams and Wilkins Co., 1925).
11   Volterra, V. Variazioni e fluttuazioni del numero d'individui in specie animali conviventi. *Mem. R. Accad. Naz. dei Lincei. Ser. VI* **2** (1926).
12   Schaefer, M. B. Some Considerations of Population Dynamics and Economics in Relation to the Management of the Commercial Marine Fisheries. *J Fish Res Board Can* **14**, 669-681 (1957).

13   Einstein, A. Zur Electrodynamik bewegter Körper. *Randiconti del Circolo Matematico di Palermo* (1905).

14   Borrell, B. A big fight over little fish. *Nature* **493**, 597-598 (2013).

15   Dragesund, O., Østvedt, O. J. & Toresen, R. in *Norwegian Spring Spawning Herring and North East Atlantic Cod*   (ed O. Nakken) 41-82 (Tapir Academic Press, 2008).

16   Garcia, S. M. *et al.* Reconsidering the Consequences of Selective Fisheries. *Science* **335**, 1045-1047, doi:DOI 10.1126/science.1214594 (2012).

17   Sharpe, D. M. T. & Hendry, A. P. Life history change in commercially exploited fish stocks: an analysis of trends across studies. *Evol Appl* **2**, 260-275, doi:DOI 10.1111/j.1752-4571.2009.00080.x (2009).

18   Olsen, E. M. *et al.* Maturation trends indicative of rapid evolution preceded the collapse of northern cod. *Nature* **428**, 932-935, doi:Doi 10.1038/Nature02430 (2004).

19   Law, R., Plank, M. J. & Kolding, J. On balanced exploitation of marine ecosystems: results from dynamic size spectra. *Ices J Mar Sci* **69**, 602-614, doi:DOI 10.1093/icesjms/fss031 (2012).

20   Hamre, J. & Moen, S. Flerbestandsmodellen Systmod. Bruken av modellen for vurdering og forvaltning av fiskeressursene i Barentshavet. *Fisken og Havet* **11**, 41pp (2008).

Author contributions

JH developed the growth function and the Systmod simulation model. JH, KH and EJ discussed and formulated the concepts of exact science and a real population dynamic growth model and wrote the manuscript.

Author information

Reprints and permissions information is available at www. nature.com/reprints

There are no competing financial interests connected to this manuscript

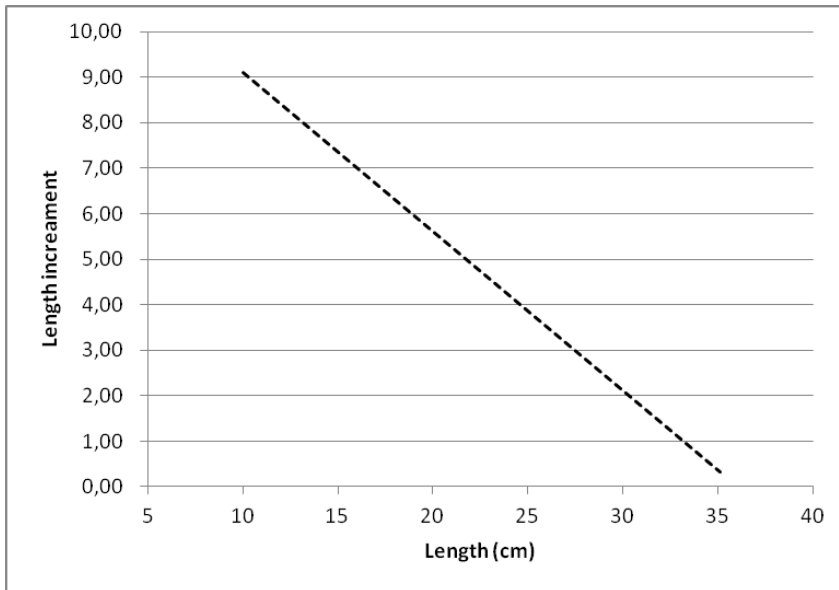Correspondnece and requests for materials should be addressed to Kristin Hamre.

Figure Legend

Figure 1. Modeled and observed growth in the 1983 year class of Norwegian Spring Spawning herring with *k*-value 0.35 and Lmax=36.0 cm a) Instantaneous growth: Length
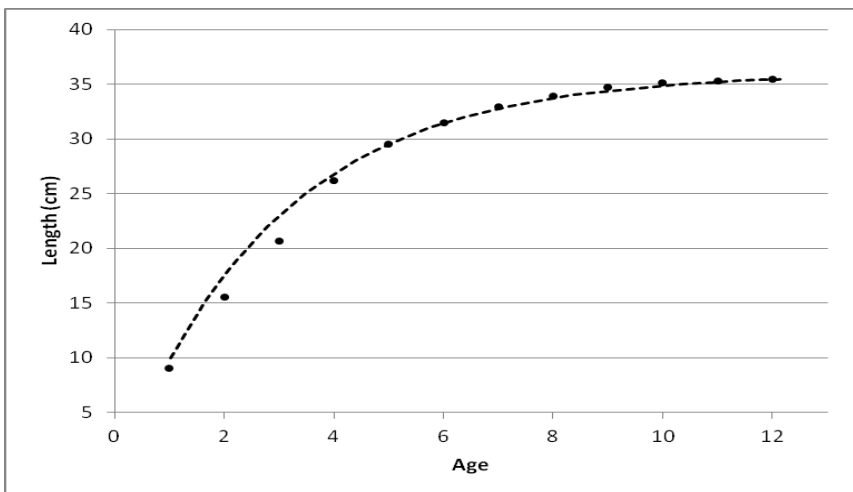
increment as function of length, and b) Average length by age, calculated from 1a (dashed line) and observed (points).

Table 1. **Diagnosis of the Barents Sea capelin stock.** The estimated number of capelin by length and age group measured during the acoustic survey in autumn 1980.

Total length (cm)	Age					Total number x 10^7	Biomass ton x 10^3
	1	2	3	4	5		
6.5 - 6.9	105					105	1.0
7.0 - 7.4	411					411	4.1
7.5 - 7.9	418					418	4.2
8.0 - 8.4	862					862	14.7
8.5 - 8.9	2354					2354	47.1
9.0 - 9.4	3760					3760	87.9
9.5 - 9.9	3928	25				3953	120.3
10.0 - 10.4	3690	75				3765	145.7
10.5 - 10.9	5731	388				6119	284.1
11.0 - 11.4	6134	1186	13			7333	387.5
11.5 - 11.9	3314	2556	4			5874	363.4
12.0 - 12.4	1276	3456	52			4784	353.1
12.5 - 12.9	595	3221	170	4		3990	346.2
13.0 - 13.4	256	3115	459	14		3844	390.8
13.5 - 13.9	59	2724	1131	14		3928	452.5
14.0 - 14.4		1836	2317	108		4261	561.5
14.5 - 14.9		756	2811	197		3764	554.0
15.0 - 15.4		422	2776	381		3579	604.5
15.5 - 15.9		92	1800	464	1	2357	447.6
16.0 - 16.4		43	1453	469	29	1994	437.3
16.5 - 16.9		7	878	410		1295	327.2
17.0 - 17.4		7	510	384		901	257.2
17.5 - 17.9			442	339		781	250.8
18.0 - 18.4			271	230		501	182.8
18.5 - 18.9			178	108		286	115.0
19.0 - 19.4			131	85		216	91.3
19.5 - 19.9			19	55		74	36.5
Number x 10^7	32893	19909	15415	3262	30	71509	
Number > 14.4 cm	0	1327	11269	3122	30	15748	
Biomass (ton x 10^3)							6868.3
Biomass fish >14.4 cm							3304.2

a

b

Figure 1