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Validation of a bioenergetic model for juvenile salmonid hatchery production using growth data from independent laboratory feeding studies

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ABSTRACT

The long-term goal of this research program is to develop and validate bioenergetic models for juvenile salmonid production oriented toward practical hatchery applications. As an initial step toward attainment of this goal, the efficacy of the model was evaluated by comparing model simulations with published data for the growth of a wild strain of coho salmon and a domestic strain selected for its rapid growth characteristics. Model simulations were consistent with the observed growth for each strain when the consumption rate model coefficient was adjusted to account for differences in the stomach size. In an independent study, the growth and proximate composition of juvenile Chinook salmon were measured in response to high and low lipid diets supplied at two different feeding rates. Model simulations were closely comparable to these data when the model coefficients for consumption and apparent respiration rate were adjusted to account for ration and body lipid content. These insights and the successful simulation of measured growth data for eight different combinations of ration, food composition, and coho strain are useful and necessary steps needed to support the development of credible production-scale management models for juvenile salmonid fish production and waste by-product generation from aquaculture and mariculture activities.

1. Introduction

The State of Michigan Department of Natural Resources (MDNR) operates the Platte River State Fish Hatchery (PRSFH). This is the main coho salmon (*Oncorhynchus kisutch*) egg-take facility in the Great Lakes region and produces all of the coho salmon and more than half of the Chinook salmon (*Oncorhynchus tshawytscha*) needed by the MDNR Great Lakes Fishery Management Program. The hatchery is located on the Platte River 18 km upstream from Big Platte Lake and 29 km upstream from Lake Michigan (44° 39′ 45.56″ N, 85° 56′ 10.84″ W).

Big Platte Lake is an oligotrophic dimictic system with an annual average total phosphorus concentration of about 8.0 mg/m^3. A highly restrictive phosphorus discharge limit for the PRSFH of 80 kg P/yr (with no more than 25 kg P in any three month period) has been mandated to protect the water quality of Big Platte Lake. These loading limits have largely been attained using micrometer filtration disks and ferric chloride precipitation of phosphorus in the waste stream. Solids are subsequently removed from the system following a two-step thickening process. The fish are fed a low phosphorus diet to further reduce the phosphorus discharge. Despite this advanced technology, the phosphorus discharge limits have been violated on occasions during recent years. The hatchery managers need quantitative tools that can be used to optimize production costs and determine production targets that are compatible with the phosphorus loading limits.

An important component of such a quantitative approach is a fish growth model based on energy balance and bioenergetics. The model must be capable of predicting the growth and feed requirements as a function of control variables such as temperature and food composition. If such a model can be calibrated and subsequently validated, it can then be combined with mass balance equations for phosphorus and used to optimize the management and operation of hatchery systems. Stigebrandt et al. (2004) described a similar approach for Atlantic salmon (*Salmo salar*) fish farms in Norway. Similarly, Brigolin et al. (2010) developed models for biomass yields and the environmental impacts of gilthead seabream (*Sparus aurata* L.) mariculture activities in the Adriatic seas.

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2. General approach

Bioenergetic models have been used for many years to simulate fish growth for a number of applications and much has been written regarding their strengths and weaknesses (Chipps and Wahl, 2008; Hansen et al., 1993; Hanson et al., 1997; Kitchell et al., 1977). Perhaps the greatest challenge involved in developing reliable models is quantifying numerous model inputs and coefficients, as has been discussed most recently by Bajer et al. (2003, 2004a, 2004b), Whitledge et al. (2006, 2010), Beauchamp et al. (2007), and Csargo et al. (2012). These tasks are particularly difficult for wild fish applications, where it is arduous to quantify the predator population along with its associated prey type and availability (Ney, 1993). On the other hand, the application of bioenergetic models for hatchery systems should be relatively straightforward, because fish numbers and growth rates, food amount and composition, temperature, dissolved oxygen concentrations, flow rates, and other variables can be more easily measured and controlled.

As a preliminary step toward advancing production-scale hatchery applications, the reliability of bioenergetic growth models can be enhanced using extensive data that are available in the literature for smaller-scale controlled laboratory studies. Neely et al. (2008) compared the growth, feed intake, and nutrient efficiency of the Dømsea strain of coho salmon selected for its rapid growth characteristics with its source stock (Skykomish). The goal of that study was to identify and quantify the mechanisms associated with observed rapid growth rates of the Dømsea strain. Shearer et al. (1997) performed feeding and growth experiments with juvenile Chinook salmon to determine if fish growth rates and adiposity could be manipulated independently. This was done by monitoring fish growth and proximate composition in response to varying the ration and the lipid content of two high-protein diets. The goal of the current paper is not to break new ground on model development by adding more detailed mechanisms and dependent variables. Rather, it is to rigorously test the veracity and accuracy of conventional modeling frameworks using data from these independent controlled growth studies.

3. Energy balance

Bioenergetic models for fish growth are based on well-known equations that require conservation of energy. The net energy available ($\dot{E}_{Net}$) to growing fish can be used to increase their body weight or energy density and can be calculated from the energy available from food consumption after subtracting various losses and non-growth metabolism. Eq. (1) describes the continuity rate equation for these processes (Brett and Groves, 1979). The dot above the E terms is standard notation for rate of change, and the subscripts indicate the particular processes. All the terms in Eq. (1) have units of calories per day (cal/day).

$$\dot{E}_{Net} = \dot{E}_C - \dot{E}_F - \dot{E}_E - \dot{E}_S - \dot{E}_R \tag{1}$$

$\dot{E}_C$ is the energy from consumed food; $\dot{E}_F$ is the energy lost by egestion of feces; $\dot{E}_E$ is the energy lost by excretion of nitrogenous wastes in urine or by ammonia lost across the gills; $\dot{E}_S$ is specific dynamic action (SDA) or the energy utilized for ingestion, digestion, and assimilation of food; and $\dot{E}_R$ is the energy used by respiration (standard and active). Eq. (1) neglects the energetic cost of reproduction, and therefore is only valid prior to sexual maturity.

The energy associated with an individual fish is the product of its wet weight and energy density. The rate of change of this total body energy can be described by Eq. (2).

$$\frac{d[\varepsilon_{Fish} \cdot W]}{dt} = \dot{E}_{Net} \tag{2}$$

where ε_{Fish} is the energy density of the fish in cal/g of whole wet weight of fish, W is the whole wet weight of an individual fish in grams, and t is time (usually days). All references to weight in this paper are whole body wet weights. The following section examines in detail the individual terms in Eqs. (1) and (2).

4. Model inputs

4.1. Fish energy density

The energy density of a fish is a function of its proximate composition as described by Eq. (3).

$$\varepsilon_{Fish} = \varepsilon_{Lipid} \cdot L + \varepsilon_{Protein} \cdot P \tag{3}$$

where L and P are the lipid and protein fractions of the whole-fish wet weight, and ε_{Lipid} and $\varepsilon_{Protein}$ are the energy densities of lipids (8660 cal/g) and proteins (5650 cal/g) as recommended by Brett and Groves (1979). Shearer (1994) performed a comprehensive review of the factors that affect the proximate composition of cultured salmonids from eggs to sexual maturity. The review included endogenous factors such as size and life cycle, as well as exogenous factors such as temperature, diet composition, and ration. Shearer (1994) found that the concentration of lipid and protein, and therefore energy density, increases with body wet weight. Highly significant correlations were developed between the log of the body wet weight and the log of the lipid mass and the log of the protein mass. Similar observations regarding proximate composition have been made by Elliott (1976a) for brown trout (*Salmo trutta*); Gunther et al. (2005) for lake trout (*Salvelinus namaycush*) and brook trout (*Salvelinus fontinalis*); and Persson (1988) for rainbow trout (*Oncorhynchus mykiss*). These log–log correlations can be conveniently approximated by a single power function that relates the energy density and the wet weight of an individual fish as in Eq. (4).

$$\varepsilon_{Fish} = \alpha \cdot W^{\beta} \tag{4}$$

The coefficients α and β are empirical constants.

Hayes et al. (2000) and Brigolin et al. (2010) have applied power equations similar to Eq. (4) to express the relationship between fish energy density and fish weight in bioenergetic models. Others, such as Munch and Conover (2002) and Libralato and Solidoro (2008), have employed constant values to represent the energy density. Stewart and Ibarra (1991), Hanson et al. (1997), and Roy et al. (2004) expressed the energy density as a linear function of fish weight. Finally, sometimes explicit time–variable functions are used to account for changes in

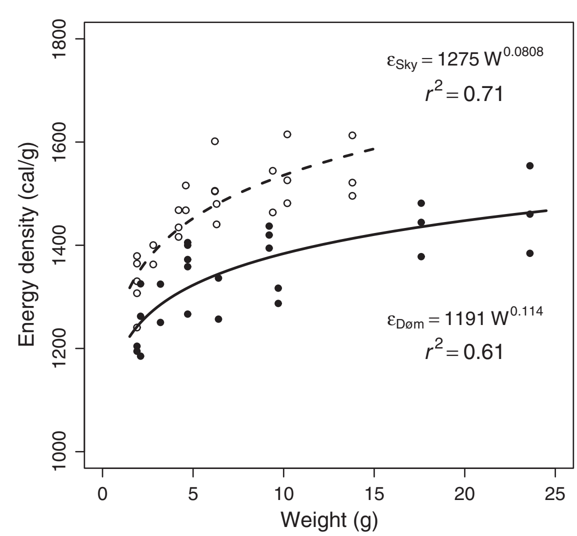

Fig. 1. Energy density of coho salmon based on proximate composition data from Neely (2006). Curves are power-function fits of data.