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Development of optimum feeding rate model for white sturgeon (*Acipenser transmontanus*)

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ABSTRACT

Establishing the optimum feeding rate (OFR; % body weight per day) for a cultured fish is a significant step toward the success of the aquaculture operation. Therefore, the objectives of this study were 1) the estimation of OFR for 19 datasets with different initial body weights by applying broken-line and quadratic regression models and 2) an investigation of potential OFR prediction models using 19 estimated OFRs from objective 1.

Objective 1) Nineteen datasets were obtained from five published studies (14 datasets) and one unpublished study (5 datasets) which were carried out to evaluate the effects of feeding rate on growth performance in white sturgeon of initial body weights varying from 0.05 g to 764 g. Each dataset, containing feeding rate (independent variable) and specific growth rate (% body weight increase per day; dependent variable) was used to estimate OFR by one-slope straight broken-line, two-slope straight broken-line, quadratic broken-line, and quadratic models for each body weight class. Calculations of model selection criteria, including the adjusted coefficient of correlation, Akaike information criterion, and corrected Akaike information criterion were performed to compare model performance on OFR estimation for each dataset. Three models (two-slope straight broken-line, quadratic broken-line, and quadratic models) were considered acceptable for the estimation of OFR, and the three sets of estimated OFRs obtained by these models were used in objective 2.

Objective 2) Several regression models, including polynomial models of order from 1 to 6, a simple exponential model with a constant, and a bi-exponential model, were fitted to each set of the 19 estimated OFRs against transformed initial body weights. A power function model was also fitted to the estimated OFRs against untransformed initial body weights. The model selection criteria for objective 2 were the same as those for objective 1. Overall model performance on the estimation of OFR for the 19 datasets shows that the quadratic broken-line model performed best, followed by the quadratic, two-slope straight broken-line, and one-slope straight broken-line models. Given the overall performance of model fitness to the sets of the OFR estimates, the bi-exponential regression model emerged as the most favorable one. As a result, the bi-exponential model equation,

$$OFR\ (\%\ body\ weight\ per\ day) = 0.00344(\pm 0.0123)\, e^{-5.684(\pm 2.309)\ \ln(\sqrt{\text{body weight}})} + 8.695(\pm 0.606)\, e^{-0.549(\pm 0.065)\ \ln(\sqrt{\text{body weight}})}$$

obtained by fitting the estimated OFRs derived from the quadratic broken-line model analysis, can be used to predict the OFR for white sturgeon from about 0.05 g to 800 g.

1. Introduction

White sturgeon are a commercially important aquaculture species providing meat and caviar for human consumption, and France, Italy, and the USA are the main producers around the world. The total quantities of meat and caviar produced by these countries in 1996 were recorded as approximately 600 t and 1 t, respectively (Bronzi et al., 1999). Estimates of 2012 production for sturgeon aquaculture in the USA alone were approximately 1350 t of meat and between 15 and 20 t of caviar. The majority of this production came from the white sturgeon, 95% from California (F. S. Conte, University of California, Davis, CA, USA; personal communication).

Estimation of optimum feeding rate (OFR; % body weight per day) is an important component for the success of aquaculture operations because feeding rate, water temperature, and fish size are three critical elements for fish growth (Brett and Groves, 1979). Cui and Hung (1995) developed a prototype feeding model to provide OFR for white sturgeon

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from 50 g to 1000 g. However, the prototype model was developed on the basis of the outcomes of analysis of variance (ANOVA) and multiple range tests, assuming that the OFR is estimated as the minimum feeding rate that results in a response which is not significantly different from the maximum response. Generally, growth response to feeding rate is continuous, in that the response increases with increasing feeding rate up to a peak and then it plateaus at the feeding rate beyond the peak. Furthermore, the responses to nutrient or feeding levels show fairly similar patterns.

In his critique, Shearer (2000) stated that it is inappropriate to use the ANOVA and multiple range tests to determine optimum nutrient levels because the nutrient levels are treated as discrete rather than continuous. Shearer also provided a good example of the use of those statistical analyses giving less accurate estimates compared to the application of a regression model such as a second-order polynomial curve for the estimation of optimum nutrient levels. In order to find a more accurate estimate than the ANOVA and multiple range test yield, many researchers have commonly used regression models, such as broken-line and quadratic (also called second-order polynomial) models accounting for dose–response relationships (Pesti et al., 2009; Robbins et al., 1979, 2006; Shearer, 2000; Zeitoun et al., 1976). The broken-line model can be described as a linear line or a quadratic ascending line with either an ascending line, a plateau line, or a descending line, which represents the dose–response relationship between nutrient levels (or feeding rate) and growth. A breakpoint between the two lines indicates the optimum nutrient requirement or the OFR. The quadratic model is represented as a symmetric parabola having a unique maximum point which suggests the optimum nutrient requirement or the OFR that produces the maximum growth. However, a single model application for the estimation of OFR may not provide a best estimate because the design for that particular experiment and the resulting variations in the response can contribute to the selection of an inappropriate model (Shearer, 2000). In addition, the prototype model by Cui and Hung (1995) does not provide OFR for white sturgeon smaller than 50 g. Thus, testing various regression models is appropriate in order to select the best-fit model for the estimation of OFR.

Therefore, the objectives of this study were 1) the estimation of OFR for 19 datasets with different initial body weights by applying broken-line and quadratic regression models and 2) the development of an OFR prediction model that can predict OFR for white sturgeon from about 0.05 g to 800 g using the 19 estimated OFRs from objective 1.

2. Materials and methods

2.1. Description of dataset

Nineteen datasets were obtained from five published (De Riu et al., 2012; Deng et al., 2003; Hung and Lutes, 1987; Hung et al., 1993a, 1995) studies and one unpublished study, which were carried out to evaluate the effects of feeding rate on growth performance in white sturgeon of initial body weights varying from 0.05 g to 764 g. All the studies were carried out by the same laboratory (Dr. Silas Hung, Department of Animal Science, University of California, Davis, CA, USA) and at the same facility (the Center for Aquatic Biology and Aquaculture, University of California, Davis, CA, USA) except the Dataset 19 (a growth trial was performed at a local commercial farm; The Fishery, Galt, California, USA). The datasets, including initial body weight (weight class), number of replications, feeding rate (independent variable), and specific growth rate (SGR; % body weight increase per day) corresponding to the feeding rate (dependent variable) are listed in Table 1. The initial body weight was the average weight of the fish in all tanks when the growth trial began. The number of replications was the number of tanks assigned to each feeding rate. The feeding rate (% body weight per day) was the treatment tested for the evaluation of its effects on SGR. The SGR was the growth response at each feeding rate, calculated from the equation, $100 \times (ln(FBW) - ln(IBW)) / days$ *of feeding*, where the *FBW* and *IBW* were the average final and initial body weights, respectively. The water temperature and the feed compositions used for the experiments are described in Table 1. In most of the experiments, continuous automatic feeders were used except the one experiment (Dataset 19) where a demand feeder was used. Other experimental conditions such as water quality (e.g. flow rate, total ammonia, dissolved oxygen, pH, etc.) and tank system, affecting growth performance can be found in the references as indicated in Table 1.

2.2. Estimation of OFR for the 19 datasets (objective 1)

One-slope straight broken-line (One-slope BL), two-slope straight broken-line (Two-slope BL), quadratic broken-line (Quadratic BL), and quadratic (Quadratic) models are common regression models used to estimate optimum nutrient levels or feeding rates. The functional equation forms and the graphical illustrations of the models are shown in Table 2 and Fig. 1, respectively. A brief description of each model is given here.

The One-slope BL model (Equation [1] and Fig. 1[A]) represents a single breakpoint which is the intersection of a positive slope line and a plateau line. The breakpoint is the OFR where SGR is at a maximum.

The Two-slope BL model (Equation [2] and Fig. 1[B]) represents a single breakpoint which is the intersection of a positive slope line and a positive or a negative slope line. The breakpoint is the OFR where SGR is at a maximum.

The Quadratic BL model (Equation [3] and Fig. 1[C]) represents a single breakpoint which is the intersection of a quadratic line and a plateau line. The breakpoint is the OFR where SGR is at a maximum.

The Quadratic model (Equation [4] and Fig. 1[D]) is a second-order polynomial where the OFR is the vertex of the polynomial curve.

The statistical model for the ith SGR (y_i) was stated as follows:

$$y_i = f(\boldsymbol{\theta}, x_i) + e_i$$

where x_i was the ith feeding rate and e_i was an error term, assumed to have a mean of zero and a variance of σ^2 (assumption of variance homogeneity was evaluated using the Levene's test ($p > 0.05$; Ritz and Streibig, 2008) in all but one dataset (Dataset 19; $p = 0.0406$); the Dataset 19 was included in the datasets for the development of OFR model because this probability was sufficiently close to 0.05). The vector θ was the functional parameters as described in Table 2.

Estimation of OFR for each dataset was performed through the application of the One-slope BL, Two-slope BL, and Quadratic BL models using a nls (nonlinear least-squares) function and of the Quadratic model using a lm (linear model) function, located in the standard library of R 3.0.1 (R Development Core Team, 2013). The R codes for fitting each model to the 19 datasets are provided in Supplementary Material.

To produce a criterion for the comparisons of model performance on OFR estimation for each dataset, the adjusted coefficient of correlation (R^2_{adj}), Akaike information criterion (AIC), and corrected AIC (AICc) were calculated as follows:

$$R^2_{adj} = 1 - \frac{MSE}{MST} = 1 - \frac{SSE/(n-k-1)}{SST/(n-1)}$$

$$\mathrm{AIC} = -2ln(L) + 2k$$

$$\mathrm{AICc} = -2ln(L) + \frac{2nk}{n-k-1} = AIC + \frac{2k(k+1)}{n-k-1}$$

where *SSE* and *SST* are residual sum of squares and total sum of squares corrected for the mean, respectively, n is the total number of observations, k is the number of parameters, and L is the maximum of the likelihood function. All three aforementioned criteria balance goodness-of-fit and model complexity to different extents. AICc penalizes model