Short communication

Asymptotic size and natural mortality of long-lived fish for data poor stock assessments

Kate I. Andrews [a],[*], Marc Mangel [b],[c]

[a] *NOAA, National Marine Fisheries Service, Beaufort Laboratory, 101 Pivers Island Road, Beaufort, NC 28516, United States*
[b] *Center for Stock Assessment Research, University of California, Santa Cruz, CA 95064, United States*
[c] *Department of Biology, University of Bergen, Bergen, Norway*

ABSTRACT

An assessment of the California sheephead (*Semicossyphus pulcher*) was conducted in 2004 despite the lack of critical data to estimate life history parameters, as often occurs for other species in need of assessment. Among other parameters, natural mortality, M, and the parameters of the von Bertalanffy growth equation were estimated using data poor methods. We assess the difference between those results and the results of applying a more recent set of data poor methods to the same data. We use a Bayesian model with only sheephead length data to estimate asymptotic size; our estimate is similar to previous work using the von Bertalanffy growth equation but includes statements about uncertainty in asymptotic size. We use weight-based methods for calculating age-specific mortality and compare the estimate to the constant of 0.2 used in the sheephead assessment. Finally, since the sheephead is a long-lived fish, we determine the age at which fish must recruit to the fishery in order for a constant M to be appropriate. Our estimate of constant mortality stabilizes if the fish recruit after age two.

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1. Introduction

Calculating key life history parameters such as natural mortality, M, and asymptotic size, L_∞, for long-lived fish is often difficult. We rarely have sufficient data (e.g. catch-at-age or tagging data) to derive the parameters directly. Natural mortality would ideally be estimated empirically; however, those studies are extremely difficult, and thus rare. Calculating the parameters of the von Bertalanffy growth equation can be problematic even with a good sample size because asymptotic size and individual growth rate (k) are inversely related (e.g. Mangel, 2006). An error in calculating one of those parameters will propagate throughout the entire population dynamics model. For stock assessments where age data are poor or lacking entirely, age and growth parameters must still be derived. In such cases we cannot depend on established growth models or methods for estimating natural mortality that require complete age data.

An example of a stock assessment without age data or empirical data of the natural mortality rate is that for California sheephead, *Semicossyphus pulcher* (Alonzo et al., 2004). California sheephead is an exploited fish found in the waters off of California with a range that extends into the waters of Mexico. The California Department of Fish and Game regulates California sheephead under

their Nearshore Fishery Management Plan (CDFG, 2002) and they required an assessment be conducted for management purposes. Alonzo et al. (2004) conducted the first quantitative assessment of California sheephead in 2004 after nearly a century of its recreational and commercial exploitation.

Natural mortality, age, and growth are essential to fully describe the population dynamics of a stock. Natural mortality is often an elusive parameter and has been the subject of multiple studies, many of which have attempted to develop a model to estimate natural mortality using correlated life history information (e.g. Vetter, 1988). Many stock assessments are still conducted using constant M, which is usually seen as a concession due to a lack of data or the continuation of a precedent from a previous assessment. Age and growth studies require sizeable data sets requiring the sacrifice of the animals in order to gather hard parts used for aging. In the case of fisheries for which there are few sampling programs, a complete age and growth study may not be available.

We compare what was done in the California sheephead assessment with results using newer methods. The broader application is substantial, in that a large proportion of the assessments conducted around the world are data poor. Also, the practical use of multiple methods for estimating life history parameters is always a subject of considerable debate.

Here, we compare estimates of asymptotic size using a Bayesian method based on the physiological basis of the von Bertalanffy growth equation with the estimates used in the sheephead assessment. We also compare estimates of natural mortality using weight

* Corresponding author. Tel.: +1 252 728 8721; fax: +1 252 728 8619.
E-mail address: Kate.Andrews@noaa.gov (K.I. Andrews).

and life history-based methods with the constant value used in the California sheephead assessment. We begin by considering methods that can be used to estimate asymptotic size, since that is crucial when characterizing size-dependent mortality. We then turn to three different methods for estimating size-dependent mortality and finally consider the question "at what age can size-dependent mortality be treated as if it were size-independent for purposes of stock assessment?"

2. Methods and results

2.1. Estimating L_∞

Alonzo et al. (2004) had limited data at their disposal for the assessment. California sheephead cannot be aged by their otoliths; dorsal spines are the only available hard part that can be used for an analysis of age and growth. Alonzo et al. relied on the work of Warner (1975) and Cowen (1990) for estimates of age as well as survivorship. Their analyses utilized visual survey transects in the waters off of the Catalina Islands, and produced rough estimates of survivorship. The sample sizes were low; samples were non-random and limited to those fish that could be categorized by their coloration.

The ages from spines are only reliable for younger individuals (Warner, 1975) because the band deposition in later ages is questionable. Warner acknowledges that larger, older fish have been observed apart from his study, and that there are difficulties with aging using the dorsal spines. With such questionable age data, there is a need for a method that can quantify the uncertainty when only reliable length data are available. For the assessment, Alonzo et al. (2004) tried using the length data with Ford plots, with both an unconstrained and constrained L_∞. Then they tried the age at length data in a Schnute parameterization of the von Bertalanffy growth equation, both with an estimated L_∞ and an observed maximum size.

Bayesian methods allow us to quantify the uncertainty around the estimation of each stock assessment parameter (Punt and Hilborn, 1997; Ellison, 2004). We employed a Bayesian model developed by Siegfried and Sansó (2006) for estimating asymptotic size, L_∞, from the von Bertalanffy growth equation:

$$L(t) = L_\infty(1 - e^{-k(t-t_0)}) \tag{1}$$

In the above equation, $L(t)$ is the length at age t, k is the growth coefficient, and t_0 is a theoretical placeholder corresponding to the age at which size is zero (von Bertalanffy, 1938). The Bayesian model was developed for data poor stocks, such as sharks, where length data are easy to gather but age data are very difficult to collect. Since asymptotic size involves the von Bertalanffy growth parameter k, giving L_∞ and k independent priors is incorrect.

The method proceeds as follows. We let $\{x_1, \ldots, x_n\}$ denote the individual lengths and

$$Y_i = \log\left(\frac{x_i/\theta}{1 - (x_i/\theta)}\right) \quad \text{where } x_i < \theta \tag{2}$$

where θ is a proxy for L_∞, and it is constrained to be larger than the maximum observed data point. The logit transformation of the data, Y_i, is assumed to be normally distributed, $Y_i \sim N(\mu, \sigma^2)$. Siegfried and Sansó used the Gibbs algorithm to estimate μ and σ^2 and the Metropolis Hastings algorithm with a random walk jumping distribution to find θ (Hastings, 1970).

To apply this method, we used Jeffreys priors for μ and σ^2 (Gelman et al., 2004), the maximum data point as an initial estimate, and a flat prior for θ, which is sufficient for finding the posterior for θ, with the length data used in the sheephead assessment (n = 1296, min = 20.89 cm, max = 79.1 cm). We used a 1000
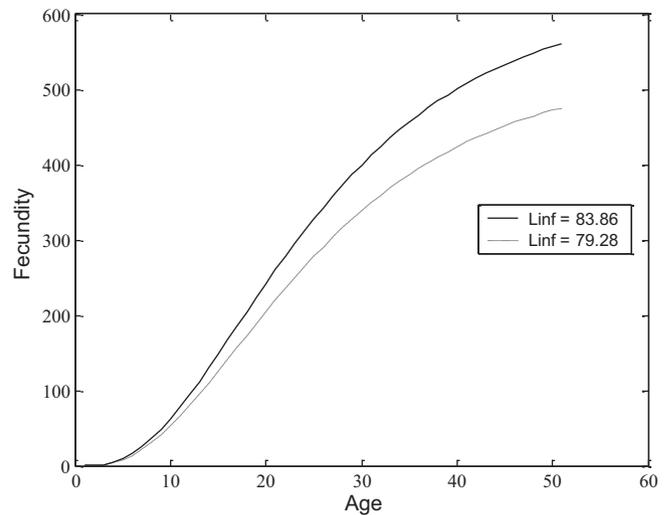

Fig. 1. The effect of different estimates of asymptotic size—83.86 cm for the sheephead assessment (Alonzo et al., 2004) and 79.28 cm using the Bayesian analysis—on fecundity (ovary weight in g).

sample burn-in period and multiple chains to determine if the starting value affected the final posterior mode, and we followed Siegfried and Sansó for the sampling protocol. Our final estimate for L_∞ was a mean of 79.3 cm total length with a 95% Bayesian credible interval of [68.4, 90.1 cm]. Alonzo et al. (2004) put forward their best estimate of asymptotic size as 83.9 cm using a Ford plot with no constraints and could not provide any consistent measure of uncertainty.

To illustrate the difference between the estimates, we compared the fecundity, measured by O_W was ovary mass in g, and related to length L in cm by (Alonzo et al., 2004),

$$O_W = 0.00131L^{2.95} \tag{3}$$

As Fig. 1 shows, even small differences in the estimates of asymptotic size can have a significant effect on the expected fecundity. Assuming there is no mechanism in the assessment model for incorporating error around the von Bertalanffy growth parameters, the error around the parameter point estimates would not be carried forward.

2.2. Estimating M

We used a number of published methods to calculate size-dependent natural mortality (for review see Vetter, 1988). The sheephead assessment was based on the weight-length relationship (Alonzo et al., 2004):

$$W = 2.6935 \cdot 10^{-5}(FL^{2.857}) \tag{4}$$

where W is weight in kg and FL is fork length in cm. We also used Eq. (4) for our analyses. Given W, the Peterson and Wroblewski (1984) equation relating mortality to weight is

$$M_W = 1.92 \, \text{year}^{-1} \cdot W^{-0.25} \tag{5}$$

where M_W is natural mortality at mass W. Since this method assumes a dry weight, we used the conversion factor of one-fifth as suggested by Cortés (2002) to convert dry weight equation from wet weight (Peterson and Wroblewski, 1984). The Peterson and Wroblewski model may be appropriate when it is assumed that the mortality decreases with increasing weight. Lorenzen (1996, 2000) provides a slightly different relationship

$$M_W = 3.00 \, \text{year}^{-1} \cdot W^{-0.288} \tag{6}$$

Table 1
A summary of the estimates of natural mortality using the methods of Peterson and Wroblewski, Lorenzen, Jensen and the results of the sheephead assessment. When a range of estimates is provided, it is with respect to a range of body weights: 5.84–0.15 kg respectively, or a range of ages at maturity.

	Model	Parameters	M estimates
Peterson and Wroblewski (1984)	$M_W = 1.92 \, \text{year}^{-1} \cdot W^{-0.25}$	$W = 2.6935 \cdot 10^{-5}(FL^{2.857})$	0.22–0.55
Lorenzen (1996, 2000)	$M_W = 3.00 \, \text{year}^{-1} \cdot W^{-0.288}$	$W = 2.6935 \cdot 10^{-5}(FL^{2.857})$	0.24–0.71
Jensen	$\frac{M}{k} = 1.5$	$k = 0.0683$	0.10
(1996)	$M = \frac{1.65}{x_m}$	$x_m = 4$–6 years	0.41–0.28
Alonzo et al. (2004)	Sensitivities of the assessment model indicate the best estimate of 0.2		

based on a study comparing the mortality of fish in natural ecosystems versus those held in aquaculture ponds. Jensen (1996) used life history invariants to derive two models to estimate M

$$M = 1.5k \tag{7}$$

$$M = \frac{1.65}{x_m} \tag{8}$$

where x_m is age at maturity and k is the growth coefficient from Eq. (1). We used $k = 0.0683$ and $x_m = 4$–6 years for our analysis, which is consistent with Alonzo et al. (2004). Weight based methods are gaining popularity in stock assessments. We also chose Jensen's methodologies to be able to compare the results of the estimates when different life history parameters are estimated for the same stock. There are many other methods to choose from, but we are illustrating a theoretical point rather than exploring the entire list of potential estimates. In Table 1, we show the estimates of M using each of the models.

Jensen's method using the growth coefficient from the von Bertalanffy equation provides the smallest estimate of natural mortality. The two weight-based methods (Peterson and Wroblewski and Lorenzen) have similar lower limits (0.22 and 0.24) but their upper limits diverge from one another—0.55 and 0.71, respectively. Lorenzen (1996, 2000) found a larger positive relationship between M and body mass than Peterson and Wroblewski (1984), which explains the discrepancy in estimates. Jensen's method based on age at maturity gives constant natural mortality ranging from 0.28 to 0.41, which falls within the range calculated by the weight-based methods. However, the two Jensen methods are not consistent with each other, which begs the question of which life history invariant best relates to natural mortality.

2.3. When can we treat mortality as a constant?

Due to the fact that a constant M is often used in stock assessments, it is prudent to determine when the use of a constant may be appropriate, if ever. To do this, we calculate average natural mortality across a population (Beverton and Holt, 1959) by assuming individuals follow von Bertalanffy growth Eq. (1). Then average natural mortality is

$$\bar{M}(t_r) = \frac{1}{T} \sum_{t=t_r}^{T-1} M_W(t) \tag{9}$$

where $\bar{M}(t_r)$ is the estimate of average mortality when fish recruit to the model at age t_r, T is the maximum age, and $M_W(t)$ is given by Eq. (5) or (6), with the understanding that mass is age dependent.

To determine whether a later recruitment to the fishery may impact the average M that is used for fish in the stock assessment, we ran the following scenario. We plotted $\bar{M}(t_r)$ as a function of the age the fish recruit to the model, which illustrates an interesting result. After age two, the estimates of $\bar{M}$ become more stable for California sheephead since the high mortality in early life is not considered.

Using Lorenzen's model for mortality, we calculated an average natural mortality rate of 0.54. Using Peterson and Wroblewski's

mortality model, we calculated 0.60 as the average natural mortality rate (Fig. 2), both of which clearly differ from a constant $M = 0.2$ across the entire lifespan.

3. Discussion

In the California sheephead assessment, scientists explored the available data well, and provided a sound assessment that could be used to inform the fishery managers (Alonzo et al., 2004, 2008). As a case study of a data poor assessment, we explored an alternative method for estimating life history parameters that became available after the assessment was final. The Bayesian method is particularly appropriate for data poor fisheries because of the minimal data required and the ability to incorporate expert opinion. We compared the results of the Bayesian analysis to the results in the sheephead assessment. For the Bayesian method, we used a Jeffreys (truly uninformative) prior; however, that can be improved upon if expert knowledge or data are available for a stock of the same species elsewhere or for a similar species. The credible interval provided by the Bayesian method is useful for both modeling and management purposes. The estimate used in the sheephead assessment is within the credible interval we provide, but the range of values the Bayesian method provides is useful to incorporate an upper and lower bound of productivity represented by the change in fecundity of the individuals in the stock. Managers can incorporate that knowledge into their decision-making when setting regulations for the uncertain state of nature for a stock.

In stock assessments, analysts often fix natural mortality M. The alternatives to a constant M are often derived from studies of a variety of taxa and environmental conditions (e.g. lake whitefish in Jensen's study to fish-sized particles in Peterson and

Fig. 2. Comparing average mortality estimates, both with different ages of recruitment to the model, and different mortality models. When fish recruit to the model at age two, we see a dramatic change in the average mortality estimate—approximately 0.2 and 0.1 compared to 0.6 and 0.54 when the fish immediately recruit to the model.

Wroblewski's study). Our study shows that the age at which the fish are assumed to recruit to the fishery can have a large impact on the estimate of a constant *M*. Assuming a weight-based mortality in fish, Fig. 2 shows that mortality is severe in the first few years, and average natural mortality will change drastically—likely an order of magnitude or more—if those first few years are excluded from the calculation. Alonzo et al. (2004) used a best estimate of 0.2, and, as shown in Fig. 2, our analysis supports their decision if they can assume California sheephead recruit to the fishery at age two.

Acknowledgements

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