Fisheries Research 149 (2014) 43–54

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Comparisons of meta-analytic methods for deriving a probability distribution for the steepness of the stock–recruitment relationship

André E. Punt[a,*], Martin Dorn[b]

[a] University of Washington, School of Aquatic and Fishery Science, 1122 NE Boat Street, Seattle, WA 98195, United States
[b] Alaska Fisheries Science Center, 7600 Sand Way Point Way, NE, Seattle, WA 98115, United States

ARTICLE INFO

Article history:
Received 6 May 2013
Received in revised form 6 September 2013
Accepted 21 September 2013

Keywords:
Bayesian methods
Groundfish
Simulation
Steepness
Stock–recruitment relationship

ABSTRACT

The steepness parameter of the stock–recruitment relationship (the proportion of unfished recruitment when spawning biomass is reduced to 20% of its unfished level) is a key parameter in stock assessment models, and hence in the provision of scientific management advice for many fisheries. Prior probability distributions for steepness have been used when conducting assessments of US west coast groundfish in the absence of data to estimate steepness reliably. These priors have been developed by applying meta-analytic methods to the results from stock assessments, but the performances of these methods have not been evaluated. Three potential methods for applying meta-analysis to construct steepness priors are available: non-linear mixed models, Bayesian hierarchical methods, and a novel method which approximates marginal likelihoods using likelihood profiles. These methods are evaluated using simulation. The profile method is found to perform best. Estimates of the parameters which define the steepness prior are uncertain owing primarily to uncertainty associated with the results of the stock assessments which provide the input for the meta-analysis methods, and because of the small number of stocks available for inclusion in the meta-analysis.

1. Introduction

Integrated (or "statistical") models have been used for stock assessment worldwide, and are the method of choice for fish stocks off Australia, New Zealand, South Africa and the west coast of North America (Maunder and Punt, 2013). Stock–recruitment relationships can play an important role when applying the integrated approach, because it is common practice to include an assumed relationship between spawning biomass (or egg production) and subsequent recruitment as a structural element in the model (Fournier and Archibald, 1982; Methot and Taylor, 2011; Maunder and Punt, 2013). The stock–recruitment relationship provides a central tendency for the annual recruitment strengths, which are commonly parameterized as deviations from the stock–recruitment relationship.

The stock–recruitment relationship used in integrated approaches is almost always of the Beverton-Holt or Ricker form (but see Taylor et al., 2013 for a stock–recruitment relationship which is applicable to low-productivity species such as sharks, and Maunder and Deriso (2013) for a stock–recruitment relationship which is applicable to highly fecund species). The Beverton-Holt and Ricker stock–recruitment relationships are usually reparameterized in terms of the recruitment at unfished equilibrium, R_0, and the "steepness" of the stock–recruitment, h (the fraction of R_0 expected when the spawning biomass is reduced to 20% of its unfished biomass, i.e. $0.2B_0$) (Mace and Doonan, 1988; Francis, 1992), when these relationships are included in integrated stock assessments.

Misspecification of the value for steepness (or its distribution) can substantially impact assessment results and projected rebuilding times for depleted populations (Brodziak and Legault, 2005). However, as has been shown through simulation (Haltuch et al., 2008; Conn et al., 2010), steepness is generally poorly estimated given the data typically available for stock assessment purposes. Accurate estimation of steepness requires data that span a wide range for spawning biomass because the precision of steepness estimates will be poor if data on spawning biomass and recruitment are only available when spawning biomass is high (or low) relative to the unfished level (Walters and Martell, 2004). Therefore, steepness is often pre-specified in integrated stock assessments, or a prior distribution (penalty functions in a maximum likelihood context) is placed on the value for the steepness parameter.

Groundfish (rockfish, flatfish, and gradoids) off the US west coast are managed by the US National Marine Fisheries Service and the Pacific Fishery Management Council (PFMC). A lack of guidance on how to treat steepness in assessments of these species has led to inconsistent approaches. For example, some assessments have pre-specified steepness without a good rationale for the selected values,

---

* Corresponding author. Tel.: +1 206 221 6319; fax: +1 206 685 7471.
E-mail addresses: aepunt@uw.edu, aepunt@u.washington.edu (A.E. Punt).

0165-7836/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fishres.2013.09.015

which differed among stocks. Other assessments attempted to estimate steepness, resulting in estimates of steepness that now, at least in retrospect, appear to be relatively extreme (e.g. a steepness less than 0.3).

Meta-analysis is a proven technique to reduce uncertainty when estimating parameters such as steepness (Myers et al., 1999; Myers and Mertz, 1998; Dorn, 2002; Hilborn, 2003). Many exploited species lack the long and comprehensive time series needed to obtain estimates of steepness with high accuracy and precision. Meta-analysis techniques pool information from stocks with similar characteristics, and analyze all of the data simultaneously to overcome this problem. The first attempt at developing a prior for steepness which was applicable for US west coast rockfish stocks was conducted by Dorn (2002), who applied a Bayesian meta-analysis method to stock and recruitment data for 11 rockfish stocks. This meta-analysis was updated by Forrest et al. (2010).

All stock assessments for US west coast groundfishes are currently based on statistical catch-at-age analysis (see Maunder and Deriso, 2013 for a review of these methods), which can include priors for steepness. Starting in 2007, a meta-analysis approach was developed to improve consistency in the treatment of steepness in stock assessments for US west coast groundfish. Assessment authors were asked to provide a likelihood profile for steepness based on the final assessment model in the most recent assessment. A meta-analysis was conducted based on an approach which approximated the marginal likelihood over all parameters except for steepness using likelihood profiles (see below) to provide priors for the next assessment. The meta-analysis was intended to be an iterative process in which information gained from previous assessments would be used to inform subsequent assessments. Although this approach could in principle be used to estimate the fishing mortality rate corresponding to MSY, F_{MSY}, for use in harvest control rules, proxies for F_{MSY} based on spawning biomass-per-recruit have been used instead for US west coast groundfish, due to concerns about the reliability of F_{MSY} estimates from single species stock assessments.

All of the methods applied to construct prior distributions for US west coast fish stocks make simplifying assumptions or use approximations which are likely to be violated. Moreover, even if those assumptions are correct, it is not clear how accurate and precise the resulting prior distributions will be. This study therefore uses simulation to compare the non-linear mixed model approach of Myers et al. (1999, 2002), the approach of Dorn (2002), and the approach used most recently for west coast groundfish. Although the analyses could have been based on any form for the stock–recruitment relationship, they are based on Beverton-Holt stock–recruitment relationship because assessments of US west coast groundfish are currently based on this stock–recruitment relationship.

2. Methods

2.1. Meta-analysis methods

2.1.1. Nonlinear mixed effects (NLME) method

The nonlinear mixed effects method (Pinheiro and Bates, 2000) uses biomass and recruitment data from a stock assessment method (Myers et al., 1999; see below). Given the estimates of spawning biomass and recruitment from the assessment method, the Beverton-Holt model is defined as in Eq. (1) for each stock i and observation t in the time series.

$$R_{it}=\frac{0.8R_{0i}h_iB_{it}}{0.2\phi_{0i}R_{0i}(1-h_i)+(h_i-0.2)B_{it}}e^{\varepsilon_{it}-\sigma_i^2/2};\ \varepsilon_{it}\sim N(0;\sigma_i^2) \qquad (1)$$

where h_i is the value of steepness for stock i, R_{0i} is the value of R_0 for stock i, φ_{0i}, is the spawner biomass-per-recruit in the absence of exploitation for stock i, B_{it} is the spawning biomass for year t and stock i, and R_{it} is the recruitment (at age 0) for year t and stock i.

This method assumes that the stock-specific values for φ_{0i} are known, and estimates the stock-specific unfished recruitment, R_{0i}, for each stock as a fixed effect. Given values for R_{it} and B_{it} from a stock assessment, the steepness parameter after logit transformation is assumed to be a random effect and normally distributed, i.e.:

$$\beta=\log\left(\frac{h-0.2}{1-h}\right);\quad \beta\sim N(\mu,\tau^2) \qquad (2)$$

where μ and τ are respectively the mean and standard deviation of the distribution of logit-transformed steepness.

The process errors (the ε_{it} in Eq. (1)) are assumed to be temporally independent, and independent among species. The nonlinear mixed effects model is fit using maximum likelihood, and a marginal distribution is calculated for the steepness parameter. Both this method and the following method use estimates of recruitment and spawning biomass from a stock assessment method, which usually includes a structural assumption that recruitment is distributed about a stock–recruitment relationship, or mean recruitment.

2.1.2. Bayesian hierarchical method

The second method that has been used to construct informative priors for steepness is hierarchical Bayesian analysis (Dorn, 2002). The assumptions for this method are the same as for the nonlinear mixed model method, except that hyperpriors are imposed on the mean and variance of logit-transformed steepness. The hyper-prior for the mean is uniform, i.e. $\mu\sim U(-1000, 1000)$, while that for the variance is scaled inverse chi-squared, i.e. $\tau^2\sim \mathrm{Inv}\chi^2(10, 0.5)$, proportional to $1/\tau^2$ or the prior probability associated with τ is assumed to be proportional to $1/\tau$.

A non-hierarchical prior is placed on unfished recruitment R_0 to stabilize the estimation. The prior mean for R_0 for each species is set to the average recruitment when spawning biomass was greater than the median observed spawning biomass, $\tilde{R}_{0i}$, making this estimator effectively an empirical Bayes approach. The variance is set by assuming a coefficient of variation, CV, of 2.0 i.e.:

$$R_{0i}\sim N(\tilde{R}_{0i}, (\tilde{R}_{0i}CV)^2) \qquad (3)$$

The marginal posterior distribution for steepness for each stock, and those for the values for the parameters of the distribution for steepness are based on the posterior distribution for the parameters of Eq. (2), which is computed using the MCMC algorithm included in the AD Model Builder package (Fournier et al., 2012). MCMC runs of length 1,100,000 with a burn-in of 100,000 cycles and a thinning interval of 500 are used for each simulation so that the final inferences for each simulation are based on a sample of 200 parameter vectors.

2.1.3. Likelihood profile method

The posterior distribution for the Bayesian method can be generalized as follows:

$$p(\vec{h},\Theta,\mu,\tau^2|D)\propto p(D|\vec{h},\Theta)p(\Theta)p(\vec{h}|\mu,\tau^2)p(\mu,\tau^2) \qquad (4)$$

where $\vec{h}$ is the vector of steepness parameters, Θ are the nuisance parameters and D is the data. The right hand side of Eq. (4) consists of: the likelihood for the data, the prior distribution for any nuisance parameters, the prior distribution for the steepness parameters given the hyperparameters for the steepness distribution and the hyperprior distribution for the steepness hyperparameters.

The 'profile method' replaces the data likelihood (or equivalently, the data distribution), with the profile likelihood $L^p(\vec{h})$. The profile likelihood method accounts for all nuisance parameters by obtaining maximum likelihood estimates for 21 equally-spaced