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FISH-4623; No. of Pages 6
ARTICLE IN PRESS
Fisheries Research xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Fisheries Research
journal homepage: www.elsevier.com/locate/fishres

Searching for *M*: Is there more information about natural mortality in stock assessments than we realize?

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A R T I C L E I N F O

Article history:
Received 1 July 2016
Received in revised form 6 December 2016
Accepted 9 December 2016
Available online xxx

Keywords:
Fisheries stock assessment
Natural mortality
Production function

A B S T R A C T

Natural mortality (*M*) is both a highly consequential and difficult process to estimate in stock assessments. Because of its correlation with other influential parameters, and the inadequacy of data to understand how it varies with time and ontogeny, estimates of *M* from integrated assessment models are often considered implausible. This has lead to the assumption that estimates of *M* are highly uncertain within integrated assessments and it is commonly fixed at values consistent with understanding about the stock's life history or derived from external analyses. Researchers recently used simulation analysis to challenge this assumption and provided evidence that *M* might be estimable under certain conditions. Our research builds upon those results by using the recently proposed age-structured production model diagnostic to help identify the conditions under which *M* might be estimable. This diagnostic aims to determine if changes in the scale and trend of stock abundance can be explained by catch alone, which is a key indicator of the presence of a production function. We apply the production model diagnostic to the same suit of assessments used in the aforementioned simulations to determine if a relationship between estimability of *M* and the presence of a production function can be identified. Statistical and subjective approaches to interpreting the production model diagnostic were developed with the aim of providing guidance on when *M* might be estimable. Statistical approaches to identifying the presence/absence of a production function did not outperform the subjective measure, but meaningful guidance about estimating *M* is still apparent. Our results provide more weight to the notion of *M* being estimable under certain conditions, and we provide guidance on identifying those conditions.

1. Introduction

Natural mortality (*M*) is one of the most influential processes in stock assessment, and also one of the most difficult to estimate (Brodziak et al., 2011). The productivity of a stock is defined by growth, recruitment and *M*, and thus helps determine its resiliency and the fishery yields that can be obtained. Accurately estimating *M* is difficult because the data to measure it directly (experimentally designed mark-recapture studies) are seldom available (Chapman, 1961; Seber, 1982) and model estimates of *M* are highly correlated with other model processes (e.g. recruitment, selectivity etc.), which are also highly uncertain (Magnusson and Hilborn, 2007; Maunder and Piner, 2015). Complicating matters, *M* varies with age, sex, environmental, and density-dependent factors (Fournier and Schweigert, 1993; Hampton, 2000; Vetter, 1988), and is driven by a wide range of processes, including predation, disease and senescence.

Because direct estimation of *M* is not common; for stock assessment purposes, it is frequently borrowed from other stocks (or species), derived from life history theory (Charnov, 1993; Roff, 1984), empirical relationships (Gunderson, 1997; Hoenig, 1983; Pauly, 1980), or based on meta-analyses of those methods (Hamel, 2015). The validity of these approaches has been questioned and the results of such studies almost always ignore the temporal or ontogenetic variability in *M* (Lorenzen, 1996).

More recently, stock assessments have been internally estimating *M* using integrative analysis of a wide variety of data (Cadigan, 2015; Fournier et al., 1998; Hampton and Fournier, 2001). Lee et al. (2011) used simulation methods and a suite of peer-reviewed stock assessments from a range of life history and exploitation patterns, which also included fishery independent survey data, to evaluate the reliability of estimates of *M* from integrated assessment models

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http://dx.doi.org/10.1016/j.fishres.2016.12.009

Table 1
Comparisons of the reliability of *M* estimates and production function strength from US west coast groundfish stock assessments used in this study.

Species	Abbr.	Ability to estimate *M* (Lee et al., 2011)	Correlation ΔSSB (final 20 yrs)	Average Normalized Absolute Difference (final 20 yrs)	Proportion of CI overlap (final 20 yrs)	Production function evident (this study)
Arrowtooth Flounder[a]	ATF	Weak/Weak (female/male)	0.52	0.15	1.0	No
Blue Rockfish[a]	BLR	Moderate/Strong (female/male)	0.13	0.25	0.35	No
Canary Rockfish[b]	CNR	Weak/Moderate (old/young)	0.94	0.17	0.35	Yes
Chillipepper Rockfish	CPR	Strong	0.72	0.16	0.25	Yes
Darkblotched Rockfish	DBR	Strong	0.95	0.21	0	Yes
English Sole	ENS	Weak	0.75	0.24	0	No
Hake[b]	HAK	Weak/Weak (old/young)	0.06	3.01	0	No
Northern Black Rockfish[b]	NBR	Weak/Moderate (old/young)	NaN	1565	0	No
Sablefish	SAB	Weak	0.71	0.08	1.0	Yes
Southern Black Rockfish[b]	SBR	Weak/Weak (old/young)	0.36	0.19	0.70	No
Yelloweye Rockfish	YER	Moderate	0.95	0.09	0.35	Yes

Ability to estimate *M*.
Weak: *M* outside of 5% or 95% quantiles.
Moderate: *M* inside between 5% and 40% or 60% and 95% quantiles.
Strong: *M* inside between 40% and 60% quantiles.
[a] *M* split into separate sexes in Lee et al. (2011).
[b] *M* split into separate age categories in Lee et al. (2011).

fit to abundance indices and composition data. That study concluded that *M* was estimable with a correctly specified model, age composition data, and observations of the stock when its size was low. However, reliability of the estimates of *M* in actual assessments was questioned because correctly specified models are unlikely (Francis, 2012).

This paper further extends the results of Lee et al. (2011) to better understand under what conditions *M* estimates are reliable. Using the same suite of assessments, we apply new model diagnostics to evaluate if the presence of an elucidated production relationship is related to the reliability of *M* estimates. The age-structured production model diagnostic (ASPM) as proposed by Maunder and Piner (2015) is used to gauge the relative strength of a production function in the datasets. The reasoning underlying the use of an ASPM diagnostic is that if population scale and trend are reliably estimated by both the assessment model (AM) and the ASPM, assuming both use the same stock recruitment (SR) functions, then fishing mortality (*F*) can be considered similar and estimable in both models and catch can thus be assumed to be the main influence on stock abundance. Knowing that composition data also informs total mortality (*Z*, as well as other parameters), it is reasoned that information about *M* is derived simply as the difference between *Z* and *F*. As a result, we hypothesize that evidence of a strong production function in a stock is consistent with *M* being reliably estimated in Lee et al. (2011). These results are used to provide guidance to assessment scientists regarding when the estimation of *M* within the stock assessment model should be considered.

2. Materials and methods

Stock Synthesis II (Methot and Wetzel, 2013) (SS hereafter) model files (data and model configurations) were obtained from 11 stocks of US West Coast groundfish (Arrowtooth flounder (ATF), Blue rockfish (BLR), Canary rockfish (CNR), Chillipepper rockfish (CPR), Darkblotched rockfish (DBR), English sole (ENS), Hake (HAK), Northern black rockfish (NBR), Southern black rockfish (SBR), Sablefish (SAB), Yelloweye rockfish (YER)). These are the same assessments used in Lee et al. (2011), excluding Shortbelly Rockfish because SS v.1.19 used in that assessment did not allow recruitment deviations to be turned off to generate the ASPM diagnostics. Each assessment was reviewed by panels of independent experts before being accepted for use by the Pacific Fisheries Management Council (http://www.pcouncil.org/groundfish/stock-assessments/by-species/). Model configurations and data types for the original assessments were summarized by Lee et al. (2011). They used the same configuration for *M* as original assessments to generate simulated datasets, which included some sex- or age-specific estimates.

2.1. Simulation results of Lee et al. (2011)

Lee et al. (2011) used parametric bootstrapping in SS to simulate 500 new data sets based on the original model configurations for each stock. The bootstrapped datasets were then fit with the model to re-estimate *M*, creating a distribution to which maximum likelihood estimates (MLE) of *M* from the original assessments could be compared. Relative bias, or the difference between the simulated and true values of *M* and the resulting CV were used as indicators of the estimability of the parameter. We use the same simulated distributions to characterize estimates of *M* as strong, moderate, or weak based on where the true value fell within the distribution of simulated data. Strong was defined as the true value falling inside the 40–60% quantile, moderate within the 5–40% or 60–95% quantiles, and weak outside of the 5 or 95% quantile. The characterizations of estimability and presence of a production function from the ASPM diagnostic are compared to look for correspondence, which can guide assessment scientists on the potential for reliably estimating *M* in integrated assessment models.

2.2. ASPM

2.2.1. Detection of production function

The ASPM diagnostic (Maunder and Piner, 2015) was used to determine if trends in indices of abundance (and therefore population abundance) are caused primarily by fishing (elucidation of the production function) or fluctuations in recruitment (in the AM recruitment variability was generally modelled as deviation from the expectation of the spawner-recruit relationship). If a dynamic model using catch and fitting only to indices without estimation of recruitment variability can estimate the abundance trends in