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Exploring model structure uncertainty using a general stock assessment framework: The case of Pacific cod in the Eastern Bering Sea

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ABSTRACT

An assessment framework is developed that allows analysts to conduct stock assessments for fish and invertebrate stocks based on age-, size- and age-size-structured population dynamics models. The size-structured model is nested within the age-size-structured model. The framework can use catch, discard, index of abundance, size- and age-composition, conditional age-at-length, mean length-at-age, and tagging data to estimate model parameters. It is used to explore the sensitivity of key model outputs for Pacific cod in the Eastern Bering Sea by applying model configurations that use the same data, same likelihood functions, and same data weighting schemes. Base model configurations using the three model types all fit the available data adequately, but the age-structured model fits the data better than the size-structured model. Variation in estimates of spawning biomass and the overfishing level was higher among model-types than within model-types. This result highlights the need for assessment analysts to focus more on applying and presenting results for multiple models.

1. Introduction

Management advice for many of the world's fish and invertebrate stocks is based on quantitative stock assessments. Stock assessments based on fitting population dynamics models to monitoring data are commonly used to estimate biomass and recruitment trajectories, biomass relative to reference points, and to form the basis for applying harvest control rules. There has been an increasing focus on evaluating the uncertainty associated with outputs from stock assessments in recent years, particularly in jurisdictions such as the USA where the maximum catch limit has to be less than or equal to the catch corresponding to an F_{MSY} catch control rule, and reduced based on the extent of scientific uncertainty (Anon, 2007).

Scientific uncertainty in stock assessments arises from three main sources: process uncertainty, measurement uncertainty, and model uncertainty (Francis and Shotton, 1997). Methods for accounting for measurement (or observation) uncertainty are well developed, with assessments quantifying this source of uncertainty using frequentist (e.g., asymptotic approximations, likelihood profiles, and bootstrapping) and Bayesian methods. Limited simulation studies (e.g., Magnusson et al., 2013) suggest that Bayesian methods provide the best coverage probabilities, at least in the absence of model misspecification. Process uncertainty has traditionally been accounted for by estimating deviations in recruitment about an assumed stock-recruitment function or by allowing fishery selectivity to change over time, using an errors-in-variables formulation. State-space models have been developed for surplus production models (e.g., Meyer and Miller, 1999; Ono et al., 2012) and age-structured models (e.g., Miller and Meyer, 2000; Nielsen and Berg, 2014), which handle process errors more formally by treating them as random effects, and can be shown in some cases to lead to improved estimation performance (e.g., Punt, 2003; Ono et al., 2012). However, most approaches to stock assessment (see Dichmont et al. (2016) for a summary of the stock assessment packages used in the USA) still account for process error using the errors-in-variables approach, owing primarily to the computational demands of state-space models.

In contrast to process and measurement uncertainty, methods for accounting for model uncertainty are less well developed. These methods range from approaches for detecting when an assessment model is mis-specified (e.g., Carvalho et al., in press; Hurtado Ferro et al., 2015), and applying multiple models and attempting to synthesize their results (e.g., blue marlin in Atlantic Ocean, ICCAT 2012). Most analyses that explore model mis-specification involve changing the values for pre-specified parameters (such as

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the value assumed for natural mortality), changing assumptions regarding the form of the relationship between selectivity and age or size, changing how individual data sets are weighted, and changing which data sets are used for parameter estimation. It is very uncommon to change the fundamental structure of the population dynamics model on which an assessment is based. It is hard to synthesize results from assessments based on fundamentally different model structures (e.g., production model vs age-structured model), except when they use the same data and ideally the same likelihood function. The differences in results among different models can often be much larger than the differences due to the factors commonly explored in sensitivity analyses.

In general, model-based assessments of fish stocks are conducted using production models or age-structured models, while such assessments of invertebrate stocks are increasingly conducted using size-structured models (Maunder and Punt, 2013). This observation holds most strongly when the assessment is based on the 'integrated' paradigm (Maunder and Punt, 2013). This paper describes a model that unifies age- and size-structured population dynamics models. Assessments can consequently be conducted using a method based on an age-, size- or age-size-population dynamics model, fitted to the types of data sets typically used when conducting assessments of fish and invertebrate populations (i.e., catch, index of abundance, discard, age-composition, size-composition, conditional age-at-length, and tagging data). This assessment approach fills a gap identified by Dichmont et al. (2016) that there is a lack of models that can handle age- and size-structured dynamics simultaneously.

The method is illustrated by applying it to Pacific cod (*Gadus macrocephalus*) in the Eastern Bering Sea. This species is currently assessed (Thompson, 2015) using Stock Synthesis (Methot and Wetzel, 2013) in an assessment approach based on an age-structured model that can be fitted simultaneously to size-composition and conditional age-at-length data.

2. Methods

2.1. Overview

The population dynamics model, on which the assessment method is based, is outlined in Section 2.2, while Section 2.3 specifies the likelihood functions for the data on which the example application is based (the likelihood functions for the data types not considered in the example application, but that can be included in assessments based on the age-size-structured model are given in the Supplementary Appendix A). Section 2.4 outlines some key aspects of the biology and fishery for Pacific cod, the data available for assessment purposes, and the scenarios considered in the example analyses.

The population dynamics in the age-size-structured assessment model are represented using a model that explicitly tracks both age and size, with the dynamics of size governed by a size-transition matrix, in which expected growth follows a von Bertalanffy growth curve (i.e., the mean growth increment is a linear function of pre-growth size), while the variability in growth increment about the expected growth increment is assumed to be governed by a normal, log-normal, or gamma distribution (normal for the purposes of the example application). The size-at-age distributions within the age-structured model are assumed to be normal about means based on an (age-specific) von Bertalanffy growth curve. Unlike the age-size-structured population dynamics model, the age-structured population dynamics model does not allow fishing to change the distribution of size-at-age, unless allowance is made for platoons.

The age-size-, size- and age-structured models allow for 'platoons' or 'growth morphs' (Goodyear, 1984; Punt et al., 2001; Taylor and Methot, 2013). Platoons are subsets of a cohort that have their own growth trajectory. Including platoons enables the impact of fishing on population size-structure, as well as mean length-at-age, to be included in a population dynamics model. Taylor and Methot (2013) illustrate how to account for platoons within the context of an age-structured model. The approach of Taylor and Methot (2013) is generalized here for use in size-structured models.

The model matches the catches that are supplied exactly, using the 'hybrid method' for calculating annual fishing mortality (Methot and Wetzel, 2013) to avoid treating each fishing mortality rate as an estimable parameter. Thus, the assessment does not include a likelihood component related to the ability to mimic the observed catches. The number of new recruits (age-0 animals) is determined by a Beverton-Holt stock-recruitment relationship. This relationship was selected as it is commonly included in fisheries assessments based on the integrated paradigm (although the Ricker and hockey-stick forms are used in some assessments). Recruitment is bias-corrected using the method developed by Methot and Taylor (2011), such that the value calculated from the stock-recruitment relationship equal the expected recruitment.

In common with most of the approaches currently used to conduct fisheries stock assessments, the model allows for multiple fishing fleets and can be fit to a variety of data sources, in particular, indices of abundance, estimates of discards, information on the size-structure of the catches or the surveys, conditional age-at-size data for the catches and surveys, and tagging data. There is no need for all types of data to be available for all applications. However, there is a need for catch data (in numbers or mass), and estimation performance will be poor without an index of abundance.

2.2. The population dynamics model

2.2.1. Basic population dynamics

The dynamics of the modeled population account for mortality due to fishing and natural causes as well as growth, recruitment, and ageing at the end of the year. The model has an annual time-step that leads to the following equation for the population dynamics for an age-size cohort (Eq. (1a)) and an age-cohort (Eq. (1b)).[1]

[1] The model allows for parameters and variables to depend on sex, but this is ignored in this presentation and in the example application.