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# The effects of applying mis-specified age- and size-structured models

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ABSTRACT

Stock assessments estimate biomass and fishing mortality in absolute terms and relative to reference points. Most of the world's stock assessments are based on age- or size-structured population dynamics models, with few stock assessments directly accounting for both age and size dynamics. However, the life history parameters of fish and invertebrate populations are often functions of both age and size. An operating model that is based on an age- and size-structured population dynamics model is used to evaluate the performance of assessment methods based on age-, size- and age- and size-structured population dynamics models. Variants of the operating model and the assessment methods, which include 'platoons' to better represent individual variation in growth, are considered to explore the impact of this source of uncertainty on the performance of stock assessment methods. Simulation experiments based conceptually on the assessment for Pacific cod in the Eastern Bering Sea are used to explore the consequences of applying assessment methods that are mis-specified in terms of the population dynamics model and the way variation in growth is modelled. The age-structured assessment methods perform poorest, most likely because they mis-represent how mortality, due to fishing, is removed from the population in the operating model, but also because of mis-specification of the growth curve. The assessment methods with platoons can outperform those that ignore platoon structure when this is present, but their performance when there are no platoons is such that, overall, simpler assessment methods based on size-structured, or age- and size-structured population dynamics models, appear best. Conducting assessments using multiple model types and selecting the best model based on the lowest AIC was, however, the best approach overall.

## 1. Introduction

Management of many of the world's marine fish and invertebrate stocks is supported by scientific advice based on stock assessments (Mace et al., 2001). Stock assessments are used primarily to provide management advice and estimate quantities that are of management interest (e.g., Dichmont et al., 2016). Many fisheries in countries such as the United States (USA), Canada, Australia, and New Zealand, as well as fisheries in European waters and international fisheries that are managed by Regional Fishery Management Organizations, base management advice on estimates of abundance and fishing mortality derived from stock assessments. These estimates are typically expressed both in absolute terms and relative to reference points. They often are used as the basis for applying harvest control rules or evaluating proposed regulatory measures (such as total allowable catches or limits on fishing effort) that will frame management actions.

Stock assessments that estimate fishing mortality and biomass can be based on a variety of population dynamics models. The assessment methods most commonly used (see Dichmont et al. (2016) for a summary of stock assessment packages used in the USA) are based on surplus production models, age-structured population dynamics models, and size-structured population dynamics models. Most of the model-based assessments of fish stocks in USA are based on age-structured population dynamics models. These models can be used to predict the population size-composition under the assumption that fishing does not change the distribution of size-at-age (Methot and Wetzel, 2013). Consequently, most age-structured models ignore the impact of size-selective fishing mortality. In contrast, assessments of prawns, crabs, and rock lobsters, which are difficult or impossible to age, are often based on size-structured population dynamics models (Punt et al., 2013), which ignore age-based processes. In reality, populations are governed by both age- and size-based processes, and it would be expected that treating age-based processes as size-based or the inverse could lead to biased estimates of quantities that are of management interest, such as fishing mortality and spawning biomass.

In principle, some of the above concerns can be overcome by using age- and size-structured population dynamics models, i.e.,

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models that track the numbers of animals by age and size. However, there are very few examples of age- and size-structured population dynamics models. De Leo and Gatto (1995) outline an age- and size-structured model and fit it to the data for European eel, *Anguilla anguilla*. However, that application considered only a single year of data. Deriso and Parma (1988) outline a full age- and size-structured population dynamics model and describe the likelihood function which could be used to estimate its parameters for Pacific halibut, *Hippoglossus stenolepis*, and Quinn et al. (1998) extend this approach by discretising the size distributions. Gilbert et al. (2006) developed an age- and size-structured model for New Zealand snapper, *Pagrus auratus*, which allowed growth to be a function of both age and size and to vary over time. McGarvey et al. (2007) modified a standard age-structured model to allow for a legal minimum size, and Tanimoto et al. (2012) fitted a monthly age- and size-structured model to data for barramundi, *Lates Calcarifer*, in the Fitzroy River, Queensland.

This paper first introduces a generalized operating model based on an age- and size-structured population dynamics model that includes "platoons" (Goodyear, 1984; Punt et al., 2001; Taylor and Methot, 2013). Platoons are subsets of a cohort that each have their own growth trajectory. Allowing for 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 operating model is used to evaluate the ability of simpler model formulations based on the integrated analysis paradigm (Maunder and Punt, 2013) to estimate spawning stock biomass. Specifically, the performance of three alternative assessment methods that use basically the same data types (an age-structured assessment method; a size-structured assessment method; an age- and size-structured assessment method) are contrasted.

Simulations are used to evaluate estimation performance. Specifically, the age- and size-structured operating model (with or without platoons) is used to represent the true dynamics of the population. A set of assessment methods is then used to estimate the values of the population dynamics parameters, and hence model outputs of management interest under various assumptions related to how much the operating model differs structurally from the model on which the assessment method is based.

The simulation evaluation is based conceptually on Pacific cod, *Gadus macrocephalus*, in the Bering Sea. However, the simulation scenarios are designed to explore a wide range of scenarios related to the current status of the stock, and hence the amount of contrast in the available data.

## 2. Methods

### 2.1. Operating model

#### 2.1.1. General structure

The operating model is based on a single-sex age- and size-structured population dynamics model that includes platoons. It has 21 age-classes (ages 0–20, where age-class 20 is treated as a plus-group) and 24 size-classes of 5 cm starting at 0 cm. The basic population dynamics are:

$$N_{p,y,a,i}=\begin{cases} R_{p,y,i} & \text{if } a=0\\ \sum_j X_{p,j,i}N_{p,y-1,a-1,j}e^{-Z_{p,y-1,a-1,j}} & \text{if } 1\le a<a_{\max}\\ \sum_j X_{p,j,i}\Big(N_{p,y-1,a_{\max}-1,j}\,e^{-Z_{p,y-1,a_{\max}-1,j}} \\ \qquad +N_{p,y-1,a_{\max},j}e^{-Z_{p,y-1,a_{\max},j}}\Big) & \text{if } a=a_{\max}\end{cases} \tag{1}$$

where $N_{p,y,a,i}$ is the number of animals of age $a$ in platoon $p$ at the start of year $y$ that are in size-class $i$, $a_{\max}$ is the maximum age-class,$X_{p,j,i}$ is the probability of an animal in platoon $p$ growing from size-class $j$ to size-class $i$ during a year, $Z_{p,y,a,i}$ is the total mortality on animals of age $a$ in platoon $p$ that are in size-class $i$ during year $y$, $R_{p,y,i}$ is the number of age-0 animals in platoon $p$ and size-class $i$ during year $y$:

$$R_{p,y,i}=R_0\,e^{\varepsilon_y-\sigma_R^2/2}\,\omega_p\,P(L_i|a=0) \tag{2}$$

$R_0$ is the number of age-0 animals at unfished equilibrium, $\varepsilon_y$ is the recruitment deviation for year $y$, $\sigma_R$ is the extent of variation in recruitment about the stock-recruitment relationship, $\omega_p$ is the proportion of the total number of age-0 animals that settle to platoon $p$, and $P(L_i|a=0)$ is the proportion of age-0 animals that recruit to size-class $i$. The bias-correction factor is needed to ensure that the expected recruitment is equal to $R_0$ on average. Recruitment has been taken to be independent of spawning stock size because this assumption was made in the most recent assessment of Pacific cod (Thompson, 2015) and was justified as it is consistent with the harvest policy for fish stocks in the North Pacific.

The total mortality during each year accounts for (time-invariant) natural mortality ($M$) and fishing mortality. The operating model allows for both age-specific and size-specific selectivity patterns:

$$Z_{p,y,a,i}=M+F_y\,S_{y,i}\,\tilde{S}_{p,y,a} \tag{3}$$

where $S_{y,i}$ is the selectivity on animals in size-class $i$ during $y$, $\tilde{S}_{p,y,a}$ is the selectivity on animals of platoon $p$ and age $a$ during year $y$, and $F_y$ is the fully-selected ($S_{y,i}\,\tilde{S}_{y,a}\to 1$) fishing mortality during year $y$. For an age-structured model, age-specific selectivity is computed from size-based selectivity using the equation:

$$\tilde{S}_{p,y,a}=\sum_i \phi_{p,a,i}S_{y,i} \tag{4}$$

where $\phi_{p,a,i}$ is the proportion of animals of age $a$ in platoon $p$ that are in size-class $i$ (Methot and Wetzel, 2013). The spawning stock biomass during year $y$, $S_y$, is given by[1]:

$$S_y=\sum_i m_i\,w_i\sum_p\sum_a N_{p,y,a,i} \tag{5a}$$

$$S_y=\sum_p\sum_a\left(\sum_i \phi_{p,a,i}\,m_{s,i}\,w_{s,i}\right)N_{p,y,a} \tag{5b}$$

where $m_i$ is the proportion of animals in size-class $i$ that are mature, and $w_i$ is the mean weight of an animal in size-class $i$ at the start of the year.

The landed (retained) catches for animals of age $a$ during year $y$ are given by:

$$C_{y,a,i}=\sum_p \frac{S_{y,i}\,\tilde{S}_{p,s,a}\,F_y}{Z_{p,y,a,i}}N_{p,y,a,i}(1-e^{-Z_{p,s,a,i}}) \tag{6}$$

The catch in weight is computed accounting for weight-at-length in the middle of the year:

$$\tilde{C}_y=\sum_a\sum_i C_{y,a,i}\,w_i \tag{7}$$

The initial conditions correspond to unfished equilibrium. The population is then projected forward for 30 years with stochastic

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[1] Eq. (5a) pertains to size- and age-and size-structured models while Eq. (5b) pertains to age-structured models.