Abstract—Stock assessment models use data influenced by distribution patterns that are due to the nonrandom movement of fish, which can create bias in the assessment. For many stocks, length data are used to characterize the age structure of the population, and therefore there is a need for unbiased estimates of growth. Because of the influence of size-selective fishing gear, growth and length-based selectivity are often estimated as part of an assessment model to account for the size selection of gear. However, estimated selectivity can include not only length-based gear selection, but the biological aspects of the spatial availability of the target species. If availability to the fishing gear is a function of age, an approximation of an age-based process as a length-based one can bias growth estimates. The magnitude of the bias would be greater for fish with highly variable growth and for those with strong age-based distribution patterns.

Bias in estimates of growth when selectivity in models includes effects of gear and availability of fish

Kevin R. Piner (contact author)[1]
Hui-Hua Lee[1]
Lennon R. Thomas[2]

Email address for contact author: kevin.piner@noaa.gov

[1] Southwest Fisheries Science Center
   National Marine Fisheries Service, NOAA
   8901 La Jolla Shores Drive
   La Jolla, California 92037

[2] Bren School of Environmental Science and Management
   University of California Santa Barbara
   2400 Bren Hall
   Santa Barbara, California 93106

Spatial patterns in the distribution of sizes and ages of fish (patterns due to the behavior of fish) are common. Because movement rates may be difficult to estimate as part of a population dynamics model (Lee et al., 2017a), the spatial patterns in size or age are often modeled implicitly as selectivity (Hurtado-Ferro et al., 2014; Waterhouse et al., 2014; Lee et al. 2017a). Implicit treatment of spatial patterns uses the model estimate of the selectivity process to represent both spatial availability, as well as the selectivity of the gear (Maunder et al., 2014). Gear selectivity represents the probability that a fish is captured when it encounters the gear, whereas availability is the probability that a fish will encounter the gear. It is common practice to estimate fleet selectivity as a function of fish length (Crone and Valero, 2014) because it is generally assumed that gear selectivity is related to fish size (Stewart, 1975; Yanase et al., 2007), whereas availability due to movement could be a function of size (Nøttestad et al., 1999) or age (Francis, 2016; McDaniel et al., 2016).

Length-based, age-structured modeling is used for many migratory fish stocks because routine age determination of fishery samples is not always provided. In these assessment models the length composition data are used to approximate the age structure of the catch. To use the observed lengths reliably, an unbiased estimate of the length-at-age relationship is needed. Unless properly accounted for, the processes of availability of fish and gear selectivity can cause bias in comparisons with the actual total population, which can bias estimates of growth (Piner et al., 2016; Lee et al., 2017b) and ultimately the management of catch quotas (Maunder and Piner, 2017).

Age–length data used to estimate growth must satisfy at least one of two assumptions depending on how they are used (Francis, 2016). With the random-at-age method for estimating growth, lengths are assumed to be random with respect to age. Estimates from this method can be biased without a proper accounting for length-based processes (e.g. length-based gear selectivity). Length-at-age

Table 1

Parameter values used in creating the hypothetical population of a small, migratory pelagic fish to show bias in the estimates of fish growth. Growth was estimated by using a deterministic population dynamic model in which selectivity includes effects of gear and fish availability. Sensitivity analyses in this article provided changes in the base parameter values. CV=coefficient of variation.

Parameter	Base values	Sensitivity analyses
Maximum age	10	
Total mortality (Z)	0.5/year all ages	
Asymptotic length (L_{inf})	20 cm	
Growth coefficient (K)	0.4	
Hypothetical age when average length is zero (a_0)	−1	
CV of length at age	0.15 all ages	0.1 all ages
Availability in sampling area (d_a)	5% at ages 0–3, 100% at ages 4 and older	100% at ages 0–3, 5% at ages 4 and older
Gear selectivity (s_l)	Asymptotic pattern (Fig. 1B)	Domed pattern (Fig. 3B)

can also be estimated by using random-at-length methods (Hoyle and Maunder[1]; Piner et al., 2016). Random-at-length estimation methods provide a comparison of observed and expected age distribution for a specific length with the assumption that ages are random with respect to length. Age-based processes, such as age-based movements (McDaniel et al., 2016) can lead to biased growth estimates with the use of random-at-length methods (Lee et al., 2017b).

In many studies where fish growth is estimated, the biological (e.g., movement) and observation processes (e.g., selectivity) are ignored, which, if ignored, can lead to violations of the assumptions about randomness (a review by Maunder and Piner, 2017). Estimating growth parameters simultaneously with these processes as part of an integrated model (Fournier et al., 1990; Methot and Wetzel, 2013) can account for these sources of potential bias. Proper use of the integrated model is based on the knowledge of biological and fisheries processes involved in the collection of data.

The evolution of integrated assessment modeling has generally lead to the inclusion of a greater number of factors in an attempt to reduce estimation biases. Simultaneously estimating growth and the length-based effects of gear selectivity have been thought to remove selectivity bias (Parma and Deriso, 1990; Taylor et al., 2005; Schueller et al., 2014; Piner et al., 2016). However in this study we show that a bias can be induced when estimates of mean length-at-age (random at age assumption) are derived by using a selectivity that is a combination of length-based gear and age-based availability. This is an approximation bias that is the result of approximating an age-based effect by using a

length-based process. The magnitude and direction of the bias is dependent on the spatial areas sampled and variability in the length-at-age relationship.

Materials and methods

We use a deterministic population dynamics model to show the effects on growth estimates of combining both age-based availability and length-based gear selectivity, into a single length-based process. Conceptually the stock is distributed in two areas: one area is primarily a juvenile area and the other is primarily an adult area. The deterministic model approximates the spatial dynamics by using age-based availability as implicit areas in a single well-mixed area. Availability is defined as the proportion of each age class found in an area. In our study, the life history and fishery characteristics of a small migratory pelagic fish are used to create the hypothetical population (Table 1). To further simplify the example, we assume that all fishing takes place at the same time each year and therefore length-at-age can be calculated without the additional complication of within year growth.

The mean length-at-age from fishery data collected in the adult area is calculated in three ways: 1) true (used to generate population numbers at age/length), 2) observed (does not account for length-based selectivity or age-based availability), and 3) estimated (which accounts for the observed length-based selection, which is a combination of length-based gear selectivity and an approximation of age-based availability). Sensitivity of the estimates of mean length-at-age to changes in life history and fishery characteristics are illustrated as single-instance changes to the example given in Table 1. The equations governing the simulated population are given below.

The value for population proportions-at-age is given by

[1] Hoyle, S. D., and M. N. Maunder. 2005. Status of yellowfin tuna in the eastern Pacific Ocean in 2004 and outlook for 2005, 102 p. Inter-Am. Trop. Tuna Comm., La Jolla, CA. [Available from website.]

$$p(a) = \frac{e^{-aZ_a}}{\Sigma_a e^{-aZ_a}}, \qquad (1)$$

where Z_a = instantaneous total mortality rate at age a.

We assume that the lengths in each age class are normally distributed around their mean length and the mean lengths at age are determined by the von Bertalanffy (1938) growth model (VBGM). The population proportions-at-age and proportions-at-length can be calculated by using

$$p_{a,1} = (P(l/a)p(a)), \qquad (2)$$

where conditional probability $P(l/a)$ of being in a discrete length l given age a follows a normal distribution around the predicted length-at-age (L_a) based on the VBGM:

$$L_a = L_{inf}(1 - e^{-K(a-a_0)}) + \varepsilon, \qquad (3)$$

where, L_{inf} = the asymptotic length;
K = the growth coefficient;
ε = the error; and
a_0 = the hypothetical age (expressed in years) when average length is zero.

The error (ε) is the variation in length at age and is assumed to be normal with a mean of 0 and a standard deviation of $CV_a L_a$

The observed proportions at age and length from the fleet is given by:

$$q_{a,1} = d_a s_1 p_{a,1}, \qquad (4)$$

where $p_{a,1}$ = the population proportion at age and length; and
$d_a s_1$ = the combined effects of age-based probability that a fish is in the area where the fleet occurs (d_a, availability) and the length-base probability that an encountered fish will be caught (s_1, gear selectivity).

The observed length-based selectivity that includes the length-based gear selectivity that is adjusted for the approximation of age-based availability is given by
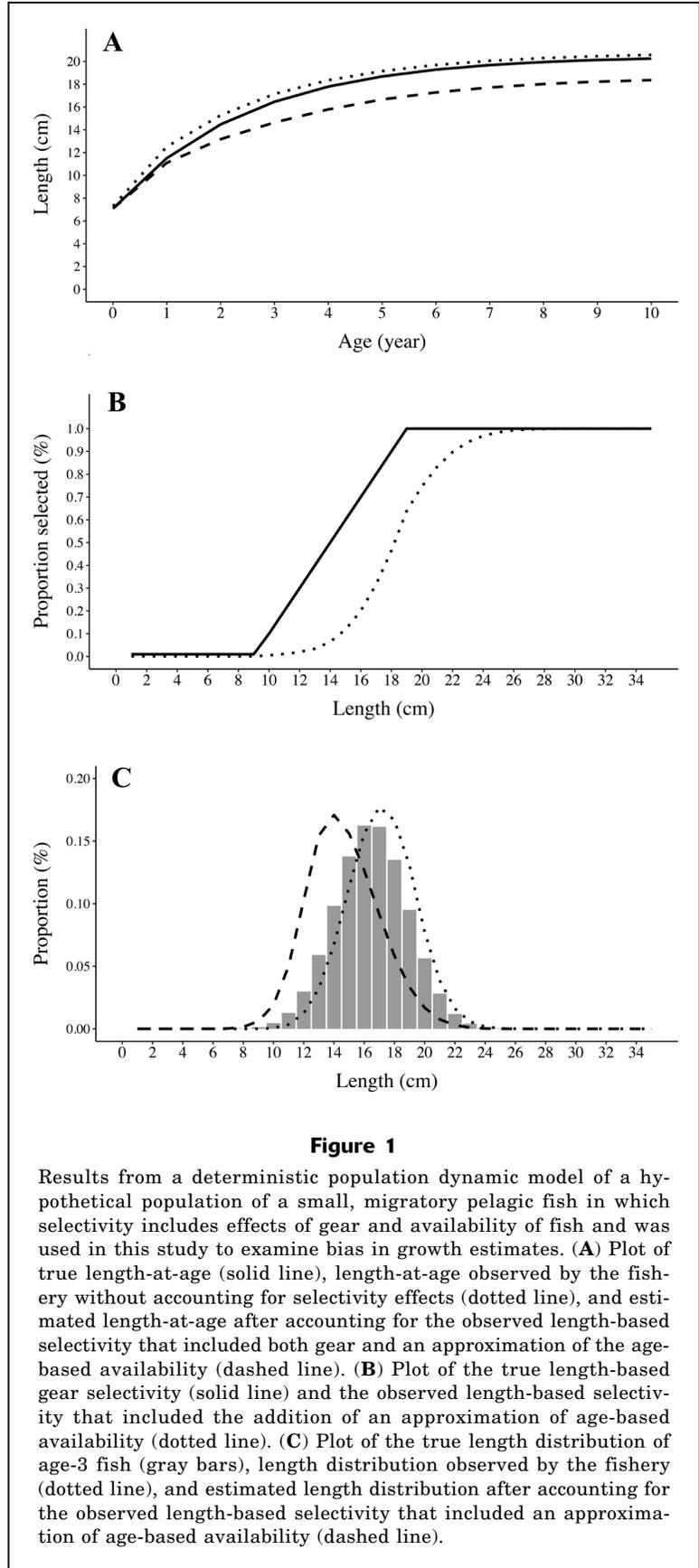
$$v_1 = \frac{\Sigma_a q_{a,1}}{\Sigma_a p_{a,1}}, \qquad (5)$$

where $q_{a,l}$ = the observed; and
$p_{a,l}$ = the population proportions-at-age and -length.

The selectivity-adjusted proportions-at-age and proportions-at–length are given by

$$m_{a,1} = \frac{q_{a,1}}{v_1}, \qquad (6)$$

where $q_{a,l}$ = the observed proportion-at-age and proportion-at-length; and

Figure 1

Results from a deterministic population dynamic model of a hypothetical population of a small, migratory pelagic fish in which selectivity includes effects of gear and availability of fish and was used in this study to examine bias in growth estimates. (**A**) Plot of true length-at-age (solid line), length-at-age observed by the fishery without accounting for selectivity effects (dotted line), and estimated length-at-age after accounting for the observed length-based selectivity that included both gear and an approximation of the age-based availability (dashed line). (**B**) Plot of the true length-based gear selectivity (solid line) and the observed length-based selectivity that included the addition of an approximation of age-based availability (dotted line). (**C**) Plot of the true length distribution of age-3 fish (gray bars), length distribution observed by the fishery (dotted line), and estimated length distribution after accounting for the observed length-based selectivity that included an approximation of age-based availability (dashed line).
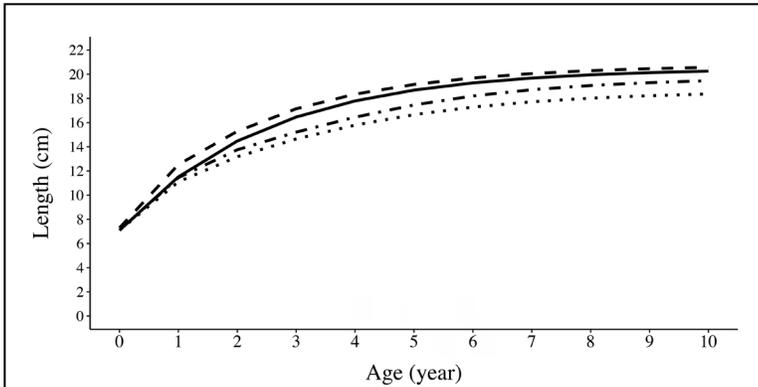
Figure 2

Plot of the true length-at-age (solid line) and estimated length-at-age accounting for the observed length-based gear selectivity that included an approximation of age-based availability of fish. The estimated lengths-at-age are from the example described in Table 1 (dotted line), from a change in the example reducing the coefficient of variation (CV) for the true length-at-age relationship to CV=0.1 (dotted and dashed line), and from a change in the example where the observations are taken from an area with 5% availability of age-4+ fish and 100% availability of fish of ages 0–3 (dashed line).
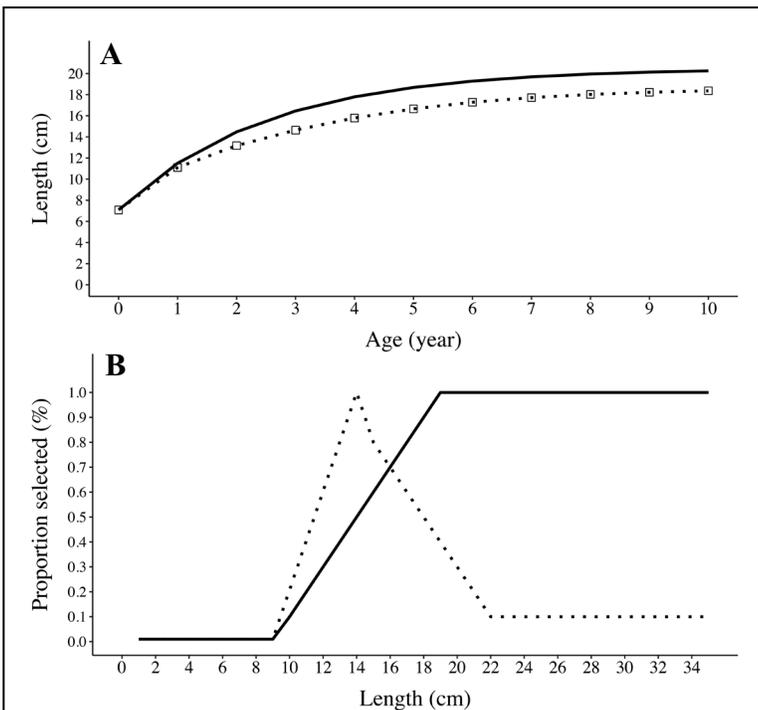

Figure 3

(**A**) Plot of true length-at-age (solid line) and the estimated length-at-age accounting for the observed length-based selectivity that included an approximation of age-based availability. Two different true length-based gear selections were used: asymptotic (dotted line) and domed shaped (open squares). (**B**) Plot of the true length-based gear selectivity without accounting for age-based availability and used in the estimation of length-at-age in plot A. The two examples depicted are asymptotic (solid line) and domed (dotted line).

v_l = the observed length-based selectivity as estimated by an integrated model.

The mean length-at-age for the true population is given by

$$\overline{L}_{a,true} = \frac{\Sigma_l p_{a,l} l}{\Sigma_l p_{a,l}}. \tag{7}$$

Similarly, we can replace $p_{a,l}$ with $q_{a,l}$ to calculate the mean length-at-age for the observed lengths-at-age from the fishery and with $m_{a,l}$ to calculate the mean length-at-age after accounting for the observed selectivity.

Results

A bias in the estimate of mean length-at-age occurs when expected lengths-at-age account for the observed selectivity (v_l) that incorporated an approximation of age-based availability in addition to the length-based gear selectivity (Fig. 1A). Incorporating the approximation results in an alteration of the true length-based process (Fig. 1B). In this example, the asymptotic true length-based gear selectivity has the well-known effect of observing larger than true fish, and this observed bias is unaffected by the age-based availability. However after accounting for the observed length selectivity that includes the additional approximation of age-based availability of fish, the selectivity over-corrects the observed lengths-at-age and results in an estimated length distribution that is shifted to smaller fish (Fig. 1C).

The magnitude and direction of the approximation bias on the estimated length-at-age is affected by several factors. The variability in the length-at-age relationship affects the magnitude of the approximation bias, and larger variability leads to larger bias in the example (Fig. 2). The magnitude and direction of the approximation bias is also affected by the pattern of age-based availability (Fig. 2), and the direction of the bias changes if the availability is reversed and young fish are fully available and older fish are largely unavailable. After the observed selectivity is accounted for, the true shape of the length-based gear selectivity does not affect the estimated mean length-at-age (Fig. 3, A and B).

Discussion

In a growing body of research, the effects of spatial structure on important model processes such as selectivity (Waterhouse et al., 2014; O'Boyle, 2016), and the reliability of

estimates of management quantities (Lee et al., 2017a) are being examined. Lee et al. (2017b) have shown the importance of accounting for age-based movement when estimating growth with random at-age methods. However, little research has shown the effects of approximating age-based processes together with length-based ones (Lee et al., 2017a). This article shows that the widespread application of estimated length-based selection in integrated assessment modeling argues that researchers are assuming unrealistic instantaneous mixing, size-based movements, or are ignoring potential approximation biases.

Our results apply even when fleet distribution covers the entire stock area because the spatial distribution of fishing mortality may not be the same as the spatial distribution of stock abundance. If spatial patterns in the stock are due to age-based movement, then the observed composition data and estimated selectivity would include age-based spatial patterns. Making matters more complicated, as spatial patterns of the stock or the fishery change, the age-based availability of fish would also change annually (Lee et. al., 2017a). Similarly, the approximation bias is not confined to the estimation of growth. Even if an unbiased growth curve is specified in the assessment model, length-based models that do not correctly model both age- and length-based processes would still contain this approximation bias.

Given the wide range of possible biotic and abiotic processes influencing fishery data, it may be difficult to provide a recipe for how best to approach the issues of estimating the growth of fish in fishery assessments. In situations with both age- and length-based processes impacting data, incorporating the relevant processes by using the correct biological units as part of the assessment model may provide the best option. Yet for length-based, age-structured assessment models, estimating growth greatly complicates the analysis. Growth estimates may be confounded by estimates from other model processes (Maunder and Piner, 2015) and therefore require dubious assumptions, such as forcing asymptotic selectivity on a fleet.

Analysts should give additional consideration to the estimation of growth when using only length-based selectivity. Modeling length-composition data is quite challenging, often requiring subjective choices about managing the inevitable misfit to these data (Francis 2011; Lee et al., 2017a). These issues may be of greater importance for stocks assessed by using length-based, age-structured assessment models because of the importance that model predictions match observed length data. Research that is focused on understanding the relative roles of length and age on many important fishery processes should be undertaken (McDaniel et al., 2016).

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