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Predicting changes in mean length with an age-structured stock assessment model

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Abstract

Several studies have shown that mean length is only slightly biased and hence a robust indicator of the total mortality (fishing and natural mortalities). However, these studies use models that typically assume equilibrium conditions and are expected to predict a much stronger relationship between mean length and fishing mortality than would be obtained from a model with more realistic assumptions. Here we predict changes in annual mean length with stochastic stock reduction analysis (SRA)—an age-structured model—that accounts for recruitment variation around an average stock-recruitment relationship and time-varying exploitation rate. We found that SRA-predicted mean length fluctuates considerably over exploitation rate, as opposed to equilibrium mean length, which consistently declined as exploitation rate climbed. Our finding suggests that the inference obtained from examining the relationship between fishing effects and mean length under equilibrium conditions could be misleading.

Recommendations for resource managers

- Previous studies showed that equilibrium mean length—that is, assuming continuous and constant

recruitment and constant total mortality over time—is a reliable indicator of fishing and natural mortalities, where changes in the observed mean length mimic the total mortality of the harvested population.

- By estimating mean length under sensible assumptions, such as accounting for recruitment variability around an average stock-recruitment relationship, and time-varying exploitation rate (fishing mortality), high exploitation rate does not necessarily result in a low mean length.

- Given that equilibrium approaches to estimate mortality as a function of mean length are still appealing, due to their simplicity and basic data requirement, caution must be exercised when interpreting the results.

1 | INTRODUCTION

Fishing pressure changes the mean length of the exploited fish populations. This is mainly attributed to the selective nature of fisheries, fishing removes large individuals from the stock, often because they are more valuable (Shin et al., 2005) and because some fishing gears are designed to be selective so as to protect fish recruitment. There have been considerable attempts to use mean length along with other life-history characteristics, (e.g., mean maximum age, mean size at maturity) to evaluate the responses of fish communities to the exploitation level exerted by fisheries (e.g., Jennings & Dulvy, 2005; Jennings, Greenstreet, & Reynolds, 1999). Other studies have assumed near equilibrium length frequency distribution each year and have used equilibrium mean length to estimate total mortality (fishing and natural); that is, changes in the observed mean length mirror the current total mortality of the exploited stock. A notable example is the Beverton–Holt estimator, which calculate total mortality as a function of mean length (Beverton & Holt, 1956). Ehrhardt and Ault (1992) have modified the Beverton–Holt estimator to account for the upper truncation in the length frequency distributions caused by the highly selective fishing gears used in the tropical fisheries. They showed that, under equilibrium conditions, the total mortality estimate from mean length is unbiased. A more recent study investigated the biases introduced by recruitment trends on the mean length estimator of mortality rate and compared mortality estimates with those from other data sources and stock assessment models on a range of reef fish species (Ault, Smith, & Bohnsack, 2005). The study concluded that mean length represents a robust indicator of the fishing mortality rate and, secondarily, the exploitation status of the stocks under investigation (Ault et al., 2005). Such estimators have been applied to a wide range of species (e.g., spiny lobster (Groeneveld, 2000), spotted tilapia (King & Etim, 2004), and a suite of coral reef fishes (Nadon, Ault, Williams, Smith, & DiNardo, 2015)).

However, the underlying assumptions of the equilibrium approaches—like constant and continuous recruitment, and constant mortality—are rarely encountered in marine systems; for example, fish recruitment might fluctuate by an order of magnitude annually (Glantz, 2005). In this paper, we show that the relationship between mean length and exploitation rate (or fishing mortality) is not as clear-cut, in particular, when taking into consideration the effects of more realistic assumptions—including recruitment variation around a stock-recruitment curve and time-varying exploitation rate—on mean length. To address these effects, we predict changes in the observed annual mean length as part of the stochastic stock reduction analysis (SRA) fitting procedure (i.e., an age-structured model; described in detail in Walters, Martell, & Korman, 2006).

2 | METHODS

We used biological and fisheries information drawn from the yellow-fin seabream (*Acanthopagrus latus*) stock in Kuwait waters. The catches of this highly sought-after species have declined rapidly during recent years, raising concerns about the status of the stock, particularly considering that such decline is unprecedented in the historical catches (Central Statistical Office, 1979–2015). *A. latus* stock is targeted by different fisheries, including trap, gillnet, and bottom trawling. However, it is most likely that the largest fraction of catches come from the bottom trawling fishery (Chen, Almatar, AlSaffar, & Yousef, 2012). The length frequency data (total sample size (n) = 2,749 fish) from which the observed annual mean length was derived, has been collected over the periods 1980–1985, 1989–1990, 1992–1994, 1997–2000, and 2002–2004. In addition, the length data contained length at age data for 1,873 fish, where the aging process followed the same approach described in Al-Husaini et al. (2002). To fit the SRA model to an abundance index, we obtained catch and effort data from the bottom trawl fishery for the period 1997–2012. The input parameters used to construct the life-history schedules for *A. latus* are presented in Table 1.

We used the following equation to predict numbers over age a and year t (Walters et al., 2006):

$$N_{a+1,\,t+1} = N_{a,t}\,S\,(1 - v_a U_t),\tag{1}$$

where S is the survivorship from natural mortality rate M ($S = e^{-M}$), v_a denotes the mean vulnerability at age, and U_t is the exploitation rate in year t. We calculated v_a by integrating the length-vulnerability function over the length at age distribution for each age to get the correct mean vulnerability, rather than calculating vulnerability at age only from mean length at age (Table 1). We estimated the vulnerable biomass B_t in year t as

$$B_t = \sum N_{a,t} v_a w_a,\tag{2}$$

where w_a refers to the average weight at age, which is modelled as a power function of the average length L

$$w_a = g L_a^b,\tag{3}$$

TABLE 1 Parameter values used in the stochastic stock reduction analysis model to construct life-history schedules for the yellow-fin seabream *Acanthopagrus latus* from Kuwait waters

Parameters	Value	Source
Maximum age (A_{max})	12 years	This study
Asymptotic length (L_∞)	38 cm	This study
von Bertalanffy metabolic rate (k)	0.35/year	This study
Scale parameter of growth curve (t_0)	−0.50 years	This study
Age at maturity (A_m)	3 years	Vahabnezhad, Taghavimotlagh, and Ghodrati Shojaei (2017)
Natural mortality (M)	0.32	This study*
Length at 50% vulnerability to capture (L_v)	21.32	This study
Coefficient of variation (cvl)	0.13	This study
Vulnerability at age (v_a)	$v_1 = 0.15$, $v_2 = 0.52$, $v_3 = 0.77$, $v_4 = 0.88$, $v_5 = 0.92$, $v_{6+} = 1$	This study

Note. The values of von Bertalanffy parameters (L_∞, k, t_0) are obtained from pooled sexes. All quantities except for the length at 50% vulnerability to capture (L_v) and coefficient of variation (cvl) were prespecified from outside the fitting procedure using the length-frequency and length at age data.
*Using Hoenig$_{nls}$ equation from Then, Hoenig, Hall, & Hewitt (2015).

where *g* is a scaling constant and *b* is the allometric growth parameter. We modelled the average length at age L_a using the von Bertalanffy growth curve

$$L_a = L_\infty (1 - e^{(-k(a-t_0))}), \tag{4}$$

where L_∞ is the asymptotic length, *k* is the rate at which the individual fish approaches its L_∞, and t_0 is a scale parameter of the growth curve. In the SRA model, exploitation rate *U* is varied so as to force the model to exactly predict the observed catches *C* given model predicted vulnerable biomass *B* (Walters et al., 2006)

$$U_t = \frac{C_t}{B_t}, \tag{5}$$

where C_t is the catch in year *t*. We used the Beverton-Holt model to describe the stock-recruitment relationship (Walters et al., 2006)

$$R_{1,t} = \frac{\alpha G_t}{1 + \beta G_t} e^{(x_t)}, \tag{6}$$

where α and β are stock-recruitment parameters, G_t is the egg production in year t $G_t = \sum N_{a,t} f_a$, where f_a is the fecundity at age; and $e^{(x_t)}$ refers to the stochastic variation in maximum recruitment in year *t*, where recruitment anomalies x_t are assumed to be sampled from a normal distribution with mean zero and standard deviation set to 0.6, consistent with the average standard deviation of the annual recruitment anomalies for many fish species

(Beddington & Cooke, 1983; Maunder & Deriso, 2003). It bears noting that most fisheries models assume constant natural mortality, growth, and vulnerability over time (Punt & Hilborn, 1997); the SRA model presented here is not different from these models.

We predicted the length frequency distribution of *A. latus* by conducting the following series of procedures:

i. Divide length classes on a 1-cm interval from 7 to 45 cm, following the recommendation by Neumann, Guy, Willis, Zale, & Parrish (2012).

ii. Set up the matrix $P(L|a)$, (i.e., proportions at length L given age a; Hilborn & Walters, 1992).

$$P(L|a) = \varnothing\left(\frac{L_{j+1}^{u} - L_a}{\sigma_{L_a}}\right) - \varnothing\left(\frac{L_j^{u} - L_a}{\sigma_{L_a}}\right), \tag{7}$$

where $\varnothing$ denotes the standard cumulative distribution, L_j^u the upper bound of length class j, and σ_{L_a} is the standard deviation of mean length at age, calculated as the product of mean length at age L_a and the coefficient of variation (cvl; Taylor, Walters, & Martell, 2005);

Given that the mean vulnerability at length is assumed to follow a logistic function (Taylor et al., 2005), the total proportions of each length class were summed over all ages and multiplied by the mean vulnerability at length to calculate the predicted vulnerable numbers at length over years.

Next, we predicted the annual mean ($\bar{L}$) and variance ($\bar{V}$) of lengths (i.e., length frequency distribution moments: first moment is the mean, and second moment is the variance as described by Fournier & Doonan, 1987)

$$\bar{L} = \sum \sum L_j P_t, \tag{8}$$

where L_j is the length at class j and P_t is the standardized proportion of predicted vulnerable numbers at length over year t

$$\bar{V} = \sum \sum (L_j - \bar{L})^2 P_t. \tag{9}$$

3 | RESULTS AND DISCUSSION

The observed mean length exhibited high fluctuations, particularly over the first 7 years; while the predicted mean length showed a steady decline in recent years (2008–2015; Figure 1a). Such changes in the mean length of *A. latus* can be attributed to several reasons recruitment events, the bottom trawling fishery is retaining high numbers of small fish, and/or changes in fish growth. While the observed mean length was reasonably predicted, the observed variances are consistently lower than the predicted variances for most years (Figure 1b). The sample data showed much less variance in measured lengths than should have occurred given the growth, vulnerability, and mortality rate parameters (Figure 1b). The overpredicted variance might be a sign that length frequency sampling was biased, likely due to the fishery being concentrated in areas of high abundance of younger, smaller fish. Chen et al. (2012) reported that *A. latus* occurred in >80% of the time in the bycatch samples of the bottom trawling fishery, ranking sixth out of 55 species. However, the study did not record the length/age class of the retained
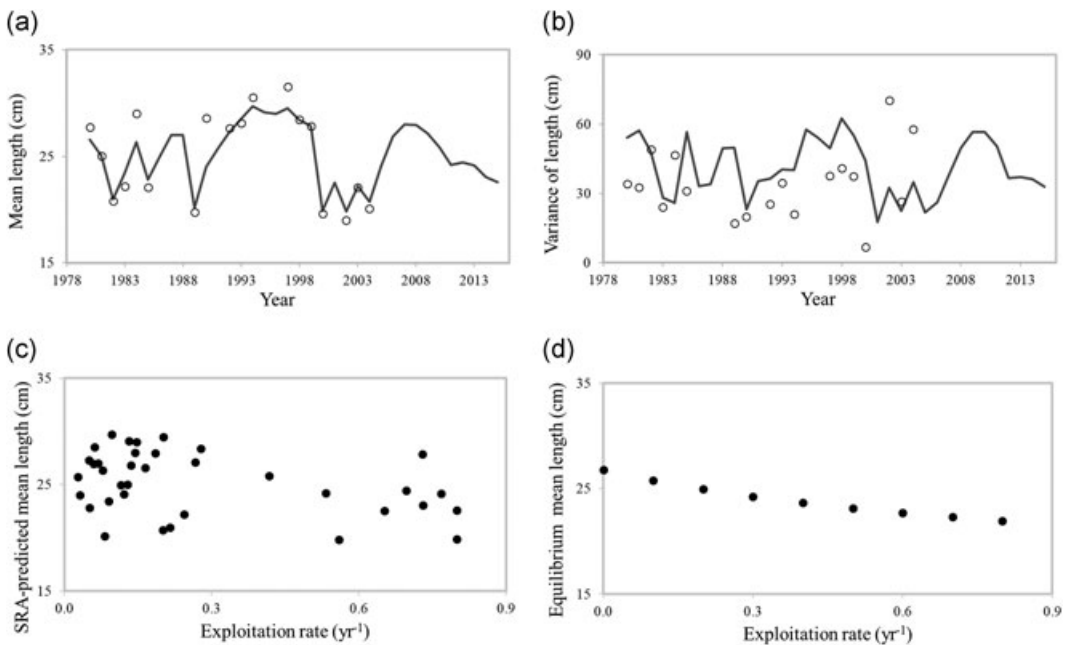
FIGURE 1 (a) SRA-predicted (solid line) and observed (unfilled circles) mean lengths for the yellow-fin seabream *Acanthopagrus latus* in Kuwait waters over time (1980–2015). (b) SRA-predicted (solid line) and observed (unfilled circles) variance of length. (c) SRA-predicted mean length over time-varying exploitation rate (Equation (5)). (d) Equilibrium mean length, which was calculated as a function of the equilibrium numbers at age per recruit as a function of exploitation rate (assumed to increase from 0 to 0.8/year at an increment of 0.1). SRA: stock reduction analysis

species. It bears noting that in the case where the fishery selection function (i.e., size-vulnerability curve) is changing over time, due to either larger fish moving out of the coastal fishing area (e.g., Pacific halibut; Stewart & Martell, 2014) or becoming less vulnerable for other reasons (e.g., escaping fishing gears; Ryer, 2008), the mean and variance of length frequency distribution fail to contain any information about changes in mortality rate or recruitment, even if the sampling program has been fully representative (Maunder, Crone, Valero, & Semmens, 2014).

Figure 1c,d compares two methods of predicting changes in mean length over exploitation rate: (a) predicting changes in mean length from SRA model, where exploitation rate changes over the years, depending on the observed catch and estimated biomass (Equation (5)); and (b) equilibrium mean length calculated as a function of the equilibrium numbers at age per recruit as a function of exploitation rate, where exploitation rate is assumed to increase from 0 to 0.8/ year at an increment of 0.1. We noticed wide variations in the SRA-predicted mean length at low exploitation rates (<0.3/year), whereas higher exploitation rates (>0.5/year) generally corresponded with lower predicted mean lengths (Figure 1c). In addition, while the lowest SRA-predicted mean length (19.8 cm) corresponded to the highest exploitation rate (0.8/year), very low exploitation rate (0.08/year) was associated with similar SRA-predicted mean length (20.1 cm). On the contrary, the equilibrium mean length demonstrated a consistent relationship with the exploitation rate, in the sense that higher exploitation rates corresponded with lower equilibrium mean length and vice versa (Figure 1d). The fluctuations noticed in the SRA-predicted mean length violates the restrictive assumptions of the equilibrium conditions,

including constant and continuous recruitment and constant mortality over time. Ault et al. (2005) indicated that mean length is a robust and nearly unbiased indicator of total mortality; particularly, fishing mortality. However, their results might be optimistic, given that their assumptions included knife-edge selection and lack of recruitment variation over time around stock-recruitment curve; all of which applied to long-lived species (e.g., groupers, wrasses), where high fishing mortality targeting large individuals typically result in a pronounced decline in mean length (e.g., McClenachan, 2009).

The comparison between the equilibrium mean length and that predicted from the SRA suggests that when variability in annual recruitment and exploitation are accounted for, equilibrium mean length does not accurately reflect exploitation rate. Given that equilibrium-based mortality estimators are still appealing (e.g., Beverton-Holt estimator; Then, Hoenig, Gedamke, & Ault, 2015)—owing to the ease of application and basic data needs—we recommend that their findings are interpreted with care.

The scope of this paper was to predict changes in the mean length using an age-structured stock assessment model and to compare this prediction with equilibrium mean length, thus we did not test the sensitivity of the model to, for example, different values of natural mortality or shapes of vulnerability function. However, it bears noting that the outcomes of such stock assessment model may largely depend on a variety of input parameter values, functions, and data (Quinn & Deriso, 1999; Walters & Martell, 2002).

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