Fisheries Research 171 (2015) 33–41

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Catch curve stock-reduction analysis: An alternative solution to the catch equations

James T. Thorson *, Jason M. Cope

*Fisheries Resource Assessment and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Boulevard East, Seattle, WA 98112, United States*

ARTICLE INFO

*Article history:*
Received 28 December 2013
Received in revised form 27 March 2014
Accepted 29 March 2014
Handling Editor A.E. Punt
Available online 22 May 2014

*Keywords:*
Stock-reduction analysis
Catch curve
Catch data
Overfishing limit
Recruitment variability
Effort dynamics
Age-composition sampling
Data-poor stock assessment
Stock status

ABSTRACT

Legislative changes in the United States and elsewhere now require scientific advice on catch limits for data-poor fisheries. The family of stock reduction analysis (SRA) models is widely used to calculate sustainable harvest levels given a time series of harvest data. SRA works by solving the catch equation given an assumed value for spawning biomass relative to unfished levels in the final (or recent) year, and resulting estimates of recent fishing mortality are biased when this assumed value is mis-specified. We therefore propose to replace this assumption when estimating stock status by using compositional data in recent years to estimate a catch curve and hence estimating fishing mortality in those years. We compare this new “catch-curve stock reduction analysis” (CC-SRA) with an SRA or catch curve using simulated data for slow or fast life histories and various magnitudes of recruitment variability. Results confirm that the SRA yields biased estimates of current fishing mortality given mis-specified information about recent spawning biomass, and that the catch curve is biased due to changes in fishing mortality over time. CC-SRA, by contrast, is approximately unbiased for low or moderate recruitment variability, and less biased than other methods given high recruitment variability. We therefore recommend CC-SRA as a data-poor assessment method that incorporates compositional data collection in recent years, and suggest future management strategy evaluation given a data-poor control rule.



## 1. Introduction

Improving the scientific basis for management of “data-poor” fisheries remains a central challenge for fisheries science in the 21st century. Fisheries may have few available data for a variety of reasons, including having low economic value, being in development and/or in the developing world, and having small population size and localized dynamics. In the United States and elsewhere, many such data-poor fisheries have an accurate time series of catch or landings data (Vasconcellos and Cochrane, 2005), though the interpretation of catch data remains an important and highly-contested subject of research (Daan et al., 2011; Pauly et al., 2013).

Since the publication of *Stock reduction analysis, another solution to the catch equations* (Kimura and Tagart, 1982), researchers have commonly combined a time series of catch data with an assumption of final biomass relative to unfished or initial biomass to estimate population productivity and reconstruct historical abundance and exploitation rates. The resulting family of “stock reduction analysis” (Kimura et al., 1984) has since been expanded to incorporate stochastic variability in population dynamics (Walters et al., 2006) and a flexible shape for the production function describing expected changes in population abundance (Dick and MacCall, 2011). Stock reduction analysis can also include age-structured population dynamics (Cope, 2013) and prior information regarding population abundance at the start of the catch time series (Martell and Froese, 2013). Despite these differences, this family of models shares a common dependence upon prior assumptions regarding final depletion, and simulation testing indicates that these methods perform well when assumptions regarding final abundance are met and poorly otherwise (Wetzel and Punt, 2011).

Alternative research has sought to develop rules-of-thumb for population abundance given changes in catch over time (Kleisner et al., 2012). These methods are typically justified by demonstrating that predictions of abundance and/or productivity match stock assessment estimates for assessed species (Froese et al., 2012; Srinivasan et al., 2010), although the degree of match remains contested (Cook, 2013). Alternatively, statistical models may seek to estimate the average relationship between changes in catch and population abundance (Costello et al., 2012; Thorson et al., 2012).

* Corresponding author. Tel.: +1 206 302 1772; fax: +1 206 860 6792.
*E-mail addresses:* James.Thorson@noaa.gov, JamesT.esq@gmail.com (J.T. Thorson).

http://dx.doi.org/10.1016/j.fishres.2014.03.024
0165-7836/Published by Elsevier B.V.

One possible justification for these statistical methods is that they implicitly reconstruct the coupled dynamics of population abundance and fishing effort (Thorson et al., 2013). However, many species show little predictive relationship between past and future changes in fishing effort (C. Szuwalki, Bren School of Environmental Science and Management, University of California, personal communication 2014), so these effort-based methods of informing population abundance may not be appropriate for many stocks.

Finally, decades of research have developed methods to estimate fishing mortality rates from samples of the age or length composition of the population (Chapman and Robson, 1960). Such estimates can be assessed relative to optimal levels of fishing mortality whenever auxiliary information regarding species' life history is available (Hordyk et al., 2014). Methods using samples of age composition from a fishery are typically called 'catch curves,' and catch curves have been modified since their inception to account for variable recruitment (Schnute and Haigh, 2007) and fishery selectivity (Thorson and Prager, 2011; Wayte and Klaer, 2010). However, catch curves that analyze multiple biological cohorts within a single year (i.e. treating different ages within a year as a "synthetic cohort") must assume that fishing mortality rates are approximately constant over time, and this assumption is rarely met in practice.

In this study, we demonstrate that these disparate research trajectories can be combined to their mutual benefit. Specifically, we repeat the derivation of Kimura and Tagart (1982) that introduced stock-reduction analysis, and show that pre-specifying final depletion is only necessary to obtain a single degree of freedom during parameter estimation. This degree of freedom can also be obtained by estimating fishing mortality in the final year via a catch curve. Therefore, a combined catch curve stock-reduction analysis (CC-SRA) accomplishes the goals of both catch curve and reduction analysis methods, while relaxing problematic assumptions in each method individually. We then use simulation modelling to evaluate the relative performance of catch curves, stock-reduction analysis, and CC-SRA when estimating spawning biomass relative to unfished levels and fishing mortality. We also reposit all code necessary to replicate this analysis or apply CC-SRA to a new data set in the first-author's website (https://sites.google.com/site/thorsonresearch/code/ccsra).

## 2. Methods

### 2.1. The original derivation of stock reduction analysis

In its original development (Kimura and Tagart, 1982), stock reduction analysis seeks to calculate a time series of fishing mortality rates $F_t$ for all years $t_1$ through $t_n$, as well as the (constant) annual recruitment rate $R$, given a fixed (assumed known) value for natural mortality $M$, initial population abundance $B_1$, and change in abundance ("depletion") between initial and final years $D$. This therefore involves calculating $N+1$ parameters (one parameter $F_t$ for each of $N$ estimated years, plus one parameter $R$). Stock reduction analysis gains $N$ degrees of freedom by specifying the Baranov catch equation and using a catch time series $C_1$ through $C_n$ to solve for $F_1$ through $F_n$:

$$C_t = B_t \frac{F_t}{F_t + M}(1 - \exp\{-F_t - M\}) \quad (1)$$

It also uses the following equation for population dynamics:

$$B_t = B_{t-1} \exp\{-F_{t-1} - M\} + R \quad (2)$$

where $R$ here includes both juvenile production and growth, and selectivity is constant among ages. These equations can be solved via forward projection given known values for biomass in the initial year ($B_1$) and natural mortality ($M$), except that annual recruitment $R$ is unknown. This latter degree of freedom is gained by the assumption that the total change in abundance is known:

$$D = \frac{B_{n+1}}{B_1} \quad (3)$$

In essence, this approach acknowledges that, given a known value for natural mortality, initial biomass, and catch, there is exactly one possible solution (i.e. one level of annual recruitment) that results in a given change in biomass by the end of the time series. This derivation involves determinstic calculations (for $F_1$ through $F_N$, and $R$) and hence has no way to characterize uncertainty about these calculations, although subsequent developments of stock-reduction analysis have developed formal estimation methods that characterize uncertainty using Bayesian priors or penalties (e.g., on total change in abundance, $D$, Dick and MacCall, 2011).

### 2.2. Catch-curve stock reduction analysis

This derivation for stock reduction analysis must be modified in several ways to make it consistent with contemporary assumptions about population dynamics and stock assessment practices. First, many researchers now use age-structured population dynamics and fishery selectivity (Hilborn, 1990). We therefore replace the population dynamics equation (Eq. (2)) with dynamics of abundance at age $N_{a,t}$ for age $a$ and year $t$:

$$N_{a,t} = \begin{cases} R_t & \text{if } a = 0 \\ N_{a-1,t-1} \exp\{-S_a F_{t-1} - M\} & \text{if } a > 0 \end{cases} \quad (4)$$

where $R_t$ is recruitment in year $t$ and $S_a$ is fishery selectivity at age (which is defined to have a maximum of 1.0). Fishery selection is now assumed to be age-specific, and hence $F_t$ in the age-structured model (Eq. (4)) is the fishing mortality at the age of maximum selectivity, as opposed to the constant selectivity of the original SRA model (Eq. (2)). Spawning biomass $SB_t$ includes the effect of individual weight at age $w_a$ and maturity at age $m_a$:

$$SB_t = \sum_{a=0}^{a_{\max}} w_a m_a N_{a,t} \quad (5)$$

while fishery catch at age $C_{a,t}$ (in numbers) again uses the Baranov catch equation:

$$C_{a,t} = N_{a,t} \frac{S_a F_t}{S_a F_t + M}(1 - \exp\{-S_a F_t - M\}) \quad (6)$$

and total catch $C_t$ (in weight) in year $t$ is inner product of catch at age and weight at age. Recruitment is a lognormally distributed random variable with mean derived from a parametric stock-recruit relationship. In this case, we use the steepness parameterization of the Beverton–Holt function:

$$\ln(R_t) \sim Normal\left(\ln\left(\frac{4hR_0 SB_t}{SB_0(1-h) + SB_t(5h-1)}\right) - \frac{\sigma_R^2}{2}, \sigma_R^2\right) \quad (7)$$

where steepness $h$ governs the degree of compensation in recruitment. Future research could explore more-flexible stock-recruit curves in CC-SRA (Dick and MacCall, 2011; Mangel et al., 2010), although we do not do so here. We critically assume that abundance at age at the beginning of available catch data is from an approximately unfished state:

$$\ln(N_{a,t_1}) \sim \text{Normal}\left(\ln(R_0 \exp\{-aM\}) - \frac{\sigma_R^2}{2}, \sigma_R^2\right) \quad (8)$$

and the implied link between $N_{a,t_1}$ and $R_0$ replaces the requirement for assuming a value of $B_1$ in conventional stock-reduction analysis.