Fisheries Research 181 (2016) 186–197

Contents lists available at ScienceDirect

Fisheries Research

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

Management implications of temporally and spatially varying catchability for the Gulf of Mexico menhaden fishery

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ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form 19 April 2016
Accepted 20 April 2016
Handled by A.E. Punt
Available online 6 May 2016

Keywords:
Catchability
Hypoxia
Spatio-temporal variation
Stock assessment
Gulf menhaden

ABSTRACT

Catchability relates fishing effort to fishing mortality, and is an important component in fishery stock assessment models. Mis-specifying catchability can lead to inaccurate estimation of model parameters and bias in the determination of stock status. The Gulf of Mexico has one of the largest seasonal occurrences of hypoxia in the world and it overlaps in time and space with the Gulf menhaden *Brevoortia patronus* fishery, potentially leading to temporal and spatial patterns in stock distribution and thus catchability. These patterns are not currently modeled in the Gulf menhaden stock assessment. To better understand the implications of spatial and temporal patterns in catchability due to hypoxia, we constructed an operating model of Gulf menhaden fishery dynamics under various assumptions of spatial coverages and temporal patterns, and used the output from the operating model as input into estimation models with alternative approaches on modeling catchability. Under the most extreme assumptions about the spatial coverage and magnitude of variation in catchability, median absolute error in estimates of fishing mortality and spawning stock reference points ($F_{30\%}$ and $S_{30\%}$) was 73% and 29%, respectively, and median absolute error in estimates of fishing mortality and spawning stock based stock status was 23% and 79%, supporting the notion that errors in catchability are important. Under more reasonable assumptions, median absolute error declined to 20% and 2.9% for $F_{30\%}$ and $S_{30\%}$, respectively, and to 3.8% and 2.4% for fishing mortality and spawning stock-based stock status, respectively. Modeling catchability as a random walk further reduced median absolute error to 5.0% for $F_{30\%}$ and 1.4% for $S_{30\%}$, but slightly increased median absolute error for stock status indicators to 4.0% and 3.3%. Our results show generally that the spatial coverage, temporal pattern, and estimation approach of catchability affects the influence of mis-specifying catchability; and show specifically that the Gulf menhaden stock assessment is robust to the effects of hypoxia on catchability if assuming random-walk catchability.

Published by Elsevier B.V.

1. Introduction

Catchability is an important parameter in fishery stock assessment models (Arreguin-Sanchez, 1996). Catchability scales abundance indices from fishery-dependent or –independent sources to absolute abundance. Typically, catchability is defined as the proportion of a stock captured by a single unit of effort (Ricker, 1975), but it can also be defined as the proportionality constant that relates fishing effort to fishing mortality (Gulland, 1977). Stock assessment models often assume catchability is constant despite substantial evidence to the contrary (Harley et al., 2001; Wilberg et al., 2010). Parameters estimated in stock assessment models may be inaccurate if changes in catchability are not properly accounted for, leading to bias in the determination of stock status indicators used for management decisions.

Given that catchability relates the fishing or survey process to absolute abundance, it is affected by spatial and temporal changes in the dynamics of the stock and the dynamics of the fishery. The effects of temporal changes in fishing practices on temporal patterns in catchability are well documented (Wilberg et al., 2010). Similarly, temporal changes in stock area have

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http://dx.doi.org/10.1016/j.fishres.2016.04.013
0165-7836/Published by Elsevier B.V.

been shown to lead to density-dependent catchability (Pitcher, 1995; Wilberg et al., 2010). For example, Winters and Wheeler (1985) showed that catchability of Atlantic herring (*Clupea harengus*) was inversely proportional to the spatial area of the stock, implying that the abundance index for herring was correlated with population density rather than population biomass. Temporal changes in the spatial aggregation of the fishery can also affect catchability (Salthaug and Aanes, 2003), as can changes in the environment such as increased oxygen minimum zones (Stramma et al., 2012) or shifting ocean conditions (Csirke, 1989).

Inaccurate estimation of catchability can lead to bias in stock assessments and associated management advice. Fishing mortality will often be underestimated and biomass overestimated if a population contracts and catchability increases but is assumed constant, leading to non-conservative management advice. Among case studies, Rose and Kulka (1999) suggested that inaccurate interpretations of increasing catch rates for northern cod (*Gadus morhua*) contributed to the fishery's collapse. The increased catch rates were assumed to reflect increased abundance, but actually masked declines in the population because the spatial area over which cod were distributed had contracted. Similar misinterpretations of increasing catch rates were shown for California Pacific sardine (*Sardinops sagax caerulea*) (MacCall, 1976) and Peruvian anchoveta (*Engraulis ringens*) (Csirke, 1989). Among simulation studies, the presence of density-dependent catchability has been shown to increase the probability of stock collapse (Katsukawa and Matsuda, 2003; Shertzer and Prager, 2007).

Despite the extensive literature addressing the presence and causes of variation in catchability, few studies have explored the implications of inaccurately assuming constant catchability on management outcomes in fish stock assessment models (but see Pope and Shephard, 1985 and Patterson and Kirkwood, 1995), and as far as we know none have explored alternative assumptions about the spatial extent of the effect. Wilberg and Bence (2006) compared the performance of approaches for estimating time-varying catchability based on data generated from various functional forms, but did not consider constant catchability in their estimation models. Similarly, Thorson and Berkson (2010) used simulations to determine the best approach to estimate the catchability time series itself. Thorson et al. (2012) found that improving sampling methods to account for spatially-varying catchability resulted in less bias in indices of abundance, but they did not assess implications for stock status indicators. Overall, the literature recommends incorporating variable catchability into stock assessment models, and describes the ways to do so, but the consequences of assuming constant catchability across various spatial scales on management advice from stock assessments have received little attention.

The northern Gulf of Mexico experiences one of the largest areas of seasonal hypoxia (DO concentrations $\leq$2 mg/L) in the world (Rabalais et al., 2002), and with areas of hypoxia overlapping in both time and space with the Gulf menhaden fishery. Aggregation along the edges of or up into the water column above areas of hypoxia can enhance catch rates of targeted species (Craig, 2012; Kraus et al., 2015; Zhang et al., 2009). Smith (2001) hypothesized the potential for increased susceptibility of Gulf menhaden (*Brevoortia patronus*) to the commercial purse seine fishery in the northern Gulf of Mexico due to hypoxic conditions. Langseth et al. (2014) tested the potential for hypoxia to affect the distribution of the fishery and found that as dissolved oxygen declined, the fishery moved to the west and towards shore, and that capture probabilities increased over a portion of the fishery's range. However, whether these changes in distribution or capture probabilities are important to the stock assessment of Gulf menhaden remains untested.

The purpose of this study was to determine the implications of incorrectly assuming constant catchability in a stock assessment model on the stock status indicators used for management of Gulf menhaden. We constructed an operating model to simulate annual catch-at-age data based on two alternative assumptions about the area of overlap between hypoxia and the fishery, four alternative patterns about changes in catchability, and two assumptions about the magnitude of annual variation in the catchability patterns. Each pattern of changes in catchability was applied to the portion of the fishery assumed to overlap with hypoxia. We then applied an estimation model similar to the actual Gulf menhaden stock assessment model to compare estimated model parameters, biological reference points, and stock status indicators to the true values from the operating model. We also explored the effects of alternative estimation approaches for catchability, either as a constant or as a random walk. We discuss the implications of our results on management of the Gulf menhaden fishery specifically, but also on stock assessment models in general.

2. Material and methods

Our research methodology comprised three components: the operating model, the estimation model, and the scenarios used for our simulations. Details for each component are described below, as is a description of the metrics used to compare performance among the scenarios.

2.1. Operating model

The operating model was based on the structural assumptions of the most recent Gulf menhaden stock assessment (SEDAR, 2013), but spanned fewer years to accommodate the time period when hypoxia data were available. We simulated the stock and fishery using an age structured model for years 1985–2011 and age classes 0–4+ years. The final age class was an accumulator age (plus group), and included information for all ages 4 and older. Parameter inputs specific to each scenario, which we describe in Section 2.3, along with parameter values from the SEDAR (2013) stock assessment were used to generate annual catches and proportions at age in the catch. The operating model was coded using the R software package, version 3.1.0 (R Core Team, 2014).

Full details of the operating model can be found in Appendix A (equations, Table A1; parameters; Table A2), but here we provide a general summary. First, annual instantaneous fishing mortality at age a in year y ($F_{a,y}$) was calculated as $F_{a,y} = pq_y^{dev}qs_aE_y + (1-p)qs_aE_y$, which represented the sum of fishing mortality from areas affected and unaffected by changes in catchability. The proportion of area over which variation in catchability was applied (p) and the annual variation in catchability (q_y^{dev}) were dependent on the simulation scenario used, whereas mean catchability (q), selectivity at age (s_a), and annual effort from the fishery in number of sets (E_y) were constant across scenarios. Next, fishing mortality and natural mortality at age (M_a) were used to establish the population dynamics. Abundance at age ($N_{a,y}$) for ages 1–4+ in the initial year (1985) was calculated assuming a stable age distribution based on natural mortality and the average fishing mortality in the first three years. Abundance at age in later years was calculated by applying age-specific total mortality ($Z_{a,y} = F_{a,y} + M_a$) to the population. Recruitment occurred at age 0 and was calculated following a Beverton-Holt recruitment model with a steepness value of 0.75 based on spawning stock in the beginning of the year. Once abundance at age was established, catch at age per year ($C_{a,y}$) in numbers was then calculated based on the Baranov catch equation, and was multiplied by weight in the middle of the year and then summed across ages to determine annual catches (L_y) in weight. Lastly, pro-