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A comparison of age- and size-structured assessment models applied to a stock of cisco in Thunder Bay, Ontario

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ABSTRACT

Stock assessments are critical to modern fisheries management, supporting the calculation of key reference variables used to make informed management decisions. However, there is still considerable uncertainty as to which class of assessment models is appropriate to use under different circumstances. A common class of models used when age data are available are statistical catch-at-age assessment (SCAA) models, which track annual cohorts through time. When age data are unavailable, as is often the case in invertebrate fisheries where the lack of a bony structure such as otoliths makes aging difficult, statistical catch-at-size assessment (SCSA) models are more often employed, tracking fish or invertebrates through time by size-classes rather than ages. Do SCAA models actually perform better than SCSA models when age data are available, or is this just an assumption we make in fisheries research and management? We examined this question by evaluating the effectiveness of both SCAA and SCSA models in characterizing cisco, *Coregonus artedi*, population dynamics in Thunder Bay, Ontario. Both models were fit using an integrated framework with multiple sources of data including hydroacoustic estimates of spawning stock, fishery-dependent and -independent age/length compositions, and harvest data. Our results suggest that for cisco in Thunder Bay, data-limitations related to lack of size-composition data over the size range for which cisco growth is rapid resulted in difficulty estimating relative year-class strength within a SCSA. This led to parameter confounding and ultimately the inability to estimate natural mortality within a SCSA. This hampered the utility of a SCSA model in comparison with a SCAA model when age-composition data were available.

1. Introduction

Stock assessment is a critical aspect of fisheries research and management, supporting the calculation of key quantities such as spawning biomass, abundance, exploitation rate, recruitment, and their associated uncertainties. Most assessments conducted in the United States are based on age-structured assessment methods (Punt et al., 2017), which, when statistically fit, can be referred to as statistical catch-at-age assessment (SCAA) models. SCAA models are based on the assumption that most population processes are a function of age, and they work by tracking cohorts of fish through time, using observations of catch-at-age and auxiliary information to estimate population parameters (Fournier and Archibald, 1982; Deriso et al., 1985). When catch-at-age data are unavailable for a species of interest, as is the case in many invertebrate fisheries where lack of a bony structure such as an otolith makes aging difficult, size-structured assessment methods are often employed (Punt et al., 2013). Similarly, when statistically fit these types of models can be referred to as statistical catch-at-size assessment (SCSA) models. SCSA models, contrary to SCAA counterparts, are largely based on the assumption that most population processes are a function of size rather than age. Sullivan et al. (1990) developed and applied a framework for SCSA, which differs from SCAA in that it utilizes observations of catch-at-size and tracks fish in size bins rather than age-classes through time, often making use of a growth model that determines transition probabilities of size bins in subsequent time steps. Although age-structured models can be fit using harvest size-composition data, generally by using a model to convert predicted age-compositions to size-compositions (Fournier et al., 1990, 1998), contemporarily the use of SCSA is preferred when the sole or primary harvest composition data are for sizes rather than ages (Punt et al., 2013).

Each method offers distinct advantages and disadvantages. For size-based methods, the model can directly account for the size structure of

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removals from a population (Punt et al., 2017), it thus can more appropriately model some fishery processes such as selectivity as size-based. While the observation model of a SCAA can account for size-based selectivity, accounting for how size-at-age of the survivors is altered by fishing is more challenging (see Methot (2000) for one approach). In addition, size-composition data is almost always more abundant because it is both easier and cheaper to collect. SCSA models can also considerably decrease the number of fish that need to be aged, as age-compositions of the catch are not required. SCSA is not without its challenges. Primary among them is the need for a growth model to determine transition probabilities through size bins for each time step, where additional aspects such as time-varying or density-dependent growth can add complexity. Although growth models are often specified outside of SCAA models to convert abundances-at-age to biomass, their derivation is not critical to model fit as they are often not used to predict data (provided yield is predicted using mean weights-at-age from harvest data). The transition of fish from one year to the next is much simpler within SCAA models, which benefit from the fact that a fish must be a year older in the next (yearly) time step; a caveat being that our ability to observe ages is not perfect, as there is measurement error involved in aging organisms, and ignoring this error can result in biased assessment output (Coggins and Quinn, 1998; Reeves, 2003; Bertignac and De Pontual, 2007). Although aging error is not always accounted for in SCAA models, it can be (Thompson et al., 2011; Methot and Wetzel, 2013). In addition, the effects of aging error can be minimized using quality control in aging techniques (Campana, 2001).

Perhaps due to the deterministic transition of fish through age bins, and advantages associated with this, very seldom are SCSA models developed for species when age data are available. Additionally, few studies have compared the two methods. One such study, Punt et al. (2017), used simulation analysis to compare the performance of age-, size-, and age- and size-structured assessment methods and concluded, based on an age- and size-structured operating model, that size-structured and age- and size-structured assessment methods performed best, while age-structured methods performed poorest. A key factor specified in the operating model for this study was that growth was modeled using a size-transition matrix, which likely gave the size structured approaches an advantage. This highlights that this study was done, as are most simulation studies, based on known population dynamics pre-specified by researchers. The advantage of this approach is the ability to compare assessment results to what is pre-specified in the operating model as the true population dynamics of the stock. This specification of the operating model can also limit the applicability of results, if the researchers' conception on the dynamics of the stock and fishery (e.g., survey selectivity as age-based process in Punt et al., 2017) do not actually reflect underlying processes. Fitting alternative models to empirical data can be highly useful in helping to better define plausible processes and informing the direction of future simulation studies.

We develop and fit both integrated SCAA and SCSA models for a stock of cisco, *Coregonus artedi*, in Thunder Bay (Lake Superior), Ontario. Our objective was to compare and contrast performance of the different assessment methods when applied to an actual stock and to provide recommendations on which type of model may be preferred under different scenarios. We were specifically interested in the overall question: "Does the collection of age-composition data, and its use in a SCAA lead to an improvement in assessment performance over what could be obtained using a size-structured model, without using age composition data?" Given the expenses associated with collecting age-composition data, it is important to know if as good or better results can be obtained with size models, perhaps because they better model fishery processes. To our knowledge, only one study has performed a comparison between age- and size-structured models on a actual stock with true dynamics unknown (Akselrud et al., 2017, concluding that age-structured fit data best). In a time of shrinking natural resource agency budgets, it seems these comparisons could provide managers with valuable information on how they might implement their overall assessment programs.

2. Methods

2.1. Study species

Cisco are a planktivorous species native to the Laurentian Great Lakes. They are largely pelagic and form annual spawning aggregations during the month of November in nearshore bays and areas of western Lake Superior, where contemporary spawning stocks are primarily located (Stockwell et al., 2009). These aggregations support a lucrative commercial roe fishery, as fishers generally target spawning fish during November using suspended gillnets (Ebener et al., 2008). Additionally, since 2005 these aggregations have been surveyed annually using hydroacoustic surveys in Thunder Bay. Current management in Thunder Bay relies on a fixed exploitation rate control rule where 10% of spawning biomass estimated from the hydroacoustic surveys is allocated as quota in the subsequent year to a limited number of fishers. No formal assessment models have previously been developed for this or any other stock in western Lake Superior.

2.2. Stock area

We treated Ontario Ministry of Natural Resources and Forestry (OMNRF) Quota Management Areas 1–4 (QMAs; Fig. 1) as the stock area for Thunder Bay cisco. This stock has been hypothesized to be discrete because cisco in an adjacent embayment (i.e., Black Bay) have not shown any sign of recovery since a collapse in the 1980s. If cisco from Thunder Bay belonged to a non-discrete spawning stock that inhabited a broader geographic range, it is expected there would have been some level of recovery in Black Bay over the last 30+ years (Ebener et al., 2008). Additionally, this area was chosen based on coverage of the hydroacoustic surveys, which generally sample over QMAs 1–4 in Thunder Bay.

2.3. Data

The SCAA and SCSA models made use of six main sources of observed data in the fitting process (Table 1): (1) Number of cisco > 250 mm in Thunder Bay estimated from hydroacoustic surveys (2005, 2007–2015), age- or size-composition of cisco caught in fisheries-independent (2) mid-water trawls (2005, 2007–2010, 2015) and (3) multi-mesh gillnets (2009, 2013–2015), (4) age- or size-composition of the commercial fishery catch subsamples (1999–2015), and (5) male and (6) female biomass harvested by the fishery each year (1999–2015). The SCSA made use of one additional source of data; (7) individual growth increments of cisco back-calculated from otolith increment data. Details on how data were processed for input into assessment models can be found in Fisch (2018).

2.4. Process model

Predicted quantities needed to compare to the observed data listed above were calculated using a variety of equations describing the stock and fishery. The assessment models ran from 1999 to 2015, with parameters estimated using a Bayesian framework. The SCAA model ages began at 2 and ended at a plus group age of 15 (denoting all cisco older than 14) while the SCSA model size bins were divided in 10 mm increments beginning at 170 mm and ending at a plus group of 410 mm (denoting all cisco ≥410 mm). The SCSA model starting size bin of 170 mm was chosen as this is effectively the minimum size for age 2 fish (Online Supplemental Fig. 1). Age or size bins are referenced throughout the manuscript with subscript j. Given the fishery operates primarily as a roe fishery, it captures a disproportionate number of females in Thunder Bay each year (81% on average; Online Supplemental Fig. 2). For this reason, it was decided to make the