Fisheries Research 180 (2016) 161–168

Contents lists available at ScienceDirect

Fisheries Research

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

Estimation of size–transition matrices with and without molt probability for Alaska golden king crab using tag–recapture data

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ARTICLE INFO

Article history:
Received 30 December 2014
Received in revised form 25 April 2015
Accepted 27 April 2015
Available online 22 June 2015

Keywords:
Alaska
Golden king crab
Growth
Size–transition matrix

ABSTRACT

Size-structured population dynamics models are used for stock assessments of hard to age invertebrate species, such as crabs, and size–transition matrices play an important role in modeling growth in those models. Crabs grow by molting and then incrementing in size. Therefore, the size–transition matrix should ideally contain sub-models for the probability of molt and the growth increment. Size–transition matrices were estimated in an integrated model setting, which included tagging data. Various models, including those that explicitly model molt probability and that include the molt implicitly in the size–transition model, were applied to data for golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands region. Several diagnostic statistics (e.g., covariance matrix, likelihood, AIC, mean growth increment metric, sensitivity of estimates of mature male biomass, and the fits to the tag recapture, catch-per-unit effort, and length frequency data) were used to investigate the implications of the way growth was modeled. Overall, the fit of the integrated model that included the molt probability sub-model was better than that of the model that did not include this sub-model. However, the trends in key stock assessment outputs did not differ markedly between approaches for modeling growth even though the estimates of the size–transition matrices differed.

1. Introduction

Crustaceans are hard to age, and size-structured population dynamics models have consequently often been used for stock assessment purposes for these species (e.g., Zheng et al., 1995; Chen et al., 2005; Haist et al., 2009; Punt et al., 2013, Punt et al., 2015). In age- or stage-structured models, the population dynamics process is described by cohorts moving through different ages or stages over time. On the other hand, the process of aging in size-structured models is described by growth in size through a suitable growth function, and the population dynamics process is described by cohorts moving through different size-classes over time (Punt et al., 2015).

The size–transition matrix, which governs the probability of animals moving from one size class to the others, plays an important role in size-structured models. The molt increment and the time between molt events have been modeled separately and combined to compute size–transition matrices for crustacean growth (e.g., Zheng et al., 1995; McGarvey and Feenstra, 2001). The size–transition matrix has also been estimated disregarding molting (i.e., assuming that the animals molt with certainty at each time step or by lumping the molt probability and molt increment processes together) (e.g., Punt et al., 1997; Haist et al., 2009). The molt increment has often been modeled assuming a linear increment from pre- to post-molt size (e.g., Punt et al., 1997; Chen et al., 2003; Montgomery et al., 2009; Hillary, 2011; Zheng and Siddeek, 2014). The variability in molt increment has been accounted for by assuming a probability distribution, such as the normal or a gamma (e.g., Zheng et al., 1995; Punt et al., 1997). The time period between the two consecutive molts has been modeled using a variety of functions (Chang et al., 2012); for example, a logistic function for Bristol Bay red king crab (*Paralithodes camtschaticus*) (Zheng et al., 1995).

Tag release-recapture and size frequency data have been used to estimate the parameters of size–transition matrices, either within or outside stock assessment models (Fournier et al., 1990; Punt et al., 1997; Zheng et al., 1998; Lloyd-Jones et al., 2014).

Golden king crab, *Lithodes aequispinus*, support a valuable commercial fishery in the Aleutian Islands, Alaska. This stock has been managed as two sub-stocks; the eastern and the western Aleutian Islands sub-stocks. The fisheries on the two sub-stocks are

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http://dx.doi.org/10.1016/j.fishres.2015.04.013
0165-7836/

managed with a constant annual total allowable catch. There is no annual fishery-independent stock abundance survey, and the status of the fishery is assessed largely based on catch, catch-per-unit-effort, and catch size-composition data (Pengilly, 2014). A male-only size-structured assessment model, with size measured by carapace length, is under development for the two golden king crab sub-stocks in the Aleutian Islands (Siddeek et al., 2014). Several tagging experiments have been conducted in the eastern Aleutian Islands region (e.g., Watson et al., 2002).

This paper examined approaches for estimating size–transition matrices for the eastern Aleutian Islands sub-stock. Specifically, we investigated the effect of (1) including or (2) ignoring the molt probability sub-model when developing the size–transition matrix on stock assessment-related outputs (henceforth referred to as approaches 1 and 2). We considered the case in which the estimation of the size–transition matrix was integrated into the stock assessment, as is becoming common practice (Punt et al., 2015). A number of diagnostic statistics (e.g., covariance matrix, likelihood, AIC, mean growth increment metric, sensitivity of estimates of mature male biomass, and the fits to the tag recapture, catch-per-unit effort, and length frequency data) were used to investigate the implications of the choice between the two size–transition matrix estimators.

2. Materials and methods

2.1. Data sources

The data sets included in analyses for the eastern Aleutian Islands golden king crab fishery are: (1) commercial pot fishery retained catch (1985/86 to 2012/13 fishing seasons), (2) total catch estimated from observer samples and fish ticket landings data (1990/91 to 2012/13), (3) groundfish fishery bycatch (1995/96 to 2012/13), (4) retained catch length compositions (1985/86 to 2012/13), (5) total catch length compositions (1990/91 to 2012/13), (6) groundfish bycatch length compositions (1995/96 to 2012/13), (7) standardized catch-per-unit effort (CPUE) index from observer samples (1995/96 to 2012/13), and (8) tag release-recapture lengths from releases during 1991, 1997, 2000, 2003, and 2006.

The Alaska Department of Fish and Game (ADF&G) uses fish tickets to record details of a fishing trip such as fishing area, dates of fishing, number of trap hauls made, and total crab catch by species. Since the entire landed catch is recorded on the fish tickets, the annual retained catch by species was estimated by adding the fish ticket landings records for the entire fishing season. Onboard observers count and measure all crabs caught in the sampled pots and categorize the catch as females, sublegal males, retained legal males, and non-retained legal males. Annual mean nominal CPUE of retained and total crabs were estimated considering all sampled pots within each season. The annual total (landed and discarded) catch in the fishery was estimated as the product of the observer nominal total CPUE and the total effort (number of pot lifts).

In relation to the tagging data, rectangular, king crab pots were used to capture crabs for tagging in all experiments, with the exception of the 1991 experiment where smaller, conical pots were used. The tags were released during summer (July–September) before the fishery started. Location, date, and fishing depth were recorded for each pot retrieved. Upon pot retrieval, the carapace lengths (CL) of crabs were measured to the nearest millimeter and shell condition recorded. Isthmus-loop ("spaghetti") tags were used to tag crabs (Gray, 1965) larger than 90 mm CL, and tagged crabs were released on or adjacent to the capture location. The majority of tag recaptures were obtained from the fishers during the commercial pot fishery. The tagging data used in the analyses comprised CL-at-release, CL-at-recapture, and time-at-liberty. Table 1 provides a brief summary of the tag release data and Table 2 provides the number of recaptures grouped by time (in years)-at-liberty. The tagging records were restricted to male golden king crab releases in the size-range 101–185 mm CL given the size-range included in the population dynamics model. There were 27,131 tagged crab releases in this size-range with a 6.33% return rate.

Table 1
Summary of the eastern Aleutian Islands male golden king crab tag release data with the release size range.

Release year	Number released	Release size range (mm CL)
1991	3611	93–197
1997	7659	87–187
2000	7768	85–179
2003	6170	88–186
2006	5235	90–190
Total	30,443	

Paul and Paul (2000) observed captive crab in the lab molting every month of the year with the highest frequencies molting during May–October. We assumed that tag returns that were at-liberty for at least 9 months would likely have gone through the first molt cycle after release and disregarded recaptures with growth increment <−5 mm CL (an arbitrary cut off point) because they were assumed to be errors. We assumed that growth increments between 0 and −5 mm to be measurement errors and set those increments to 0 (Table 2). Less than 1% of the data were discarded.

2.2. Size transition matrix

Appendix A outlines key aspects of the stock assessment (see Siddeek et al. (2014) for full details). The assessment is based on the 'integrated' approach to stock assessment; with parameter estimation implemented using AD Model Builder (Fournier et al., 2012). The structure of the size–transition matrix for molt increment is described in Punt et al. (2015). It is a square nXn matrix subject to the condition $\sum_{j=1}^{n} X_{i,j} = 1$ where n is the number of size-classes (each of 5 mm CL) and $X_{i,j}$ is the probability of growing from size-class i to each size-class j, subject to the constraint that $X_{i,j} = 0$ for $j < i$. We assumed size transition to occur from July 1 in year t to July 1 in year $t+1$. Following Zheng et al. (1995), we used a linear model to predict growth increment from pre-molt length. A variety of probability functions, such as normal, Student's t, and gamma can be used to describe the distribution of observed growth increments (Sullivan et al., 1990; Hillary, 2011). We chose the normal distribution with a constant standard deviation (σ) (Hamazaki and Zheng, 2014). Independent analysis of golden king crab tag release-recapture data indicated no systematic increase in the spread of molt increments by size (Siddeek et al., 2005; Watson et al., 2002). Hence the assumption of constant standard deviation is plausible. The two model variants considered in this paper differ in terms of

Table 2
Summary of the eastern Aleutian Islands male golden king crab tag recapture data. The summary pertains to the crab size range 101–185 mm CL that was considered in the size-structured model. The overall recovery rate was 6.33%.

Time-at-liberty (years)	Number of recoveries by time-at-liberty
1	936
2	491
3	214
4	51
5	13
6	12