Ecological Modelling 285 (2014) 39–53

Contents lists available at ScienceDirect

Ecological Modelling

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

Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay

André E. Punt[a,*], Dusanka Poljak[a], Michael G. Dalton[b], Robert J. Foy[c]

[a] School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, WA 98195, United States
[b] Alaska Fisheries Science Center, 7600 Sand Way Point Way, NE, Seattle, WA 98115, United States
[c] Alaska Fisheries Science Center, Kodiak Laboratory, 301 Research Ct, Kodiak, AK 99615, United States

ARTICLE INFO

Article history:
Received 28 November 2013
Received in revised form 12 April 2014
Accepted 16 April 2014
Available online 13 May 2014

Keywords:
MSY
MEY
North Pacific
Ocean acidification
Red king crab

ABSTRACT

A stage-structured pre-recruit model was developed to capture hypotheses regarding the impact of ocean acidification on the survival of pre-recruit crab. The model was parameterized using life history and survival data for red king crab (*Paralithodes camtschaticus*) derived from experiments conducted at the National Marine Fisheries Service Kodiak laboratory. A parameterized pre-recruit model was linked to a post-recruit population dynamics model for adult male red king crab in Bristol Bay, Alaska that included commercial fishery harvest. This coupled population dynamics model was integrated with a bioeconomic model of commercial fishing sector profits to forecast how the impacts of ocean acidification on the survival of pre-recruit red king crab will affect yields and profits for the Bristol Bay red king crab fishery for a scenario that includes future ocean pH levels predictions. Expected yields and profits were projected to decline over the next 50–100 years in this scenario given reductions in pre-recruit survival due to decreasing ocean pH levels over time. The target fishing mortality used to provide management advice based on the current harvest policy for Bristol Bay red king crab also declined over time in response to declining survival rates. However, the impacts of ocean acidification due to reduced pre-recruit survival on yield and profits are likely to be limited for the next 10–20 years, and its effects will likely be masked by natural variation in pre-recruit survival. This analysis is an initial step toward a fully integrated understanding of the impact of ocean acidification on fishery yields and profits, and could be used to focus future research efforts.

1. Introduction

The world's oceans are absorbing atmospheric carbon dioxide (CO_2) from burning fossil fuels, deforestation, cement production, and other human activities that contribute to climate change (Feely et al., 2004). The increase in oceanic CO_2 has caused an average decrease of surface ocean pH by 0.1 units from pre-industrial levels, the equivalent of a 30% increase in acidity, and global average pH in surface waters, now 8.1, is predicted to fall to 7.8 before 2100 in a standard climate scenario (Malakoff, 2012). This ocean acidification (OA), in addition to decreasing the pH, reduces the saturation of calcium carbonate, making it more difficult for some calcifying organisms to sequester calcium and carbonate to build shells. Unlike global warming which has a robust literature on impacts (see Sumaila et al. (2011) for a review of fisheries impacts), few studies have assessed the wider impacts of OA on human society. An important early study by Cooley and Doney (2009) focused mainly on future economic impacts (i.e., potential revenue losses) from OA for US mollusk production, and this sector has received the most attention. However, these studies do not differentiate OA effects on different life-history stages, and therefore, the same type of analysis cannot be applied to animals where demographic factors are a critical feature of population dynamics, which is true for many commercially-important species. In particular, commercially-important crab stocks in the waters off Alaska have complicated population dynamics and are susceptible to the physiological and ecological effects of OA.

The saturation horizon of calcium carbonate in the North Pacific Ocean is an order of magnitude shallower than in the North Atlantic (Doney et al., 2009). In the Bering Sea, waters below 40 m are seasonally undersaturated in aragonite while calcite saturation states are low (<2.0) below 50 m (Mathis et al., 2011). In the Arctic Region, OA effects on organisms and ecosystems are imminent with current

* Corresponding author. Tel.: +1 206 221 6319; fax: +1 206 685 7471.
E-mail addresses: aepunt@uw.edu, aepunt@u.washington.edu (A.E. Punt).

http://dx.doi.org/10.1016/j.ecolmodel.2014.04.017
0304-3800/

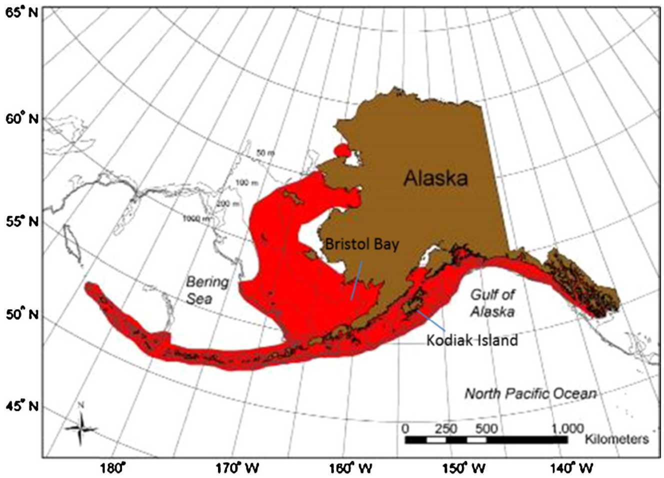

Fig. 1. Red king crab general distribution in the North Pacific Ocean, identifying the area of the largest stock in Bristol Bay in the eastern Bering Sea.

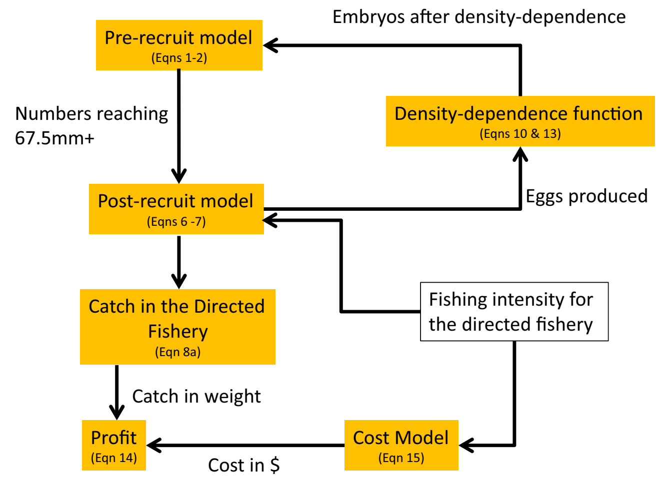

Fig. 2. Conceptual overview of the pre- and post-recruit models.

seasonal undersaturation in the surface waters (Fabry et al., 2009; Steinacher et al., 2009).

Bristol Bay red king crab (*Paralithodes camtschaticus*), BBRKC (see Fig. 1 for the distribution of BBRKC), inhabit waters less than 100 m as juveniles and adults. Larval stages of BBRKC are pelagic between 40 and 84 days followed by a transitional pelagic-epibenthic stage that lasts approximately 14 days depending on temperature and food availability (Kovatcheva et al., 2006; also see Weber, 1967 and Armstrong et al., 1981 for review). Bristol Bay red king crab are targeted by one of the largest crab fisheries in the Bering Sea and Aleutian Islands (BSAI) region of the North Pacific. In 2009–2011, the BBRKC fishery produced an annual average of a little more than eight and a half million pounds of finished products, and was estimated to have generated real (i.e., 2011 dollars) first-wholesale revenues of about one hundred fifteen million dollars per year (Garber-Yonts and Lee, 2012, Table 10).

The BBRKC fishery may be impacted in the future by OA as crab respond to the decreases in pH and decreased availability of calcium carbonate. Experiments conducted at the National Marine Fisheries Service (NMFS) Kodiak Laboratory in Kodiak, Alaska, concluded that although calcification rates in juvenile red king crab were not affected, survival rates decreased as a function of lower pH (Long et al., 2013a). Other studies on decapod crustaceans also found calcification rates not to be affected by ocean acidification (e.g. Kurihara et al., 2008; Ries et al., 2009) while higher mortality rates at juvenile stages were similarly found in other crab species (Ceballos-Osuna et al., 2013). A broader consideration of crustaceans found a range of responses presumed to be a function of physiological capacity to compensate for the changes in pH (Whiteley, 2011).

The BBRKC fishery is managed jointly by the North Pacific Fishery Management Council (NPFMC) and the State of Alaska. The federal assessment process for this species provides estimates of the Overfishing Limit (OFL, the level of catch corresponding to the proxy for the fishing mortality which achieves Maximum Sustainable Yield, MSY, F_{MSY}) and the Acceptable Biological Catch (ABC, a level of catch lower than the OFL to account for scientific uncertainty), while the State of Alaska sets the Total Allowable Catch (TAC). The OFL for BBRKC is currently based on a harvest control rule used for stocks for which stock biomass and $F_{35\%}$ (the fishing mortality rate in the directed fishery which reduces mature male-per-recruit to 35% of its unfished level) can be estimated, but there are no reliable estimates of F_{MSY} and corresponding biomass, B_{MSY} (NPFMC, 2008).

The stock assessments for BBRKC which are used to provide the estimates of biomass and productivity required to compute OFLs, ABCs and TACs are based on a statistical catch-at-length analysis technique (Punt et al., 2013). This technique (see Zheng and Siddeek, 2009, 2010, 2011 for applications to BBRKC) involves estimating the parameters of a length-, shell condition-, and sex-structured population dynamics model by fitting to catch, survey and fishery length–frequency data, and survey indices of abundance.

In this paper, we develop an integrated bioeconomic model to estimate maximum sustainable yield (MSY) and maximum economic yield (MEY) for the BBRKC fishery, and evaluate how these quantities change over time in response to the physiological impact of OA (see Fig. 2 for a conceptual overview of the model and how the projections are undertaken). The integrated bioeconomic model consists of three components: (a) a pre-recruit model which models red king crab from the embryo stage to the length at which they are included in the models used for providing management advice, (b) a model of post-recruit crab which includes the impact of the directed fishery for red king crab and a trawl fishery which incidentally takes red king crab, and (c) a model of profits for the commercial fishing sector arising from red king crab harvesting. The combined bioeconomic model is used then to forecast the relationship between yield and profit over time, and hence that between MSY and MEY over time.

2. Methods

2.1. The pre-recruit model

A stage-structured population model was used to forecast the changes over time in recruitment to the first length-class in the post-recruit model (67.5 mm carapace length, CL; Zheng and Siddeek, 2010):

$$\underset{\sim}{N}_{T+t+1} = \mathbf{G}_T \Omega_T \underset{\sim}{N}_{T+t} \quad (1)$$

where $\underset{\sim}{N}_{T+t}$ is the vector of numbers-at-stage at time $T+t$ (all embryos enter the first stage when they are spawned), $\mathbf{G}_T$ is the transition matrix (i.e. the matrix of probabilities of growing from one stage to each other stage for embryos spawned at time T; consistent with assessments for most crustaceans, the matrix $\mathbf{G}$ is assumed to be lower triangular, reflecting the assumption that very few animals shrink following molting), and Ω_T is the survival matrix for embryos spawned at time T. The survival and growth rates for animals spawned at time T over their time as pre-recruits are set to those calculated for time T. This is an adequate approximation