Biological Conservation 158 (2013) 155–166

Contents lists available at SciVerse ScienceDirect

Biological Conservation

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

Management strategy evaluation applied to the conservation of an endangered population subject to incidental take

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ARTICLE INFO

Article history:
Received 20 April 2012
Received in revised form 24 August 2012
Accepted 25 August 2012
Available online 29 November 2012

Keywords:
Chinook salmon
Extinction risk
Fishery
Management strategy evaluation
Oncorhynchus tshawytscha
Simulation

ABSTRACT

Management strategy evaluation (MSE) is a simulation method commonly used to evaluate the expected performance of harvest strategies with respect to target populations. However, MSE is also useful for evaluating strategies designed to manage incidental take from endangered populations. We adapted MSE to the case of Sacramento River winter Chinook salmon, an endangered population that is subject to incidental take by mixed-stock ocean salmon fisheries that target more abundant stocks. Pursuant to the US Endangered Species Act, the US National Marine Fisheries Service called for a new fishery management strategy that would link the allowable fishing mortality to the population's risk of extinction. Our objective was to evaluate extinction risk under different harvest strategies. We simulated the dynamics of the salmon population and the management process simultaneously. The management process included harvest strategies that set allowable fishing mortality rates as a function of population size. Strategies that reduced fishing mortality rates in response to low estimates of population size resulted in lower extinction risk than strategies that set fishing mortality rates at current or historical levels. The number of years of data taken into account by a strategy and the extent of reductions in fishing mortality resulted in different frequencies and durations of reduced fishing opportunity. By quantifying the trade-off between the risk of extinction of an endangered population and the opportunity for fisheries to harvest target stocks, our study illustrated the utility of MSE for applications to endangered populations.

1. Introduction

Management and conservation of wildlife populations often involve the regulation of direct removals in the form of culls, harvests, or mortality incidental to other human activities. Science in support of such management aims to find the number and types of removals that will afford a desired balance between social, economic and ecological objectives. Fishery science and management have an especially long tradition of designing and implementing regulations on fishing effort and harvest in an attempt to strike a satisfactory balance between catch and conservation of fish stocks. More recently, the importance of considering conservation status has increased for fish populations that are now at a small fraction of their estimated historical size, some of which are endangered (e.g., Atlantic and southern bluefin tuna, *Thunnus thynnus* and *Thunnus maccoyii*, IUCN, 2011; Atlantic cod, *Gadus morhua*, COSEWIC, 2010). Even when targeted fishing of depleted populations is restricted, incidental catch in other fisheries can be a concern (e.g., northeastern Pacific rockfish, *Sebastes* spp.; Parker et al., 2000).

During the past several decades computer simulation has become a popular method for developing strategies for managing anthropogenic removals from wildlife populations and testing their performance in terms of specific, quantitative management and conservation objectives (Wade, 1998; Milner-Gulland et al., 2001; Punt and Donovan, 2007; van Kooten, 2008; Chee and Wintle, 2010). Much of the early development of these techniques occurred in fishery science (Walters and Hilborn, 1976; Hilborn, 1979). More recently, fishery management science in several parts of the world has embraced the 'management procedure' or 'management strategy evaluation' (MSE) approaches whereby the harvested fish population is simulated along with the human processes of monitoring, assessment, control and implementation (Punt, 1992; Smith et al., 1999; Kell et al., 2006; Butterworth, 2007). By modeling the complete biological and management system, as well as the stochasticity and uncertainty in the system, these approaches aim to evaluate how well a management strategy would perform in practice with respect to predefined management objectives. The applicability of the MSE framework to conservation has been recognized (Bunnefeld et al., 2011), with social and economic considerations receiving increasing attention in the design

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http://dx.doi.org/10.1016/j.biocon.2012.08.031

of management strategies (Milner-Gulland, 2011). For the most part, fishery applications of the MSE framework have been concerned with fishery and sustainability objectives related to the target populations, but social, economic and ecosystem objectives are increasing in importance (Dichmont et al., 2008; Mapstone et al., 2008). The MSE approach is also applicable to the management of fisheries when incidental catch or risk of extinction is a priority. For example, Cass and Riddell (1999) used a management strategy simulation approach to evaluate trade-offs between fishing opportunity and catch and the risk of extinction of Chinook salmon (*Oncorhynchus tshawytscha*) along the west coast of Vancouver Island, B.C., Canada.

Multiple populations of Pacific salmon (*Oncorhynchus* spp.) are listed as endangered or threatened under the United States (US) Endangered Species Act (ESA), and many of these populations are subject to incidental take in ocean salmon fisheries. Salmon populations are defined by the timing of return to freshwater and location of spawning, but the ocean distributions of these populations can overlap substantially. While fisheries can target salmon by species, the stock or population of origin cannot be readily determined at sea. The ocean fisheries are conducted as 'mixed-stock' fisheries, in which fish are harvested from multiple stocks and populations including protected populations. Strategies for managing fishing effort or total catch in mixed-stock fisheries affect the risk of extinction of the individual populations (Ricker, 1958; Hilborn, 1976; Kope, 1992).

Winter Chinook salmon from the Sacramento River in California, USA, are an example of a protected population that is subject to incidental take in mixed-stock ocean salmon fisheries that target other, more abundant stocks off the coast of California. The winter Chinook population declined precipitously during the 20th century from at least an estimated 60,000–120,000 spawners per year (late 1960s) to <1000 spawners in 1989 (Fisher, 1994), resulting in its listing under the ESA as threatened, the first listing for a salmon species (NMFS, 1989). Its status was then changed to endangered (NMFS, 1994) after a series of years with low numbers of spawners (<1000 on average). Multiple anthropogenic factors contributed to the decline including freshwater habitat loss and alteration and river and ocean harvest (Yoshiyama et al., 1998). Around the time of the ESA listing, several measures were taken to protect the population such as improved passage for migrating spawners and fishery restrictions (NMFS, 1997). Also, in the late 1990s Livingston Stone National Fish Hatchery began to supplement the population's natural production by spawning primarily natural-origin fish and releasing their hatchery-raised juvenile offspring back into the river (USFWS, 2011a). The annual number of spawners in the river recovered somewhat after the late 1990s to an estimated 16,000 and 17,000 in 2005 and 2006, respectively (Killam, 2009), but has since declined again for reasons which are unclear (800 in 2011; PFMC, 2012).

While winter Chinook are incidentally caught in commercial and recreational ocean salmon fisheries, their contribution to the total catch is very low. On average, winter Chinook represent <2% of the total number of Chinook spawners in the Central Valley of California and represent an even smaller percentage of the total number of Chinook state wide. Nevertheless, the population's endangered status has made it a high priority for management of the ocean salmon fisheries. Following the ESA listing, several fishery restrictions were implemented to protect the population including a shortened fishing season, time-area closures, and minimum size retention limits (NMFS, 1997). Coded wire tagging of hatchery fish has allowed post-season estimation of fishery exploitation rates on winter Chinook. Estimated catch has been greater in the recreational fishery than the commercial fishery, and the estimated overall fishery exploitation rate on adult winter Chinook has been about 20% since the late 1990s, except during years when the fisheries were closed (O'Farrell et al., 2012b). The exploitation rate prior to the late 1990s was likely >20% as a result of greater fishing effort and the absence of fishery restrictions (O'Farrell et al., 2012b). In 2010 the US National Marine Fisheries Service (NMFS) issued a Biological Opinion pursuant to the ESA regarding the reauthorization of the ocean salmon fisheries (NMFS, 2010). The Biological Opinion concluded that the fisheries, as operated at the time, were likely to jeopardize the continued existence of winter Chinook and offered as a Reasonable and Prudent Alternative (RPA) the development and implementation of a fishery management framework that would be expected to reduce the risk to the population. In particular, it was specified that the management framework should allow for reductions in fishery impacts when the conservation status of the population is 'declining or unfavorable', although quantitative status thresholds were not specified.

We adapted the MSE approach to the management of incidental take from an endangered population and applied it to the case of Sacramento River winter Chinook salmon. Our objective was to evaluate the performance of alternative fishery management strategies in terms of pre-defined extinction risk criteria for winter Chinook. We simulated the population into the future while also simulating the estimation of population size over time (monitoring), management controls related to the estimates of population size, and the resulting impacts of the ocean fisheries. We also evaluated the implications of the management strategies for the fisheries and quantified trade-offs between conservation and fishing opportunity.

2. Methods

2.1. Operating model

At the core of our simulations was an 'operating model' (Rademeyer et al., 2007). The operating model had several components including the dynamics of the winter Chinook population, fishery impacts, and monitoring of the population (Tables 1 and 2).

2.1.1. Population dynamics

The population component of the operating model was structured by sex, age and origin (natural or hatchery; Figs. S1.1 and S1.2), and aspects of it were similar to previous models of this population (Botsford and Brittnacher, 1998; Newman et al., 2006; Newman and Lindley, 2006; O'Farrell et al., 2012b). Demographic stochasticity was incorporated in transitions between ages (Eqs. (T1.1–T1.4)). Compensatory density dependence was incorporated through the number of juveniles produced per spawner in the natural spawning area following a stochastic Beverton-Holt stock recruitment relationship (Eqs. (T1.6), (T1.7) and (T1.9)). We also accounted for the collection of natural-origin spawners for hatchery broodstock and the subsequent hatchery contribution to juvenile production (Eqs. (T1.5), (T1.8) and (T1.10)). We assumed that there was a target number of fish to be collected for this purpose, subject to it not exceeding 20% of the number of natural-origin spawners. All returning hatchery-origin spawners were assumed to spawn in the natural spawning area thereby contributing to future natural production. The juvenile freshwater outmigration period and the first year in the ocean was modeled as a single phase represented by a stochastic, potentially autocorrelated juvenile survival rate (Eqs. (T1.11–T1.16)). Most of the population dynamics parameter values were derived from analyses of recent winter Chinook population dynamics that included a statistical population model with supplementary analyses (A.J.W. et al., unpublished data) and a cohort analysis (O'Farrell et al., 2012b). There were no available estimates of temporal autocorrelation in the juvenile survival rate, so we conducted simulations with two alternative