Ecological Modelling 337 (2016) 79–95

Contents lists available at ScienceDirect

Ecological Modelling

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

Exploring the implications of the harvest control rule for Pacific sardine, accounting for predator dynamics: A MICE model

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ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form 3 June 2016
Accepted 5 June 2016
Available online 25 June 2016

Keywords:
Northern anchovy
Brown pelican
California sea lion
California Current
Ecosystem based fisheries management
Harvest strategies
Management strategy evaluation
Pacific sardine

ABSTRACT

An ecosystem approach to forage fish management is required because forage fish support large fisheries, are prey for many valued species in marine food webs, and provide important social and cultural benefits to humans. Complex ecosystem models are often used to evaluate potential ecosystem consequences of forage fish fisheries, but there is seldom sufficient data to parameterize them, and full consideration of uncertainty is impossible. Models of Intermediate Complexity for Ecosystem assessment (MICE) provide a link between full ecosystem models and tactical (usually single-species) models typically used in fisheries management. MICE are ideal tools to form the basis for management strategy evaluations that compare the ability of candidate strategies to achieve goals related to target fisheries and broader ecosystem protection objectives. A MICE model is developed for the California Current Ecosystem (CCE) that focuses on the fishery for the northern subpopulation of Pacific sardine (*Sardinops sajax*) and the indirect impacts of the fishery on place-based predators, in particular brown pelicans (*Pelecanus occidentalis*) and California sea lions (*Zalophus californianus*), in the Southern California Bight. The model includes three forage species (sardine, northern anchovy *Engraulis mordax*, and 'other forage'), an 'other prey' category, and two predator species (brown pelican and California sea lion) and evaluates the impacts of variable forage availability on adult predator reproductive success and survival. Parameterization of the model is based on available monitoring data and assessment outputs. The model is used to assess the ecosystem and fishery consequences of the current sardine management systems for Mexico, the USA, and Canada, with a focus on identifying which among a long list of sources of uncertainty in the system are most consequential for predictions of fishery impacts on predators. Key sources of uncertainty to consider in ecosystem assessments for the CCE are how prey abundance and availability impact predator demography and the extent to which the dynamics of prey populations are driven by environmental factors. Data are available for some of these sources of uncertainty for CCE sardine management, but much uncertainty remains, necessitating exploration of sensitivity to alternative model formulations and parameter values when providing advice on management strategies to decision makers.

1. Introduction

Implementation of harvest control rules that are expected to achieve management goals is considered 'best practice' in fisheries management (FAO, 1996; Punt, 2006; Anon, 2014). Candidate management strategies (combinations of data collection schemes, methods for estimating the inputs for the harvest control rules, and the harvest control rules themselves) can be evaluated in terms of how well they satisfy management objectives using simulation, i.e., by applying the management strategy evaluation (MSE) approach (Smith, 1994; Punt et al., 2016). Management strategies have been broadly evaluated to achieve single-species objectives and, to a lesser extent, multi-species and ecosystem objectives (Punt et al., 2016).

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http://dx.doi.org/10.1016/j.ecolmodel.2016.06.004
0304-3800/

An MSE involves several steps: (a) identification of the management objectives; (b) identification of a broad range of uncertainties to which the management strategy should be robust; (c) development of a set of models (often referred to as 'operating models') that provide a mathematical representation of the system to be managed; (d) specification of the parameters governing the operating model(s); (e) identification of candidate management strategies that could realistically be implemented for the system; (f) application of each management strategy to each operating model using simulation; and (g) summary and interpretation of the performance statistics. Of these steps, (c) and (d) are the most challenging technically because complex multi-species and spatially-explicit operating models require rich and diverse data inputs, which may not be available.

It is necessary, however, for operating models used in MSE to explicitly include ecosystem components if the management objectives include habitat protection, avoiding adverse impacts on threatened and endangered species, or indirect effects of fishery removals on other valued species. To this end, Plagányi et al. (2014) introduced 'Models of Intermediate Complexity for Ecosystem assessments' (MICE). The following ideas underlie MICE: restrict the model to focus on the main management questions under consideration and include properties that advance their use as ecosystem assessment tools. MICE are particularly useful for addressing questions such as the effects of fisheries on predator-prey relationships. For example, MICE have been developed to address the effects of Cape fur seals *Arctocephalus pusillus* on the hake *Merluccius capensis* and *M. paradoxus* fishery off the west coast of South Africa (Punt and Butterworth, 1995), the inter-relationships of a multi-species prawn fishery off northern Australia (Dichmont et al., 2008), impacts of sardine fisheries on African penguins *Spheniscus demersus* (Robinson et al., 2015), and the interaction between crown of thorns starfish *Acanthaster planci* and coral reef ecosystems on Australia's Great Barrier Reef (Morello et al., 2014). The benefit to fisheries decision-making of MICE, as opposed to more complex ecosystem models, is that MICE tend be focused on a single question of interest, rather than whole-of-ecosystem models such as Atlantis (Fulton et al., 2007) and Ecopath with Ecosim (Walters et al., 1997; Pauly et al., 2000) (Plagányi et al., 2014). Furthermore, MICE are computationally simpler, allowing for exploration of a wider range of scenarios and more opportunity to incorporate uncertainty.

The California Current Ecosystem (CCE) off the west coast of North America is a dynamic upwelling system (Checkley and Barth, 2009), with important interactions between fisheries and the ecosystem, especially for small planktivorous pelagic fish such as northern anchovy *Engraulis mordax*[1] and Pacific sardine *Sardinops sagax caerulea;* Clupeidae[2]. The management objectives for these 'coastal pelagic species' (CPS) in the USA include (a) achieving 'optimum yield' (i.e., maximum sustainable yield as reduced by ecological and economic factors), (b) preventing overfishing, and (c) providing adequate forage for dependent species (PFMC, 2011). In relation to (c), sardine and anchovy are preyed on by dozens of upper trophic level predator species (Szoboszlai et al., 2015), including threatened and endangered species (e.g., southern resident killer whales *Orcinus orca*, humpback whales *Megaptera novaeangliae*, marbled murrelet *Brachyramphus marmoratus*, salmon *Oncorhynchus* spp., and yelloweye rockfish *Sebastes ruberrimus*), as well as species exhibiting recent declines in abundance (e.g., brown pelican *Pelecanus occidentalis*). The impact of "bottom-up" climate forcing on sardine and anchovy can be modelled owing to long-term data sets on density of both species, and available data on predator diets through time. Moreover, the management system for anchovy and sardine off the coasts of the USA and Canada is well-established and documented, so a robust MSE can be implemented.

Here, we develop a MICE model for the CCE to evaluate the USA and Canadian sardine harvest control rules and management questions related to the interactions of sardine with anchovy and a selected group of top predators. Although the model structure is general, the focus is on top predators of the Southern California Bight (southern CCE), and in particular the brown pelican for which most of the diet appears to be sardine and anchovy (Szoboszlai et al., 2015) and which have shown breeding failures in many recent years (S.P. Henry, US Fish & Wildlife Service, pers. commn). Our MICE model considers sardine and anchovy, 'other forage' species, 'other prey', and two predators (brown pelicans, and California sea lions *Zalophus californianus*). The information available for modelling purposes differs among species, but parameter values regarding prey species are based on fitting the model to data (c.f., Plagányi et al., 2014), to the extent possible, and parameter values regarding predator species are based primarily on literature values in the absence of formal assessments of these species.

The focus for the current paper is not on conducting a full evaluation of alternative harvest control rules for anchovy and sardine, but rather to understand the consequences of the current USA and Canadian harvest control rules for sardine in terms of the USA management objectives for CPS. Consequently, the paper presents a baseline version of the MICE model, along with several variants that modify its specifications, specifically related to which sources of process error are modelled, the diets of the predators, demographic responses of predators to changes in prey availability, and the dynamics of the prey species, specifically their relationship to environmental drivers. The paper then outlines a set of model outputs that quantify the three major conceptual USA objectives for CPS and summarizes projections for each alternative MICE model formulation to determine how sensitive model outputs are to key model specifications. The results of the projections are then evaluated in terms of which areas of uncertainty have the greatest impact on evaluating harvest control rules for CPS in the CCE. Last, the MICE model is appraised in the context of the suite of modelling tools available for supporting management objectives.

2. Methods

2.1. History of sardine and anchovy fisheries

Pacific sardine is harvested off the coasts of Mexico, the USA, and Canada. The biomass and catch of sardine increased rapidly from the 1930s until the mid-1940s, and declined thereafter. The decline was likely due to a combination of environmental conditions leading to poor recruitment and high fishing mortality rates (Murphy, 1966). Rebuilding began during the 1980s, and by 1991 a directed fishery was re-established in the USA. Sardines were first re-observed in the diets of seabirds off central California in 1992 (Sydeman et al., 2001). The sardine population began to decline again around 2007 (Hill et al., 2015); the Canadian sardine fishery, which had been inconsequential before 1995, ceased in 2013, and the directed fishery in the USA was closed in 2015 because biomass was below the escapement threshold in the harvest control rule. The reason for the decline in abundance was primarily poor recruitment, a result of unfavourable environmental conditions (Hill et al., 2015).

The central subpopulation of northern anchovy is found from northern Baja California to northern California, but is found primarily in the southern California Bight. This subpopulation has been harvested commercially, primarily in the late 1970s and early

[1] Henceforth referred to as 'anchovy'.
[2] Henceforth referred to as 'sardine'.