Deep-Sea Research II 134 (2016) 360–378

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models

Kirstin K. Holsman[a,*], James Ianelli[a], Kerim Aydin[a], André E. Punt[b], Elizabeth A. Moffitt[b,1]

[a] Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Building 4, Seattle, Washington 98115, USA
[b] University of Washington School of Aquatic and Fisheries Sciences, 1122 NE Boat St., Seattle, WA 98105, USA

ARTICLE INFO

Keywords:
Multi-species model
Stock assessment
Fisheries
USA
Alaska Bering Sea
Groundfish
Predator prey
Bioenergetics
Biological reference points

ABSTRACT

Multi-species statistical catch at age models (MSCAA) can quantify interacting effects of climate and fisheries harvest on species populations, and evaluate management trade-offs for fisheries that target several species in a food web. We modified an existing MSCAA model to include temperature-specific growth and predation rates and applied the modified model to three fish species, walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*) and arrowtooth flounder (*Atheresthes stomias*), from the eastern Bering Sea (USA). We fit the model to data from 1979 through 2012, with and without trophic interactions and temperature effects, and use projections to derive single- and multi-species biological reference points (BRP and MBRP, respectively) for fisheries management. The multi-species model achieved a higher over-all goodness of fit to the data (i.e. lower negative log-likelihood) for pollock and Pacific cod. Variability from water temperature typically resulted in 5–15% changes in spawning, survey, and total biomasses, but did not strongly impact recruitment estimates or mortality. Despite this, inclusion of temperature in projections did have a strong effect on BRPs, including recommended yield, which were higher in single-species models for Pacific cod and arrowtooth flounder that included temperature compared to the same models without temperature effects. While the temperature-driven multi-species model resulted in higher yield MBPRs for arrowtooth flounder than the same model without temperature, we did not observe the same patterns in multi-species models for pollock and Pacific cod, where variability between harvest scenarios and predation greatly exceeded temperature-driven variability in yield MBPRs. Annual predation on juvenile pollock (primarily cannibalism) in the multi-species model was 2–5 times the annual harvest of adult fish in the system, thus predation represents a strong control on population dynamics that exceeds temperature-driven changes to growth and is attenuated through harvest-driven reductions in predator populations. Additionally, although we observed differences in spawning biomasses at the accepted biological catch (ABC) proxy between harvest scenarios and single- and multi-species models, discrepancies in spawning stock biomass estimates did not translate to large differences in yield. We found that multi-species models produced higher estimates of combined yield for aggregate maximum sustainable yield (MSY) targets than single species models, but were more conservative than single-species models when individual MSY targets were used, with the exception of scenarios where minimum biomass thresholds were imposed. Collectively our results suggest that climate and trophic drivers can interact to affect MBRPs, but for prey species with high predation rates, trophic- and management-driven changes may exceed direct effects of temperature on growth and predation. Additionally, MBRPs are not inherently more conservative than single-species BRPs. This framework provides a basis for the application of MSCAA models for tactical ecosystem-based fisheries management decisions under changing climate conditions.

Published by Elsevier Ltd.

---

[*] Corresponding author.
E-mail addresses: kirstin.holsman@noaa.gov (K.K. Holsman), jim.ianelli@noaa.gov (J. Ianelli), kerim.aydin@noaa.gov (K. Aydin), aepunt@uw.edu (A.E. Punt), elizabeth@seastarscientificediting.com (E.A. Moffitt).
[1] Present address: Sea Star Scientific Editing, Seattle, WA 98115, USA.

http://dx.doi.org/10.1016/j.dsr2.2015.08.001
0967-0645/Published by Elsevier Ltd.

"Behind these numbers lies, of course, an infinity of movements and of destinies." – von Bertalanffy, 1938

1. Introduction

Increasing global demand for food resources (Delgado et al., 2003) concomitant with climate-driven alterations to marine food webs and declining trends in fisheries catch per unit effort worldwide, suggests little room for fisheries expansion and increased need for efficient and holistic fisheries management approaches (Merino et al., 2012; Worm and Branch, 2012; Link, 2010; Link and Browman, 2014). Ecosystem-based harvest strategies are essential for sustainable fisheries management in a changing and uncertain future (US Commission on Ocean Policy, 2004; MEA, 2005; Murawski and Matlock, 2006; Fogarty, 2014), and of paramount importance is the ability to distinguish fishery impacts from large-scale climate drivers and short-term physical and trophodynamic processes (Murawski and Matlock, 2006; Hollowed et al., 2009, 2013; Gamble and Link, 2012). Ecosystem-based fisheries management (EBFM) has been proposed as a place-based, rather than species-based, management approach (Fogarty, 2014) that can account for fishery effects on food web structure and function, balance biodiversity and yield objectives, and improve management in systems characterized by large seasonal, decadal, and long-term climate variability (Pikitch et al., 2004; Arkema et al., 2006; Link, 2010; Agardy et al., 2011; Levin et al., 2013; Link and Browman, 2014).

A variety of analytical tools have been developed that can address EBFM needs (see reviews in Hollowed et al., 2000, 2009, 2013; Plagányi et al., 2014, Link, 2010, Link and Browman, 2014, Fogarty, 2014). Multi-species statistical catch-at-age models (MSCAA) are an example of a class of multi-species 'Models with Intermediate Complexity for Ecosystem assessments' (i.e., MICE; Plagányi et al., 2014), which have particular utility in addressing both strategic and tactical EBFM questions (Hollowed et al., 2013; Fogarty, 2014; Link and Browman, 2014; Plagányi et al., 2014). MSCAA models may increase forecast accuracy, may be used to evaluate propagating effects of observation and process error on biomass estimates (e.g., Curti et al., 2013; Ianelli et al., 2016), and can quantify climate and trophic interactions on species productivity. As such MSCAA models can address long recognized limitations of prevailing single species management, notably non-stationarity in mortality and maximum sustainable yield (MSY), and may help reduce risk of overharvest (Link, 2010; Plagányi et al., 2014; Fogarty, 2014). Because multispecies biological references points (MBRPs) from MSCAA model are conditioned on the abundance of other species in the model (Collie and Gislason, 2001; Plagányi et al., 2014; Fogarty, 2014), they may also have utility in setting harvest limits for multi-species fleets, evaluating population dynamics in marine reserves or non-fishing areas, and quantifying trade-offs that emerge among fisheries that impact multiple species in a food web (see reviews in Pikitch et al., 2004; Link, 2010; Levin et al., 2013; Link and Browman, 2014; Fogarty, 2014).

Depending on their structure, MSCAA models can be used to evaluate climate- and fisheries-driven changes to trophodynamic processes, recruitment, and species abundance (Plagányi et al., 2014). MSCAA models differ somewhat among systems and species, but most use abundance and diet data to estimate fishing mortality, recruitment, stock size, and predation mortality simultaneously for multiple species in a statistical framework. Similar to age structured single species stock assessment models widely used to set harvest limits, MSCAA models are based on a population dynamics model, the parameters of which are estimated using survey and fishery data and maximum likelihood methods (e.g., Jurado-Molina et al., 2005; Kinzey and Punt, 2009; Van Kirk et al., 2010; Kempf et al., 2010; Curti et al., 2013; Tsehaye et al., 2014). Unlike most single-species models, MSCAA models additionally separate natural mortality into residual and annually varying predation mortality, and model the latter as a series of predator-prey functional responses. Thus, natural mortality rates for each species in MSCAA models depend on the abundance of predators in a given year and vary annually with changes in recruitment and harvest of each species in the model.

MSCAA models have specific utility in quantifying direct and indirect effects of fisheries harvest on species abundance and size distributions (see reviews in Hollowed et al., 2000a, 2013; Link, 2010; Fogarty, 2014; Link and Browman, 2014; Plagányi et al., 2014), which is important for EBFM and trade-off analyses of various management strategies. Rapidly shifting climate conditions are also of growing concern in fisheries management as changes in physical processes are known to influence individual growth, survival, and reproductive success of fish and shellfish (Hanson et al., 1997; Kitchell et al., 1977; Morita et al., 2010; Hollowed et al., 2013, Cheung et al., 2015). Climate-driven changes in water temperature can directly impact metabolic costs, prey consumption, and somatic or gonadal tissue growth, with attendant indirect effects on survival, production, and sustainable harvest rates (e.g., Hanson et al., 1997; Morita et al., 2010, Cheung et al., 2015). Temperature-dependent predation, foraging, metabolic, and growth rates are common in more complex spatially-explicit food web or whole of ecosystem models such as GADGET (e.g., Howell and Bogstad, 2010; Taylor et al., 2007), Atlantis (e.g., Fulton et al., 2011; Kaplan et al., 2012, 2013), and FEAST (Ortiz et al., 2016). Temperature functions for growth and predation can also be incorporated into MSCAA models, allowing this class of models to be used to evaluate interacting climate, trophodynamic, and fishery influences on recommended fishing mortality rates.

Numerous studies point to the importance of using multi-species models for EBFM (see review in Link, 2010). Multi-species production models produced different estimates of abundances and harvest rates than single species models for Northeast US marine ecosystems (Gamble and Link, 2009; Tyrrell et al., 2011), and MSY of commercial groundfish stocks estimated from aggregated production models are different than the sum of MSY estimates from single-species assessments (Mueter and Megrey, 2006; Gaichas et al., 2012; Smith et al., 2015). Multi-species models have been used to demonstrate long-term increases in yield of Icelandic stocks of Atlantic cod (*Gadus morhua*) and reductions in capelin (*Mallotus villosus*) and Northern shrimp (*Pandalus borealis*) catch associated with short-term decreases in cod harvest (Danielsson et al., 1997). Kaplan et al. (2013) demonstrated the disproportionately large ecosystem impacts of applying the same Fx% (e.g., Fx%, or the harvest rate that reduces spawning stock biomass to *x*% of unfished spawning stock biomass, SSB_0; Caddy and Mahon, 1995; Collie and Gislason, 2001) harvest control rule approach to forage fish as is used for groundfish in the northeast Pacific, and trophodynamics in a southern Benguela ecosystem resulted in higher carrying capacity for small pelagic species under fishing (versus no-fishing) scenarios (Smith et al., 2015).

Since natural mortality and recruitment rates in a MSCAA model are conditioned on harvest rates of predators in the model, an ongoing area of research is evaluating MSCAA model analogs to single-species biological reference points (see Moffitt et al., 2016), such as harvest rates that correspond to maximum yield (F_{MSY}) or proxies thereof (e.g., Fx%). Other multi-species models have been used to derive and evaluate MBRPs, although these have largely focused on MSY (e.g., Kaplan et al., 2013; Smith et al., 2015). A notable exception is Collie and Gislason (2001), who evaluated a variety of MBRPs using a multi-species, virtual population analysis and found MBRPs to be sensitive to variation in natural mortality