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When are estimates of spawning stock biomass for small pelagic fishes improved by taking spatial structure into account?

André E. Punt[a,*], Daniel K. Okamoto[a,b], Alec D. MacCall[c], Andrew O. Shelton[d], Derek R. Armitage[e], Jaclyn S. Cleary[f], Ian P. Davies[g], Sherri C. Dressel[h], Tessa B. Francis[i], Phillip S. Levin[g,j], R. Russ Jones[k], Harvey Kitka[l], Lynn Chi Lee[m], Jim A. McIsaac[n], Melissa R. Poe[d,o], Steve Reifenstuhl[p], Jennifer J. Silver[q], Jörn O. Schmidt[r], Thomas F. Thornton[s], Rudiger Voss[r], John Woodruff[t]

[a] School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA
[b] Department of Biological Sciences, Florida State University, USA
[c] Farallon Institute for Advanced Ecosystem Research, 101 H. Street, Suite Q., Petaluma, CA, 94952, USA
[d] Northwest Fisheries Science Center, National Marine Fisheries Service, 2725 Montlake Boulevard East, Seattle, WA 98112, USA
[e] School of Environment, Resources and Sustainability, University of Waterloo, Waterloo, ON N2L 3G, Canada
[f] Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, Canada
[g] School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195, USA
[h] Division of Commercial Fisheries, Alaska Department of Fish and Game, Juneau, AK 99811, USA
[i] Puget Sound Institute, University of Washington Tacoma, Tacoma, WA, 98421, USA
[j] Nature Conservancy in Washington, 74 Wall St., Seattle, WA, 98121, USA
[k] Haida Oceans Technical Team, Council of the Haida Nation, PO Box 98, Queen Charlotte, BC V0T 1S1, Canada
[l] Sitka Tribe of Alaska, Sitka, AK 99835, USA
[m] Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site, Canada
[n] T. Buck Suzuki Foundation, Victoria, BC V8Z 4B8, Canada
[o] Washington Sea Grant, University of Washington, Seattle WA 98105, USA
[p] Northern Southeast Regional Aquaculture Association, Sitka, AK 99835, USA
[q] Department of Geography, University of Guelph, 50 Stone Road East, Guelph, ON, N1G 2W1, Canada
[r] Sustainable Fisheries, Department of Economics, Kiel University, 24118 Kiel, Germany
[s] Environmental Change Institute, School of Geography & the Environment, University of Oxford, Oxford OX1 3QY, UK
[t] Icicle Seafoods Inc., 4019 21st Ave. W, Seattle, WA 98199, USA

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ABSTRACT

A simulation-estimation approach is used to evaluate the efficacy of stock assessment methods that incorporate various levels of spatial complexity. The evaluated methods estimate historical and future biomass for a situation that roughly mimics Pacific herring *Clupea pallasii* at Haida Gwaii, British Columbia, Canada. The baseline operating model theorizes ten areas arranged such that there is post-recruitment dispersal among all areas. Simulated data (catches, catch age-composition, estimates of spawning stock biomass and its associated age structure) generated for each area are analyzed using estimation methods that range in complexity from ignoring spatial structure to explicitly modelling ten areas. Estimation methods that matched the operating model in terms of spatial structure performed best for hindcast performance and short-term forecasting, i.e., adding spatial structure to assessments improved estimation performance. Even with similar time trajectories among sub-stocks, accounting for spatial structure when conducting the assessment leads to improved estimates of spawning stock biomass. In contrast, assuming spatial variation in productivity when conducting assessments did not appreciably improve estimation performance, even when productivity actually varied spatially. Estimates of forecast biomass and of spawning stock biomass relative to the unfished level were poorer than estimates of biomass for years with data, i.e., hindcasts. Overall, the results of this study further support efforts to base stock assessments for small pelagic fishes on spatially-structured population dynamics models when there is a reasonable likelihood of identifying the sub-stocks that should form the basis for the assessment.

* Corresponding author.
E-mail address: aepunt@uw.edu (A.E. Punt).

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1. Introduction

Management strategies for many of the world's major fisheries are based on model-based harvest control rules (HCRs), which use the outputs from stock assessments that fit population dynamics models to available monitoring data (e.g., IWC, 2012). Population dynamics models that underlie these stock assessments range from those that consider only sex- and age-aggregated measures of biomass (e.g., ASPIC, Prager, 1992, 1994, 2002) to those that consider the sex, age, stage and spatial structure of the fished population (e.g., Stock Synthesis, Methot and Wetzell, 2013; MULTIFAN, Fournier et al., 1998). The type of model used for a stock assessment depends, *inter alia*, on the model outputs needed to apply the HCR, and on the available data, especially regarding the age and sex structure of the population.

Few stock assessments are currently based on population dynamics models that attempt to capture the spatial structure of fish or invertebrate populations, and those that do seldom involve a large number of spatial areas (2–3 is most common; Punt, in press). The main reason for this is that including a large number of areas in a population dynamics model can increase the complexity of the model and hence the number of estimable parameters. Most assessment analysts follow the principle of parsimony, and thus select simple models with few parameters to minimize the perceived variance of the estimates of the model outputs. Another oft-mentioned reason for not adopting spatially-structured stock assessments is lack of tagging data that would provide information about movement rates (A.E. Punt, pers. obs). Unfortunately, it is well known that ignoring spatial structure or assuming the incorrect spatial structure when applying a spatially-structured stock assessment can lead to biased (and often very imprecise) estimates of key model outputs, including estimates of spawning stock biomass, fishing mortality and recruitment (in absolute terms and relative to biological reference points) (e.g., Punt and Methot, 2004; Fu and Fanning, 2004; Cope and Punt, 2011; Garrison et al., 2011; Dougherty et al., 2013; Guan et al., 2013; Martien et al., 2013; Benson et al., 2015; Goethal et al., 2015; McGilliard et al., 2015; Punt et al., 2015). Furthermore, HCRs based on biased or imprecise stock assessments can result in unintended ecological, economic, and social consequences (Punt et al., 2016).

Of the few spatially-structured stock assessments that have been developed, most have been applied to relatively long-lived species such as groundfish and tunas (but see Dichmont et al., 2006; O'Neil et al., 2014; De Moor and Butterworth, 2015). Small pelagic species (e.g., sardines, anchovies, herrings) form the basis for some of the world's largest fisheries. However, with the exception of Cunningham et al. (2007) and de Moor and Butterworth (2015), pelagic species have not been assessed using spatially-structured methods of stock assessment. Ignoring spatial structure in management decision making for Pacific herring *Clupea pallasii* has been a concern among local and traditional knowledge holders in North Pacific communities where concentrated commercial fishing takes place on increasingly condensed spawning stocks (e.g., of herring for roe) considered critical for subsistence, trade, and other uses (Jones, 2000; Powell, 2012; Thornton et al., 2010; Thornton and Kitka, 2015; Levin et al., 2016). Further, commercial fishers and shoreworkers have identified several imperatives for Pacific herring management, including the need to build a collaborative understanding of the state of herring in its shared ecosystem,[1] with the hope that this will better acknowledge the livelihoods and fishing communities that depend on the herring fishery. This understanding could include appropriately accounting for spatial structure in stock assessments.

Spatial structure in small pelagic fishes exists at both large and small spatial scales. For example, the range of the northern subpopulation of Pacific sardine (*Sardinops sagax*) changes as a function of biomass and/or environmental conditions (e.g., Clark and Janssen, 1945); if ignored, this has been shown to lead to biased estimates of management-related quantities, including biomass (Hurtado-Ferro et al., 2014). Our paper focuses on relatively small-scale (10–100 s of km rather than 100 s–1000 s of km) spatial structure, with a focus on Pacific herring in British Columbia, Canada. The distribution and abundance of Pacific herring has varied substantially even within conventional 'stock areas' during the era of modern fisheries management. Nevertheless, current British Columbia herring stock assessments are based on the assumption that it is valid to pool data into five major and two minor stocks (Benson et al., 2015). Beyond the performance of stock assessment models, mismatches between the scales of observed or perceived population structure and aggregations used in assessment models can have consequences throughout the social-ecological system, including loss of trust in management bodies and conflict, in part because of the fine spatial scale at which traditional herring harvest practices occur (Levin et al., 2016). Problems of mismatch or fit among institutions of governance and social-ecological contexts are recognized more broadly as an enduring problem in the resource management literature (e.g., Epstein et al., 2015).

This paper uses a simulation-estimation approach to evaluate the consequences, in terms of the bias and precision of estimates of historical and projected spawning stock biomass, of various approaches to the assessment of stocks of short-lived fishes that exhibit spatial structure, based on the biological characteristics of Pacific herring at Haida Gwaii, British Columbia, Canada. Management for Pacific herring at Haida Gwaii is based on biomass estimates projected beyond the last year with data. Thus, the quantities used to evaluate estimation performance in this study include estimates of historical spawning stock biomass ('hindcast estimates') and projected biomass.

This paper aims to improve the basis for conducting stock assessments for small pelagic species, such as Pacific herring. Consequently, the key questions the analyses address are: (a) Are estimates of spawning stock biomass unbiased and precise (i.e., on average do the estimates equal the true values and is there little variation in estimates among replicate simulations) if the structure of the estimation method matches that of the spatially-explicit operating model? (b) How poor are the estimates of spawning stock biomass if the spatial structure of the operating model and estimation method differ? (c) How much spatial structure in the estimation method is sufficient to overcome any bias? and (d) How robust are the conclusions to key assumptions of the operating model, including the sample sizes for the data available for assessment purposes?

2. Materials and methods

2.1. Overview

An operating model is used to generate simulated data sets based on various specifications for the underlying system being assessed, including the number of 'sub-stocks'[2] (Table 1). It is spatially-structured and roughly mimics the population dynamics and fishery for Pacific herring (e.g., post-recruitment dispersal among sub-stocks, a fishery directed toward spawning fish only, and the possibility that an entire sub-stock skips spawning in a particular year). It includes multiple sub-stocks that are linked through dispersal. The generated data sets are analyzed using stock assessment methods (estimation methods) that range in the degree to which the assumptions of population structure match those of the operating model, from matching exactly to being

[1] See for example the open letter from the United Fisherman and Allied Workers Union to the Nuu-chah-nulth Tribal Council and British Columbia commercial herring fishermen (https://www.hashilthsa.com/news/2015-01-08/support-united-fisherman-and-allied-workers-union-herring-fishery).

[2] The term "sub-stock" is used here as these populations are neither demographically nor genetically distinguished.