Fisheries Research 158 (2014) 102–115

Contents lists available at ScienceDirect

Fisheries Research

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

Use of multiple selectivity patterns as a proxy for spatial structure

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ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form 3 October 2013
Accepted 7 October 2013
Available online 10 November 2013

Keywords:
Spatial structure
Selectivity
Stock assessment
Stock Synthesis
Pacific sardine

ABSTRACT

There is widespread recognition that spatial structure is important for fisheries stock assessment, and several efforts have been made to incorporate spatial structure into assessment models. However, most studies exploring the impact of ignoring spatial structure in stock assessments have developed population models with multiple subpopulations, rather than exploring the impact spatial dynamics may have on performance of non-spatially structured assessment methods. Furthermore, the data available for stock assessments usually do not include tagging or other data necessary to estimate movement rates. One solution to this problem is to include several fleets, each with a different selectivity pattern to represent availability, within a spatially-aggregated assessment method. In this study, the impacts of ignoring spatial structure, and the effectiveness of using multiple selectivity patterns as a proxy for spatial structure, are evaluated for the northern subpopulation of Pacific sardine (or California sardine; *Sardinops sagax*). A spatially-explicit operating model is used to explore three spatial factors: the existence of size-dependent seasonal migrations across large geographical areas, the influx of another stock into the area of the assessed stock, and the occurrence of recruitment outside the area where it is assumed to occur. Two other factors related to data were evaluated: data availability and data collection design. The assessment model (AM) is based on the 2010 stock assessment for Pacific sardine, implemented in Stock Synthesis, and includes two seasons per year and six fleets, each with a different selectivity pattern. Ignoring spatial structure is found to negatively impact estimation performance, with seasonal movement having the largest impact. The AM compensates for ignoring movement and spatial structure by adjusting the selectivity patterns, but selectivity alone is not able to account for all biases caused by spatial structure.

1. Introduction

There is widespread recognition that acknowledging spatial structure is important for fisheries stock assessment (Cadrin and Secor, 2009), and several efforts have been made to incorporate spatial structure into assessment models (e.g., Booth, 2000; Goethel et al., 2011). However, most studies exploring the impact of ignoring spatial structure in stock assessments have dealt with complex stock structure and multiple subpopulations (e.g., Cadrin and Secor, 2009; Ying et al., 2011), rather than the impact spatial dynamics may have on estimation ability.

Different ways to incorporate spatial structure into stock assessments have been described in the literature. One of the first examinations of spatial structure involved a box-transfer model, i.e., a discrete approximation to a dispersion model (Beverton and Holt, 1957). This model was expanded to make use of tagging data in an application for skipjack tuna, *Katsuwonus pelamis* (Sibert, 1984), and later for parameter estimation to be based on maximum likelihood estimation, with the tagging data being assumed to be Poisson-distributed (Hilborn, 1990). With increasing computing power, more complex models were developed, such as advection–diffusion-reaction models (Sibert et al., 1999), and MULTIFAN-CL (Fournier et al., 1998), which fully integrates advection–diffusion processes into a length-based, age-structured model. Some of these models have been expanded into tag-integrated models (e.g., Hampton and Fournier, 2001). Models integrating spatial structure have also allowed for varying population structure, ranging from a single-species in multiple areas (e.g., Fournier et al., 1998; Methot and Wetzel, 2013), to metapopulation models (e.g., Porch et al., 2001), to discrete, but potentially overlapping populations (Punt et al., 2000; Taylor et al., 2009).

Despite the attention given to spatial structure in stock assessments in the literature, most fisheries lack the tagging data required to parameterize models of spatial dynamics explicitly. Thus, it is increasingly common to approach spatial structure in stock assessments by dividing the geographical area where the stock is distributed into spatial strata, and treating the data from each stratum as coming from a different fleet (e.g., Cope and Punt,

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http://dx.doi.org/10.1016/j.fishres.2013.10.001

2011; Berger et al., 2012). This ‘fleets-as-areas’ approach makes the implicit assumption that the stock is homogeneously distributed across its range, and that any differences in age or length compositions are due to ‘gear selectivity’, even if ‘true’ gear selectivity may actually not differ spatially, but the proportion of the population by length differs among areas. Although this approach has been used to address spatial structure across a stock’s geographical range, the same considerations apply to a stock for which the population age or length structure differs with depth.

Here, we evaluate the effects on the estimation performance of a stock assessment of treating the complex spatial dynamics of a single stock as multiple fleets. The northern subpopulation of Pacific sardine (or California sardine; *Sardinops sagax*) is used as a case study. A spatially-explicit operating model (OM) is used to explore three spatial factors: the existence of size-dependent seasonal migrations across a large geographical area, the influx of another stock into the area of the assessed stock, and the occurrence of recruitment outside the area where it is assumed to occur. The effects of these factors on the estimation of biomass and other parameters of interest are evaluated, with special focus given to selectivity.

The northern subpopulation of Pacific sardine currently supports the second largest federally-managed fishery off the U.S. west coast, and Pacific sardine has, at times, been the most abundant fish species in the California Current system (Hill et al., 2010). In addition, sardine are forage for a wide variety of species, including those that are of considerable commercial value, such as tunas and Pacific whiting, and those that are listed as overfished (e.g., rockfish spp.) or threatened (e.g., salmon and several species of marine mammals). The population dynamics and ecological role of this subpopulation have been studied intensively since the 1930s (e.g., Clark and Marr, 1953; Murphy, 1966). It is generally accepted that sardines off the West Coast of North America consists of three subpopulations or ‘stocks’. A northern subpopulation (northern Baja California to Alaska), a southern subpopulation (outer coastal Baja California to southern California), and a Gulf of California subpopulation were distinguished on the basis of serological techniques (Vrooman, 1964) and in a study of temperature-at capture (Felix-Uraga et al., 2004, 2005). Although the ranges of the northern and southern subpopulations overlap, the adult spawning stocks may move north and south in synchrony and hence not overlap significantly (Hill et al., 2010).

The conventional model of the dynamics of the northern subpopulation of Pacific sardine is that it concentrates in a “core” area off southern California and northern Mexico during periods of low abundance, but expands its range to the north during periods of high abundance. Recent stock assessments of the northern subpopulation of Pacific sardine have been based on the assumption that sardines are fully-mixed from northern Baja California to British Columbia, but that fishery selectivity differs among Mexico, California, and the Pacific Northwest. However, historical tagging data for Pacific sardine (Clark and Janssen, 1945), and contemporary catch length-frequency data (Lo et al., 2010) suggest that the large animals generally migrate northward during spring and return southward during fall so while selectivity may differ spatially, differences in catch length-compositions also reflect differences in availability. It has also been postulated that sardine subpopulations along the west coast of North America have specific temperature affinities, that their seasonal and interannual distributions are limited, in part, by the upper and lower temperature bounds for each respective group, and that the southern subpopulation could be entering the area usually assumed inhabited by the northern subpopulation at some times during the year (Smith, 2005; Felix-Uraga et al., 2005). The 2010 assessment for this stock (Hill et al., 2010) was based on the package Stock Synthesis 3 (SS) (Methot and Wetzel, 2013).

A simulation study is therefore used to determine the ability to estimate biomass at the start of 2011 (the 2011 biomass). The management decisions for sardine are based on a harvest control rule that uses an estimate of the size of the age 1+ component of the population at the start of the current fishing season (the 1+ biomass) and a level of fishing mortality that, until 2010, depended on the temperature at Scripps Pier to determine a harvest guideline (PFMC, 1998).

2. Materials and methods

2.1. Overview

An operating model (OM), developed and parameterized based on the 2010 Pacific sardine stock assessment (Hill et al., 2010), is used to generate data under various hypotheses regarding population structure and other factors. These data are used in simulated applications of the stock assessment procedure (AM), which is based on SS. SS (Methot and Wetzel, 2013) is a state-of-the-art statistical framework for conducting stock assessments for marine fisheries management. It is based on an age population dynamics model and can represent several sub-areas. Fishery and index selectivity can be represented as age-specific or size-specific, with the ability to capture the major effects of size-specific survivorship. Parameters are estimated to maximize goodness-of-fit.

The OM is a spatially-structured population dynamics model that allows for multiple sub-stocks and regional growth (see Appendix A for full model specification). Specifically, it includes the four main regions (northern Baja California, southern California, northern California, and the Pacific Northwest (PNW)) on which fishery management for the northern subpopulation is based, but is constructed with a fine spatial resolution (i.e., as a 2° one-dimensional grid) to allow recruitment and movement dynamics to be tracked at a fine scale (Fig. 1). The OM assumes that the northern subpopulation is composed by two growth morphs (i.e., two sub-stocks); one morph is migratory and the other is resident to the area between northern Baja California and central California. Biological parameters (natural mortality, growth, maturity and fecundity) are the same for the two morphs, and recruitment is allocated evenly to each morph. The southern subpopulation is not modeled explicitly (i.e., its population dynamics are not modeled, and its age- and length structure is assumed to be the same as that of the component of the northern subpopulation in the Ensenada area). Rather, the OM allows for the occasional presence of the southern subpopulation in the modeled area (so that catches off northern Baja California and southern California sometimes include animals from both the northern and southern subpopulations). The probability of the presence of the southern subpopulation in waters normally associated with the northern subpopulation is modeled as a function of sea surface temperature, SST. The values for the parameters of the OM are based on the 2010 stock assessment, along with the results of additional, more local, data on abundance (e.g., Emmett et al., 2005; Lo et al., 2010).

The OM keeps track of the number of animals by week, age, length, and location. The population is modeled at this level of resolution not only to be able to adequately capture migration during the year, but also so that the data used for assessment purposes can be generated in a realistic manner. These data are: (a) samples of the age and length structure of the catches for each of the fisheries, aggregated to “season” (6 month semester) for consistency with how such data are used in actual assessments of Pacific sardine, (b) indices of spawning stock biomass based on the daily egg production model (e.g., Lo, 2008), and (c) estimates of abundance for the component of the population between Point Conception and the Canadian border which mimic the outcomes from aerial