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Forecasting herring biomass using environmental and population parameters

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ABSTRACT

Forecasting abundance and understanding year class strength is key to the ecosystem-based fisheries management of herring and other small pelagic fish. Using the San Francisco Bay herring population, we tested the hypothesis that abundance (spawning stock biomass; SSB) could be predicted prior to the commencement of annual fisheries using estimates of i) previous SSB (SSB_{lag1}), ii) young-of-the-year production (YOY), and iii) environmental conditions. A time series model including SSB_{lag1}, YOY lagged 3 years (YOY_{lag3}), and environmental conditions in the season before spawning explained 67% of the variance in annual biomass, with better predictive error in comparison with simpler models. YOY_{lag3} was by far the strongest predictor. It was robust over the entire study period (1980–2017) and also for a more limited period (1991–2017) when observed variance in SSB increased. We attribute the predictive power of YOY productivity to age structure, as almost 70% of the population is comprised of young fish. We hypothesize that an age truncation effect, probably resulting from a combination of long-term environmental effects and fisheries impacts, supports this model, which effectively predicts year class strength. Assuming the population age structure remains the same in the future, our model provides management with an early warning indicator of upcoming SSB with a 3-year lead, which could be applied in harvest control rules.

1. Introduction

Since the early days of fisheries oceanography, one of the principal goals has been to understand and predict population fluctuations of small pelagic fish relative to production, recruitment, and ocean conditions (Hjort, 1914; Freon et al., 2005; Watanabe, 2007). Though hundreds of studies on fish production and recruitment have been conducted on a wide diversity of species, our ability to forecast small coastal pelagic fish populations is fraught with issues, including weak to non-existent stock-recruitment relationships (e.g., Stocker and Noakes, 1988) and non-stationary relationships (Myers, 1998). Today, with the confounding effects of fisheries removals, which may exacerbate effects of ocean conditions (Essington et al., 2015), and climate change, which may cause fish redistributions (reviewed by Poloczanska et al., 2013), the challenge of prediction has become both more acute and urgent. Understanding how marine climate impacts future abundance is fundamental to stock assessment and designing and implementing appropriate harvest control rules (Lindegren et al., 2010; Hollowed et al., 2013). In particular, a combination of environmental or fisheries-related changes to population age structure may result in unexpected consequences for production, recruitment, and population dynamics (Anderson et al., 2008).

Owing to their neritic distribution and centurial history of exploitation (e.g., Cushing, 1961), herring have been the focal point of dozens of observational and modeling studies seeking to understand and predict variation in abundance for management purposes. In northern Europe, herring have been exploited since the 10th century, and time series research on landings clearly shows decadal-scale fluctuations in abundance relative to various interrelated meteorological and hydrographic variables (Alheit and Hagen, 1997). Similar relationships in herring abundance, growth, and size-at-age have been established at interannual time scales using observations (e.g., Williams and Quinn, 2000a,b; Beamish et al., 2004; Cardinale et al., 2009) and models (e.g., Hay et al., 2008; Rose et al., 2008; Ito et al., 2015). In the northeastern Pacific, Pacific herring (*Clupea pallasii*) are important for fisheries and food chains (Beamish et al., 2004; Szoboszlai et al., 2015). A recent meta-analysis of herring population trends and variability in the California Current Ecosystem (CCE) showed a secular decline in biomass estimates since 1980 for many stocks along the U.S. west coast, but data were limited to a ~30-year period (Thompson et al., 2017).

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Table 1
Environmental and herring population data used in this study. Period of data, resolution, location/region and source are specified.

Data	Label	Period	Location	Units	Temporal resolution	Source
Herring						
Spawning stock biomass	SSB	1980–2016	SFB	Kmt	Seasonal sum across months Dec–Mar, upscaled from eggs to Kmt	CDFW, Herring Management Program
Trawl CPUE Age-0, Age-1, and Age-2+	YOY, Age-1, Age-2+	1980–2015	SFB	Number of fish	Seasonal average over several months, Age-0: Apr–Oct, Age-1: Feb–Apr, Age-2+: Dec–Mar.	CDFW, San Francisco Bay Study/Interagency Ecological Program for San Francisco Estuary
Herring Condition Index	HCI	1984–2015	SFB	No units	Seasonal average of Fulton's K across winter months	CDFW, ABMP/HMR
Environmental						
Midwater trawls temperature and salinity	Trawl-T Trawl-S	1980–2016	35 stations throughout SFB	°C, PSU	3-month running averages, over 9 months each year	CDFW, San Francisco Bay Study/Interagency Ecological Program for San Francisco Estuary
Sacramento River Delta outflow	Outflow	1996–2016	SFB	Acre-ft.	3-month running average	California Department of Water Resources
Farallon Islands sea surface salinity	Far-SSS	1979–2015	Gulf of the Farallones	PSU	3-month running average	SIO, Shore Station Program
Buoy N26 sea surface temperature	N26-SST	1982–2015	37.8°N, 122.8°W	°C	3-month running average	National Data Buoy Center/National Oceanic and Atmospheric Administration (NOAA)
Bakun Upwelling Index	BUI	1979–2015	39°N	$m^3/s/100m$	3-month running average	Pacific Fisheries Environmental Laboratory/NOAA
Multivariate El Niño Southern Oscillation Index	MEI	1979–2015	Tropical Pacific	No units	3-month running average	Earth System Research Laboratory/NOAA
Pacific Decadal Oscillation	PDO	1979–2015	North Pacific	No units	3-month running average	Joint Institute for the Study of the Atmosphere and Ocean, University of Washington
North Pacific Gyre Oscillation	NPGO	1979–2015	North Pacific	No units	3-month running average	E. Di Lorenzo
Multivariate Ocean Climate Indicator	MOCI	1979–2015	Central California (34.5–38°N)	No units	Seasonal value for winter, spring, summer, and fall	Farallon Institute

Notably, in the same study, stocks along the Canadian west coast studied over a longer period (~60 years) demonstrated decadal-scale variability.

At the southern-most end of its range in the northeast Pacific, the San Francisco Bay (SFB) herring stock biomass has become more variable through time (Thompson et al., 2017), but nonetheless remains relatively large compared to other stocks in the CCE south of British Columbia (Siple and Francis, 2016). Variability in the SFB spawning stock biomass (SSB) is poorly understood, with occasional biomass levels low enough to trigger fisheries closures (e.g., 2009–2010; CDFW, 2017a). From November–March, adult herring enter SFB and spawn in the shallow subtidal habitats of the shoreline. Upon hatching, larval fish develop in the bay; juveniles typically migrate to the ocean in September–October (Fish et al., 2012). Management of the fishery on this stock includes the following data collections: 1) annual fall-winter surveys of spawning and egg deposition, conducted by California Department of Fish and Wildlife (CDFW), which are subsequently scaled up to estimate standing stock biomass, 2) monthly mid-water trawl surveys of reproductive output by CDFW to estimate production of young-of-the-year (YOY) (Feyrer et al., 2015), and 3) an annual general assessment of ecosystem conditions before each spawning season (CDFW, 2017a). A variety of regional measurements of environmental conditions within SFB and in the adjacent ocean are collected during monthly CDFW surveys, including measurements of temperature and salinity. Other related environmental factors are available for synthesis, including regional to large-scale ocean climate indicators. García-Reyes and Sydeman (2017) synthesized many of these indicators into seasonal Multivariate Ocean Climate Indicators (MOCI). MOCI couple the shared variation in basin-scale drivers, such as the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO), with regional oceanographic processes such as upwelling (e.g., Bakun upwelling index) and local oceanic responses (e.g., temperature and winds).

We took a broad exploratory approach to understanding potential environmental and biological predictors of the SFB herring population. An exploratory approach was needed because prediction of population fluctuations was a key goal of the study and both basin-scale and regional environmental drivers are known to affect fish, seabirds, and marine mammals of the central-northern California Current (e.g., Thompson et al., 2012; García-Reyes et al., 2013; Sydeman et al., 2014). We therefore surmised that herring would be similarly responsive to drivers at multiple temporal and spatial scales. Moreover, it is well known that environmental conditions within and outside SFB, in the Gulf of the Farallones and even further afield, may strongly covary (Cloern et al., 2010; Feyrer et al., 2015). Consequently, we test a general hypothesis that lagged ocean conditions and herring productivity can be used to predict fluctuations in the SFB herring population. We expected herring biomass to be positively related to herring productivity, lagged 2 or 3 years to the year in question and assuming that higher productivity resulted in higher recruitment and higher biomass. We expected herring biomass to be positively correlated with regional upwelling and associated features (cold temperatures, high ocean salinity, negative PDO/positive NPGO). We did not have *a priori* expectations concerning other features of the environment such as outflow of freshwater into SFB, nor SFB temperature and salinity. To test this hypothesis, we integrated herring population data with information on bay and ocean conditions. This study is designed to contribute to a new fisheries management plan (FMP) for the SFB herring fishery under development by the State of California in partnership with commercial fishers and the conservation community. Forecasting tools are needed for SFB herring abundance assessments, management strategy evaluation, and in application of harvest control rules that may be designed to maintain escapement and productivity as well as the trophic role of herring in the coastal ecosystem (Rice and Duplisea, 2014).