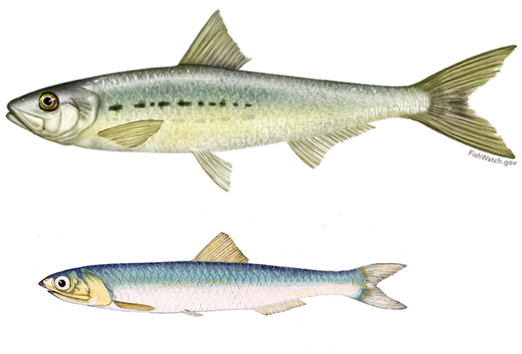

Mechanistic population projections for sardine and anchovy in the California Current under ocean warming and changing food availability

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The combined impacts of different environmental drivers and fisheries to the population dynamics of marine fish stocks remain incompletely understood. In the California Current, contrary to traditional expectations, after recent warm ocean conditions Pacific sardine (*Sardinops sagax*) remains at low biomass, while Northern anchovy (*Engraulis mordax*) has increased substantially.

We developed process-based population models for sardine and anchovy driven by high-resolution ocean-biogeochemical models, simulating early life stage survival and offshore transport, food availability for larvae and adults, predation, migration and egg production. An ensemble model configuration set fit to observations is used to identify response mechanisms, quantify ecological uncertainty, and project stocks under three downscaled earth system models (ESM).

The ensembles reproduce the last boom-and-bust of sardine and the recent resurgence of anchovy. Ensemble projections show a likely sardine recovery to early 2000's abundance and catch by mid-century, driven by increasing recruitment success under warming temperatures. A long-term anchovy increase is prevented by low egg production under decreasing food availability. Ecological uncertainty is of similar magnitude as divergence among ESMs.

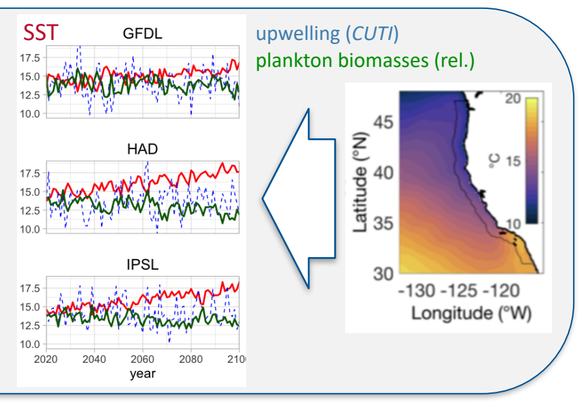
This work advances understanding of the combined impacts of multiple drivers on fish population dynamics, abundance and distribution under novel environmental conditions, and quantifies sources of uncertainty in linking to regional ocean models, helping to develop climate-responsive fisheries management strategies under both climate variability and change.

Observational data

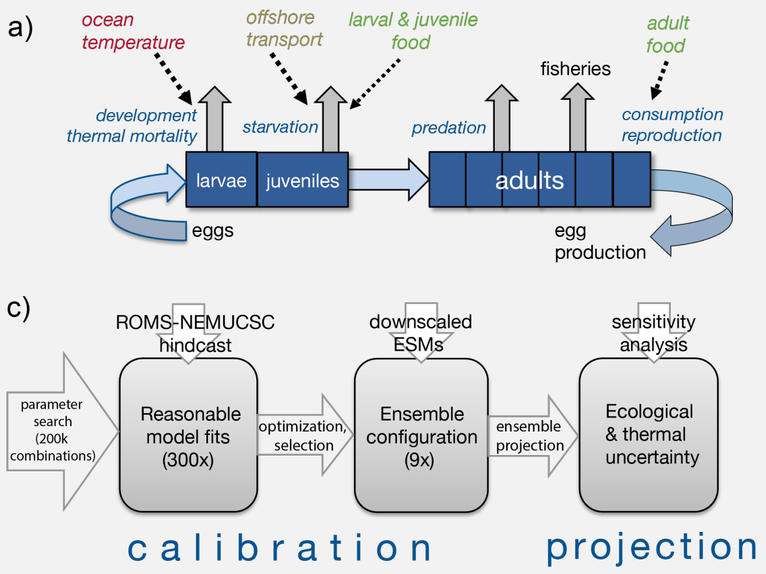
- Egg and larval distribution from CalCOFI (*California Cooperative Oceanic Fisheries Investigations*), and NOAA acoustic trawl surveys are used to define spawning and adult feeding areas
- Sardine model fit to no.-at-age and catch-at-age from a long-term stock assessment model (*Kuriyama et al.*)
- Anchovy model fit to multiple survey time series: *Rockfish Recruitment & Ecosystem Assessment Survey,* California sea lion diet data *(Curtis et. al)* and *CalCOFI* eggs and larvae

Regional ocean & plankton model input

- *NEMUCSC* ROMS-biogeochemical model output (*oceanmodeling.ucsc.edu*), aggregated into 24 spatial zones (**b.**):
  - Hindcasts with physical data-assimilation 1980-2019 for fitting
  - Downscaled projections to 2100 from 3 ESMs (CMIP5; right fig.) with different rates of warming and changes in plankton biomass, under RCP 8.5 emissions (*Pozo Buil et al. 2021*)
- SST, upwelling strength (*Jacox et al. 2018*) and 5 plankton compartments drive biological processes in sardine and anchovy populations (**a.**)



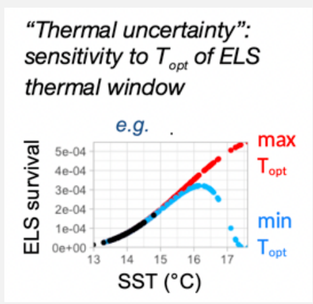
Population model (*Model of Intermediate Complexity*)



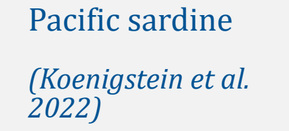
Calibration & projections

- Ensemble configurations: A wide range of different parameter combinations that produce good model fits during the historical period are used to estimate ecological uncertainty (**c.**)
- Sardine stock boom-and-bust during 1980-2020 reproduced, recent lack of recovery explained by low food (testing period 2011-18)
- Recent anchovy resurgence explained by temporary period of increased egg production (2010-2013)

- Projections start 2020 from actual abundance estimates; years do not predict actual years due to earth system model limitations
- Sardine projections assume constant fishing exploitation rate at MSY, adaptive spatial migration to spawning habitat at SST (±13.5°C), and feeding in areas of best food availability
- Thermal uncertainty is quantified by sensitivity analysis of early life stage (ELS) thermal windows for each model configuration



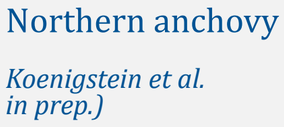
Projections



Pacific sardine

(Koenigstein et al. 2022)

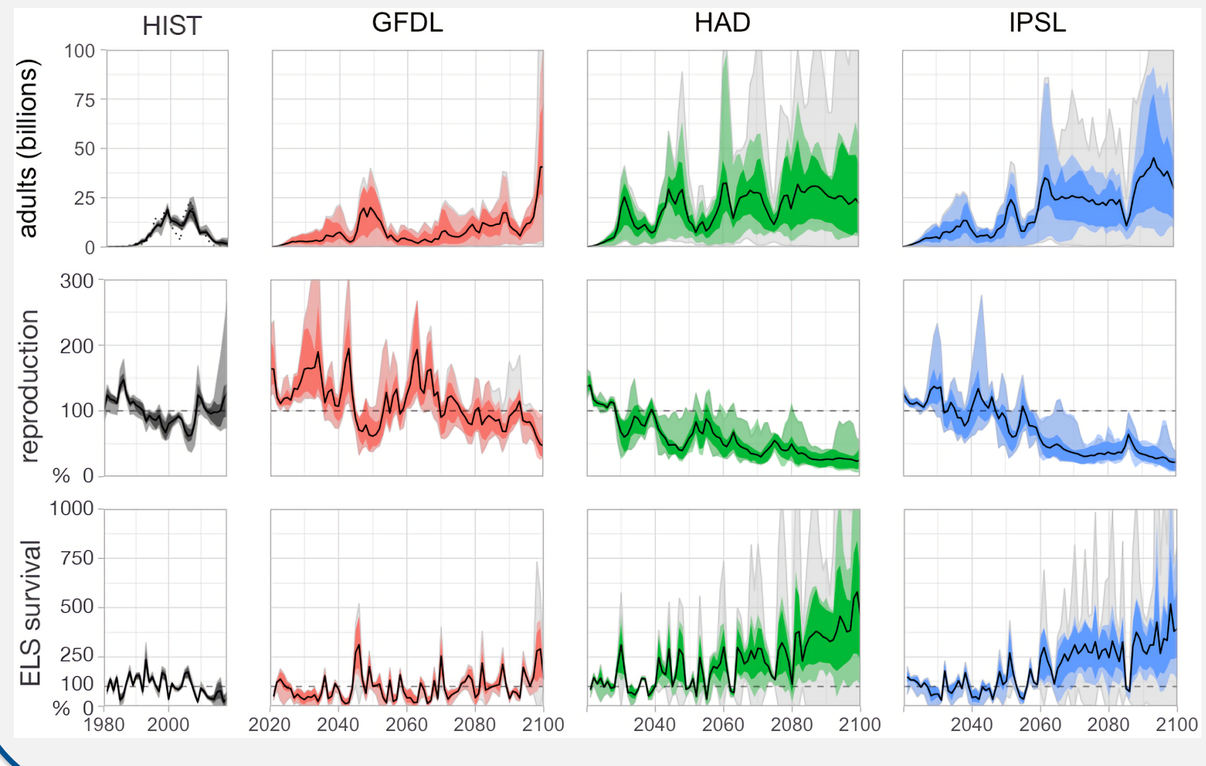
- Pacific sardine (northern stock) shows decadal-scale fluctuations, produced from process variations and cohort resonance
- Population trajectories vary among GCMs: ELS food availability limits stock increases under slower warming (GFDL). Fast-warming models show return to historical high levels through improved ELS survival, and adult food limitation later
- ELS thermal uncertainty dominates towards end of century
- Spawning shifts northward faster than feeding habitat, increasing share for Pacific Northwest fishing fleet (not shown; see paper)

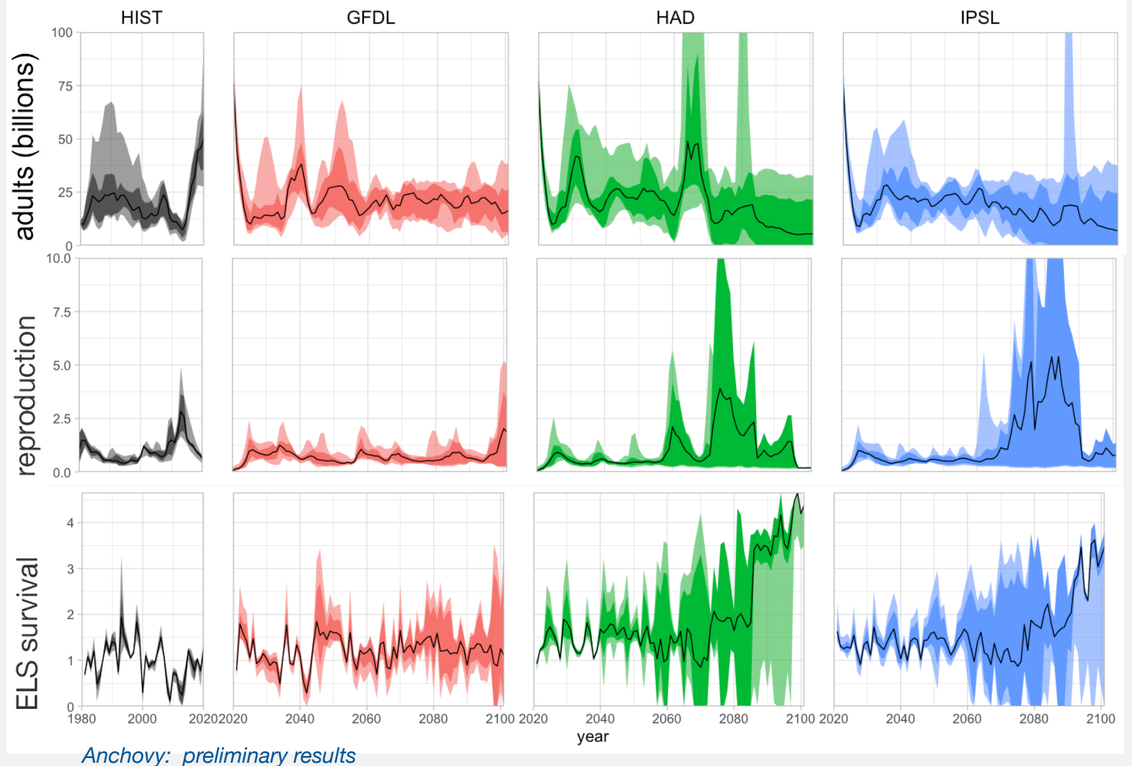


Northern anchovy

Koenigstein et al. in prep.)

- Northern anchovy population (central stock) shows short periods of stock resurgence, but no long-term increase
- Preliminary results: Assuming no spatial distribution shift and no fisheries, further sensitivity analyses underway
- Recruitment success diverges strongly among model configurations, egg production shows only temporary increases





Anchovy: preliminary results

mean; 7 (9) sardine, 4 (6) anchovy ensemble members

thermal response uncertainty (sardine)

stock assessment estimate (sardine HIST)

reproduction & ELS survival shown as relative to historical

1 Kuriyama et al. submitted; Kuriyama, P. T., Zwolinski, J. P., Hill, K. T., & Crone, P. R. (2020). Assessment of the Pacific sardine resource in 2020 for US management in 2020-2021. NOAA

2 www.oceanmodeling.ucsc.edu

3 Jacox, M. G., Edwards, C. A., Hazen, E. L., and Bograd, S. J. 2018. Coastal upwelling revisited: Ekman, Bakun, and improved upwelling indices for the U.S. West Coast. JGR Oceans, 123: 7332–7350.

4 Pozo Buil, M., Jacox, M. G., Fiechter, J., Alexander, M. A., Bograd, S. J. et al. 2021. A dynamically downscaled ensemble of future projections for the California Current System. FMarS, 8: 324

5 Koenigstein, S., Jacox, M. G., Pozo Buil, M., Fiechter, J., Muhling, B. A. et. al 2022. Population projections of Pacific sardine driven by ocean warming and changing food availability in the California Current. ICES JMS 79(9), 2510-2523.