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Comment on "Impacts of historical warming on marine fisheries production"

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Free *et al.* (Reports, 1 March 2019, p. 979) linked sea surface temperature (SST) to surplus production and estimated a 4% decline in maximum sustainable yield (MSY) since 1930. Changes in MSY are expected when fitting production models to age-structured data, so attributing observed changes to SST is problematic. Analyses of recruitment (a metric of productivity in the same database) showed increases in global productivity.

Climate change is projected to have implications for conservation and food production in marine ecosystems. Free *et al.* (*1*) linked changes in the productivity of exploited stocks to sea surface temperature (SST) by fitting surplus production models to data from exploited populations held in the RAM Legacy Stock Assessment Database (*2*). They then estimated a 4% decline in global maximum sustainable yield (MSY) since 1930. However, I argue that their choice of model in this analysis calls into question their results.

Changes in MSY are expected when fitting production models to data derived from age-structured populations, even in the absence of climate forcing (*3*). For example, I simulated surplus production from an age-structured, cod-like stock (without stochastic variation in demographic rates) and resolved two distinct production curves (Fig. 1). The apparent decline over time in MSY resulting from fitting a production model to these different time periods (similar to Free *et al.*'s figure 1, C to E) was ~21%. This is 5 times the reported difference in Free *et al.*, yet no linkage to temperature or other time variation in parameters existed. In this analysis, the difference in MSY came from higher production during the "fish down" phase due to high exploitation rates and a more complete age structure. Lower productivity in the rebuilding phase arose from a truncated age structure after exploitation rates were decreased. This simple example demonstrates the endogenous pattern present in surplus production resulting from ignoring age structure. The reader can explore the endogenous changes in surplus production over time for simulated stocks with other exploitation histories, biological characteristics, and stochasticity in recruitment using the app referenced in Fig. 1. Changes in perceived MSY generally persist even when recruitment is stochastic, and the direction and magnitude of changes in MSY are strongly related to exploitation patterns.

To test the ability of Free *et al.*'s base model to identify the influence of SST, I simulated data from the same population dynamics model above, but inserted a term for the influence of SST on the unfished recruitment that linearly decreased the productivity of the population by 14% over the period of the simulation (MSY of 0.64 to 0.55; Fig. 2). Fitting Free *et al.*'s model to these data resulted in an estimated decline in MSY of 50% (MSY of 0.68 to 0.34; Fig. 2). Some of these differences in estimated MSY would likely be constrained by the use of a hierarchical model, and the direction and magnitude of the error would depend on the exploitation pattern and biology of the stock. However, if the model cannot perform with a single instance of deterministic data, I might question its utility.

The authors also presented a null model that exchanged the observed SST for simulated data with similar properties to rule out the influence of model misspecification. An appropriate null model would preserve the endogenous pattern in production and randomize the exogenous driver of SST, so that the changes in MSY attributed to SST are not an artifact of ignoring age structure. The authors have assumed that including the trend and autocorrelation in observed SST would accomplish this, but there is no way of affirming this assumption because data on the age structure are not available. It is likely that the timing and magnitudes of shifts in "regime" (*4*) and changes in management are important components of the endogenous pattern, but these were not preserved in the simulated SST time series.

Given endogenous changes in surplus production, the inability of the model to return accurate estimates of changes in MSY with deterministic data, and the difficulty in specifying a null model without additional information, it is not advisable to attempt to explain changes in surplus production with environmental covariates.

Estimated recruitment (i.e., the number of new fish entering a population) can be a better (but still imperfect) metric to explore changes in productivity and is also available from the RAM database. Recruitment does not integrate over many years (so a comparison with a single year of SST is more reasonable) and does not have an endogenous pattern caused by ignoring age structure. Productivity of 61% of stocks in the RAM database with usable recruitment estimates ($N = 224$) appears to be more strongly driven by environmental factors than spawning biomass, and 85% of these stocks exhibit decadal shifts in productivity (*5*). Britten *et al.* (*6*) used these recruitment estimates to quantify the extent of time variation in recruitment dynamics and found that 71% showed support for time variation in productivity. This variation resulted in a 3% decline in productivity per decade on average, but they found little support for the influence of SST on productivity. A reinterpretation of Britten *et al.*'s analysis (*7*) showed that if changes in productivity were weighted by catch coming from a stock (rather than allowing each stock similar weights), a 1% increase in productivity has occurred. Analysis of recruitment suggests that the historical impacts of a changing environment on fisheries productivity are more widespread than Free *et al.* reported, but stock-specific knowledge is likely required to tease out underlying relationships.

The impact of climate change on fisheries is one of the most important research questions in fishery science, and there is ample evidence that the environment has an impact on the productivity of fisheries. Even so, the status of stocks in the RAM database has improved over the past 30 years [thanks to improved management (*8*)], and marine fisheries are one of the most environmentally friendly ways of supplying animal protein for human consumption (*9*). To protect these successes, we must remain vigilant. Identifying and projecting the impacts of climate change will be critical in preparing for changes in ocean resources, but the right tools must be used in these projections to avoid error. These errors can be particularly problematic if methods from global analyses (which often gloss over details) are implemented at a local level. I hold great respect for each of the authors and their work, but, as a scientific community, we should move beyond using production models to evaluate time variation in the productivity of fished stocks.

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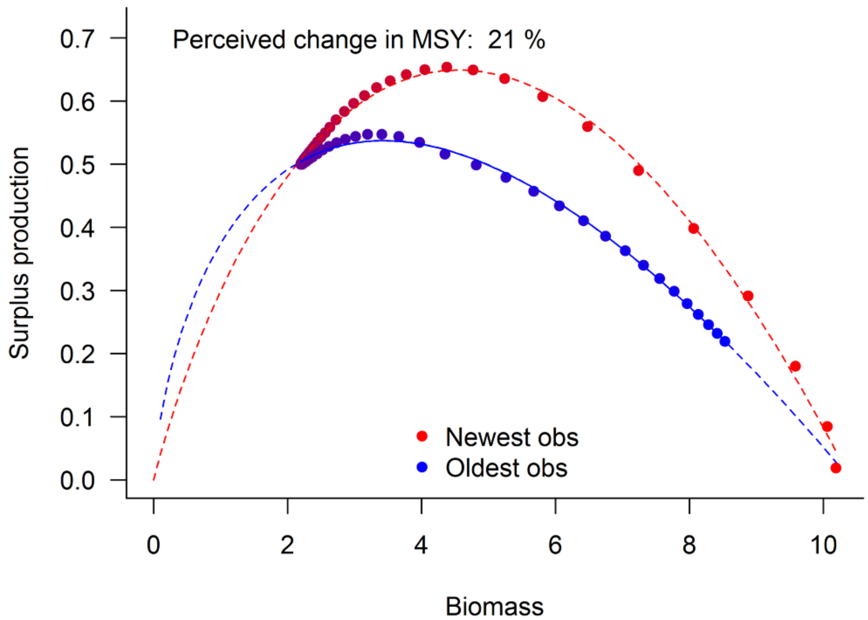

Fig. 1. Surplus production from a simulated cod-like stock with surplus production model fits. Lines are the fits of Pella-Tomlinson models to data gathered from the "fish down" and "rebuilding" periods. No environmental forcing is present in this simulation (compare to figure 1, C to E, of Free *et al.*). Figures like this for stocks with other exploitation patterns and life histories can be created at https://szuwalski.shinyapps.io/surplus_production/, where the model description and a link to the code can also be found.

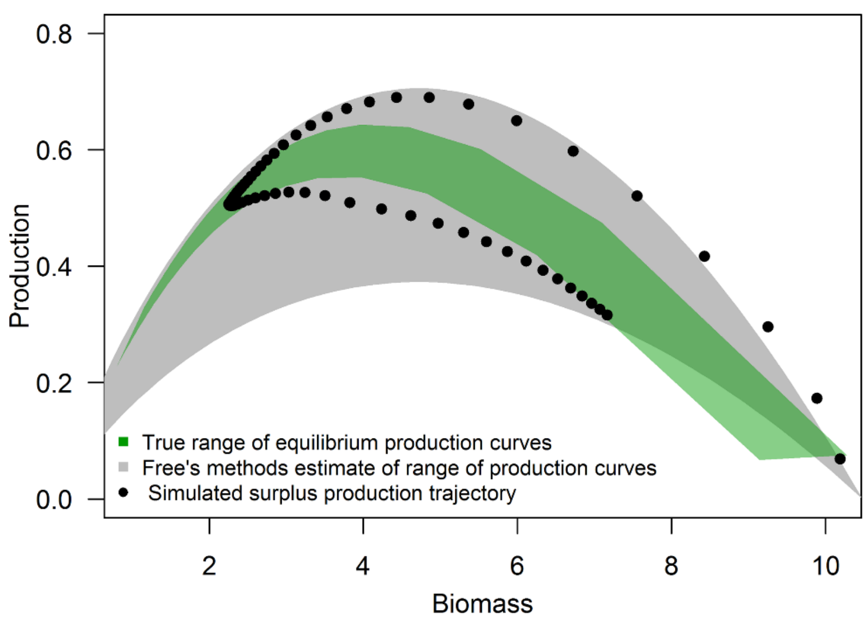

Fig. 2. True changes in simulated MSY compared to estimated changes from Free *et al.* Data were simulated from an age-structured model with environmental forcing acting on recruitment (green). Estimated changes in MSY from Free *et al.*'s methods are overlaid in gray. The polygons represent the range of equilibrium production curves. The distance from the maximum of the top border of a polygon of a given color to the maximum of its bottom border represents the total change in MSY. Black dots represent the simulated data to which Free *et al.*'s methods were applied.

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