Two-compartment models of Main Hawaiian Islands Yellowfin Tuna Population

John Sibert*
Joint Institute of Marine and Atmospheric Research
University of Hawai'i at Manoa
Honolulu, HI 96822 U.S.A.

November 22, 2014

Introducetion

The Yellowfin Tuna (YFT) population in main Hawaiian Islands (MHI) is embedded in a larger pan-Pacific stock. Nevertheless, local fishermen believe that the MHI supports a "resident" yellowfin population. Some scientific observations are consistent with this belief. Recent tagging, tracking and studies show that the rate of exchange between the MHI population and the larger stock is low (Itano and Holland 2000). Analysis of YFT otoliths sampled from throughout the Pacific conclude that approximately 90% of the MHI population was reared in the MHI (Wells et al 2012). The Hawaii based longline along with various small-scale fisheries land a combined catch

*sibert@hawaii.edu

approximately 5000 mt of YFT annually (ref). Management of these fisheries is an important an important local issue deserving of scientific support.

This paper explores some potential models that might be used to analyze options for the management of fisheries for YFT in the MHI.

Data

Two sources of data used are used in this analysis:

1. Yellowfin catch weights reported to the Hawaii Department of Aquatic Resources (HDAR) from 1949 to 2014 from the Offshore Handline, Toll, Inshore Handline, Longline, and Aku Boat fleets.

2. Longline yellowfin catch weights reported to the National Oceanic and Atmospheric Administration, National Marine Fisheries Service (NMFS) unfer the federally mandated log book program from *1992 to 2014.*

3. *Estimates of yellowfin catch weight of fish sampled at the Honolulu auction by NMFS staff.*

4. Model estimates of yellowfin biomass for MFCL regions 1 and 2 provided by the Oceanic Fisheries Programme at the Secretariat of the Pacific Community (SPC) in Noumea, New Caledonia. These :w estimates span the period 1952 through 2012.

All data are reported by quarter of the year.

The catch time series for all gear are shown in Figure 1. The most obvious feature of these time series is the marked quarterly cycles suggesting a strong seasonal signal in the catches by all fleets. The time series also show both increasing and decreasing trends. These trends are more related to participation than to stock abundance. The "Aku Boat" fishery, a small pole and line fishery targeting skipjack tuna in Hawaii, for which yellowfin was an incidental catch ceased operation because of problems marketing fresh skipjack. The longline fishery has changed drastically over time. In the late 1940s, it was a relatively small fishery using traditional Okinwawan-style gear *(reference)* , usually labelled "flag line". Participation in this fishery generally declined from 1950 to 1900, as can be seen in the time series plots. In the 1990s, the longline fishery expanded rapidly with the introduction of US fishing boats from the Atlantic ocean with modern monofilament longline gear. At around this time, the mandate to collect data from the longline fleet shifted from HDAR to NMFS. *What happened to the Inshore HL fleet?*

Figure 1 also displays the first order differences between successive quarters. This statistic emphasizes the seasonal periodicity of all fishing fleets and help to identify anomalies in the data such as changes in reporting protocol. Some possible anomalies can be seen in the late 1980s in the Offshore HL fleet, the early 1990s in the longline fleet, and the mid 1950s in the Aku Boat fleet. *The 1990s longline anomaly is expected and will be rectified with the NMFS data become available.*

Correltaion structure

Models

The principle assumptions for modeling the MHI YFT population are:

1. The Pacific yellowfin population consists of two components: those that live in the MHI (region 1) and those that live elsewhere (region 2).

2. Fish immigrate from region 2 to region 1, mix thoroughly, and interact with the "resident" population according to shared population dynamics.

3. Fish emigrate from region 1 to region 2, but emigrant fish have no effect on region 2 population dynamics.

4. Immigrant fish are indistinguishable from "resident" fish (i.e. both groups of fish have the same population dynamics) and are caught by the same gear.

5. Immigration into the MHI is assumed to be dependent on the biomass of the yellowfin population outside of the MHI as estimated by MULTIFAN-CL or SEAPODYM.

6. The fishery consists of several gear types spanning different periods of time: Offshore Handline, Toll, Inshore Handline, Longline, and Aku Boat (Figure 1). Some of gear types have size (weight or length) data associated with the reported catch for more recent part of the time series. It is assumed that these gear types have characteristic size (or age) dependent selectivity functions.

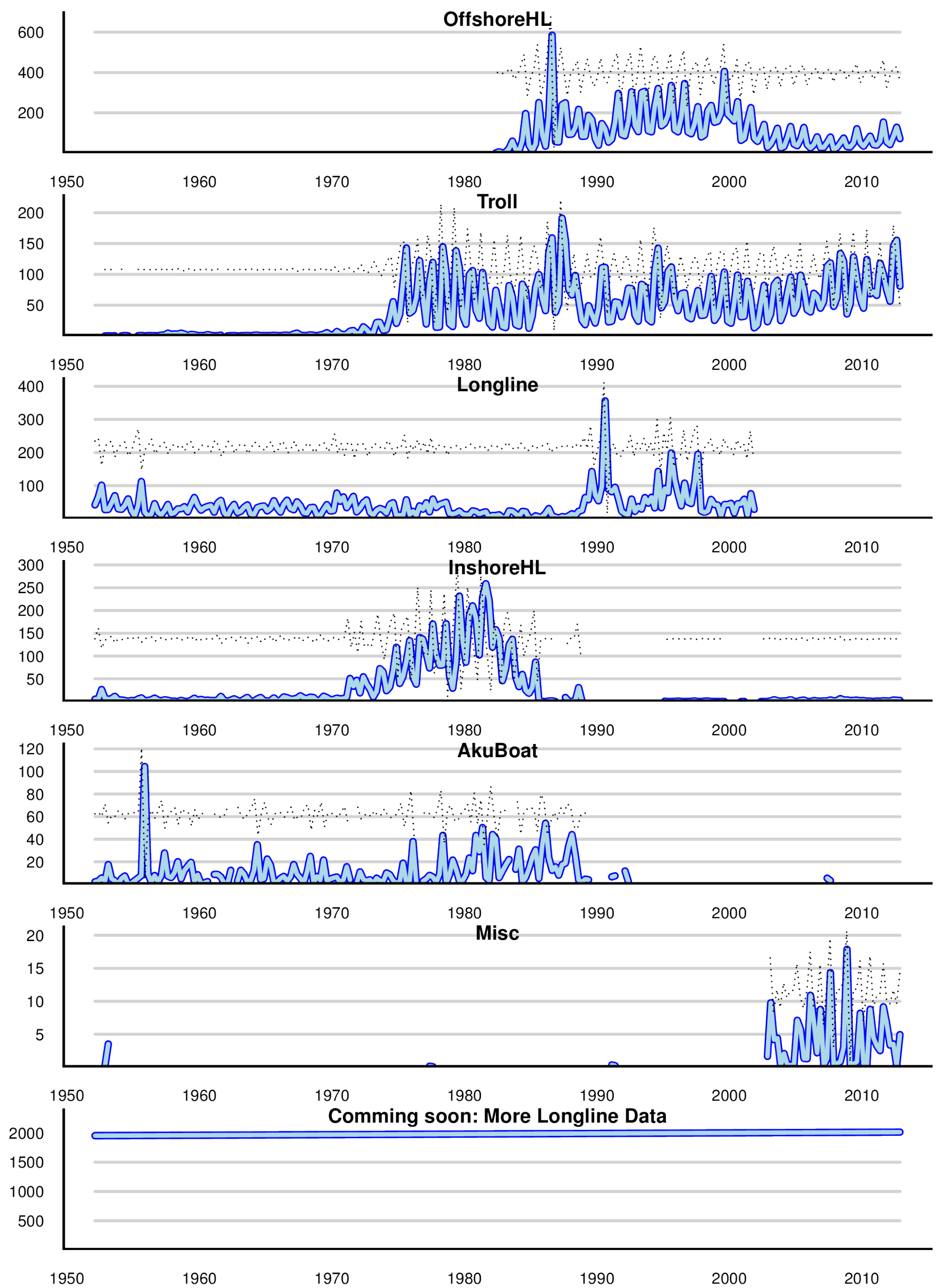

Figure 1: Yellowfin catch in metric tonnes by principle fisheries operating in the Main Hawaiian Islands. The missing data in the bottom panel is longline data reported on federal logbooks since 1992 which will be appended to the earlier longline time series.

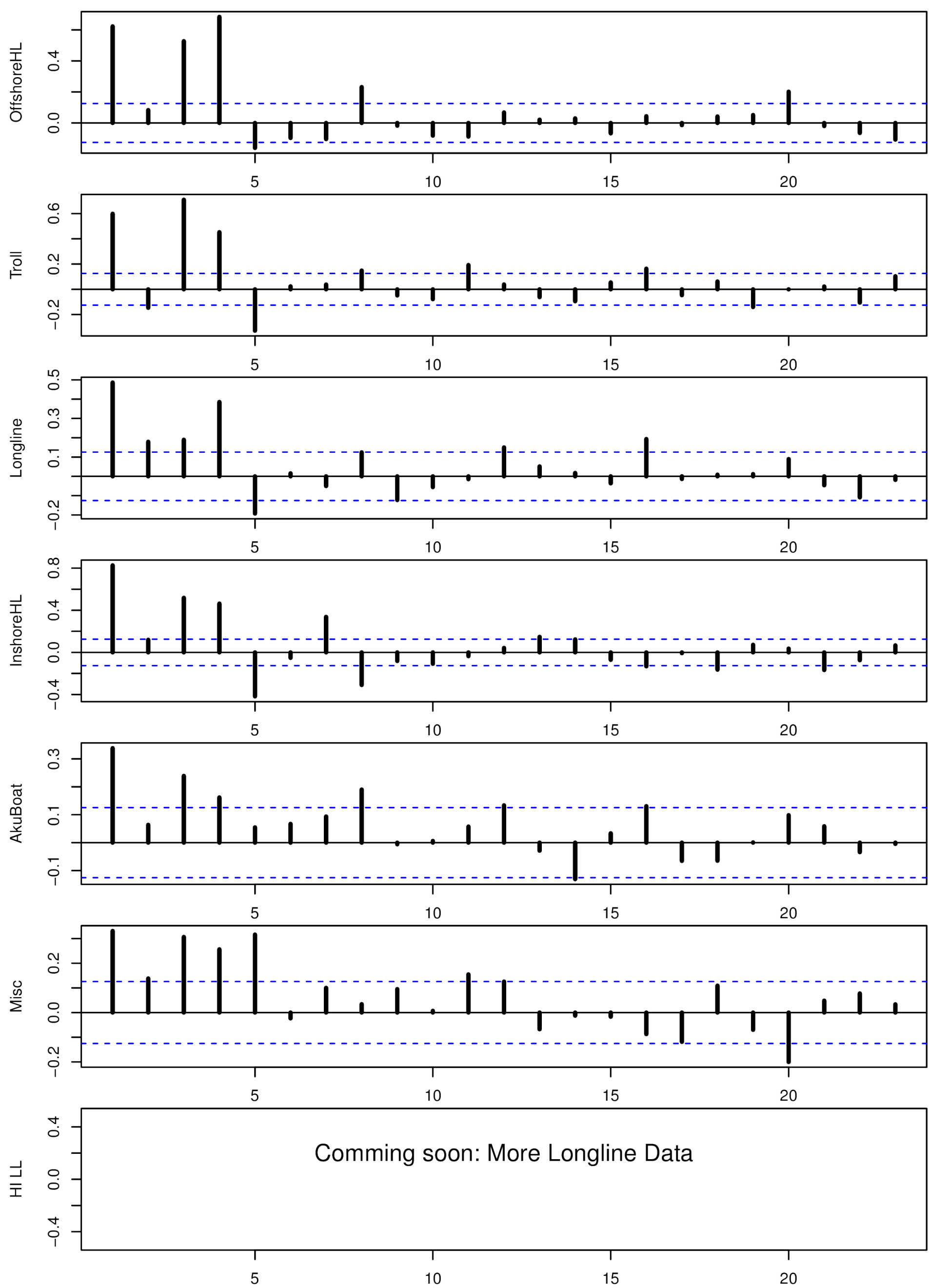

Figure 2: Partial autocorrelation coefficients of the catch time series. The dashed blue lines indicate approximate 95% confidence limits of the correlations.

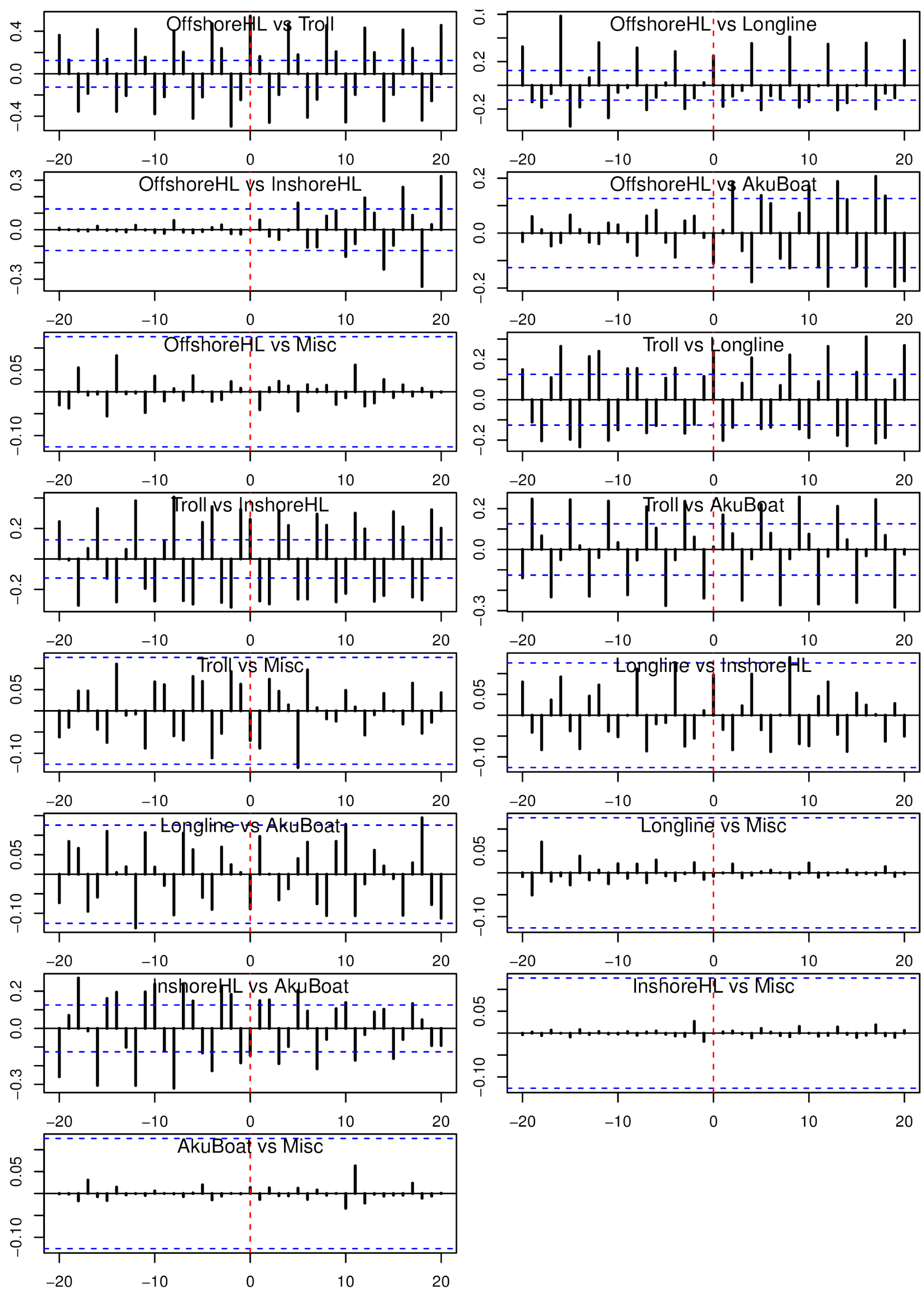

Figure 3: Cross correlation coefficients between pairs of the first order differences of each catch time series at different lags. The vertical dashed red line emphasize zero lag. The dashed blue lines indicate approximate 95% confidence limits of the correlations.

The general modeling approach to be applied will be similar to the state-space model utilized by Nielsen and Berg (2014). State-space models separate variability in the biological processes in the system (transition model) from errors in observing features of interest in the system (observation model). The general form of the transition equation is

$$\alpha_t = T(\alpha_{t-1}) + \eta_t \tag{1}$$

where the function T embodies the stock dynamics, describing the development of the state at time t from the state at the previous time with random process error, η. Similarly the general observation equation is

$$x_t = O(\alpha_t) + \varepsilon_t \tag{2}$$

where the function O describes the measurement process and with error ε Separation if process from measurement offers statistical advantages in estimating model parameters.

Age-aggregated model: logistic population dynamics (Schaefer Model)

When this project was initially proposed, I assumed that the data would not support an age-structured model. Therefore, I began to think about production model approaches. I'm retaining these ideas in case the available size data are not sufficient for an multi-gear age-structured model and because of delays in receiving data.

Let $N_{1,1}$ equal the population size of fish originating in region 1 and residing in region 1 and $N_{2,1}$ equal the population size of fish originating in region 2 but residing in region 1. The total population size of fish residing in region 1 is thus $N_{1,1} + N_{2,1}$, and the dynamics of the population in region 1 is represented as

$$\frac{d}{dt}\big(N_{1,1} + N_{2,1}\big) = \big(N_{1,1} + N_{2,1}\big)\Big[r\Big(1 - \frac{N_{1,1} + N_{2,1}}{K}\Big) - F - T_{12}\Big] + T_{21} \quad (3)$$

where r is the per capita logistic growth rate per year K is the logistic "carrying capacity" measured in the same units as $N_{1,1}$ and $N_{2,1}$, F is the fishing mortality in region 1, and T_{12} is the emigration rate from region 1 to region 2. T_{21} is the annual rate of immigration of fish from region 2 to region 1 measured in the same units as K per year.

Equivalent differential equations could be devised for the dynamics of fish residing in region 2 (i.e., $\frac{dN_{2,2}}{dt}$ and $\frac{dN_{1,2}}{dt}$) but the dynamics of the fish population in region 2 is external to this model. T_{21} can be considered to be form of population forcing from the larger stock in which the MHI population is embedded, perhaps estimated from other models, such as MULTIFAN-

CL or SEAPODYM, or perhaps represented by an autocorrelated stochastic process. The appearance of $N_{1,1} + N_{2,1}$ in the numerator of the logistic term reflects the assumption that the population dynamics fish immigrating into region 1 depend on the population dynamics in region 1. This assumption leads to an important non-linearity in the model that permits overwhelming of a local stock by a more numerous immigrant stock as is often characteristics of mixed-stock fisheries.

The ratio $\frac{N_{1,1}}{N_{1,1}+N_{2,1}}$ is of potential interest, so equation 3 needs to be expanded and rearranged leading to a set of simultaneous differential equation for the components of the population inhabiting region 1.

$$\begin{aligned}
\frac{dN_{1,1}}{dt} &= N_{1,1}\left[r\left(1-\frac{N_{1,1}}{K}\right)-F-T_{12}\right]-\frac{r}{K}T_{12}N_{1,1}N_{2,1} \\
\frac{dN_{2,1}}{dt} &= N_{2,1}\left[r\left(1-\frac{N_{2,1}}{K}\right)-F-T_{12}\right]-\frac{r}{K}T_{12}N_{1,1}N_{2,1}+T_{21} \qquad (4)
\end{aligned}$$

The non-linear term from equation 3 appears the term $N_{1,1}N_{2,1}$ in both of the above equations.

The equilibrium of this system can be found by setting $\frac{dN_{1,1}}{dt} = 0 = \frac{dN_{2,1}}{dt}$. After some simplification the result is $\frac{T_{21}}{N_{2,1}} = 0$ In other words, there is no equilibrium in this coupled system, other than the degenerate case of no immigration ($T_{21} = 0$) into the MHI. Thus, the notion of using equilibrium-based reference points such as MSY to manage fisheries for MHI yellowfin is ill advised.

Equations 4 are solved by finite difference approximations using explicit time stepping.

$$
\begin{aligned}
\frac{dN_{1,1}}{dt} \approx \frac{N_{1,1_t} - N_{1,1_{t-\Delta t}}}{\Delta t} &= N_{1,1_{t-\Delta t}}\Big[r\Big(1 - \frac{N_{1,1_{t-\Delta t}}}{K}\Big) - F - T_{12}\Big] \\
&- \frac{r}{K}T_{12}N_{1,1_{t-\Delta t}}N_{2,1_{t-\Delta t}} \\
\frac{dN_{2,1}}{dt} \approx \frac{N_{2,1_t} - N_{2,1_{t-\Delta t}}}{\Delta t} &= N_{2,1_{t-\Delta t}}\Big[r\Big(1 - \frac{N_{2,1_{t-\Delta t}}}{K}\Big) - F - T_{12}\Big] \\
&- \frac{r}{K}T_{12}N_{1,1_{t-\Delta t}}N_{2,1_{t-\Delta t}} + T_{21} \qquad (5)
\end{aligned}
$$

Rearrangement and addition of process error terms ($\eta_{r,t}$) yields a form suitable for use as the transition equation in a state-space model.

$$
\begin{aligned}
N_{1,1_t} = \Bigg[N_{1,1_{t-\Delta t}} &+ \Delta t N_{1,1_{t-\Delta t}}\Big[r\Big(1 - \frac{N_{1,1_{t-\Delta t}}}{K}\Big) - F - T_{12}\Big] \\
&- \frac{r}{K}T_{12}N_{1,1_{t-\Delta t}}N_{2,1_{t-\Delta t}}\Bigg]e^{\eta_{1,t}} \\
N_{2,1_t} = \Bigg[N_{2,1_{t-\Delta t}} &+ \Delta t N_{2,1_{t-\Delta t}}\Big[r\Big(1 - \frac{N_{2,1_{t-\Delta t}}}{K}\Big) - F - T_{12}\Big] \\
&- \frac{r}{K}T_{12}N_{1,1_{t-\Delta t}}N_{2,1_{t-\Delta t}} + T_{21}\Bigg]e^{\eta_{2,t}} \qquad (6)
\end{aligned}
$$

Letting $x_{i,j} = log(N_{i,j})$ then equation 4 can be rewritten as

$$
\begin{aligned}
\frac{d\log(N_{1,1})}{dt} = \frac{dx_{1,1}}{dt} &= r\Big(1 - \frac{N_{1,1}}{K}\Big) - F - T_{12} - \frac{r}{K}T_{12}N_{2,1} \\
\frac{d\log(N_{2,1})}{dt} = \frac{dx_{1,2}}{dt} &= r\Big(1 - \frac{N_{2,1}}{K}\Big) - F - T_{12} - \frac{r}{K}T_{12}N_{1,1} + T_{21}/N_{2,1} \qquad (7)
\end{aligned}
$$

and the finite difference equivalent of 6 becomes

$$
\begin{aligned}
x_{1,1,t} &= x_{1,1,t-\Delta t} + r\Delta t\Big(1 - \frac{N_{1,1_{t-\Delta t}}}{K}\Big) - F - T_{12} - \frac{r}{K}T_{12}N_{2,1_{t-\Delta t}} + \eta_{1,t} \\
x_{1,2,t} &= x_{1,2,t-\Delta t} + r\Delta t\Big(1 - \frac{N_{2,1_{t-\Delta t}}}{K}\Big) - F - T_{12} - \frac{r}{K}T_{12}N_{1,1_{t-\Delta t}} + T_{21}/N_{2,1_{t-\Delta t}} + \eta_{2,t} \qquad (8)
\end{aligned}
$$

This parameterization may be simple, but using my simulation, I don't get the same answer as I get from 6. Perhaps I have made a math error of did not implement it correctly in R.

Age-aggregated model: (Pella-Tomlinson Model)

Probably not worth the effort.

Age structured model

The issue of regulating MHI YFT fisheries by imposing minimum size limits on some components of the fishery has been raised yet again. Size- or age-structured models are obviously required to address catch-at-size issues. The following set of equations are a potential formulation of the transition equation in an age-structured state-space model and are based on the state-space stock assessment model of Nielsen and Bert (2014). Let $N_{r,a,t}$ represent the fish living in the MHI but originating in in region $r; r = 1, 2$ of age

$a; a = 1, 2, \ldots, A$ in time interval t.

$$\log N_{1,1,t} = \log\Big(R\big(\sum_a p_{a,t-1}(N_{1,a,t-1} + N_{2,a,t-1})\big)\Big) + \eta_{1,1,t} \tag{9}$$

$$\log N_{2,1,t} = \log T_{2,1,1,t} + \eta_{2,1,t} \tag{10}$$

$$\log N_{1,a,t} = \log N_{1,a-1,t-1} - Z_{a-1,t-1} + \eta_{1,a,t}; \qquad 1 < a < A \tag{11}$$

$$\log N_{2,a,t} = \log N_{2,a-1,t-1} - Z_{a-1,t-1} + \log T_{2,1,a,t} + \eta_{2,a,t} \tag{12}$$

$$\log N_{1,A,t} = \log N_{1,A-1,t-1} - Z_{A-1,t-1} + \log N_{1,A,t-1} - Z_{A,t-1} + \eta_{1,A,t} \tag{13}$$

$$\log N_{2,A,t} = \log N_{2,A-1,t-1} - Z_{A-1,t-1} + \log N_{2,A,t-1} - Z_{A,t-1} + \log T_{2,1,A,t} + \eta_{2,A,t} \tag{14}$$

where $Z_{a,t} = \sum_g F_{g,a,t} + M_a + T_{1,2}$ is a positive quantity representing the total mortality at fish of age a in time interval t, M_a is the natural mortality at age a, assumed to be constant over time, and $F_{g,a,y}$ is the fishing mortality exerted by gear g, on fish of age a during time period t.

Is it appropriate to use different process error time series ($\eta_{1,t}$ and $\eta_{2,t}$) for the two segments of the population under the assumption of identical population dynamics for both segments?

The immigration term, $T_{2,1,a,t}$, is the biomass of fish of age a immigrating from region 2 to region 1 during time period t. Immigration is assumed to be proportional to the biomass of yellowfin adjacent to the MHI as might be estimated by MULTIFAN-CL or SEAPODYM. Thus

$$T_{2,1,a,t} = T'_{2,1} \cdot \widehat{B_{2,a,t}} \tag{15}$$

Fishing mortality is often represented in stock assessment models as the product of several parameters and variables, for example, catchability coefficient, gear selectivity, and fishing effort. The parameters of this relationship are usually confounded and difficult to estimate. In the case of MHI yellowfin fishery, effort estimates are known to be inconsistent, and fishing practices have changed over time often requiring *ad hoc* adjustments to catchability and gear selectivity. Eliminating fishing effort would simply the model somewhat.

Fishing mortality is assumed to to follow a random walk with multivariate normal increments, with major seasonally (by quarter) variation, and to depend on gear selectivity.

$$\log F_{g,a,t} = \log F_{g,a,t-1} + \alpha_{g,Q(t)} + \beta_{g,Y(t)} + S_{g,a,t} + \varepsilon_t \tag{16}$$

α is a vector of quarterly deviations from the mean fishing mortality that sum to zero. β is a vector of autocorrelated annual deviations from the mean that reflect secular trends in fishing mortality. $S_{g,a,t}$ represents the selectivity of gear g on age class a fish during time period t.

The observation model predicting the yield or catch in the MHI under this model would be

$$C_{g,a,t} = \frac{F_{g,a,t}}{Z_{g,a,t}}\left(1 - e^{Z_{g,a,t}}\right)\left(N_{1,a,t} + N_{2,a,t}\right)e^{\varepsilon_{g,a,t}} \tag{17}$$

using the standard Baranov approximation.

References

Adam, M. S., J. Sibert, D. Itano and K. Holland. 2003. Dynamics of bigeye

(Thunnus obesus) and yellowfin tuna (T. albacares) in Hawaii's pelagic fishery: analysis of tagging data with a bulk transfer model incorporating size specific attrition. Fishery Bulletin 101(2): 215-228.

Davies, N., S. Harley, J. Hampton, S. McKechnie. 2014. Stock assessment of yellowfin tuna in the western and central pacific ocean. WCPFC-SC10-2014/SA-WP-04.

Itano, D., K. Holland. 2000. Movement and vulnerability of bigeye (Thunnus obesus) and yellowfin tuna (Thunnus albacares) in relation to FADs and natural aggregation points.Aquat. Living Resour. 13: 213-223.

Kleiber, P., J. Hampton, N. Davies, S. Hoyle, D. Fournier. 2014. MULTIFAN-CL Users Guide

Nielsen, A. and C. Berg. 2014. Estimation of time-varying selectivity in stock assessments usingstate-space models. Fisheries Research 158:96-101.

Wells, D., J. Rooker, D. Itano. 2012. Nursery origin of yellowfin tuna in the Hawaiian Islands. Mar. Ecol. Prog. Ser. 461:187-196.