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Estimating fishing and natural mortality rates for Pacific bluefin tuna (*Thunnus orientalis*) using electronic tagging data

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ABSTRACT

This paper presents estimates of fishing and natural mortality rates derived from a spatially- and seasonally structured Bayesian mark-recapture model for electronically tagged Pacific bluefin tuna (PBFT) (*Thunnus orientalis*). Fishing mortality rates (F) were estimated by age group, year, quarter and area and ranged between 0.02 and 1.92 quarter^{-1} for the northeastern Pacific Ocean (EPO) and 0.18 and 0.54 quarter^{-1} for the northwestern Pacific Ocean. Annual Fs in the EPO were on average 2–3 times higher than the estimated rate of natural mortality for Pacific bluefin tuna aged 2 and 3 and 4–6 times higher than the estimated rate of natural mortality for Pacific bluefin tuna aged 4 and older. The estimate of M for PBFT aged 5 and above (median 0.15 yr^{-1}, standard deviation = 0.10) was lower than the value currently used in the PBFT stock assessment (i.e. 0.25 yr^{-1}). In addition to estimating age-group specific natural mortality rates (M), the plausibility of alternative values for M was evaluated by fixing it at the age-specific schedules tested in the PBFT stock assessment and computing a Bayesian model selection criterion (the Deviance Information Criterion, DIC) for alternative M configurations. For models in which M was fixed, the lowest DIC was obtained for the M scenario that assumed the lowest value of M for PBFT aged 4 and above (i.e. 0.12 yr^{-1}).

1. Introduction

Pacific bluefin tuna (*Thunnus orientalis*) is a highly migratory species, having the largest home range of any tuna in the genus *Thunnus*. Pacific bluefin tuna, hereafter PBFT, are primarily distributed throughout the temperate waters of the northern Pacific Ocean but also range into the western South Pacific (Bayliff, 1994; Collette and Nauen, 1983). Two spawning areas are currently recognized; one in the southwestern North Pacific off Taiwan and the other in the Sea of Japan (Okiyama, 1974; Chen et al., 2006; Tanaka et al., 2007). PBFT in spawning condition have been taken in these waters in the months of April through August. Genetic structure has not been detected to date in PBFT, and one stock is currently recognized throughout the Pacific Ocean.

Commercial fisheries exist for PBFT throughout their range and are most intensive in the northwestern (WPO) and northeastern Pacific Ocean (EPO). Annual reported ocean-wide catches since the early 1950s have varied between 8000 and 35,000 tons (IATTC, 2005), averaging around 25,000 tons between 1950 and 1980 and 15,000 tons thereafter. Catches in the EPO have declined since the 1960s, although the last decade saw catches rapidly increase (Aires-da-Silva et al., 2007). Concomitantly, fishing effort in the EPO decreased between 1960 and 1990 but has rebounded since the late 1990s in concert with expansion of the PBFT ranching industry off Baja Mexico (Aires-da-Silva et al., 2007). PBFT are also exploited by a variety of fisheries in the WPO, including purse-seine, longline and gillnet fisheries (Bayliff, 2001).

A preliminary stock assessment was conducted for PBFT by the Inter-American Tropical Tuna Commission (IATTC) (Bayliff, 2001). However, the available catch and effort data and length-frequency data for the WPO were insufficient for calculation of abundance indices for the WPO or to conduct cohort analysis for the entire Pacific Ocean (Bayliff, 2001). A full stock assessment including updated catch and effort and length-frequency data for the WPO was conducted by the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC) in 2008 (Anon., 2008). Estimates of PBFT fishing mortality rates (F) in recent years were above fishing mortality levels corresponding to target reference points such as F_{MSY} (the fishing mortality that would achieve maximum sustainable yield) (ISC, 2008).

The stock assessment for PBFT is subject to uncertainty about several basic life-history characteristics, foremost among them the rate of natural mortality, M (Bayliff, 2001). M is of primary importance in fish stock assessments as it determines potential

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maximum sustainable yield (MSY) (Beddington and Cooke, 1983; Beamesderfer and North, 1995) and a population's response to harvest. Higher rates of natural mortality are associated with more productive stocks and their ability to sustain higher harvest rates. However, for most exploited fish populations, *M* is typically difficult to estimate because it is not feasible to monitor natural deaths (Quinn and Deriso, 1999) and it is difficult to separate the effects of natural mortality, fishing mortality and recruitment in observations of fish abundance (Hightower et al., 2001; Hilborn and Walters, 1992). Moreover, methods available for the estimation of *M* for fish populations have onerous data requirements and assumptions that are not easily satisfied. For example, estimation of *M* using catch curve analysis (Ricker, 1975; Vetter, 1988) requires data from an unexploited or very lightly exploited population and when catch-at-age data become available, exploitation rates are typically non-negligible. In contrast, tagging experiments with sufficiently rigorous tagging design and high tag recovery rates are often not feasible in many instances (Walters and Martell, 2004).

M has commonly been identified as a key source of uncertainty in fish stock assessments (Lapointe et al., 1989; Hilborn and Walters, 1992). The treatment of age-specific *M*s as fixed parameters fails to capture this uncertainty, which could ultimately lead to loss of yield or overexploitation of the stock. Currently an age-specific vector for *M*, with *M* for ages 4 and above equal to 0.25 yr^{-1} is used in the PBFT stock assessment. Lower values for *M* for fish of age 4 and older yielded estimates of the depletion of spawning biomass between 1952 and 2005 (<5%) and unfished spawning biomass (about 1.4 million tons) that were considered implausible by the working group (Anon., 2008; Aires-da-Silva et al., 2009). Currently, only the value of *M* for age-0 PBFT has been empirically derived using tagging data (Takeuchi and Takahashi, 2006). Values for fish of age 1 and older were derived using life-history based methods and estimates for southern bluefin tuna (*Thunnus maccoyi*) (Polacheck et al., 1997). However, when considered together, values for *M* of 0.25 yr^{-1} and above with moderate to high fishing mortality rates for adult PBFT may be incongruous with their reported longevity (maximum age of 26 years, Shimose et al., 2009). More information on *M* for PBFT aged 4 and above may thus be useful to help reduce the substantial uncertainty associated with this parameter.

Tagging data can be informative with respect to rates of fishing and natural mortality. A major caveat to using tagging data is a requirement that the tag reporting rate is known or can be reliably estimated (Bacheler et al., 2009; Pollock et al., 1991, 2001). Telemetry has been applied to estimate natural mortality rates (mortality rates are inferred from transmitters that stop moving over successive time periods) (Hightower et al., 2001; Waters et al., 2005). More recently, tag return data (e.g. from archival or conventional tags) and telemetry data have been combined (Pollock et al., 2004; Bacheler et al., 2009) to provide information about both return rates and natural mortality rates.

State-space Bayesian tagging models (Michielsens et al., 2006; Kurota et al., 2009; Taylor et al., 2011) offer a powerful framework for analysis of tagging data and provide a statistically rigorous means to quantify uncertainty, accounting for both observation and process error (Wade, 2000; Michielsens et al., 2006). We extend this methodology to the analysis of electronic tagging data for PBFT. In this paper we seek to use electronic tagging data to examine age-group specific rates of natural mortality and seasonal movement patterns of PBFT. The use of a sequential Bayesian approach facilitates the flow of information from different data sources whereby the posterior from one analysis becomes the prior for the next (Michielsens et al., 2008). In the context of the current analysis, posterior probability density functions (pdfs) for seasonal movement rates from analysis of pop-up satellite archival tag (PAT) data were used as the prior for the archival tag model (Kurota et al., 2009). Our analysis additionally includes quarterly locations for archival tagged PBFT between the release and recapture locations, thereby using the additional spatial information available from the electronic tag data.

The quantitative integration of conventional and electronic tag data into spatially structured assessment models is opening the door to an improved understanding of the population dynamics of highly migratory species (Goethel et al., 2011). Integrating tagging data with other fisheries data (typically catch-at-age and catch-per-unit-effort data) has advanced stock assessment models for several species (e.g. sablefish (*Anoplopoma fimbria*) (Haist, 1998); yellowfin tuna (*Thunnus albacares*) (Hampton and Fournier, 2001) and Atlantic bluefin tuna (*Thunnus thynnus*) (Taylor et al., 2011)).

The number of electronic tags placed on PBFT has increased rapidly in the past decade with several archival and satellite tagging projects on both sides of the Pacific basin (Kitagawa et al., 2000, 2007; Boustany et al., 2010). In the EPO over 550 juvenile PBFT (primarily year classes 2 and 3) have been tagged with archival and pop-up satellite technologies, and a high archival tag recapture rate has resulted in a rich data set of over 58,000 tag days (Fig. 1), including track lengths exceeding 4 years (Kitagawa et al., 2007; Boustany et al., 2010; Block et al., 2011). These data provide new

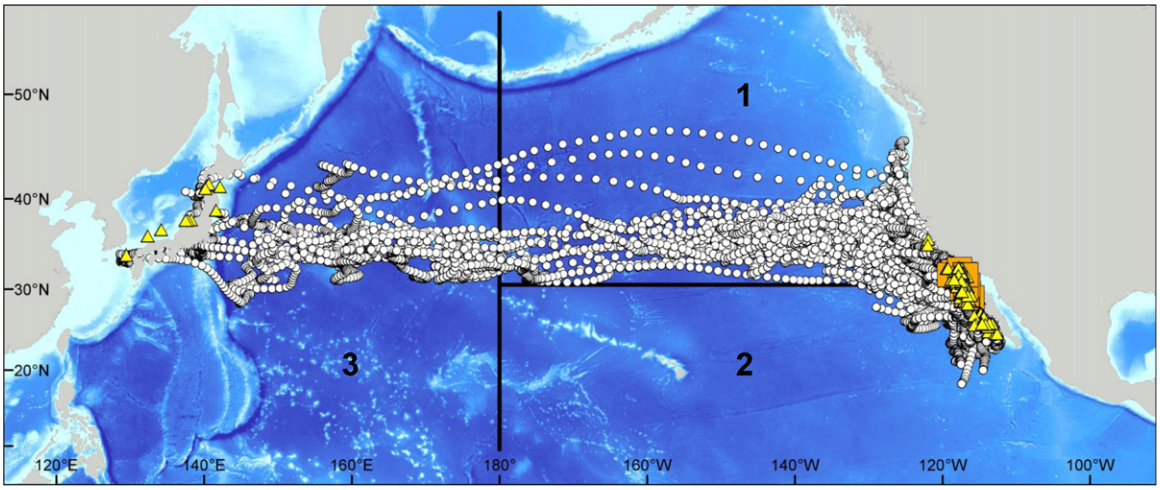

Fig. 1. Boxes used in the PAT (boxes 1 and 2) and archival (boxes 1–3) tag models for Pacific bluefin tuna. Release locations (orange squares), recapture locations (yellow triangles) and daily positions from a state-space model (white circles) for the archival tag data are overlaid.