A new zooplankton community index and recruitment model to improve understanding of the stock-recruit relationship for western Atlantic bluefin tuna

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Background

Atlantic bluefin tuna (BFT) are distributed throughout the northern Atlantic Ocean, including the exclusive economic zones of multiple European, American and African nations. This highly migratory behavior complicates effective management. The current stock assessment is completed through the International Commission for the Conservation of Atlantic Tunas (ICCAT), of which NOAA-NMFS scientists are major contributors. Two stocks are currently recognized by ICCAT: eastern and western. Both stocks have foraging grounds along the US east coast, but only the western stock spawns within US territorial waters (nearly exclusively within the Gulf of Mexico: GOM).

Despite various management measures, the western BFT stock is still considered to be overfished, and subject to overfishing (NMFS, 2014a). However, considerable uncertainty exists with respect to this evaluation. The most problematic knowledge gap is the lack of understanding of the stock-recruitment relationship (SRR). This relationship describes the mathematical association between the number of spawning fish in a population, and the number of young fish they produce. Definition of this parameter is essential for the effective use of stock assessment models, and for the implementation of rebuilding plans (Hilborn & Walters, 1992).

The most recent assessment from ICCAT considers two potential forms of the SRR, resulting in two recruitment scenarios for the western Atlantic BFT stock: "low" and "high" (Fig. 1).

- The low recruitment scenario assumes that an unspecified change in environmental conditions since 1970 will prevent high levels of recruitment from occurring in the future, even if the stock is rebuilt.
- The high recruitment scenario assumes that as stock biomass increases, recruitment will increase accordingly (ICCAT, 2012). As a result, the high levels of recruitment observed during the 1970s may be possible in the future.

There is currently insufficient evidence to favor one scenario over the other. This is highly problematic, as under the low scenario, the stock is currently above biomass levels that can support maximum sustainable yield (MSY). Under the high recruitment scenario, the stock is still heavily overfished, and will not recover within the timeframe of the current rebuilding plan. As a result, the July 2014 NMFS Atlantic HMS management-based research needs and priorities report (NMFS, 2014b) lists determination of the western Atlantic BFT stock-recruitment relationship as the *highest priority* for future research.

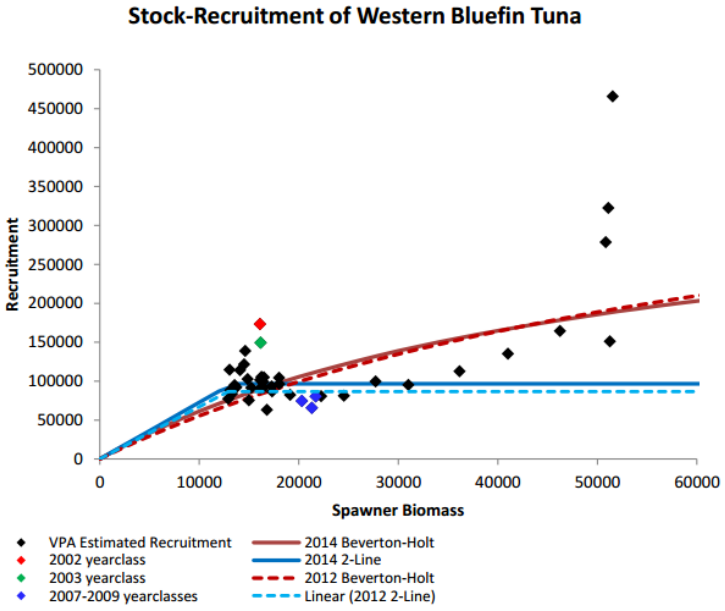

Figure 1: Spawner-recruit relationships from the 2014 stock assessment. The two-line model (blue) represents the low recruitment scenario; the Beverton-Holt model represents the high recruitment scenario (red) (Lauretta et al., 2014)

The central questions which must be addressed in order to improve the western Atlantic BFT stock assessment therefore relate to drivers of recruitment. In many pelagic fish species, recruitment is determined

during early life history stages, i.e. eggs and larvae (Pepin and Myers, 1991). Recruitment in other scombrid species has been associated with larval feeding, growth and predation processes, suggesting a link with zooplankton communities (Marguiles, 1993; Robert et al., 2007). Published studies (Llopiz et al. 2010; 2014) show that larval BFT are highly selective feeders, and that feeding success is not related to ambient primary productivity levels. Instead, the abundance of specific planktonic prey and predator species is likely to be of key importance. Environmentally-driven shifts in zooplankton communities have been linked to variability in larval growth (Buckley & Durbin, 2006), juvenile survival (Cooney et al., 2001) and fisheries recruitment (Pershing et al., 2005) in multiple economically important fish species. As a result, decadal-scale time series of zooplankton composition are maintained in several US Large Marine Ecosystems. However, no such information currently exists for the GOM.

Plankton samples have been collected during the spring spawning season of BFT in the northern GOM since 1982. These collections represent a potentially rich resource for studies of larval ecology and recruitment for BFT and many other fish species. However, they have not been analyzed beyond simple biomass estimates. We propose to address this by using recent technology to document zooplankton communities in the northern GOM. We will then combine indices of zooplankton composition with other physical and biological variables, and assess their ability to predict recent recruitment fluctuations for western BFT.

This project will directly address the FATE research objectives 1) and 2) through the development of indicators and models to "investigate specific mechanisms driving interactions between fisheries, environment and climate, including recruitment".

Approach

Our workplan for this project will involve three steps, which are described in more detail below:

1) Use a Zooscan plankton scanner to document zooplankton communities at selected, representative stations across the 34 year GOM time series
2) Use multivariate statistical techniques to derive one or more indices which summarize spatiotemporal variability in the zooplankton community
3) Combine these indices with other physical and biological environmental variables in a predictive model of recruitment fluctuations for western BFT

Zooscan analyses

Plankton samples are available for analysis through the SEAMAP program. Annual spring (April - May) cruises have been completed in the northern GOM through SEAMAP since 1982, and were designed to target the spatiotemporal extent of BFT spawning (Scott et al., 1993). Samples were collected using 60cm bongo nets with 355μm mesh, towed obliquely to 200m depth. Samples were preserved in buffered 4% formalin prior to 2010, and in 95% ethanol thereafter. Observations of plankton communities depend strongly on the mesh size used, with finer meshes under-sampling large mesozooplankton, and coarser meshes (such as used here) under-sampling smaller zooplankton such as copepod nauplii (Makabe et al., 2012). However, based on size frequency analyses of prey found in larval BFT guts, our samples should be sufficient to enumerate prey of the sizes consumed by larvae > 3mm in length (Llopiz et al., 2014).

A subset of 18 samples from each year will be analyzed; these will be selected to cover 3 bi-weekly time periods between mid-April and the end of May, stratified across 3 oceanographic regions of the GOM, with 2 stations within each. Oceanographic regions will be defined as the Loop Current, western GOM anticyclonic eddies, and offshore common waters, following Muhling et al. (2010) and Lindo-Atichati et al. (2012) (Fig. 2). CTD cast data are available for

each sampling station, providing temperature and salinity from the surface to 200m depth. Oceanographic regions will be defined using water column properties at 100m and 200m depth, as defined in Muhling et al. (2010), which showed that the Loop Current and anticyclonic eddies can be distinguished by elevated temperature and salinity at depth.

Zooplankton samples will be processed using a Zooscan plankton sampler. The NOAA Early Life History laboratory at the Southeast Fisheries Science Center has an operational Zooscan, which has been used to analyze some selected plankton samples from 2010. We will use their protocols to analyze the historical SEAMAP samples. Zooscan is an integrated analysis system for acquiring and analyzing digital zooplankton images from preserved samples. A sub-sample of each plankton sample will be scanned, measured and identified to major groups, focusing on those items identified as larval bluefin prey items (copepod nauplii, appendicularians, calanoid copepods, and cladocerans). We will use a semi-automated approach where automated classification is followed by manual validation and lower level visual classification where necessary.

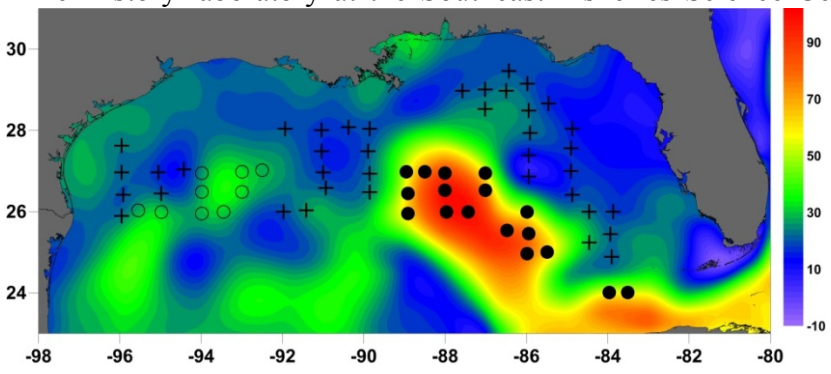

Figure 2: Sea surface height from May, 2012, with sampled stations and water masses: Loop Current (solid circles), warm core eddy (open circles), common waters (crosses)

Multivariate zooplankton community metrics

Once zooplankton communities have been documented, we will use standard multivariate analysis techniques to reduce the dimensionality of the dataset, and to investigate the main drivers of variability. Non-metric Multidimensional Scaling (NMDS) and Principal Coordinate Analysis (PCO) are particularly applicable for these objectives, and are available in Primer-E software. These ordination methods will allow us to summarize variability along several uncorrelated axes, the eigenvalues of which will then be used as variables in the predictive recruitment model described below. In addition, taxonomic groups which contribute most strongly to the variance, and which best characterize certain water masses or periods of time, can be highlighted. Similar methods have been used with success in the California Current region, where a copepod community index was developed, and used as a correlate in several recruitment models (Miller et al., 2014).

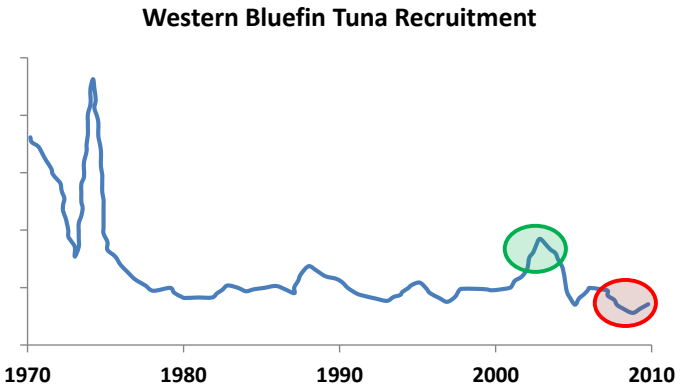

Figure 3: Western BFT recruitment from the 2014 VPA stock assessment model. Recent high and low recruitment years are highlighted

Predictive recruitment model

Recruitment to the western BFT stock has generally been low since the early 1980s. However, peaks in recruitment are estimated by the latest Virtual Population Analysis (VPA) stock assessment model for 2003 and 2004 (resulting from 2002 and 2003 spawning), with lower

values for 2007 – 2009 (2006 – 2008 spawning) (Fig. 3). This variability is not correlated with estimates of stock biomass. The 2003-4 recruitment peaks are comparable to some values recorded before 1980, when the stock biomass was much higher, while the 2007-9 recruitment values are some of the lowest ever recorded.

To investigate environmental drivers of this recruitment variability, we will combine indices of zooplankton community structure (described above), with several other predictors into a multivariate recruitment prediction model. Environmental variables considered will include:

- Surface temperature (CTDs, 20th century climate model (Liu et al.))
- Surface temperature rate of change (NDBC buoys)
- Surface chlorophyll biomass (20th century climate model)
- Wind fields (NDBC buoys, AVISO)
- Loop Current strength (Lindo et al., 2012, 1993 onwards only)
- Climate indices (AMO, ENSO) for spring, and previous winter

All variables will be extracted for each year at monthly intervals, for April – August, which will cover the spawning season, and months where small juveniles are present in the GOM.

The 20th century climate model was developed by Yanyun Liu and Sang-Ki Lee, and fields are available at a high resolution for the GOM. This model will be re-run to include biogeochemical fields, by coupling the Modular Ocean Model version 4.1 (MOM4) (Griffies et al., 2004; Gnanadesikan et al., 2006) to the TOPAZ (Tracers of Phytoplankton with Allometric Zooplankton; Dunne et al., 2005) biogeochemical model. The TOPAZ model includes all major nutrient elements (i.e., N, P, Si and Fe) and 25 tracers to describe the cycles of carbon, nitrogen, phosphorus, silicate, iron, oxygen, alkalinity and lithogenic material (Dunne et al., 2012). It uses three explicit phytoplankton groups ("small", "large", and diazotrophic), and traces dissolved oxygen, dissolved inorganic carbon and alkalinity, and includes highly flexible phytoplankton stoichiometry and variable chl:C ratios. A detailed description of the model initialization and parameters can be found in Polovina et al. (2011) and Dunne et al. (2012). The model domain will contain the Atlantic Ocean from 100°W to 20°E, 65°N to 20°S, with a horizontal resolution of 0.1° over the GOM region decreasing linearly to 0.25° in the rest of model domain. The 20th Century simulation will be driven by surface forcing fields from the 20th Century Reanalysis version 2 (20CR) dataset (Compo et al., 2011). The initial and boundary conditions will be obtained from the Simple Ocean Data Assimilation version 2.2.6 (SODA) product (Giese and Ray, 2011). The 20th century simulation is integrated for 60 years for the period of 1960-2009.

The recruitment prediction model will be built in DTREG software, using an artificial neural network (Sherrod, 2003). This technique is ideal for describing non-linear processes, with multiple complex interactions. Models are built using interconnected nodes, connected by linear transfer functions. V-fold cross-validation is used to avoid overfitting, whereby the trial model is re-run with a portion of the data withheld, and this procedure is repeated several times. Once checked for multicollinearity using variance inflation factors, all remaining environmental variables will be included in the predictive model, which will attempt to use them to predict annual recruitment. The variance explained by the model can then be quantified, and the contribution of each predictor variable assessed by rank.

Results from this model will then be used to evaluate the importance of the planktonic environment to recruitment, and thus the plausibility of the low vs. high recruitment scenarios. If recruitment is shown to be predictable based on environment, this lends support to the low

recruitment hypothesis. Variables identified as important will be examined for evidence of a regime shift since 1970 (as postulated by the low recruitment scenario), using the 20th century climate model. Zooplankton communities are not well known for the GOM prior to 1982, and so conclusions based on this variable may remain tentative. If recruitment is not correlated with any of our chosen predictor variables, then the advice provided to ICCAT will be that recruitment is likely driven by maternal condition, processes operating after juveniles leave the GOM, or by some environmental variable not considered in this study. This information will be summarized in a report, and presented to the ICCAT BFT species group at the annual assessment meeting.

Benefits

This proposal will contribute essential information to the BFT tuna stock assessment by examining larval ecology in the GOM. Our work will allow us to assess the plausibility of the two recruitment scenarios, which will contribute to the current and future status of the stock being more accurately determined. The current assessment assigns equal weight to the two recruitment scenarios. This essentially describes the stock as being equally likely to be:

- Overfished, undergoing overfishing, and unlikely to recover under the current rebuilding plan (high recruitment scenario), or
- Not overfished and not undergoing overfishing (low recruitment scenario)

The low recruitment scenario relies on the existence of some unspecified environmental regime shift, which has lowered recruitment potential since the 1970s. The nature of this shift has not yet been examined, primarily because the environmental drivers of recruitment are not known. Our project will provide a scientific basis for the evaluation of the two scenarios by describing, for the first time, potential links between environment, larval ecology, and ultimate recruitment. NMFS considers the determination of recruitment scenarios for western BFT as the highest priority for future research, which underscores the applicability and importance of this project.

Our proposal will also directly address two FATE research objectives (1 and 2) through the development of indicators and models to "investigate specific mechanisms driving interactions between fisheries, environment and climate, including recruitment". The stock-recruit relationship underpins the current assessment model, and uncertainty in this relationship reduces the certainty of recommendations provided to managers. This work will therefore use biological and environmental metrics to significantly improve the quality of an important stock assessment, for a species with significant value to NMFS. In addition, the documentation of zooplankton communities across >30 years in an important and productive US Large Marine Ecosystem (the GOM) will provide a highly valuable ecosystem indicator. Once completed, the zooplankton index can be used by NMFS and other researchers for multiple ecosystem assessment activities, including climate research, Integrated Ecosystem Assessments (IEA), and more.

Deliverables

Deliverables from this project will include:

- A zooplankton community index for the northern GOM, spanning 1982 – 2014, which will be available to other researchers for future projects
- A summary report for presentation to the annual ICCAT stock assessment meeting, evaluating the evidence for and against each recruitment scenario, based on results from the recruitment model
- At least one ICCAT contributed paper, and at least one peer reviewed publication

References

Buckley, L.J. & Durbin, E.G. (2006) Seasonal and inter-annual trends in the zooplankton prey and growth rate of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larvae on Georges Bank. Deep Sea Research Part II: Topical Studies in Oceanography 53: 2758-2770.

Compo, G. P., et al., 2011. The twentieth century reanalysis project, Q. J. R. Meteorol. Soc., 137, 1–28, doi:10.1002/qj.776.

Cooney, R. T., Allen, J. R., Bishop, M. A., Eslinger, D. L., Kline, T., Norcross, B. L., ... & Willette, T. M. (2001) Ecosystem controls of juvenile pink salmon (*Onchorynchus gorbuscha*) and Pacific herring (*Clupea pallasi*) populations in Prince William Sound, Alaska. Fisheries Oceanography 10: 1-13.

Dunne, J. P., R. A. Armstrong, A. Gnanadesikan, and J. L. Sarmiento, (2005) Empirical and mechanistic models for the particle export ratio. Global Biogeochem Cy 19: GB4026, doi:10.1029/2004GB002390.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E. N., … N. Zadeh, (2012) GFDL's ESM2 global coupled climate-carbon Earth System Models Part I: Physical formulation and baseline simulation characteristics, J Climate, doi:101175/JCLI-D-11-00560.1.

Giese, B. S., and S. Ray., 2011. El Niño variability in simple ocean data assimilation (SODA), 1871–2008, J. Geophys. Res., 116, C02024, doi:10.1029/2010JC006695.

Gnanadesikan, Anand, and Coauthors, (2006) GFDL's CM2 Global Coupled Climate Models. Part II: The Baseline Ocean Simulation. J. Climate, 19, 675–697.doi: http://dx.doi.org/10.1175/JCLI3630.1

Griffies, S. M., M. J. Harrison, R. C. Pacanowski, and A. Rosati (2004) A technical guide to MOM4, GFDL Ocean Group Tech. Rep. 5, Geophys. Fluid. Dyn. Lab., Princeton, N. J.

Hilborn, R., & Walters, C. J. (Eds.). (1992) Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty/Book and Disk. Springer, Chicago.

ICCAT (2012) Report of the 2012 Atlantic bluefin tuna stock assessment session. ICCAT SCI-033/2012, 124 pp.

Lindo-Atichati, D., Bringas, F., Goni, G., Muhling, B., Muller-Karger, F. E., & Habtes, S. (2012) Varying mesoscale structures influence larval fish distribution in the northern Gulf of Mexico. Marine Ecology Progress Series 463: 245-257.

Llopiz, J. K., Richardson, D. E., Shiroza, A., Smith, S. L., & Cowen, R. K. (2010). Distinctions in the diets and distributions of larval tunas and the important role of appendicularians. Limnology and Oceanography 55: 983.

Llopiz, J.K., Muhling, B.A., Lamkin, J.T. (2014) Feeding dynamics of Atlantic bluefin tuna (*Thunnus thynnus*) larvae in the Gulf of Mexico. ICCAT SCRS/2014/173, 6pp.

Makabe, R., Tanimura, A., & Fukuchi, M. (2012) Comparison of mesh size effects on mesozooplankton collection efficiency in the Southern Ocean. Journal of Plankton Research, 34(5), 432-436.

Miller, J. A., Teel, D. J., Peterson, W. T., & Baptista, A. M. (2014) Assessing the Relative Importance of Local and Regional Processes on the Survival of a Threatened Salmon Population. PloS one 9: e99814.

Muhling, B. A., Lamkin, J. T., & Roffer, M. A. (2010) Predicting the occurrence of Atlantic bluefin tuna (*Thunnus thynnus*) larvae in the northern Gulf of Mexico: building a classification model from archival data. Fisheries Oceanography 19: 526-539.

NMFS (2014a). National Marine Fisheries Service – 2nd Quarter 2014 Update: Summary of Stock Status for FSSI Stocks. http://www.nmfs.noaa.gov/sfa/fisheries_eco/status_of_fisheries/archive/2014/second/q2_stock_status_tables.pdf , accessed 8/14/2014.

NMFS (2014b). Atlantic HMS management-based research needs and priorities. Highly Migratory Management Division, NMFS, NOAA, July 2, 2014 http://www.nmfs.noaa.gov/sfa/hms/documents/hms_research_priorities_2014.pdf , accessed 8/14/2014.

Pepin, P., & Myers, R. A. (1991) Significance of egg and larval size to recruitment variability of temperate marine fish. Canadian Journal of Fisheries and Aquatic Sciences 48: 1820-1828.

Pershing, A. J., Greene, C. H., Jossi, J. W., O'Brien, L., Brodziak, J. K., & Bailey, B. A. (2005) Interdecadal variability in the Gulf of Maine zooplankton community, with potential impacts on fish recruitment. ICES Journal of Marine Science: Journal du Conseil 62: 1511-1523.

Polovina J.J., Dunne, J.P., Woodworth, P.A., Howell, E.A. (2011) Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. ICES J Mar Sci 68: 986-995.

Scott, G. P., Turner, S. C., Churchill, G. B., Richards, W. J., & Brothers, E. B. (1993) Indices of larval bluefin tuna, *Thunnus thynnus*, abundance in the Gulf of Mexico; modelling variability in growth, mortality, and gear selectivity. Bulletin of Marine Science 53: 912-929.