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DEVELOPING NEW EARLY LIFE HISTORY- BASED FISHERY INDEPENDENT INDICES FOR WESTERN ATLANTIC BLUEFIN TUNA

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SUMMARY

Fishery independent indices based upon larval surveys have been used to estimate spawning biomass of bluefin tuna in the western North Atlantic since the late 1970s. Using recent advances in habitat modeling and sampling gears we propose to improve the existing indices by:

- *Modifying the existing sampling grid to incorporate a model-assisted sampling scheme based upon habitat models*
- *Expanding depth-stratified sampling to define the vertical distribution of bluefin larvae. The efficiency of current sampling gears can then be estimated*
- *Incorporating annual age and mortality estimates for larvae collected in different regions within the Gulf of Mexico.*

In addition we propose the development of several new indices:

- *An index of larval prey, feeding success and growth to be used in next-generation stock assessments as an environmental driver of recruitment*
- *Development of a bluefin egg sampling effort as part of the standard spring plankton survey, which will lead to a more direct index of SSB*
- *Exploratory sampling efforts in the Caribbean and western North Atlantic to determine the significance and geographic extent of alternative spawning grounds. The inclusion of alternative spawning grounds in the development of indices may better reflect abundance trends.*

RÉSUMÉ

Des indices indépendants des pêcheries reposant sur des prospections larvaires ont été utilisés pour estimer la biomasse du stock reproducteur du thon rouge dans l'Ouest de l'Atlantique Nord depuis la fin des années 70. Sur la base des récents progrès accomplis en matière de modélisation de l'habitat et d'engins d'échantillonnage, nous proposons d'améliorer les indices actuels en :

- *modifiant la grille d'échantillonnage existante afin d'y incorporer un système d'échantillonnage assisté par modèle reposant sur des modèles d'habitat ;*
- *élargissant l'échantillonnage stratifié en profondeur pour définir la distribution verticale des larves de thon rouge. L'efficacité des engins d'échantillonnage actuels pourra ensuite être évaluée ; et*
- *en incorporant les estimations annuelles de l'âge et de la mortalité des larves recueillies dans différentes régions au sein du golfe du Mexique.*

En outre, nous proposons de développer plusieurs nouveaux indices :

- *Un indice des proies des larves, de la capacité de se nourrir et de croissance à utiliser dans les évaluations de stocks de nouvelle génération en tant que facteur environnemental du recrutement.*
- *Le développement d'un effort d'échantillonnage des œufs de thon rouge dans le cadre du relevé standard de plancton au printemps, ce qui donnera lieu à un indice plus direct de la biomasse du stock reproducteur.*

- *Les efforts d'échantillonnage exploratoire dans les Caraïbes et l'ouest de l'Atlantique Nord dans le but de déterminer l'importance et l'étendue géographique d'autres zones de frai. L'inclusion d'autres zones de frai dans le développement des indices pourrait mieux refléter les tendances de l'abondance.*

RESUMEN

Desde finales de los años 70, se han utilizado los índices independientes de la pesquería basados en las prospecciones de larvas para estimar la biomasa reproductora del atún rojo en el Atlántico noroccidental. Utilizando los avances recientes en la modelación del hábitat y en los dispositivos de muestreo, proponemos mejorar los índices actuales mediante:

- *La modificación del diseño del muestreo para incorporar un programa de muestreo asistido por el modelo basado en modelos de hábitat.*
- *La ampliación del muestreo estratificado por profundidad para definir la distribución vertical de larvas de atún rojo. De este modo se podrá estimar la eficacia de los dispositivos de muestreo actuales.*
- *La incorporación de estimaciones anuales de edad y mortalidad para las larvas recogidas en diferentes regiones dentro del golfo de México.*

Además, proponemos que se desarrollen varios índices nuevos.

- *La obtención de un índice de presas de larvas, capacidad para alimentarse y crecimiento para utilizarlo en las evaluaciones de stock de la próxima generación como un factor medioambiental de reclutamiento.*
- *Desarrollo de un esfuerzo de muestreo de huevos de atún rojo como parte de la prospección estándar de plancton de primavera, que producirá un índice más directo de SSB.*
- *Los esfuerzos de muestreo exploratorio en el mar Caribe y en Atlántico noroccidental para determinar la importancia y extensión geográfica de zonas de reproducción alternativas. La inclusión de zonas de reproducción alternativas en el desarrollo de índices podría reflejar mejor las tendencias en la abundancia.*

KEYWORDS

Bluefin tuna, Recruitment, Stock assessment

Introduction and Research to Date

Atlantic bluefin tuna are distributed throughout the north Atlantic and are exploited with a variety of fishing gears throughout their range. The western Atlantic bluefin stock is estimated to have declined precipitously during the 1970s and early 1980s, but has been relatively stable since the implementation of quotas in 1982. There are various uncertainties in the stock assessments; one avenue for reducing these uncertainties could be improvements in the various indices used in the models to reflect relative abundance trends. Most indices developed for stock assessment of bluefin tuna are fishery dependent, however, the NOAA Southeast Fisheries Science Center has developed a fishery independent index for the western bluefin stock using larval abundances from annual ichthyoplankton surveys. These surveys have been carried out since the late 1970s, and since 1982 have been completed as part of the Southeast Area Monitoring and Assessment (SEAMAP) program (Scott *et al.*, 1993, Ingram *et al.* 2010). Larvae are collected from oblique bongo net tows to 200m depth, and surface neuston net tows across a 1 x 1° grid within the U.S. EEZ in the northern Gulf of Mexico. Sampling is conducted from late April to the end of May, with sampling continuing into June in some years. Larval abundances are converted to equivalent abundances of larvae with a first daily otolith increment per 100m^2, and standardized for spatiotemporal sampling variability. The resulting larval index, is used in stock assessment models to index the spawning stock biomass.

The index shows that larval bluefin were initially abundant from 1977-1983, but catches decreased substantially from 1984 – present (**Figure 1**). Because fish larvae are typically over-dispersed due to spawning behavior and transport of the eggs and larvae by ocean processes, the resultant catch data are zero-inflated, and not normally distributed. This typically results in a dataset with many zero values, and a very few large values, leading to a high coefficient of variation around the index (Ingram *et al.* 2010).

To address this problem, work was begun in 2009 to develop a larval habitat model using historical catch data. The model used artificial neural networks to predict probabilities of larval abundance using *in-situ* environmental variables from CTD casts, and to therefore provide an additional means of standardizing the larval index. (Muhling *et al.* 2010). Results showed that bluefin tuna larvae were most likely to be collected in warm (24 – 28°C), low chlorophyll waters, outside of the Loop Current. To increase the predictive utility of the habitat model, it was then reconfigured to predict larval occurrences using only remotely sensed environmental data: sea surface temperature, surface chlorophyll, surface height, and surface current velocities. This updated model delivered similar results to the *in situ* model, and was applied to a study of the potential impacts of the 2010 Deepwater Horizon oil spill (**Figure 2**: Muhling *et al.* 2012). Similar techniques have since been used to compare environmental constraints on bluefin tuna spawning habitat in the Gulf of Mexico vs. the western Mediterranean Sea (Muhling *et al.* 2013). Habitat models successfully predicted interannual variability in larval bluefin distributions, and highlighted the importance of water temperature to spawning activity in both regions.

One hurdle to developing the habitat model has been the low number of larvae collected each year, and the large number of zero catch stations. To address this, sampling protocols were changed to include a new plankton net (S-10) in 2010. This gear is a 1 x 2 m frame with a 0.505 mm mesh net towed in an undulating fashion from the surface to 10 meters depth for 10 minutes. This sampling method resulted in significantly higher catches of bluefin larvae, and a higher overall proportion of positive stations (**Figure 3**: Habtes *et al. in press*). In view of these results, it was decided to incorporate this sampling gear into the SEAMAP surveys, and to eventually develop a new larval index using the results from this gear.

In addition, depth- stratified sampling was initiated on the 2010 cruise, using a Multiple Opening and Closing Net Environmental Sensing System (MOCNESS). This gear samples in discrete 10m depth increments from 50 meters to the surface, and has been deployed only sporadically to this point, due to time constraints. Initial results from this gear indicate that bluefin larvae are found primarily in the upper 20 meters of the water column.

While these efforts continue to improve the existing larval index, we propose additional efforts and the development of new indices:

Improvements to the Current Index

1. Expand existing sampling on annual surveys

Depth-stratified sampling has been limited to date, and as a result, the vertical distribution of bluefin tuna larvae is not well known. In order to better understand the effectiveness of our other depth-integrated sampling gears, depth-stratified sampling using the MOCNESS gear should be expanded in future years, and be made a standard component of annual surveys. Information from these samples will also be useful to ongoing studies of larval transport and dispersal potential, by providing depth distribution information for the construction of Individual-Based Models (IBMs).

In addition, the current survey grid has a very coarse spatial resolution, which, when combined with the patchiness of larval distributions, can introduce high variability in the calculated larval indices. This grid may be partially modified to incorporate a model-assisted sampling scheme (Sarndal, 1992), based on predictions from habitat models. Sufficient ship-time exists for the ~30 year time series of plankton sampling to be maintained, while allowing for some adaptive sampling in areas with high probability of larval occurrence.

2. Develop a dynamic age/growth mode and predictive recruitment model

Estimates of age at length are required for the standardization of raw larval abundances to an estimate of one day old larvae under $100m^2$ of sea surface (Ingram *et al.*, 2010). The current estimate of age at length matrix was developed by Brothers *et al*., (1983) from specimens collected off South Florida more than 30 years ago. This estimate was initially used because survey catches from 1984 onwards had become too small to support annual estimates of mortality, and as a result, it has been applied to all larval index mortality estimates ever since. The recent advances in sampling methods noted above have resulted in greatly increased larval catches, which could allow the development of annual growth and age estimates. Recent work in the western Mediterranean indicates that larval bluefin tuna growth may vary considerably on an interannual basis, which may have profound effects on recruitment variability (Garcia *et al.*, 2013). We propose to address gaps in our understanding of larval bluefin tuna growth by investigating environmental drivers of growth and mortality in the Gulf of Mexico, and developing annual age/growth curves for the eastern and western Gulf. These will be incorporated into the larval index, and will improve the accuracy of the index by accounting for interannual effects of the pelagic environment on larval growth.

Growth rates will be examined using otoliths extracted from larvae collected across a wide variety of oceanographic features from both the eastern and western Gulf of Mexico, from multiple years. Understanding these drivers is essential for improving the larval index, and also for developing a predictive recruitment model. In addition, we will examine the relationship between growth and temperature throughout the larval stage by backtracking larvae using ocean models. This will reduce variation in growth estimates and inform models of daily growth rates driven by environmental parameters. Finally, results will inform and improve the larval index by adding regional and oceanographic feature-specific growth curves.

Development of New Indices

1. Larval prey, feeding success and growth index

To understand the influence of larval survival on recruitment variability, the processes that are governing larval survival must first be understood. To survive, a larva has to eat and avoid being eaten. In addition, suboptimal feeding can influence a larva’s susceptibility to be consumed by a predator, by both extending the larval period via slower growth, and by reducing a larva’s ability to evade predation (Houde, 1987).

Recruitment processes for bluefin tuna are not well known, but appear to be episodic, and not always closely correlated to spawning stock biomass. Apparent peaks in recruitment, as determined by abundances of 1-year old fish, may be separated by decades. Given the large departure of these peaks from long term means, it appears likely that recruitment success is determined in very early life, when larvae are subject to high and variable mortality. An improved understanding of these processes should in turn lead to improved stock assessments and more effective management (e.g. this would enable better evaluations of the likely success of stock rebuilding plans). The proposed index of larval prey, feeding success and growth will fill a long-standing gap in knowledge of larval bluefin diets, feeding and survival, and potential effects on ultimate recruitment success.

This work will combine studies of larval growth (using otoliths), larval feeding success (using gut contents) and larval prey fields (using zooplankton samples). Conditions conducive to higher feeding success, faster growth and presumed enhanced survival will be defined, initially by using existing samples from recent years (2010-present). Once favorable conditions are defined, in terms of available prey and ambient environment, an index of these can be developed. This index can be extended back to 1982, using preserved samples and specimens from the SEAMAP collection, and archived plankton samples. Results will add to knowledge of how biophysical conditions may influence larval ecology and recruitment potential, and may help to explain recruitment peaks, such as that observed in 2003. In addition, if conditions favoring high recruitment can be elucidated, we may be able to search for historical supporting evidence of any past "regime shifts", an assumption implicit in the hypothesis that the western bluefin stock-recruitment relationship has changed from High to Low Recruitment Potential (Rosenberg *et al.*, 2013). The uncertainty regarding these two recruitment scenarios is a key issue in the stock assessment process.

2. Develop and index of daily egg production with continuous eggs sampling and genetic analysis of eggs

An alternative approach to assessing spawning stock biomass is through the use of a daily egg production model (DEPM). This technique provides a more direct estimate of spawning biomass than larval abundances, as it avoids the additional error associated with larval growth and mortality. The DEPM approach has been thoroughly developed on the U.S. West Coast for small pelagic fishes (Lasker, 1985). However, it has traditionally only been used on species whose eggs are easily identifiable visually, which limits its application. With current advances in genetic techniques, many previously indistinguishable fish species can now be identified from eggs. This includes species whose eggs are collected during the annual SEAMAP survey, such as bluefin tuna, yellowfin tuna, blackfin tuna, billfish, swordfish, snappers, and groupers.

To develop this index, we will use the DEPM described by Parker, (1985): $B = ((P \cdot A \cdot W)/(R \cdot F \cdot S))$, where B= biomass estimate, P = daily egg production (# of eggs produced per area per day), A = total survey area, W = average weight of mature females, R = fraction of mature female fish by weight, F = batch fecundity and S = fraction of mature females spawning per day. Eggs are collected in the same plankton sampling gears that are currently used to collect larvae, and will be identified genetically. We expect that mixtures of eggs collected could contain genomes from many species. However, it is now possible via massively parallel DNA sequencing to identify individual collections of eggs to species, and to simultaneously yield a reasonable estimate of relative abundance. We have already designed genetic assays for many species in the Gulf of Mexico, and these genetic assays can be used to identify most fish. Species not currently in our database can be identified via searches of the Fish Barcode of Life (FISBOL) or GenBank sequence repositories or the primary literature.

3. Extension of sampling efforts in the Caribbean and western North Atlantic

Several exploratory cruises in the western Caribbean Sea and Bahamas regions have been completed during spring between 2009 and 2013. Scattered collections of bluefin tuna larvae have been found in the Yucatan Channel, east of the Yucatan Peninsula, and north of the Bahamas. However, the relative amount of spawning activity that takes place in these areas is currently unknown. Current assessment models assume that larvae collected in the Gulf of Mexico encompass all of the western spawning stock. The relative importance of alternate spawning grounds therefore needs to be determined, to better test this assumption. Genetic testing of bluefin larvae collected can be used to assess the closeness of the relationship between larvae collected inside and outside the Gulf of Mexico. In addition, hydrodynamic backtracking analyses will be used to estimate original spawning locations of larvae from the Caribbean and Atlantic. This information can be combined to focus sampling efforts on particular regions in space and time, and repeated sampling across several years should be completed to determine the importance of previously unknown spawning grounds.

Of the two alternative spawning grounds identified, the area north of the Bahamas is potentially the largest (**Figure 4**). Habitat models suggest that potential spawning grounds are extensive, though it is unknown how much of the area may be utilized. The cruise in 2013 sampled only a portion of the area (**Figure 5**) but results suggest some level of spawning activity, though the extent is unknown. We propose a series of cruises in May and June over two years in this area that would cover a larger geographical extent. Approximately 200 samples would be taken in each cruise concentrated in areas identified as high probability for larval bluefin habitat.

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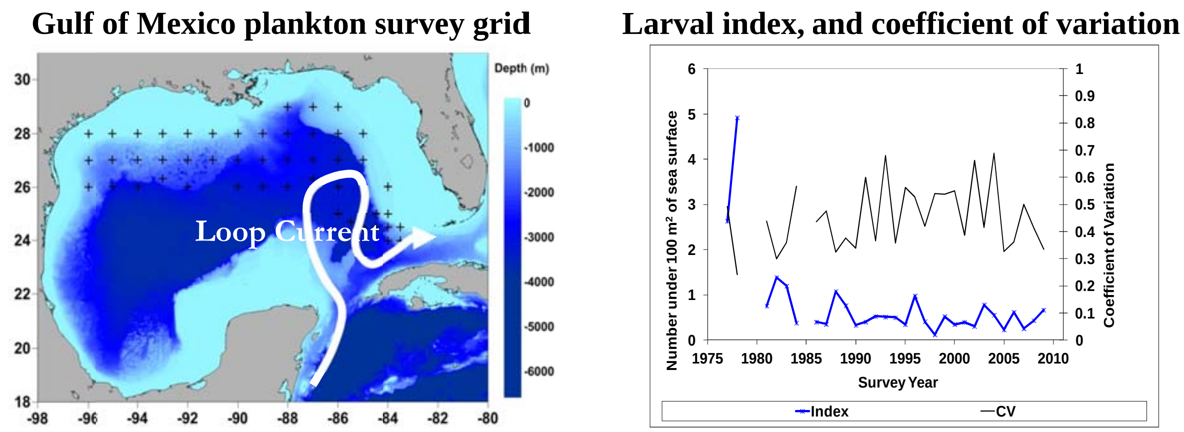

Gulf of Mexico plankton survey grid

Larval index, and coefficient of variation

Figure 1. SEAMAP spring survey stations and the bluefin larval index and coefficient of variation.

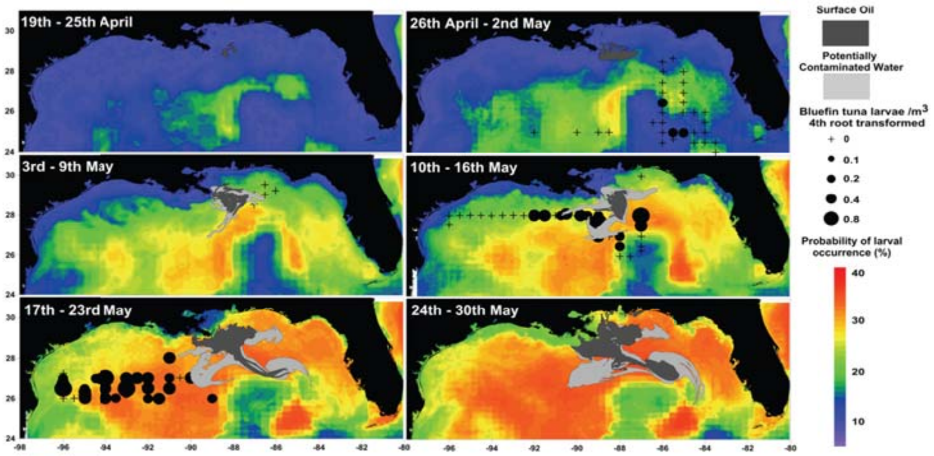
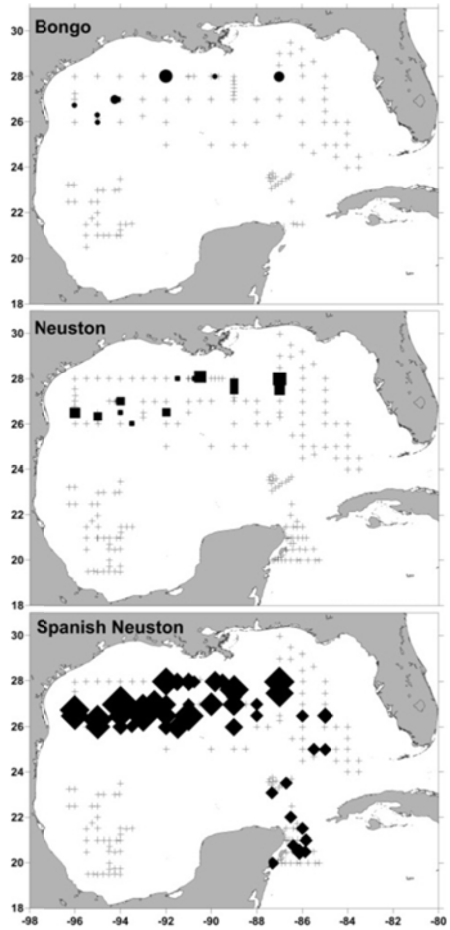


Figure 2: Predicted probabilities of occurrence for larval bluefin tuna in the northern Gulf of Mexico on a weekly basis during spring 2010. Probabilities were derived from a neural network model trained using archival larval collection data. Oil extents are derived from satellite products. Catches of larval bluefin tuna from spring 2010 (April 19th to May 23rd), are also shown.


Bongo

Neuston

Spanish Neuston

Figure 3. Bluefin tuna abundance using three gears, 0.333 mm bongo nets, 0.9 mm neuston, and 0.505 S-10 net.

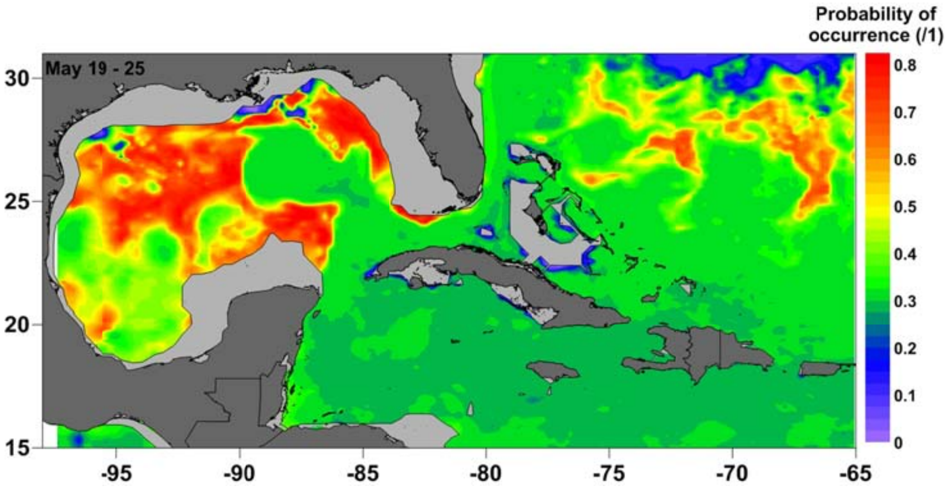


Figure 4. Probability of occurrence of bluefin tuna larvae

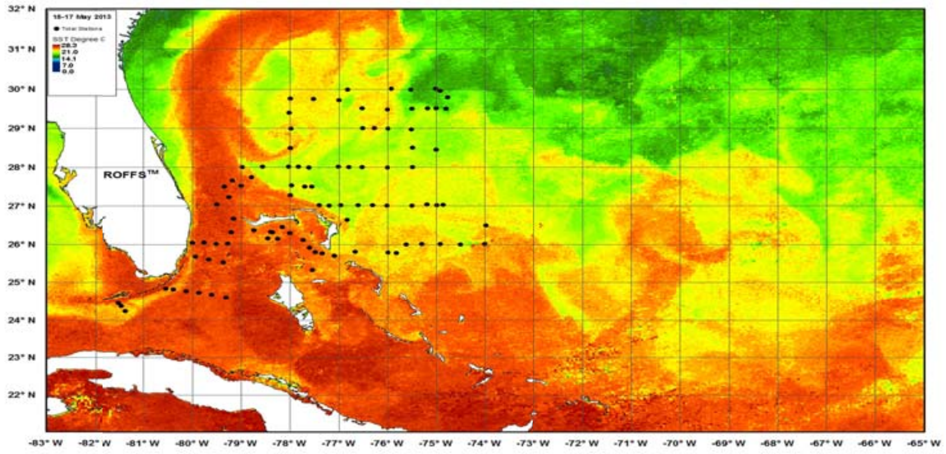


Figure 5. Stations sampled and possible extent of similar habitat.