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ANNUAL INDICES OF BLUEFIN TUNA (*THUNNUS THYNNUS*) SPAWNING BIOMASS IN THE GULF OF MEXICO (1977-2013)

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SUMMARY

Fishery independent indices of spawning biomass of bluefin tuna in the western North Atlantic Ocean are presented utilizing NOAA Fisheries ichthyoplankton survey data collected from 1977 through 2013 in the Gulf of Mexico. Indices were developed using standardized data from which previous indices were developed (i.e. abundance of larvae with a first daily otolith increment formed under 100 m^2 sea surface sampled with bongo gear). Due to the large frequency of zero catches during ichthyoplankton surveys, indices of larval abundance were developed using a zero-inflated delta-lognormal models, including following covariates: time of day, time of month, area sampled and year.

RÉSUMÉ

Des indices, indépendants des pêcheries, de la biomasse reproductrice du thon rouge de l'Atlantique Nord-Ouest sont présentés en utilisant les données de la prospection d'ichthyoplanctons réalisée par NOAA de 1977 à 2013 compris dans le Golfe du Mexique. Les indices ont été élaborés en utilisant des données standardisées sur la base desquelles les indices précédents avaient été conçus (c.-à-d. abondance larvaire avec une première augmentation quotidienne des otolithes formés au sein d'une surface maritime de 100 m^2 échantillonnée avec l'engin Bongo). En raison de la fréquence élevée des captures nulles pendant les prospections d'ichthyoplancton, des indices d'abondance larvaire ont été élaborés en utilisant des modèles delta-lognormaux à inflation de zéros, comprenant les covariables suivantes : moment de la journée, époque du mois, zone échantillonnée et année.

RESUMEN

Se presentan los índices independientes de la pesquería de la biomasa reproductora de atún rojo en el Atlántico noroccidental utilizando datos de la prospección de ictioplancton de la NOAA recopilados desde 1977 hasta 2013 en el golfo de México. Los índices se desarrollaron utilizando datos estandarizados a partir de los que se habían desarrollado índices anteriores (a saber, abundancia de larvas con un primer incremento de otolito diario en una superficie marítima de 100 m2 muestreada con una red bongo). Debido a la elevada frecuencia de capturas cero durante las prospecciones de ictioplancton, los índices de abundancia de larvas se desarrollaron utilizando modelos delta-lognormal inflados de ceros, lo que incluye las siguientes covariables: hora del día, momento del mes, área muestreada y año.

KEYWORDS

Mathematical models, Fish larvae

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1. Introduction and Methodology

The objective of this paper is to present updated annual abundance indices of bongo-collected Atlantic bluefin tuna larvae based on a zero-inflated delta-lognormal (ZIDL) model. These indices of spawning biomass are based upon the abundance of bluefin tuna larvae collected during fishery independent surveys conducted by NOAA Fisheries in the Gulf of Mexico from 1977 to 2013. The evolution of the use of this time series is detailed in numerous documents (i.e. Scott *et al.* 1993; Scott and Turner 1994, 1995, 1996, 1998, 2000, 2002; Ingram *et al.* 2006, 2008; Ingram *et al.* 2010), and the current methodologies, concerning the ZIDL approach, are detailed by Ingram *et al.* (2006, 2008) and Ingram *et al.* (2010).

Methodologies concerning general ichthyoplankton surveys conducted by NOAA Fisheries in the Gulf of Mexico have been extensively reviewed (Richards and Potthoff 1980; McGowan and Richards, 1986). Likewise, methodologies concerning the use of this survey data to assess bluefin tuna larvae were reviewed (Richards 1990; Murphy 1990).

Ichthyoplankton surveys were conducted from numerous NOAA vessels during mid to late April through May from 1977 through 2013 in the offshore waters of the U.S. Gulf of Mexico. Sampling station locations were usually located on a 30-nautical-mile grid. A double oblique plankton tow was conducted at every station through 1983 and at every other station from 1984 through 2011. Each tow was conducted to 200 m or to within 1-5 meters of the bottom if the water depth is less than 200 m and was made using a paired 61-cm bongo net plankton sampler with a 0.333 mm mesh. Ship speed during the tow was maintained at approximately 1.5 knots to maintain a 45° wire angle on the deployment cable. A flow meter inside the mouth of each bongo net was used to determine the volume of water sampled.

Identifications and measurements of larvae by the Polish Plankton Sorting and Identification Center in Szczecin, Poland were verified for all survey years, except 2013. Verification of the 2013 data was delayed due to a lapse in survey funding, and these data should be treated as provisional. The methodologies of Scott *et al.* (1993) and Scott and Turner (1994, 1995, 1996, 1998, 2000, 2002) were used to standardize larval data. The mean number of larvae per 100 m^2 at first daily otolith increment formation for each station sampled between April 20 and May 31 each year of the time series (1977-2013) were estimated and used to index abundance. These were estimated as:

(1) $$I_{s,y} = \frac{\sum_{i=1}^{k} R_D e^{-Z(D_{s,y,i-1})}}{A_{s,y}}$$

where y indexes year, s indexes sampling station, i (= 1,..., n) indexes individual larvae, A the surface area sampled, Z the larval daily loss rate, D the larval daily ring count, and R, the gear efficiency estimate applied. Estimates were constructed using the preferred method as described in Scott *et al.* (1993) and Scott and Turner (1994, 1995, 1996, 1998, 2000, 2002), which adjusts the density estimates sampling stations for estimated larval loss rates and gear efficiency. With these station- and year-specific estimates of larval catch, the annual index value (and variability) were developed using the zero-inflated delta-lognormal method (ZIDL) of Ingram *et al.* (2010).

The ZIDL is a modification of the delta-lognormal modeling approach presented by Lo *et al.* (1992). The delta-lognormal index of relative abundance (I_y) as described by Lo *et al.* (1992) is estimated as

(5) $$I_y = c_y p_y,$$

where c_y is the estimate of mean CPUE for positive catches only for year y; p_y is the estimate of mean probability of occurrence during year y. Both c_y and p_y are estimated using generalized linear models. Data used to estimate abundance for positive catches (c) and probability of occurrence (p) are assumed to have a lognormal distribution and a binomial distribution, respectively, and modeled using the following equations:

(6) $$\ln(\mathbf{c}) = \mathbf{X\beta} + \boldsymbol{\varepsilon}$$

and

(7) $$\mathbf{p} = \frac{e^{\mathbf{X\beta}+\boldsymbol{\varepsilon}}}{1+e^{\mathbf{X\beta}+\boldsymbol{\varepsilon}}}$$, respectively,

where c is a vector of the positive catch data, p is a vector of the presence/absence data, X is the design matrix for main effects, β is the parameter vector for main effects, and ε is a vector of independent normally distributed errors with expectation zero and variance σ^2. Therefore, c_y and p_y are estimated as least-squares means for each year along with their corresponding standard errors, SE(c_y) and SE(p_y), respectively. From these estimates, I_y is calculated, as in equation (5), and its variance calculated as

$$V(I_y) \approx V(c_y)p_y^2 + c_y^2 V(p_y) + 2c_y p_y \mathrm{Cov}(c, p), \quad (8)$$

where

$$\mathrm{Cov}(c, p) \approx \rho_{\mathrm{c,p}}[\mathrm{SE}(c_y)\mathrm{SE}(p_y)], \quad (9)$$

and $\rho_{c,p}$ denotes correlation of *c* and *p* among years.

In order to develop the ZIDL model to estimate annual indices of abundance (Ingram *et al*. 2010), the regular binomial portion of the delta-lognormal model was replaced with a zero-inflated binomial model that takes into account the high proportion of zeros in the abundance data. The zero-inflated binomial model treats the probability of observing a bluefin tuna larva as a product of the true probability of the site being occupied (*o*), and the probability of detection (*d*) when in fact the site is occupied at the time the sample is taken (Tyre *et al*. 2003; Steventon *et al*. 2005; Ingram *et al*. 2010). Multiple samples must be taken at each site in order to estimate *d*, but the number of samples per site (*m*) does not have to be equal (Tyre *et al*. 2003). The number of observations of an animal for each site over *m* samples is denoted as *x*, and the number of sites sampled as *n* (Steventon *et al*. 2005).

In the case of this study, a year was treated as a site, since the goal was to develop annual indices of abundance. Therefore, when considering one year after *m* samples have been taken (i.e., *m* bongo stations completed), the probability of observing zero bluefin tuna larvae was:

$$P(x=0) = o(1-d)^m + (1-o)(1) \quad (10)$$

and the probability of observing exactly *x* bluefin tuna larvae, where *x* is greater than zero was:

$$P(x>0) = o\binom{m}{x} d^x (1-d)^{m-x} + (1-o)(0) \quad (11)$$

after Tyre *et al*. (2003), Steventon *et al*. (2005), and Ingram *et al*. (2010). These two probabilities were then combined to form the likelihood function for a single year *y*:

$$L(o, d \mid x, m) = \begin{cases} o(1-d)^m + (1-o), x = 0 \\ o\binom{m}{x} d^x (1-d)^{m-x}, x > 0 \end{cases} \quad (12)$$

following the methods of Tyre *et al*. (2003) and Ingram *et al*. (2010).

Steventon *et al*. (2005) expressed the above probability in equation (12) as a generalized Bernoulli distribution, allowing the combination of multiple years into a full likelihood:

$$L(o, d \mid \{x_y, m_y, u_y\}) = \prod_{y=1}^{n} \left[o(1-d)^{m_y} + (1-o)\right]^{u_y} \times \left[o\binom{m_y}{x_y} d^{x_y} (1-d)^{m_y - y_y}\right]^{1-u_y} \quad (13)$$

where u_y is an indicator variable: $u_y = 1$ when $x_y = 0$ and $u_y = 0$ when $x_y > 0$. The values of *o* and *d* are not required to be constant, and are usually not over time. These values can be influenced by covariates as follows:

$$\mathbf{o} = \frac{e^{\mathbf{X\beta+\varepsilon}}}{1 + e^{\mathbf{X\beta+\varepsilon}}} \quad (14)$$

and

(15) $$\mathbf{d} = \frac{e^{\mathbf{X\beta+\varepsilon}}}{1+e^{\mathbf{X\beta+\varepsilon}}},$$

where o and d are vectors of probability of occupancy and probability of detection, respectively, X is the design matrix for main effects, β is the parameter vector for main effects, and ε is a vector of independent normally distributed errors with expectation zero and variance σ^2. Certain covariates may be common between both the above models, while others may be completely different (Steventon *et al*. 2005).

Therefore, in the case of this study, the estimated probability of collecting a bluefin tuna larva during a single ichthyoplankton station was

(16) $$p_{Z1,y} = o \times d$$

and the probability of collecting at least one bluefin tuna larva after *m* ichthyoplankton stations was

(17) $$p_{Z,y} = o\left[1-(1-d)^m\right],$$

following the methods of Steventon *et al*. (2005) and Ingram *et al*. (2010). The p_y in equations (5), (8) and (9) was replaced with $p_{Z,y}$ from equation (17) to estimate annual indices of abundance and their corresponding variance using this new zero-inflated approach [$I_{Z,y}$ and $V(I_{Z,y})$, respectively], following the methods of Ingram *et al*. (2010).

The NLMIXED and MIXED procedures in SAS (v. 9.1, 2004) were used to develop the zero-inflated binomial and lognormal submodels, respectively. Similar covariates were considered for both submodels: time of day (two categories: night, 6:00 PM to 6:00 AM, local time; day, 6:00 AM to 6:00 PM, local time), survey date category (four categories: late April, April 20 to April 30; early May, May 1 to May 10; middle May, May 11 to May 20; late May, May 21 to May 31), survey area [original survey area as defined by Scott *et al*. (1993) divided into three categories plus a category for the far west U.S. Gulf of Mexico: eastern survey area (survey area between 84˚ and 86˚ longitude); central survey area (survey area between 86˚ and 91˚ longitude); western survey area (survey area between 91˚ and 94˚ longitude); far western survey area (survey area west of 94˚ longitude)] and year. These variables were chosen to adjust the index values to account for any temporal or spatial loss in survey effort during a particular survey year. Initial SAS code for the NLMIXED procedure was provided by Steventon *et al*. (2005). This code was modified in order to use dummy variables, which were needed to include categorical variables in the model. Variables that were deemed to affect both occurrence and detection of larvae were split between occurrence and detection submodels (see Equations 14 and 15) contained in the zero-inflated binomial submodel. Model performance was evaluated using AUC (Area Under Curve) methodology presented by Steventon *et al*. (2005) and residual analyses. A backward selection procedure was used to determine which variables were to be included into the lognormal submodel based on type 3 analyses with a level of significance for inclusion of $\alpha = 0.05$. If year was not significant then it was forced into each submodel in order to estimate least-squares means for each year, which are predicted annual population margins (i.e., they estimate the marginal annual means as if over a balanced population). The fit of the lognormal submodel was evaluated using the AIC statistics and residual analyses.

2. Results and Discussion

Table 1 summarizes the data collected in bongo tows used in these analyses. For most survey years, data can be used from late April through the entire month of May. However, there were several years where surveys were started late or ended early due to mechanical, meteorological and/or other logistical factors. For bongos, the number of stations sampled during the April 20 through May 31 time period ranged from 20 to 117. The number of specimens collected in bongo tows per year ranged from 10 to 221, and ranged in length from 1.3 to 10.7 mm.

The variables that were used in the model-building process of the zero-inflated binomial (ZIB) submodel for the development of the ZIDL model for bongo-collected larvae were: time of day, survey date category, survey area, and year. All the variables except time of day were used in the occupancy submodel while only the time of day was used in the detection submodel for the ZIB submodel. The time of day variable was used in the detection submodel as was reasoned that time of day (i.e. day or night) has an effect on the probability of detecting larvae (net avoidance). Table 2 summarizes the parameters used in the ZIB model and their significance. The ZIB submodel had an AUC = 0.724. The AUC (Area Under Curve) statistic provides information on the model's lack-of-fit, and in this case it means that in 72 out of 100 instances, a station selected at random from those with larvae had a higher predicted probability of larvae being present than a station randomly selected from those that had no larvae. **Figure 1** provides residual plots by the variables used in the modeling process. While the residual plots of survey date (**Figure 1b**) and survey area (**Figure 1c**) may indicate some pattern in the residuals, plots of the other variables (**Figures 1a and 1d**) and the QQplot of the residuals (**Figure 1e**) indicate the approximately normal distribution of the residuals of the ZIB submodel.

The variables that were used in the model-building process of the lognormal submodel for the development of the ZIDL model for bongo-collected larvae were: time of day, survey date category, survey area, and year. The results of type 3 analyses for the lognormal submodel for bongo-collected larvae are summarized in **Table 3**. For the lognormal submodel, all variables were significant (i.e. at $\alpha = 0.05$) except the survey date category and survey area, which were dropped from the second and third runs of the model, respectively (**Table 3**). **Figure 2** indicates the approximately normal distribution of the residuals of the lognormal submodel.

Table 4 and Figure 3 summarize indices of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the ZIDL model. Index values were highest in the early years of the survey and much lower in recent years, and in the 1998 and 2005 survey years the index values developed were the lowest of the entire time series. Since 2008, there has been an oscillation of the index values between 0.3 and 0.9 larvae under 100 m^2 of sea surface with the index values of the 2011 and 2013 survey years being very similar.

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Table 1. Summary of bongo data used in these analyses.

Survey Year	*Number of Stations Sampled*	*Start Date*	*End Date*	*Number of Specimens*	*Mean Length (mm)*	*Size Range (mm)*
1977	20	2 May 1977	12 May 1977	22	4.98636	3.4 - 8.1
1978	69	2 May 1978	30 May 1978	221	4.00181	2.4 - 9.5
1981	35	1 May 1981	26 May 1981	20	4.62500	2.7 - 7.0
1982	92	20 Apr 1982	25 May 1982	75	4.11840	2.0 - 10.7
1983	91	22 Apr 1983	23 May 1983	65	3.56738	2.0 - 6.8
1984	71	21 Apr 1984	12 May 1984	13	4.37692	3.0 - 6.0
1986	72	23 Apr 1986	22 May 1986	12	4.86667	3.5 - 6.0
1987	77	21 Apr 1987	21 May 1987	10	4.71500	2.3 - 9.2
1988	77	20 Apr 1988	25 May 1988	72	3.53750	2.3 - 7.0
1989	85	26 Apr 1989	27 May 1989	80	4.13250	2.0 - 8.0
1990	86	21 Apr 1990	31 May 1990	23	3.86087	2.6 - 7.5
1991	69	20 Apr 1991	21 May 1991	19	2.96316	2.4 - 6.0
1992	93	22 Apr 1992	22 May 1992	40	3.57750	2.5 - 9.0
1993	90	26 Apr 1993	31 May 1993	23	5.11304	3.0 - 6.2
1994	94	28 Apr 1994	31 May 1994	34	4.49412	2.5 - 9.2
1995	117	20 Apr 1995	31 May 1995	35	2.71357	2.1 - 5.6
1996	93	20 Apr 1996	25 May 1996	131	3.25420	2.6 - 6.0
1997	93	20 Apr 1997	31 May 1997	29	3.94138	2.4 - 5.9
1998	69	26 Apr 1998	30 May 1998	10	3.74000	2.1 - 5.5
1999	90	24 Apr 1999	31 May 1999	29	3.86552	2.7 - 6.0
2000	86	20 Apr 2000	26 May 2000	25	3.50320	2.8 - 5.2
2001	93	20 Apr 2001	29 May 2001	37	3.12432	1.5 - 8.0
2002	88	20 Apr 2002	28 May 2002	15	4.36000	2.0 - 5.3
2003	49	13 May 2003	31 May 2003	35	2.77714	1.3 - 10.2
2004	37	13 May 2004	30 May 2004	28	2.80893	2.2 - 9.5
2005	106	21 Apr 2005	29 May 2005	23	2.33913	1.5 - 8.5
2006	93	23 Apr 2006	29 May 2006	35	3.31429	1.7 - 8.3
2007	65	20 Apr 2007	29 May 2007	23	3.43478	2.0 - 6.3
2008	79	20 Apr 2008	30 May 2008	18	2.92778	1.9 - 5.6
2009	45	14 May 2009	31 May 2009	30	2.99667	1.5 - 7.0
2010	74	25 Apr 2010	22 May 2010	15	4.23333	2.3 - 6.0
2011	49	3 May 2011	27 May 2011	49	3.03980	1.9 - 9.0
2012	43	30 Apr 2012	24 May 2012	11	2.96364	1.6 - 8.6
2013	104	1 May 2013	29 May 2013	149	2.31711	1.3 - 6.8

Table 2. Parameters of the zero-inflated binomial model for bongo tows. The prefix *a* denotes those parameters in the occupancy submodel, while the prefix *b* denotes those parameters in the detection submodel.

Parameter	*Estimate*	*Standard Error*	*Pr > |t|*
a0 est	-1.6558	0.3368	<.0001
amontha_est	-1.4202	0.2286	<.0001
amonthe_est	-0.4475	0.1726	0.0096
amonthm_est	0.1115	0.1539	0.4690
aareae_est	-0.08744	0.2839	0.7581
aareac_est	0.4119	0.2652	0.1205
aareaw_est	0.8087	0.2710	0.0029
a1977_est	1.1833	0.5372	0.0277
a1978_est	1.4050	0.3532	<.0001
a1981_est	-0.1637	0.5256	0.7554
a1982_est	0.2695	0.3627	0.4575
a1983_est	0.1400	0.3777	0.7110
a1984_est	-0.5594	0.5126	0.2752
a1986_est	-0.5658	0.4803	0.2389
a1987_est	-0.9943	0.5350	0.0632
a1988_est	0.3693	0.3939	0.3487
a1989_est	-0.02784	0.3950	0.9438
a1990_est	-0.3388	0.4277	0.4283
a1991_est	-0.7742	0.5391	0.1511
a1992_est	-0.04565	0.3846	0.9055
a1993_est	-1.2448	0.4944	0.0119
a1994_est	-0.2070	0.3810	0.5870
a1995_est	-0.8530	0.4530	0.0598
a1996_est	-0.3356	0.4128	0.4163
a1997_est	-0.2743	0.4052	0.4984
a1998_est	-1.0374	0.5256	0.0485
a1999_est	-0.6136	0.4361	0.1596
a2000_est	-0.8082	0.4741	0.0884
a2001_est	0.04146	0.3841	0.9141
a2002_est	-1.1395	0.5283	0.0311
a2003_est	0.09405	0.4277	0.8260
a2004_est	-0.4502	0.5160	0.3830
a2005_est	-0.09707	0.3741	0.7953
a2006_est	-0.03455	0.3705	0.9257
a2007_est	-0.4674	0.4432	0.2917
a2008_est	-0.1292	0.4188	0.7576
a2009_est	0.6611	0.4036	0.1015
a2010_est	-0.6060	0.4607	0.1885
a2011_est	0.5099	0.4084	0.2119
a2012_est	-0.09142	0.4921	0.8527
b0_est	-1.5397	0.02015	<.0001
btime_est	0.08250	0.02956	0.0053

Table 3. Type 3 tests of the lognormal submodel parameters for data collected in bongo tows.

Step #1: *Type 3 Tests of Fixed Effects for the Lognormal Submodel, AIC = 1075.0*				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	33	348	3.77	<.0001
survey date	3	348	1.11	0.3443
survey area	3	348	1.45	0.2273
time of day	1	348	6.51	0.0112
Step #2: *Type 3 Tests of Fixed Effects for the Lognormal Submodel, AIC = 1071.0*				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	33	351	3.83	<.0001
survey date		dropped		
survey area	3	351	2.10	0.1005
time of day	1	351	7.58	0.0062
Step #3: *Type 3 Tests of Fixed Effects for the Lognormal Submodel, AIC = 1069.7*				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	33	354	3.96	<.0001
survey date		dropped		
survey area		dropped		
time of day	1	354	7.82	0.0055

Table 4. Indices (with 95% confidence limits) of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the zero-inflated delta-lognormal (ZIDL) model. The total number of samples included in analyses per year, the number of samples containing larvae per year, and the nominal frequency of occurrence per year are represented by *n*, *m*, and *f*, respectively.

Survey Year	*n*	*m*	*f*	*Nominal Index*	*ZIDL Index*	*CV*	*LCL*	*UCL*
1977	20	8	0.400	2.573	2.249	0.510	0.860	5.879
1978	69	33	0.478	5.323	4.388	0.245	2.706	7.115
1979	0							
1980	0							
1981	35	6	0.171	1.149	0.812	0.491	0.320	2.057
1982	92	19	0.206	1.362	1.184	0.300	0.658	2.130
1983	91	16	0.176	0.901	0.838	0.347	0.427	1.644
1984	71	6	0.085	0.309	0.313	0.566	0.109	0.898
1985	0							
1986	72	7	0.097	0.398	0.346	0.434	0.151	0.793
1987	77	5	0.065	0.347	0.311	0.470	0.127	0.759
1988	77	15	0.195	1.119	1.113	0.347	0.567	2.187
1989	85	14	0.165	0.815	0.617	0.376	0.298	1.277
1990	86	10	0.116	0.332	0.326	0.359	0.163	0.656
1991	69	5	0.072	0.292	0.301	0.613	0.097	0.933
1992	93	15	0.161	0.513	0.422	0.359	0.211	0.846
1993	90	6	0.067	0.749	0.439	0.693	0.125	1.536
1994	94	15	0.160	0.764	0.536	0.351	0.271	1.060
1995	117	8	0.068	0.286	0.220	0.538	0.080	0.602
1996	93	11	0.118	1.356	0.792	0.518	0.299	2.102
1997	93	12	0.129	0.462	0.327	0.393	0.154	0.698
1998	69	5	0.072	0.171	0.114	0.551	0.041	0.320
1999	90	9	0.100	0.550	0.462	0.529	0.171	1.249
2000	86	7	0.081	0.315	0.252	0.538	0.092	0.690
2001	93	15	0.161	0.510	0.461	0.327	0.244	0.872
2002	88	5	0.057	0.285	0.239	0.649	0.073	0.784
2003	49	11	0.224	1.057	0.790	0.396	0.368	1.693
2004	37	6	0.162	0.984	0.554	0.706	0.155	1.977
2005	106	16	0.151	0.222	0.181	0.304	0.100	0.327
2006	93	17	0.181	0.619	0.467	0.352	0.236	0.924
2007	65	9	0.138	0.540	0.387	0.450	0.164	0.914
2008	79	11	0.139	0.349	0.312	0.392	0.146	0.665
2009	45	16	0.356	0.832	0.582	0.335	0.303	1.116
2010	74	8	0.108	0.493	0.392	0.520	0.147	1.042
2011	49	14	0.286	1.494	1.018	0.400	0.471	2.198
2012	43	7	0.163	0.388	0.300	0.491	0.119	0.760
2013	104	21	0.202	2.389	0.978	0.36	0.489	1.955

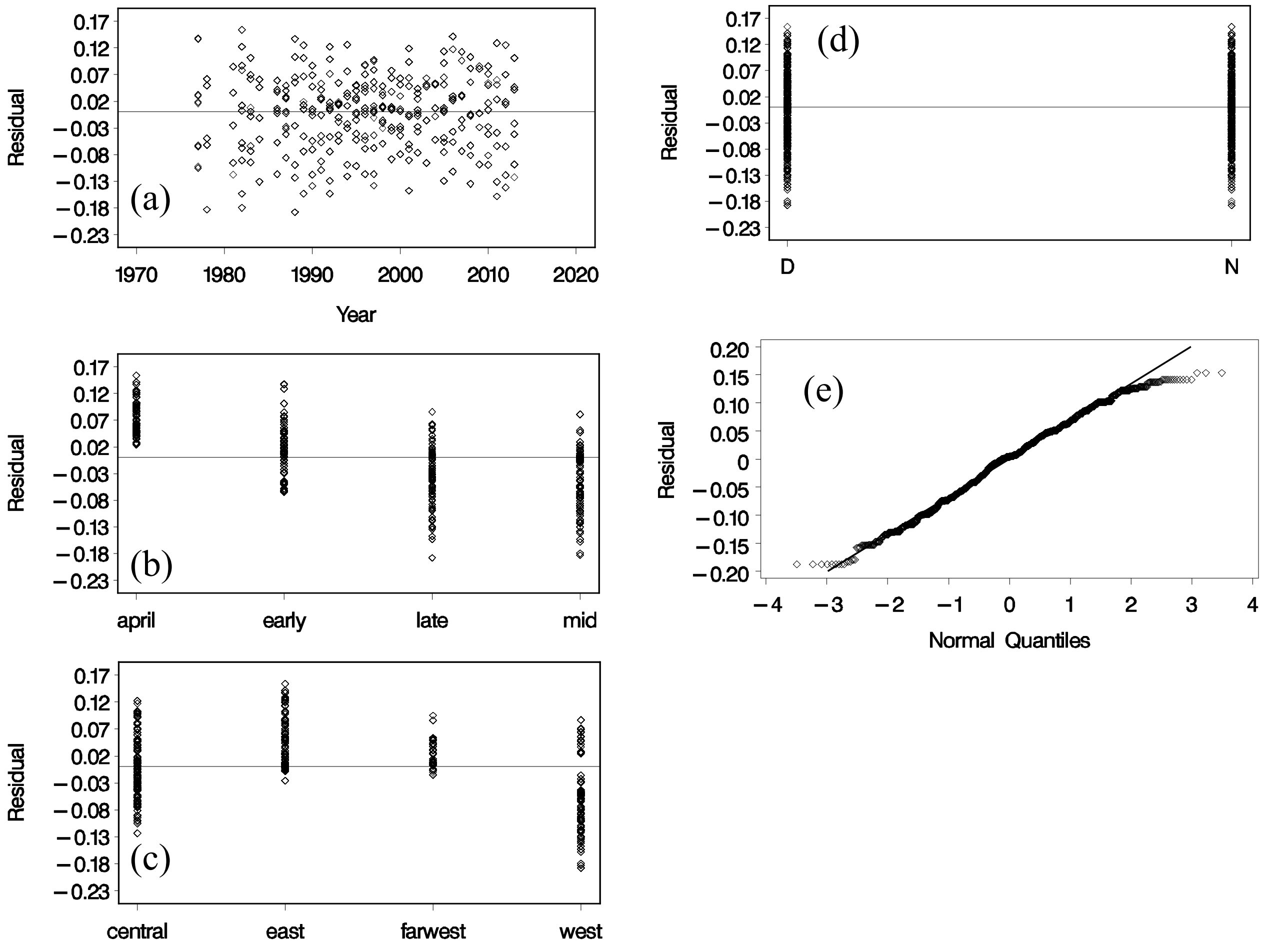

Figure 1. Residual plots of the zero-inflated binomial submodel for larvae collected in bongo tows. Plot a is a plot of residuals versus survey year; plot b is of residuals versus the survey date variable; plot c is a plot of residuals versus the survey area variable; plot d is a plot of residuals versus the time of day variable; and plot e is a QQ plot of the residuals.

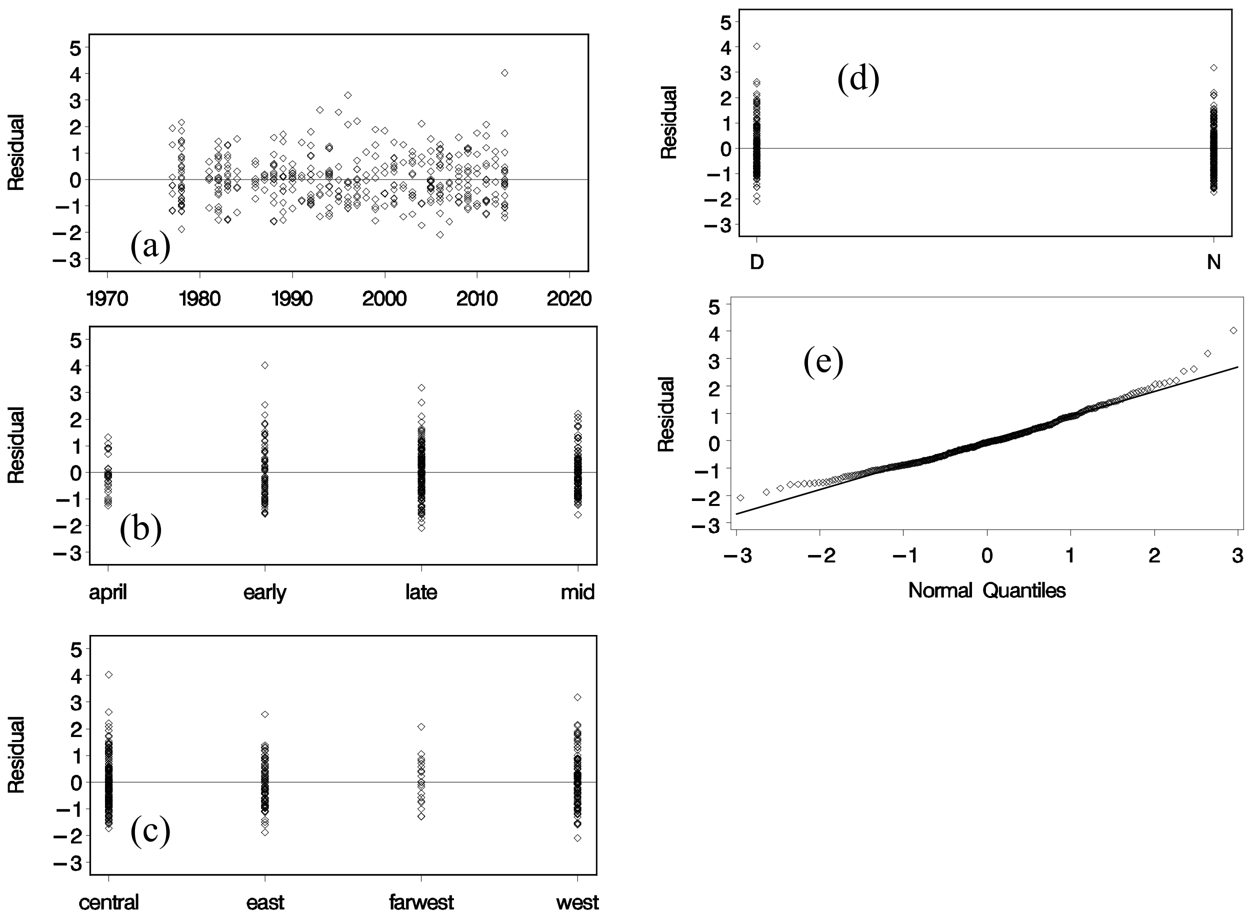

Figure 2. Residual plots of the log normal submodel for larvae collected in bongo tows. Plot a is a plot of residuals versus survey year; plot b is of residuals versus the survey date variable; plot c is a plot of residuals versus the survey area variable; plot d is a plot of residuals versus the time of day variable; and plot e is a QQ plot of the residuals.

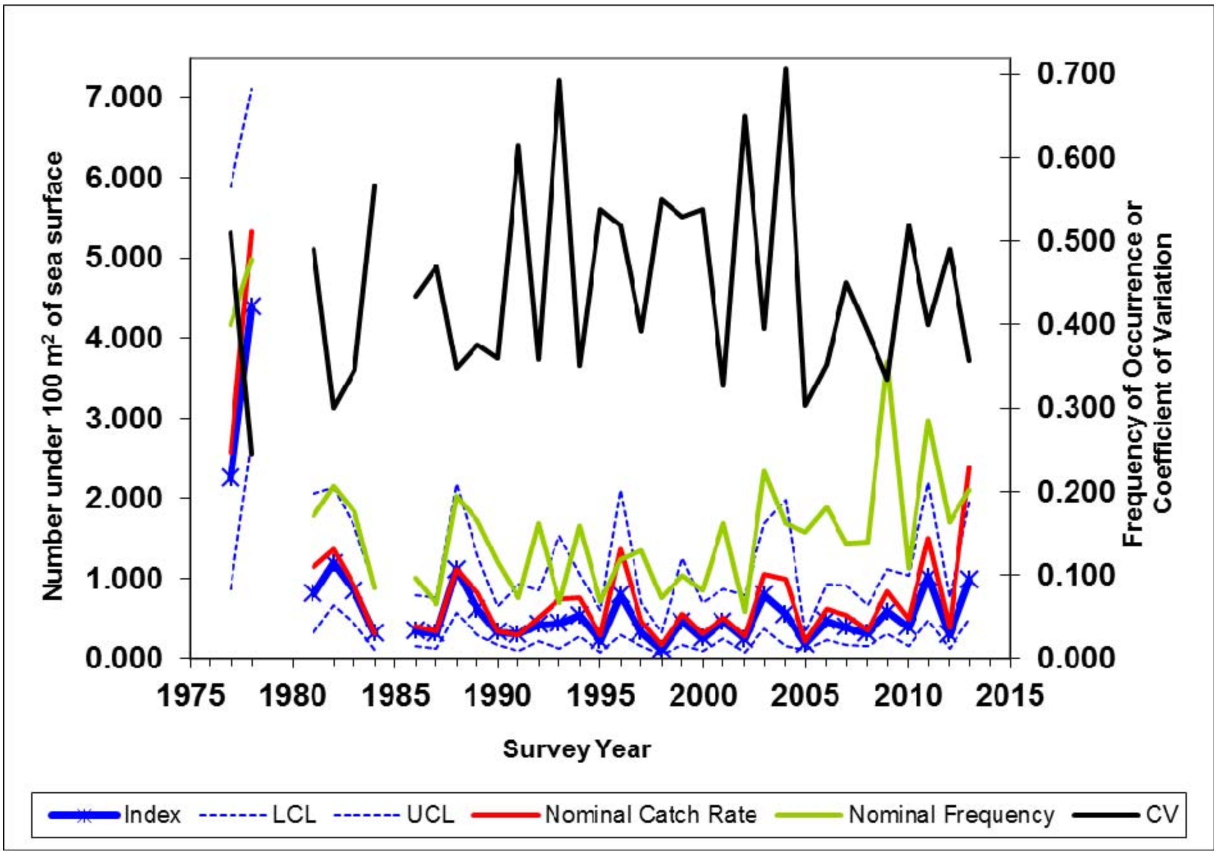

Figure 3. Annual indices (with 95% confidence limits) of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the zero-inflated delta-lognormal model. Also included in the graph are the annual frequency of occurrence, the annual nominal mean catch rate, and the coefficient of variation (CV) for the index value.