ANNUAL INDICES OF SKIPJACK TUNA (*KATSUWONUS PELAMIS*) LARVAE IN THE GULF OF MEXICO (1982-2011)

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SUMMARY

Fishery independent indices of larval skipjack tuna in the western North Atlantic Ocean are presented utilizing NOAA Fisheries ichthyoplankton survey data collected from 1982 through 2011 in the Gulf of Mexico. Indices were developed using standardized data (i.e. abundance of 2 mm larvae 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 des larves de listao à l'Ouest de l'Atlantique Nord sont présentés en utilisant les données de la prospection d'ichthyoplanctons réalisée par NOAA de 1982 à 2011 compris dans le Golfe du Mexique. Les indices ont été élaborés à l'aide des données standardisées (soit l'abondance des larves de 2 mm sur une zone de 100 m^2 à la surface de la mer 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 larvas de listado en el Atlántico noroccidental utilizando datos de la prospección de ictioplancton de la NOAA recopilados desde 1982 hasta 2011 en el golfo de México. Los índices se desarrollaron utilizando datos estandarizados (es decir, abundancia de larvas de 2 mm por debajo de 100 m^2 de la superficie del mar muestreados 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

1. Introduction and Methodology

The objective of this paper is to present annual abundance indices of bongo-collected skipjack tuna larvae based on a zero-inflated delta-lognormal (ZIDL) model. These indices are based upon the abundance of skipjack tuna larvae collected during fishery independent surveys conducted by NOAA Fisheries in the Gulf of Mexico from 1982 to 2011. The evolution of the use of this time series for bluefin tuna (*Thunnus thynnus*) 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).

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Ichthyoplankton surveys were conducted from numerous NOAA vessels during mid to late April through May from 1982 through 2011 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. The mean number of larvae per 100 m^2 at 2 mm body length for each station sampled between April 20 and May 31 each year of the time series (1982-2011) were estimated and used to index abundance. These were estimated as:

(1) $$I_{s,y} = \frac{\sum_{i=1}^{k} R_L e^{-Z\left(L_{s,y,i-1}\right)}}{A_{s,y}}$$

where *y* indexes year, *s* indexes sampling station, *i* (= 1,..., n) indexes individual larvae, *A* the surface area sampled, *Z* the larval loss rate by length, *L* the larval body length, 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 at sampling stations for estimated larval loss rates and gear efficiency. A length frequency histogram of bongo collected skipjack larvae (**Figure 1**) was employed to calculate the larval loss rate by length (*Z*). The decay in the number of larvae per mm length-class was estimated using the following equation:

(2) $$N = N_0 e^{-Z(L)}$$

where *Z* is the larval loss rate by length, *L* the larval body length-class, *N* the frequency of larvae within a certain length-class, and N_0 the theoretical number of larvae at the zero mm length-class (**Figure 1**). In this case, Z = 0.9513, and N_0 = 27845.8. The gear efficiency, *R*, was assumed to be equal to one, beginning with the 5 mm length, where the decay curve was initiated. For length-classes 2, 3, and 4, *R* was estimated by dividing the modeled frequency of each length-class by the actual frequency, and is tabulated with **Figure 1**. 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

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

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:

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

and

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

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

(6) $$V\left(I_y\right) \approx V\left(c_y\right)p_y^2 + c_y^2 V\left(p_y\right) + 2c_y p_y \mathrm{Cov}(c, p),$$

where

(7) $$\text{Cov}(c, p) \approx \rho_{\text{c,p}} \left[\text{SE}(c_y)\text{SE}(p_y)\right],$$

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 skipjack 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 skipjack tuna larvae was:

(8) $$P(x = 0) = o(1 - d)^m + (1 - o)(1)$$

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

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

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*:

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

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

Steventon *et al*. (2005) expressed the above probability in equation (10) as a generalized Bernoulli distribution, allowing the combination of multiple years into a full likelihood:

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

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:

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

and

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

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 skipjack tuna larva during a single ichthyoplankton station was

$$p_{Z1,y} = o \times d \tag{14}$$

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

$$p_{Z,y} = o\left[1-(1-d)^m\right], \tag{15}$$

following the methods of Steventon *et al*. (2005) and Ingram *et al*. (2010). The p_y in equations (3), (6) and (7) was replaced with $p_{Z,y}$ from equation (15) 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 [three categories: 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)] 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 by Ingram *et al*. (2010) 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 12 and 13) 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 mid to late April through the entire month of May and sometimes all or part of June. 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 this time period ranged from 45 to 215. The number of specimens collected in bongo tows per year ranged from 2 to 67, and ranged in length from 2.0 to 9.8 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 = 0.658. The AUC (Area Under Curve) statistic provides information on the model's lack-of-fit, and in this case it means that in 66 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 2** provides residual plots by the variables used in the modeling process. Most residual plots indicate some pattern in the residuals and the QQplot of the residuals (**Figure 2e**) indicate a departure from the 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 survey area and survey date, which were dropped from the second and third run of the model, respectively (**Table 3**). **Figure 3** indicates the approximately normal distribution of the residuals of the lognormal submodel save for extreme values.

Table 4 and **Figure 4** summarizes indices of larval skipjack tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the ZIDL model. Index values were lowest in the mid to late 1980s and highest in 2003, 2010 and 2011. When compared to other abundance indices of skipjack tuna from the western Atlantic (**Figure 5**, data from Anon. 2009), the indices do not show as dramatic a decline as at the end of the Venezuelan purse seine fishery index through 2005, but shows a generally increasing trend over time after an initial decrease.

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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)*
1982	215	15 Apr 1982	30 Jun 1982	67	4.7	2.8 - 7.9
1983	145	22 Apr 1983	30 Jun 1983	23	4.8	2.4 - 9.8
1984	140	21 Apr 1984	30 Jun 1984	24	4.5	2.0 - 6.4
1985	60	05 Jun 1985	30 Jun 1985	2	3.5	2.5 4.5
1986	90	22 Apr 1986	30 May 1986	14	4.6	2.3 - 8.0
1987	99	18 Apr 1987	30 Jun 1987	9	3.3	2.2 - 5.8
1988	91	20 Apr 1988	26 May 1988	9	4.0	2.3 - 5.3
1989	86	26 Apr 1989	19 May 1989	31	4.1	2.1 - 7.9
1990	152	21 Apr 1990	30 Jun 1990	49	3.8	2.4 - 6.5
1991	81	17 Apr 1991	21 May 1991	21	4.3	2.7 - 7.6
1992	93	22 Apr 1992	23 May 1992	19	4.4	2.6 - 9.0
1993	136	26 Apr 1993	30 Jun 1993	47	4.3	2.0 - 6.5
1994	128	28 Apr 1994	30 Jun 1994	37	3.8	2.1 - 6.8
1995	141	19 Apr 1995	07 Jun 1995	50	3.5	2.0 - 6.5
1996	99	17 Apr 1996	25 May 1996	21	4.2	2.1 - 8.1
1997	131	17 Apr 1997	30 Jun 1997	29	3.9	2.2 - 6.0
1998	88	26 Apr 1998	23 Jun 1998	29	4.0	2.4 - 6.8
1999	103	24 Apr 1999	30 Jun 1999	27	3.7	2.0 - 6.1
2000	98	20 Apr 2000	30 Jun 2000	33	3.6	2.0 - 7.6
2001	96	18 Apr 2001	29 May 2001	32	4.2	2.0 - 7.5
2002	115	19 Apr 2002	30 Jun 2002	36	4.0	2.0 - 6.8
2003	49	13 May 2003	31 May 2003	25	3.6	2.0 - 8.4
2004	69	05 May 2004	30 Jun 2004	21	4.0	2.1 - 7.0
2005	119	21 Apr 2005	25 Jun 2005	31	3.8	2.1 - 8.1
2006	112	23 Apr 2006	29 Jun 2006	34	4.0	2.1 - 7.0
2007	94	17 Apr 2007	29 Jun 2007	34	3.8	2.0 - 7.0
2008	124	20 Apr 2008	30 Jun 2008	52	3.4	2.0 - 6.2
2009	45	14 May 2009	31 May 2009	25	3.7	2.0 - 5.6
2010	54	27 Apr 2010	22 May 2010	25	4.3	2.1 - 8.0
2011	49	03 May 2011	27 May 2011	36	4.5	2.0 - 7.2

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.

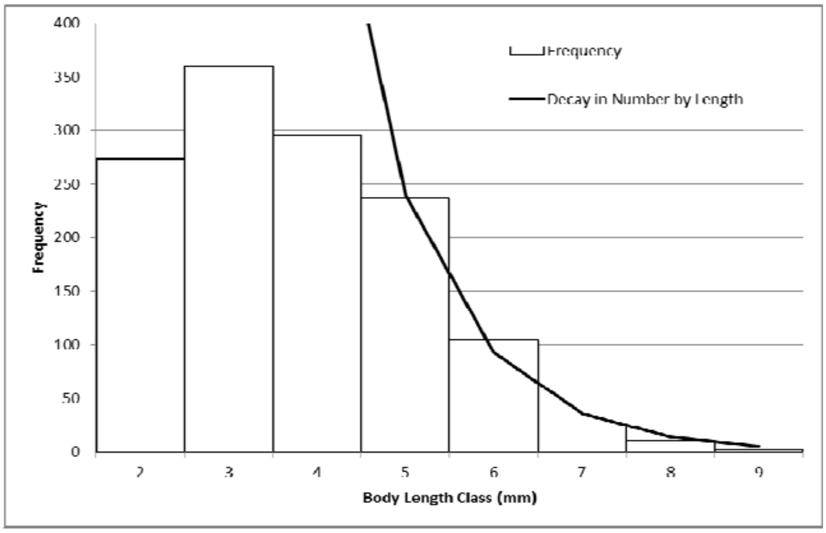
Parameter	*Estimate*	*Standard Error*	*Pr > |t|*
a0_est	0.5358	0.1139	<.0001
amontha_est	-1.5003	0.3408	<.0001
amonthe_est	-2.4338	0.3852	<.0001
amonthm_est	-2.2745	0.3870	<.0001
aareae_est	-4.6339	1.0525	<.0001
aareac_est	-2.5717	0.4349	<.0001
a1982_est	-3.5247	0.5510	<.0001
a1983_est	-3.0805	0.4854	<.0001
a1984_est	-1.6190	0.3875	<.0001
a1985_est	-1.6077	0.3573	<.0001
a1986_est	-1.9018	0.4047	<.0001
a1987_est	-2.1241	0.4066	<.0001
a1988_est	-1.4860	0.3585	<.0001
a1989_est	-1.9170	0.3737	<.0001
a1990_est	-1.7863	0.3656	<.0001
a1991_est	-2.3635	0.4153	<.0001
a1992_est	-2.2461	0.3874	<.0001
a1993_est	-1.6092	0.3881	<.0001
a1994_est	-2.2002	0.4036	<.0001
a1995_est	-1.9060	0.3926	<.0001
a1996_est	-1.6445	0.3847	<.0001
a1997_est	-1.6945	0.3764	<.0001
a1998_est	-1.4425	0.4376	0.0010
a1999_est	-1.7888	0.4240	<.0001
a2000_est	-2.0732	0.3859	<.0001
a2001_est	-1.7430	0.3764	<.0001
a2002_est	-1.8179	0.3949	<.0001
a2003_est	-1.7743	0.3710	<.0001
a2004_est	-0.8572	0.4302	0.0464
a2005_est	-1.0935	0.4138	0.0083
a2006_est	-1.1164	0.01010	<.0001
a2007_est	0.04629	0.01721	0.0072
a2008_est	0.5358	0.1139	<.0001
a2009_est	-1.5003	0.3408	<.0001
a2010_est	-2.4338	0.3852	<.0001
b0_est	-2.2745	0.3870	<.0001
btime_est	-4.6339	1.0525	<.0001

Table 3. Backward selection procedure results based on 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 = 1429.3*				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	29	652	2.40	<.0001
survey date	4	652	1.28	0.2768
survey area	2	652	0.80	0.4477
time of day	1	652	20.94	<.0001
Step #2: *Type 3 Tests of Fixed Effects for the Lognormal Submodel, AIC = 1422.8*				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	29	654	2.54	<.0001
survey date	4	654	1.24	0.2938
survey area		dropped		
time of day	1	654	20.96	<.0001
Step #3: *Type 3 Tests of Fixed Effects for the Lognormal Submodel, AIC = 1413.1*				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	29	658	2.69	<.0001
survey date		dropped		
survey area		dropped		
time of day	1	658	20.50	<.0001

Table 4. Indices (with 95% confidence limits) of larval skipjack 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. Scaled indices are scaled to a mean of one for the each time series.

Survey Year	*n*	*m*	*f*	*Nominal Index*	*ZIDL Index*	*Scaled Nominal Index*	*Scaled ZIDL Index*	*CV*	*Scaled ZIDL Index LCL*	*Scaled ZIDL Index UCL*
1982	215	64	0.298	3.60612	3.19880	1.75919	1.83357	0.16532	1.32028	2.54641
1983	145	21	0.145	3.66124	1.95213	1.78609	1.11897	0.34763	0.56943	2.19885
1984	140	21	0.150	0.94136	1.00129	0.45923	0.57394	0.25081	0.35021	0.94060
1985	60	1	0.017	0.07733	0.09354	0.03772	0.05362	1.00829	0.01004	0.28627
1986	90	12	0.133	1.62245	1.38413	0.79149	0.79339	0.41404	0.35809	1.75786
1987	99	5	0.051	0.25730	0.23729	0.12552	0.13602	0.53240	0.05008	0.36940
1988	91	8	0.088	0.39478	0.36094	0.19259	0.20689	0.38964	0.09754	0.43883
1989	86	25	0.291	2.54595	1.87813	1.24201	1.07656	0.24663	0.66217	1.75026
1990	152	42	0.276	1.43093	1.37605	0.69806	0.78876	0.16870	0.56421	1.10267
1991	81	19	0.235	2.18592	1.74034	1.06637	0.99757	0.29538	0.55940	1.77896
1992	93	17	0.183	2.51225	1.51036	1.22557	0.86575	0.32890	0.45605	1.64350
1993	136	40	0.294	1.81875	1.79483	0.88725	1.02880	0.16391	0.74285	1.42483
1994	128	27	0.211	1.92755	1.33398	0.94033	0.76464	0.24777	0.46929	1.24587
1995	141	33	0.234	0.95537	0.97214	0.46607	0.55724	0.17266	0.39552	0.78507
1996	99	15	0.152	1.42880	1.19190	0.69702	0.68320	0.33889	0.35331	1.32112
1997	131	21	0.160	0.86725	0.85135	0.42308	0.48800	0.22751	0.31138	0.76480
1998	88	24	0.273	1.39960	1.32093	0.68277	0.75716	0.21623	0.49376	1.16109
1999	103	17	0.165	0.90450	0.92994	0.44125	0.53305	0.25704	0.32141	0.88403
2000	98	21	0.214	1.66562	1.42560	0.81255	0.81716	0.25496	0.49469	1.34985
2001	96	25	0.260	2.54813	2.26108	1.24307	1.29606	0.25535	0.78401	2.14255
2002	115	28	0.243	1.65519	1.67238	0.80746	0.95862	0.21862	0.62226	1.47680
2003	49	15	0.306	4.95219	3.59698	2.41585	2.06181	0.33382	1.07627	3.94981
2004	69	15	0.217	2.08758	2.18732	1.01840	1.25378	0.31335	0.67983	2.31230
2005	119	22	0.185	1.90394	1.37807	0.92881	0.78992	0.27148	0.46340	1.34650
2006	112	27	0.241	1.84013	1.74763	0.89768	1.00175	0.21348	0.65675	1.52800
2007	94	21	0.223	1.83221	1.79533	0.89382	1.02909	0.25324	0.62504	1.69435
2008	124	30	0.242	1.45827	1.38414	0.71140	0.79340	0.19134	0.54298	1.15930
2009	45	20	0.444	2.07503	2.04490	1.01227	1.17214	0.21583	0.76497	1.79605
2010	54	21	0.389	5.85949	4.82286	2.85847	2.76449	0.29176	1.56081	4.89642
2011	49	32	0.653	5.08086	4.89291	2.47862	2.80464	0.15922	2.04382	3.84868



Body Length Class (mm)	**Modeled Frequency by Length**	**Actual Frequency**	**Gear Efficiency, *R***
2	4154	274	15.16
3	1604	360	4.46
4	620	296	2.09
5	239	237	1
6	92	104	1
7	36	24	1
8	14	10	1
9	5	2	1

Figure 1. Length frequency histogram of bongo collected skipjack larvae employed to calculate the larval loss rate by length (Z). The decay in the number of larvae per mm length-class was estimated using the following equation:

$$N = N_0 e^{-Z(L)}$$

where Z is the larval loss rate by length (Z = 0.9513), L the larval body length-class, N the frequency of larvae within a certain length-class, and N_0 the theoretical number of larvae at the zero mm length-class (N_0 = 27845.8). Gear efficiency, R, was assumed to be equal to one, beginning with the 5 mm length, where the decay curve was initiated. For length-classes 2, 3, and 4, R was estimated by dividing the modeled frequency of each length-class by the actual frequency.

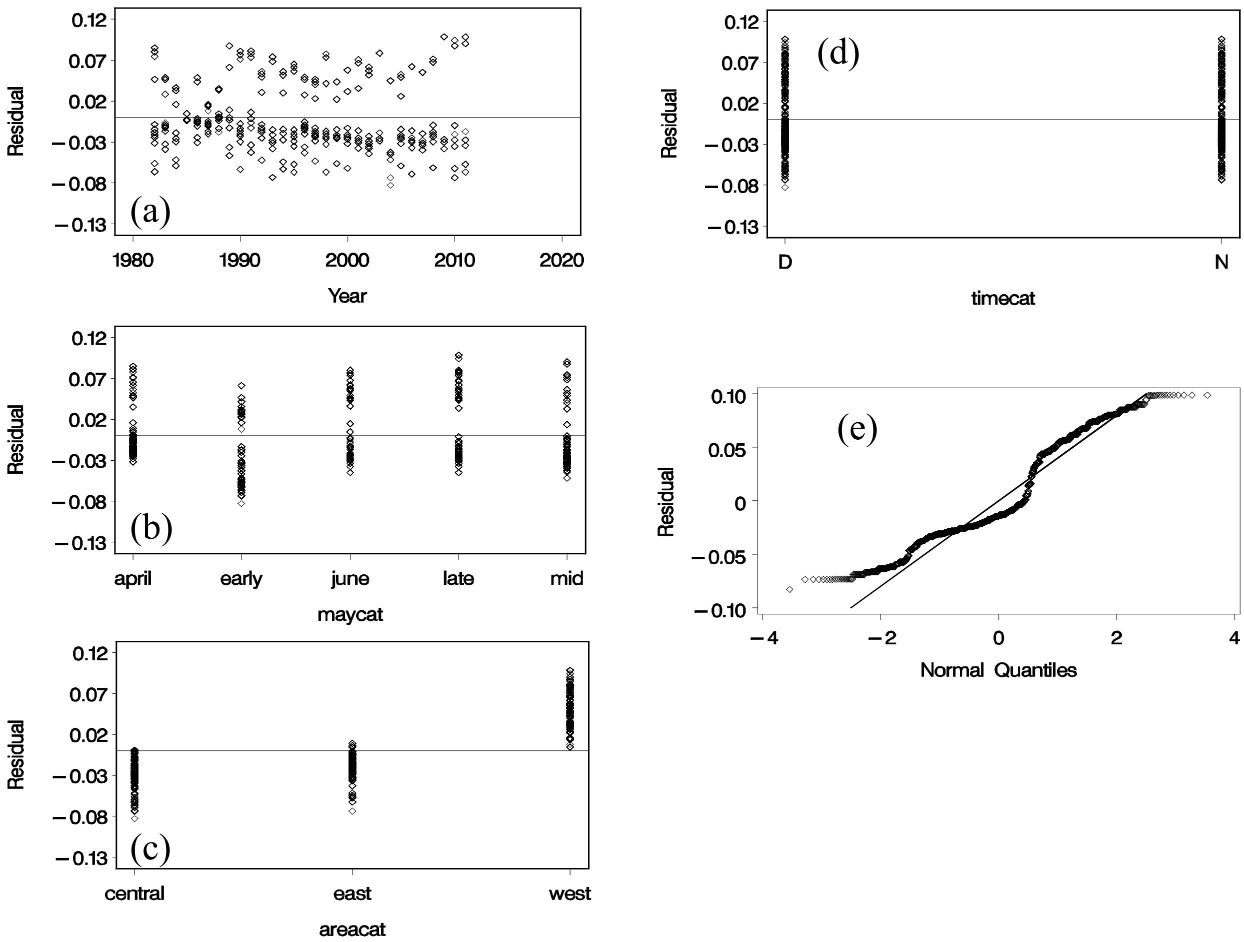


Figure 2. Residual plots of the zero-inflated binomial submodel for larvae collected in bongo tows. Plot **a** is a plot of residuals versus survey year; plot **b** is of residuals versus the survey date variable; plot **c** is a plot of residuals versus the survey area variable; plot **d** is a plot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

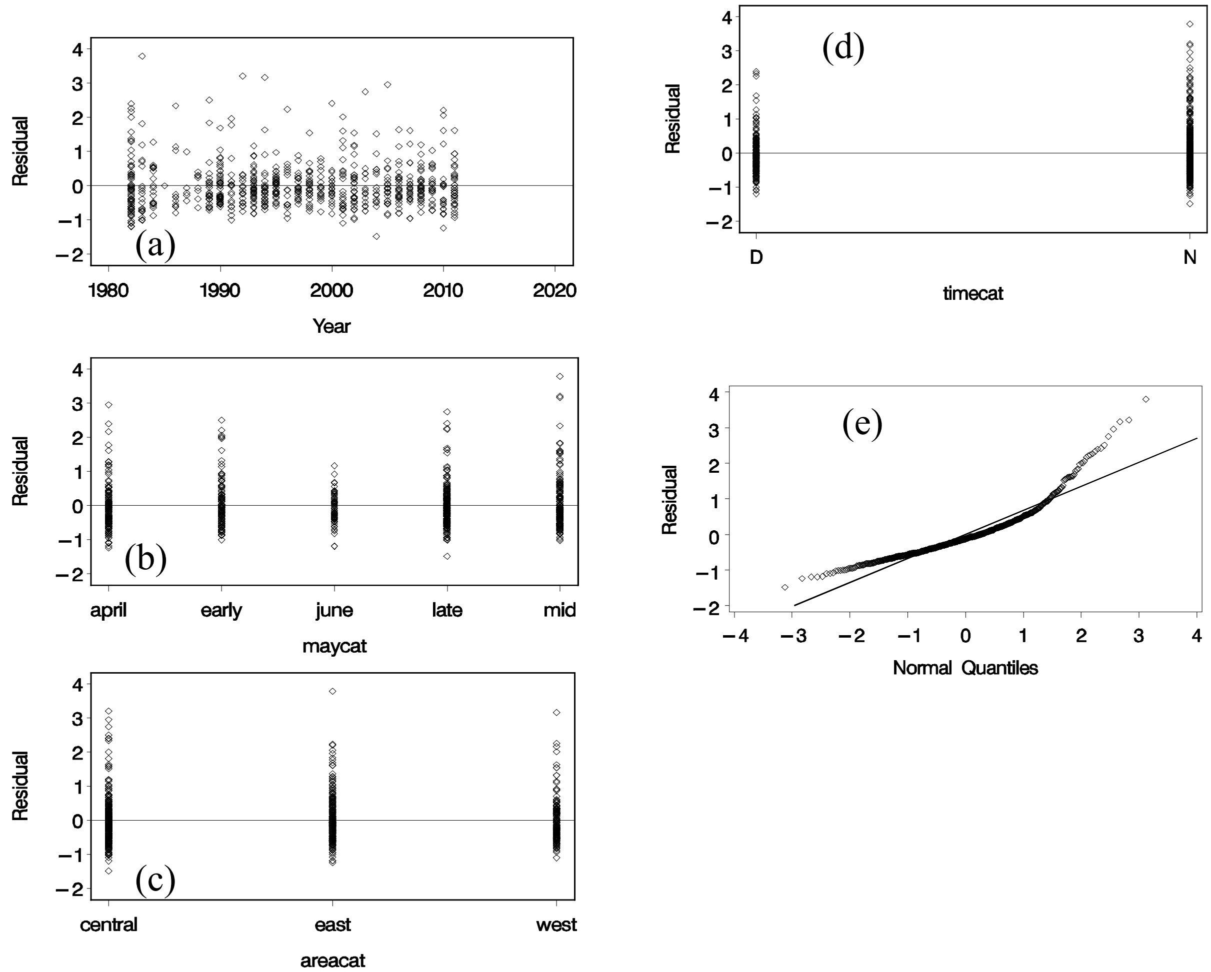
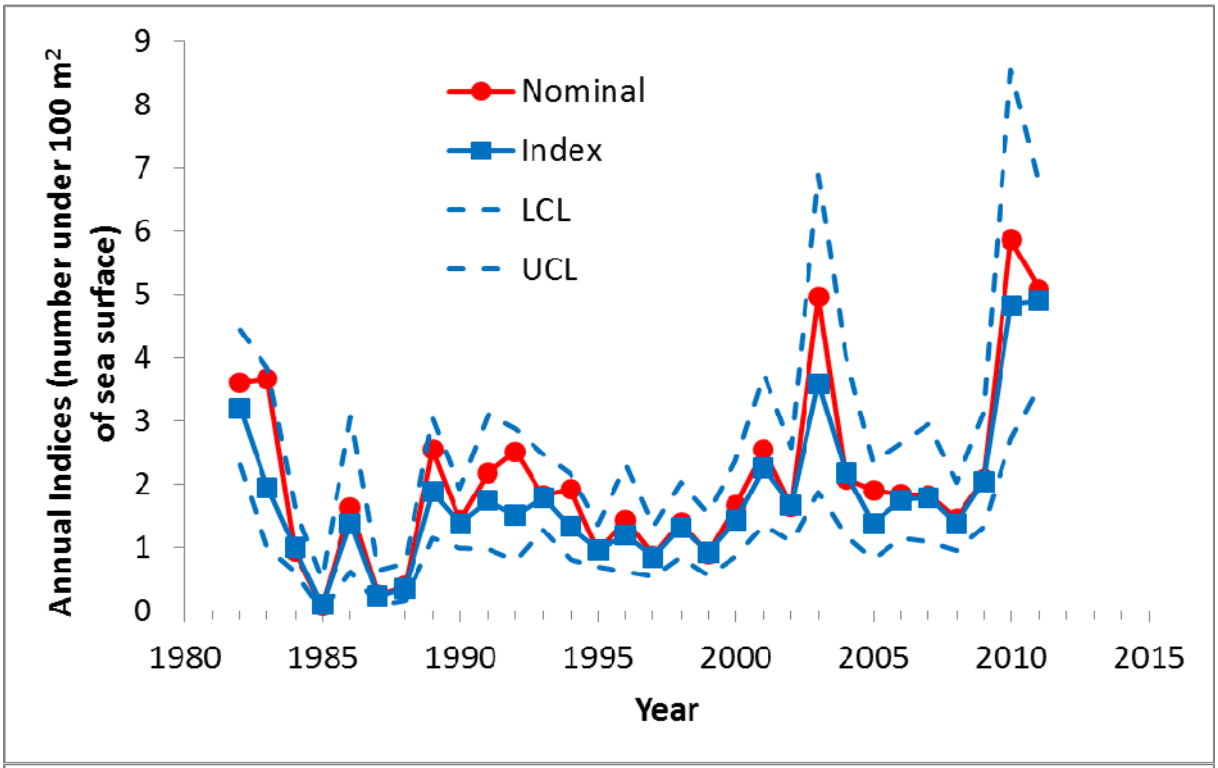


Figure 3. Residual plots of the log normal submodel for larvae collected in bongo tows. Plot **a** is a plot of residuals versus survey year; plot **b** is of residuals versus the survey date variable; plot **c** is a plot of residuals versus the survey area variable; plot **d** is a plot of residuals versus the time of day variable; and plot **e** is a QQ plot of the residuals.



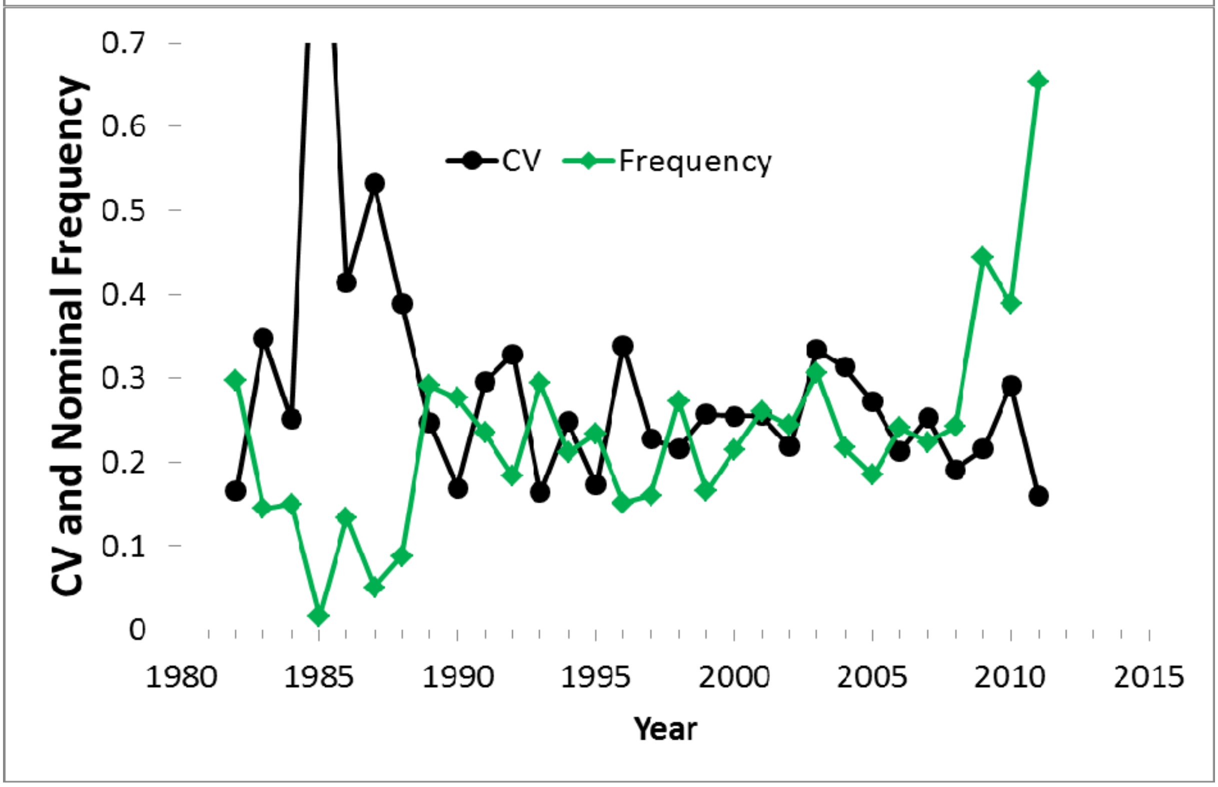


Figure 4. Upper Plot: Annual indices (with 95% confidence limits) of larval skipjack tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the zero-inflated delta-lognormal model and the annual nominal mean catch rate. Lower Plot: The annual nominal frequency of occurrence and the coefficient of variation (CV) for the index value.

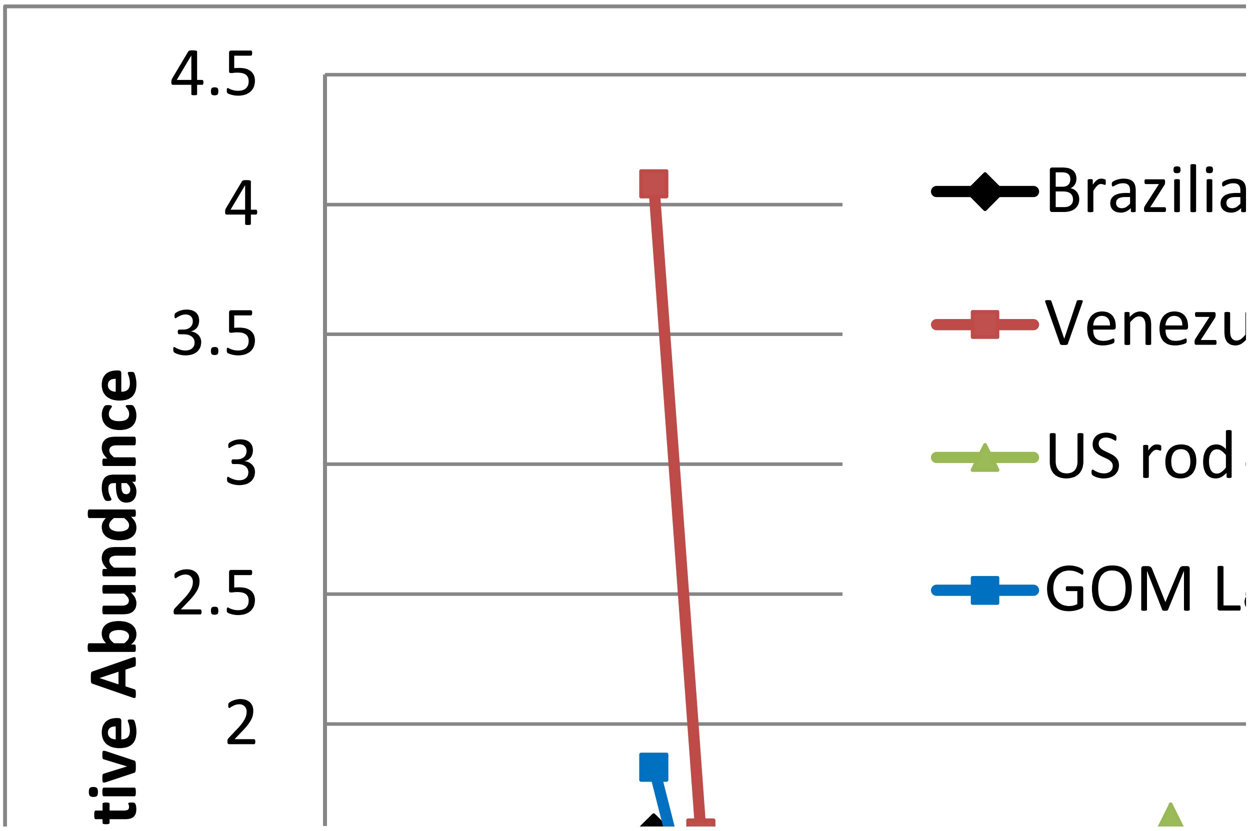


Figure 5. Comparison of abundance indices of skipjack tuna from the western Atlantic.