ANNUAL INDICES OF BLUEFIN TUNA (*THUNNUS THYNNUS*) SPAWNING BIOMASS IN THE GULF OF MEXICO DEVELOPED USING DELTA-LOGNORMAL AND MULTIVARIATE MODELS

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SUMMARY

Fishery independent indices of spawning biomass of bluefin tuna in western North Atlantic Ocean are presented which utilize NOAA Fisheries ichthyoplankton survey data collected from 1977 through 2007 in the Gulf of Mexico. Indices were developed using similarly 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). Indices were also developed for the first time from standardized data collected with neuston gear [i.e. abundance of 5-mm larvae (i.e. seven-day-old larvae) per 10 minute tow]. Indices of larval abundance were developed using delta-lognormal models, including following covariates: time of day, time of month, area sampled and year. Due to the large frequency of zero catches during ichthyoplankton surveys, a zero-inflated delta-lognormal approach was also used to develop indices. Finally, a multivariate delta-lognormal approach was employed to develop indices of annual abundance based on both bongo and neuston catches. The results of these approaches were compared with one another and with other indices of larval abundance previously developed for the Gulf of Mexico.

KEYWORDS

Mathematical models, multivariate analysis, fish larvae

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1. Introduction

The objective of fishery-independent surveys is to make inference about the size (in numbers and/or biomass) and age structure of targeted populations. Annual abundance indices based on such surveys are usually derived from catch or catch-per-unit-effort (CPUE) data and are a vital part of current management regimes of many fisheries. Collection, analysis and dissemination of such information are a paramount function of NOAA Fisheries.

Managers became concerned of the status of northern bluefin tuna, *Thunnus thynnus*, stocks in the late 1960's, and in 1975 ICCAT implemented regulations for management of the western Atlantic stock. Since then, annually conducted international assessments of western Atlantic bluefin tuna have indicated a large decline in abundance. Most abundance indices used during assessments of western Atlantic bluefin tuna were of a fishery dependent nature. Scott *et al*. (1993) presented a spawning biomass index based upon the abundance of bluefin tuna larvae collected during fishery independent surveys conducted by NOAA Fisheries in the Gulf of Mexico. Since that time, this index, which is a series of Pennington (1983) delta–distribution estimators, has been updated regularly (Scott and Turner 1994, 1995, 1996, 1998, 2000, 2002). More recently an index was developed from this data using delta-lognormal models (Ingram *et al*. 2006).

Fish larvae in many cases are overdispersed as a result of the spawning behavior of adults and/or physical oceanographic processes, resulting in catch data which are not normally distributed. Therefore, samples taken from such overdispersed populations contain many small or zero values and few very large values, and simple estimates of mean abundance from sample data may either be too low if many low values are included or too high if very large values are included. Such zero-inflated CPUE data is common in fisheries biology and becoming more important as fish stocks decline and rare species become more difficult to detect. Zero-inflation can occur due to 'true zero' observations (e.g. from the study of rare organisms) or 'false zero' observations (e.g. from sampling or observer errors) or both. Martin *et al*. (2005) reviewed many recent approaches to model such data for statistical inference with the use of generalized linear models. Data with zero-inflation due to true zeros can be modeled by two approaches: two-part modeling (e.g. delta-lognormal method [Lo *et al*. 1992]) and mixture modeling (e.g. zero-inflated Poisson [ZIP] or zero-inflated negative binomial [ZINB] [Martin *et al*. 2005, Minami *et al*. 2007]); while zero-inflation due to false zeros can be mitigated by the use of zero-inflated binomial (ZIB) mixture models (Tyre et al. 2003, Martin *et al*. 2005, Steventon *et al*. 2005). For data with zero-inflation due to both true and false zeros, Martin *et al*. (2005) reports that there is currently nothing in literature.

Model-based estimators have been popularized since they may reduce the likelihood of false conclusions about trends in abundance (McConnaughey and Conquest 1992). They may also produce estimators with better precision (Pennington 1983, 1996; Lo *et al*. 1992). One model-based alternative to the arithmetic mean of the sample is the delta-lognormal method (Lo *et al*. 1992). The index computed by this method is a mathematical combination of yearly abundance estimates from two distinct generalized linear models: a binomial (logistic) model which describes proportion of positive abundance values (i.e. presence/absence) and a lognormal model which describes variability in only the nonzero abundance data (Lo *et al*. 1992).

However, for many fishery-independent CPUE data sets, large frequencies of zeros are observed relative to what is predicted by models based on standard distributional assumptions. Recently, in many fields, it has become popular to model such data using regression models based on an assumption that the response is generated by a mixture of a standard count distribution (e.g. binomial or Poisson) with a degenerate distribution with point mass of one at zero, creating a zero-inflated distribution (Hall 2000; Vieira *et al*. 2000). Therefore, a more appropriate way to model these types of data would be to replace the binomial model portion of a delta-lognormal approach with a ZIB model.

In many surveys, multiple gear-types are used in gathering data. In many cases, CPUE values resulting from differing gears may not be directly additive, making it difficult to model with a traditional delta-lognormal approach. Therefore, a more appropriate way to model these types of data would be to replace the binomial and lognormal submodels of a delta-lognormal approach with multivariate binomial and multivariate lognormal submodels. However, if there is little correlation between catch rates of the differing gear-types (i.e. data are independent) and the sampling protocol are consistent between sampling stations, then the catches can be added and then modeled using the delta-lognormal approach.

The objective of this paper is to present abundance indices of bongo- and neuston-collected Atlantic bluefin tuna larvae based on delta-lognormal (DL), zero-inflated delta-lognormal (ZIDL), and multivariate delta-lognormal (MDL) models. The indices resulting from these methods will be compared to an index developed using the

Pennington delta-distribution (PDD) method as employed in the development of previous larval bluefin tuna indices (Scott *et al*. 1993; Scott and Turner 1994, 1995, 1996, 1998, 2000, 2002; Ingram *et al*. 2006).

2. Methodology

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). Therefore, survey methodology will not be covered here.

Identifications and measurements of bongo-collected larvae by the Polish Plankton Sorting and Identification Center in Szczecin, Poland were verified for all survey years except 2007. Data from 2007 were included in the analyses, but were considered 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 (1977-2007) were estimated and used to index abundance. These were estimated as

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

where y indexes year, s indexes sampling station, i (= 1,..., n) indexes individual larvae, A the surface area sampled, Z the larval 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, Scott *et al*. (1993) and Scott and Turner (1994, 1995, 1996, 1998, 2000, 2002) then used then delta–distribution method of Pennington (1983) to develop unbiased estimates of average annual larval density (and variability), taken to be the annual index value (and variability).

Identifications and measurements of neuston-collected larvae by the Polish Plankton Sorting and Identification Center in Szczecin, Poland were verified for all survey years except 1987, 1988, 2006 and 2007. Specimens from 1987 and 1988 were not measured and currently the location of these specimens is unknown due to damage incurred during Hurricane Katrina. If those samples cannot be recovered in the future this will permanently represent a data holiday in the time series. Data from 2006 and 2007 were included in the analyses, but were considered provisional. Both length-frequency and age-frequency histograms were evaluated to determine an appropriate standardization approach for neuston-collected data. The standardized number per 10-minute neuston tow for each station sampled between April 20 and May 31 each year of the time series (1982-2007) was estimated and used to index abundance.

Unbiased estimators of the mean and variance of the PDD method (Pennington 1983) are presented as

$$(2) \qquad I_{\Delta,y} = \begin{cases} \frac{m_y}{n_y} e^{T_y} G_{m_y} \frac{s_y^2}{2}, & m_y > 1, \\ \frac{x_1}{n_y}, & m_y = 1, \\ 0, & m_y = 0 \end{cases}$$

and

$$(3) \qquad V\left(I_{\Delta,y}\right) = \begin{cases} \frac{m_y}{n_y} e^{T_y} \left[G_{m_y}\left(2s_y^2\right) - \left(\frac{m_y - 1}{n_y - 1}\right) G_{m_y}\left(\frac{m_y - 2}{m_y - 1} s_y^2\right) \right], & m_y > 1, \\ \frac{x_1^2}{n_y}, & m_y = 1, \\ 0, & m_y = 0 \end{cases}$$

respectively, where n_y is the number of observations, m_y is the number of nonzero values, T_y and s_y^2 are the sample mean and sample variance, respectively, of the logged nonzero values, x_1 denotes the single untransformed value when m_y equals one, and

$$(4) \qquad G_{m_y}\left(\frac{s_y^{\,2}}{2}\right) = 1 + \frac{m-1}{m}\left(\frac{s_y^{\,2}}{2}\right) + \sum_{j=2}^{\infty} \frac{(m-1)^{2j-1}}{m^j (m+1)(m+3)\ldots(m+2j-3)} \times \frac{\left(\frac{s_y^{\,2}}{2}\right)^j}{j!}.$$

This PDD method (Pennington 1983) was used to further update the bongo index for continuity and to develop a new neuston index. This was done to make comparisons between the indices developed from the PDD method and those developed from DL models.

The DL index of relative abundance (I_y) as described by Lo *et al*. (1992) was estimated as

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

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 were estimated using generalized linear models. Data used to estimate abundance for positive catches (c) and probability of occurrence (p) were assumed to have a lognormal distribution and a binomial distribution, respectively, and modeled using the following equations:

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

and

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

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.

We used the GLIMMIX and MIXED procedures in SAS (v. 9.1, 2004) to develop the binomial and lognormal submodels, respectively, to develop annual DL indices for both bongo- and neuston-collected larvae and for combined catch data. Similar covariates were included in 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: 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. If any variables were not found to be at least marginally significant (i.e. at α = 0.10) based on type 3 analysis, then those variables were removed. The fit of each of the submodels were evaluated using residual analyses. In order to extend the indices of the combined gears backward in time (from 1982 to 1977, due to the lack of neuston data), we predicted both the probability of occurrence and the nonzero catch rate of larvae in the neuston tows during 1977, 1978, 1981, 1987, and 1988 using generalized linear models, including time of day, survey date, survey area, year, and bongo catch rate.

Therefore, c_y and p_y were 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 was calculated, as in equation (5), and its variance calculated as

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

where

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

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 for both bongo- and neuston-collected larvae, we replaced the regular binomial portion of the DL model with a ZIB model that takes into account the high proportion of zeros in the abundance data. The ZIB 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). 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 we considered one year after *m* samples have been taken (i.e., *m* bongo stations completed), the probability of observing zero bluefin tuna larvae was

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

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

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

after Tyre *et al*. (2003) and Steventon *et al*. (2005). We then combined these two probabilities to form the likelihood function for a single year *y*:

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

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

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:

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

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:

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

and

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

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 is

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

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

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

following the methods of Steventon *et al*. (2005). We then replace p_y in equations (5), (8) and (9) 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].

The NLMIXED procedure in SAS (v. 9.1, 2004) was employed to model the ZIB model. Initial SAS code for this procedure was provided by Steventon *et al*. (2005). We modified this code in order to use dummy variables, which were needed to include categorical variables in the model. The variables used in the model were the same as those used in the binomial submodel of the DL model. However, the time of day variable was placed in the detection submodel, while the other variables were placed in the occurrence submodel (see Equations 14 and 15) contained in the ZIB submodel. Model performance was evaluated using AUC (Area Under Curve) methodology presented by Steventon *et al*. (2005).

In order to develop MDL indices of abundance CPUE data collected with differing gears, we replaced each submodel with a multivariate counterpart. The binomial submodel was replaced with a multivariate binomial logit-normal model as described by Coull and Agresti (2000). This approach models vectors $\mathbf{Y} = (Y_1, Y_2,\ldots, Y_R)$ of binomial-type responses, by incorporating a separate random effect for each of the *R* binomial responses, such that logit($\boldsymbol{\pi}_s$) is a multivariate normal random variable. Specifically,

(18) $$\text{logit}(\boldsymbol{\pi}_s) = \alpha_s + \mathbf{X}_s\boldsymbol{\beta},$$

where $s = 1, \ldots, N$ represents subject (for this study I treated time of day as the subject), $\mathbf{X}_s$ is the $R \times p$ covariate matrix whose *r*th row is $\mathbf{x}_{sr}$ and $\alpha_s \sim \text{N}(\mathbf{0}, \boldsymbol{\Sigma})$ (where $\mathbf{x}_{sr}$ is a fixed covariate row vector and α_s are i.i.d. random variables). The parameters $\boldsymbol{\beta}$ describe the effects of the explanatory variables, while $\boldsymbol{\Sigma}$ contains parameters that reflect the heterogeneity among subjects as well as within-subject dependencies among the *R* variables. In order to estimate the index values based on the underlying common effect between both gears the following equation was used:

(19) $$p_{MV,y} = \frac{e^{\mathbf{X}_s\boldsymbol{\beta}_y}}{1+e^{\mathbf{X}_s\boldsymbol{\beta}_y}},$$

where $p_{MV,y}$ is the probability of occurrence based on the underlying common effects between both gears ($\boldsymbol{\beta}_y$) evaluated for year *y*. Likewise, lognormal submodel was replaced with a multivariate lognormal model with similar parameter structure as previously described for the multivariate binomial model in equation (18):

(20) $$\log(\boldsymbol{\pi}_s) = \alpha_s + \mathbf{X}_s\boldsymbol{\beta},$$

where the model has a log link as opposed to the logit link in the model represented in (18). Similarly, to estimate the index values based on the underlying common effect between both gears the following equation was used:

(21) $$c_{MV,y} = e^{\mathbf{X}_s\boldsymbol{\beta}_y},$$

where $c_{MV,y}$ is the estimate of mean CPUE for positive catches only based on the underlying common effects between both gears (β_y) evaluated for year *y*. Finally, the $I_{MV,y}$ is estimated as in equation (5):

(22) $$I_{MV,y} = c_{MV,y}\, p_{MV,y}$$

and its variance calculated as in equations (8) and (9). The NLMIXED procedure in SAS (v. 9.1, 2004) was employed to model the multivariate submodels of this approach. The variables included in the model were the same as above for the DL model. The fit of each of the submodels were evaluated using residual analyses.

3. Results and Discussion

Tables 1 and 2 summarize the data collected in bongo and neuston tows, respectively, 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 97, while the number of neuston tows ranged from 66 to 175. The number of specimens collected in bongo tows per year ranged from 7 to 221, and ranged in length from 1.3 to 10.7 mm; and the number collected in neuston tows per year ranged from 2 to 174, and ranged in length from 2.5 to 10.5 mm.

Both age- and length-frequency histograms of neuston-collected larvae were analyzed to determine the appropriate standardization approach (**Figure 1**). **Figure 1a** depicts the age-frequency histogram of neuston-collected larvae. The daily age of each larva were derived from body length using the age-length key provided by Scott *et al*. (1993). This histogram indicated that a larval daily loss rate (Z) could not be developed from the age-frequency data. However, the length-frequency histogram of larval body lengths (**Figure 1b**) indicated the larvae were fully recruited by 5 mm, approximately at 7 days old (i.e. 7.69 days old). Therefore, a per-millimeter loss rate of 0.8285 was derived through a nonlinear regression of the descending upper limb of the length-frequency histogram (**Figure 1b**), and was used to standardized the larval data to number of 5 mm larvae per 10-minute neuston tow. With this approach, the inclusion of larvae over 9 mm body length, which was a rare event, resulted in extremely large catches, which were deemed unrealistic. Therefore, larvae over 9 mm and under 5 mm were excluded from further analyses.

The results of type 3 analyses for both submodels used to develop the DL model for bongo-collected larvae are summarized in **Table 3**. For the binomial submodel all variables were significant (i.e. at $\alpha = 0.05$). For the lognormal submodel, all variables were significant (i.e. at $\alpha = 0.05$) except survey area, which was marginally significant (i.e. at $\alpha = 0.10$). **Figure 2** indicates the approximately normal distribution of the residuals of the binomial and lognormal submodels. The results of type 3 analyses for both submodels used to develop the DL model for neuston-collected larvae are summarized in **Table 4**. For the binomial submodel all variables were highly significant (i.e. at $\alpha = 0.0001$). For the lognormal submodel, the survey date category and survey area variables were not significant (i.e. at $\alpha = 0.05$), and were dropped from the model. **Figure 3** indicates the approximately normal distribution of the residuals of the binomial and lognormal submodels. The results of type 3 analyses for both submodels used to develop the DL model for the number of week-old larvae collected per 10-minute neuston tow plus the number of one-day-old larvae per 100 m^2 collected in bongo tows are summarized in **Table 5**. For the binomial submodel all variables were highly significant (i.e. at $\alpha = 0.0001$). For the lognormal submodel, all variables were significant (i.e. at $\alpha = 0.05$) except survey area, which was marginally significant (i.e. at $\alpha = 0.10$). **Figure 4** indicates the approximately normal distribution of the residuals of the binomial and lognormal submodels.

The same variables that were retained in the model-building process of the binomial submodel for the development of I_y for bongo-collected larvae were used in the ZIB model: 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 model. The time of day variable was used in the detection submodel as we reasoned that time of day (i.e. day or night) has an effect on the probability of detecting larvae (net avoidance). **Table 6** summarizes the parameters used in the ZIB model and their significance. The ZIB submodel had an AUC = 0.727. This means that in 73 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.

Likewise, the same variables that were retained in the model-building process of the binomial submodel for the development of I_y for neuston-collected larvae were used in the ZIB model: time of day, survey date category, survey area, and year. Again, 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 model. The time of day variable was used in the detection submodel as we reasoned that time of day (i.e. day or night) has an effect on the probability of detecting larvae with the neuston gear (net avoidance and diel vertical migration). **Table 7** summarizes the parameters used in the ZIB model and their significance. The ZIB submodel had an AUC = 0.750.

Table 8 summarizes the parameters developed for the MDL approach. **Figure 5** indicates the approximately normal distribution of the residuals of the multivariate binomial and multivariate lognormal submodels.

Table 9 and **Figures 6 and 7** summarize indices of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the PDD method, the DL model and ZIDL model. All indices and corresponding variabilities were similar when comparing years between the three different approaches. However, there was a slight increase in the many of the ZIDL index values when compared to DL index values, which was probably due to the correction for undetected larvae by the ZIDL approach. 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 via the two modeling approaches were the lowest of the entire time series.

Likewise, **Table 10** and **Figures 8 and 9** summarize indices of larval bluefin tuna (number per 10-minute tow) collected in neuston tows developed from the PDD method, the DL model and ZIDL model. All indices were fairly similar when comparing years between the two approaches, with the exception of survey years 1998 and 2003 where the two modeled indices were lower than those developed using the PDD method. Also, there was a slight increase in the many of the ZIDL index values when compared to DL index values, as described above with the bongo-collected larvae. However, all time series produced very similar patterns of abundance. Corresponding variablities of values were similar between modeled indices were very similar, while those of the PDD method were smaller. When compared to indices developed for bongo-collected larvae, index values were similarly high in the early years of the survey, except for survey 1984, and much lower in recent years, expert for survey years 1998 and 2003. Also, indices of neuston-collected larvae were much more variable between years than those of bongo-collected larvae.

The correlation between bongo and neuston catch rates was 0.161, and indices including data from the two gear-types were developed. **Table 11** and **Figure 10** summarize indices of larval bluefin tuna collected in bongo and neuston tows combined developed with the DL approach. Also, **Table 12** and **Figure 11** summarize indices of larval bluefin tuna collected in bongo and neuston tows developed with the MDL approach. Similar to the previously described indices, annual index values are higher during the early years of the time series and lower in later years. While the MDL approach is a novel approach by which to gain inference on abundance trends simultaneously from multiple gears, there was a decrease in precision in the resulting index values. This low precision may be a result of the low correlation between the catch rates of the different gears as mentioned above. As a result, we recommend the combined-gear index developed with the DL approach over the index developed with the MDL approach.

As recommended by Ingram *et al*. (2006), we again recommend using a modeling approach to develop abundance indices. Modeling allows for standardization of yearly catch estimates for those years where sampling methodology differed slightly from standard techniques. For example, in survey years 2003 and 2004, the survey did not begin until mid-May, which resulted in a Pennington estimator ($I_{\Delta,y}$) for bongo-collected larvae that was biased high for each of those years, due to lower average catch rates during late April and early May. Modeled indices (I_y, $I_{Z,y}$) for these two years were estimated to be lower as a result of the significant effect of the survey date categorical variable. Also, for both bongo- and neuston-collected larvae, time of day was a significant variable included in the various models. When included in the detection submodel of the ZIB model, some correction for lack of detection was provided with the slight increase of index values when comparing DL and ZIDL models.

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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	97	20 Apr 1982	25 May 1982	75	4.11840	2.0 - 10.7
1983	93	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	78	21 Apr 1987	21 May 1987	10	4.71500	2.3 - 9.2
1988	77	20 Apr 1988	25 May 1988	71	3.48873	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	9	3.47778	2.4 - 6.0
1992	83	22 Apr 1992	21 May 1992	39	3.56667	2.5 - 9.0
1993	83	26 Apr 1993	31 May 1993	23	5.11304	3.0 - 6.2
1994	84	28 Apr 1994	31 May 1994	28	4.42143	2.5 - 9.2
1995	97	20 Apr 1995	31 May 1995	35	2.71357	2.1 - 5.6
1996	79	20 Apr 1996	25 May 1996	130	3.24769	2.6 - 6.0
1997	74	20 Apr 1997	31 May 1997	27	3.91481	2.4 - 5.9
1998	59	26 Apr 1998	30 May 1998	10	3.74000	2.1 - 5.5
1999	71	24 Apr 1999	29 May 1999	27	3.94074	2.8 - 6.0
2000	74	20 Apr 2000	26 May 2000	23	3.51304	2.8 - 5.2
2001	71	20 Apr 2001	29 May 2001	32	2.83750	1.5 - 4.5
2002	71	20 Apr 2002	28 May 2002	14	4.52857	3.9 - 5.3
2003	38	14 May 2003	31 May 2003	35	2.77714	1.3 - 10.2
2004	32	13 May 2004	30 May 2004	28	2.80893	2.2 - 9.5
2005	74	22 Apr 2005	29 May 2005	19	2.42632	1.5 - 8.5
2006	75	24 Apr 2006	29 May 2006	34	3.35882	1.7 - 8.3
2007	48	20 Apr 2007	28 May 2007	23	2.82609	1.5 - 6.3

Table 2. Summary of neuston 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	98	20 Apr 1982	25 May 1982	174	5.67414	3.5 - 10.1
1983	92	22 Apr 1983	23 May 1983	112	5.34732	3.5 - 9.0
1984	70	21 Apr 1984	12 May 1984	2	4.90000	4.4 - 5.4
1986	72	23 Apr 1986	22 May 1986	47	5.64681	3.3 - 8.2
1989	143	26 Apr 1989	27 May 1989	166	5.51446	3.8 - 8.6
1990	147	21 Apr 1990	31 May 1990	37	5.07568	3.5 - 7.0
1991	145	20 Apr 1991	22 May 1991	61	5.20164	3.5 - 7.6
1992	145	22 Apr 1992	21 May 1992	17	5.17059	3.2 - 6.5
1993	144	26 Apr 1993	31 May 1993	61	4.81639	4.0 - 7.2
1994	132	28 Apr 1994	31 May 1994	37	5.64054	4.1 - 8.0
1995	175	20 Apr 1995	31 May 1995	94	4.68298	4.0 - 7.1
1996	142	20 Apr 1996	25 May 1996	80	5.04625	3.8 - 8.9
1997	131	20 Apr 1997	31 May 1997	78	4.13846	3.2 - 6.9
1998	117	26 Apr 1998	30 May 1998	133	5.29323	2.5 - 8.5
1999	136	24 Apr 1999	29 May 1999	78	5.15897	3.0 - 9.0
2000	144	20 Apr 2000	26 May 2000	73	4.82055	4.0 - 8.0
2001	133	20 Apr 2001	29 May 2001	51	4.88824	3.6 - 8.5
2002	123	20 Apr 2002	28 May 2002	53	5.32830	3.8 - 7.7
2003	72	14 May 2003	31 May 2003	75	5.87067	3.9 - 9.4
2004	66	13 May 2004	30 May 2004	20	5.14300	3.7 - 7.0
2005	143	22 Apr 2005	29 May 2005	25	4.84800	3.4 - 7.2
2006	126	23 Apr 2006	29 May 2006	137	5.33431	3.5 - 9.1
2007	79	20 Apr 2007	28 May 2007	29	4.88621	4.0 - 6.3

Table 3. Type 3 tests of delta-lognormal model parameters for data collected in bongo tows.

Type 3 Tests of Fixed Effects for the Binomial Submodel						
Effect	*Num DF*	*Den DF*	*Chi-Square*	*F Value*	*Pr > ChiSq*	*Pr > F*
year	27	585	82.18	2.96	<.0001	<.0001
survey date	3	1423	52.75	17.58	<.0001	<.0001
survey area	2	1514	35.29	17.64	<.0001	<.0001
time of day	1	1596	13.38	13.38	0.0003	0.0003

Type 3 Tests of Fixed Effects for the Lognormal Submodel				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	27	262	3.90	<.0001
survey date	3	262	3.82	0.0105
survey area	2	262	2.35	0.0972
time of day	1	262	5.69	0.0178

Table 4. Type-3 tests of delta-lognormal model parameters for data collected in neuston tows.

Type 3 Tests of Fixed Effects for the Binomial Submodel						
Effect	*Num DF*	*Den DF*	*Chi-Square*	*F Value*	*Pr > ChiSq*	*Pr > F*
year	22	909	97.79	4.38	<.0001	<.0001
survey date	3	1923	61.78	20.59	<.0001	<.0001
survey area	2	2230	39.10	19.55	<.0001	<.0001
time of day	1	2326	19.31	19.31	<.0001	<.0001

Type 3 Tests of Fixed Effects for the Lognormal Submodel Run 1				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	22	242	2.43	0.0005
survey date	3	242	0.88	0.4507
survey area	2	242	0.47	0.6263
time of day	1	242	2.96	0.0868

Type 3 Tests of Fixed Effects for the Lognormal Submodel Run 2				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	22	247	2.54	0.0003
time of day	1	247	3.81	0.0522

Table 5. Type-3 tests of delta-lognormal model parameters for data collected in both bongo and neuston tows combined.

Type 3 Tests of Fixed Effects for the Binomial Submodel

Effect	*Num DF*	*Den DF*	*Chi-Square*	*F Value*	*Pr > ChiSq*	*Pr > F*
year	27	148	185.15	6.17	<.0001	<.0001
maycat	3	321	80.92	26.94	<.0001	<.0001
areacat	2	305	93.65	46.81	<.0001	<.0001
timecat	1	276	17.81	17.81	<.0001	<.0001

Type 3 Tests of Fixed Effects for the Lognormal Submodel

Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
year	27	344	24.13	<.0001
maycat	3	344	5.08	0.0019
timecat	1	344	14.08	0.0002
areacat	2	344	2.82	0.0608

Table 6. Parameters of the zero-inflated binomial model for bongo tows. The prefix *o* denotes those parameters in the occupancy submodel, while the prefix *d* denotes those parameters in the detection submodel.

Parameter	*Estimate*	*Standard Error*	*DF*	*Pr > |t|*
o_intercept	-0.8864	0.3745	1958	0.0180
o_month_late_April	-1.2866	0.2445	1958	<0.0001
o_month_early_May	-0.3731	0.1961	1958	0.0572
o_month_middle_May	0.2538	0.1820	1958	0.1633
o_area_east	-1.0501	0.1949	1958	<0.0001
o_area_central	-0.4658	0.1556	1958	0.0028
o_1977	1.1803	0.6041	1958	0.0509
o_1978	1.4942	0.4414	1958	0.0007
o_1981	-0.07996	0.5858	1958	0.8914
o_1982	0.2714	0.4496	1958	0.5461
o_1983	0.1797	0.4597	1958	0.6960
o_1984	-0.5944	0.5816	1958	0.3069
o_1986	-0.5716	0.5505	1958	0.2992
o_1987	-0.9971	0.5983	1958	0.0958
o_1988	0.4207	0.4719	1958	0.3728
o_1989	-0.01864	0.4791	1958	0.9690
o_1990	-0.2895	0.4994	1958	0.5622
o_1991	-0.7399	0.6006	1958	0.2181
o_1992	0.01553	0.4760	1958	0.9740
o_1993	-1.1543	0.5607	1958	0.0397
o_1994	-0.2869	0.4850	1958	0.5543
o_1995	-0.6665	0.5268	1958	0.2060
o_1996	-0.2667	0.5006	1958	0.5942
o_1997	-0.1591	0.4977	1958	0.7492
o_1998	-0.8718	0.5940	1958	0.1424
o_1999	-0.5052	0.5257	1958	0.3367
o_2000	-0.6809	0.5430	1958	0.2100
o_2001	-0.07141	0.4953	1958	0.8854
o_2002	-1.2226	0.6396	1958	0.0561
o_2003	0.3029	0.5170	1958	0.5580
o_2004	-0.2690	0.5810	1958	0.6435
o_2005	0.07028	0.4798	1958	0.8835
o_2006	0.1275	0.4603	1958	0.7818
d_time_of day_day	-1.3831	0.02575	1958	<0.0001

Table 7. Parameters of the zero-inflated binomial model for neuston tows. The prefix *o* denotes those parameters in the occupancy submodel, while the prefix *d* denotes those parameters in the detection submodel.

Parameter	*Estimate*	*Standard Error*	*DF*	*Pr > |t|*
o_intercept	-2.5858	0.3565	2981	<0.0001
o_month_late_April	-1.4228	0.2367	2981	<0.0001
o_month_early_May	-0.5980	0.2029	2981	0.0032
o_month_middle_May	0.03528	0.1790	2981	0.8437
o_area_east	-0.8076	0.1936	2981	<0.0001
o_area_central	-0.7315	0.1531	2981	<0.0001
o_1982	2.9235	0.4128	2981	<0.0001
o_1983	1.6394	0.4722	2981	0.0005
o_1984	-0.5297	1.0753	2981	0.6223
o_1986	1.6407	0.5033	2981	0.0011
o_1989	2.1874	0.4089	2981	<0.0001
o_1990	1.0293	0.4663	2981	0.0274
o_1991	1.3180	0.4636	2981	0.0045
o_1992	0.7759	0.4900	2981	0.1134
o_1993	0.7556	0.4659	2981	0.1050
o_1994	0.7359	0.4890	2981	0.1325
o_1995	1.0806	0.4506	2981	0.0165
o_1996	0.7881	0.4875	2981	0.1061
o_1997	0.2301	0.5719	2981	0.6875
o_1998	1.4381	0.4428	2981	0.0012
o_1999	0.7427	0.4881	2981	0.1282
o_2000	1.1495	0.4514	2981	0.0109
o_2001	1.5765	0.4282	2981	0.0002
o_2002	0.5156	0.5452	2981	0.3443
o_2003	1.0263	0.5106	2981	0.0445
o_2004	0.7302	0.5535	2981	0.1872
o_2005	0.6300	0.5006	2981	0.2084
o_2006	1.6626	0.4296	2981	0.0001
d_time_of day_day	-1.9099	0.02541	2981	<0.0001

Table 8. Mutivariate delta-lognormal model parameters for data collected in bongo and neuston tows.

multivariate binomial on proportion positive				***multivariate lognormal on positive catch***			
Parameter	*Estimate*	*Standard Error*	*Pr > |t|*	*Parameter*	*Estimate*	*Standard Error*	*Pr > |t|*
beta1b	-0.7102	0.5118	0.1686	*beta1b*	-0.1491	0.1480	0.3175
beta1n	-2.1001	0.4757	<.0001	*beta1n*	0.009887	0.1014	0.9226
time_of day_day	-1.2508	0.3466	0.0005	*time_of day_day*	-0.04201	0.1209	0.7294
time_of day_night	-1.5595	0.3064	<.0001	*time_of day_night*	-0.09716	0.1074	0.3691
month_late_April	-0.8702	0.2563	0.0010	*month_late_April*	-0.02082	0.2395	0.9310
month_early_May	-0.1137	0.2284	0.6199	*month_early_May*	0.8032	0.2028	0.0002
month_middle_May	-0.1891	0.2072	0.3639	*month_middle_May*	0.3675	0.1672	0.0316
month_late_May	0.3624	0.2116	0.0902	*month_late_May*	0.7110	0.1794	0.0002
a1982	2.8336	1.5349	0.0682	*a1982*	1.3491	0.2704	<.0001
a1983	1.0864	0.6312	0.0887	*a1983*	2.0029	0.3817	<.0001
a1984	0.4909	0.9782	0.6170	*a1984*	0.9509	0.8313	0.2570
a1986	0.6604	0.7056	0.3518	*a1986*	2.0891	0.3910	<.0001
a1989	1.8829	1.3564	0.1685	*a1989*	1.0420	0.3065	0.0012
a1990	0.4410	0.6992	0.5298	*a1990*	0.1875	0.5139	0.7164
a1991	1.0334	1.0987	0.3494	*a1991*	0.2301	0.4353	0.5989
a1992	1.0567	0.5818	0.0727	*a1992*	0.2422	0.4719	0.6096
a1993	0.2319	0.7786	0.7665	*a1993*	0.9066	0.5296	0.0918
a1994	0.8963	0.5920	0.1335	*a1994*	1.7143	0.4387	0.0002
a1995	0.1811	0.7434	0.8080	*a1995*	0.6659	0.5657	0.2435
a1996	0.2515	0.6974	0.7192	*a1996*	1.6555	0.4474	0.0004
a1997	0.4454	1.0061	0.6590	*a1997*	0.08536	0.5107	0.8678
a1998	0.5296	0.7299	0.4700	*a1998*	0.7969	0.5336	0.1402
a1999	0.5810	0.7096	0.4151	*a1999*	0.6810	0.4136	0.1045
a2000	0.5095	0.6879	0.4608	*a2000*	-0.00168	0.4657	0.9971
a2001	0.8633	0.6581	0.1929	*a2001*	0.8796	0.6595	0.1870
a2002	0.6690	0.6751	0.3244	*a2002*	1.1213	0.5366	0.0406
a2003	0.8108	0.8807	0.3597	*a2003*	1.0739	0.4629	0.0235
a2004	0.5393	1.0733	0.6166	*a2004*	0.9560	1.1082	0.3916
a2005	0.4915	0.7993	0.5402	*a2005*	0.6252	0.6471	0.3376
a2006	1.1344	0.6200	0.0706	*a2006*	1.5664	0.3561	<.0001
a2007	0.5693	0.9150	0.5354	*a2007*	0.04089	0.5295	0.9387
s1	0.9498	0.1655	<.0001	*s3*	1.2893	0.2070	<.0001
cov12	-0.3338	1.3508	0.8054	*s1*	1.3406	0.2859	<.0001
s2	0.3514	1.4834	0.8133	*cov12*	-1.3083	0.3019	<.0001
				s2	0.9758	0.01669	<.0001

Table 9. Indices of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the Pennington delta-distribution method, the delta-lognormal model and zero-inflated delta-lognormal 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.

				delta-distribution method				*delta-lognormal model*				*zero-inflated delta-lognormal model*			
Survey Year	*n*	*m*	*f*	$I_{\Delta,y}$	*CV*	*LCL*	*UCL*	I_y	*CV*	*LCL*	*UCL*	$I_{Z,y}$	*CV*	*LCL*	*UCL*
1977	20	8	0.400	2.42336	0.44920	1.02809	5.71221	2.33904	0.47391	1.29237	4.23340	2.50432	0.47580	1.38073	4.54225
1978	69	33	0.478	5.21356	0.24213	3.23453	8.40345	4.80751	0.24021	3.51840	6.56893	4.86911	0.23448	3.58941	6.60505
1979	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1980	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1981	35	6	0.171	1.16307	0.43434	0.50643	2.67114	0.69655	0.43588	0.40199	1.20694	0.73453	0.43325	0.42521	1.26888
1982	97	20	0.206	1.41304	0.27546	0.82272	2.42691	1.34174	0.31216	0.89768	2.00546	1.35649	0.29227	0.93011	1.97833
1983	93	16	0.172	0.92825	0.33267	0.48558	1.77450	1.20536	0.34543	0.77435	1.87629	1.20222	0.35409	0.76428	1.89109
1984	71	6	0.085	0.30092	0.50629	0.11575	0.78229	0.33744	0.70554	0.14601	0.77987	0.36738	0.55595	0.18538	0.72807
1985	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1986	72	7	0.097	0.39921	0.40479	0.18317	0.87005	0.39621	0.59353	0.19207	0.81730	0.40386	0.43385	0.23362	0.69814
1987	78	5	0.064	0.34323	0.45458	0.14426	0.81665	0.32038	0.47751	0.17630	0.58222	0.34578	0.47568	0.19067	0.62708
1988	77	15	0.195	1.13992	0.32757	0.60196	2.15862	1.04070	0.31487	0.69396	1.56069	1.08380	0.31674	0.72104	1.62906
1989	85	14	0.165	0.79710	0.36165	0.39536	1.60706	0.70155	0.35127	0.44752	1.09979	0.76487	0.36807	0.47814	1.22354
1990	86	10	0.116	0.33784	0.33444	0.17615	0.64795	0.33056	0.43985	0.18990	0.57541	0.33186	0.33696	0.21540	0.51130
1991	69	5	0.072	0.27724	0.53561	0.10154	0.75697	0.37045	0.62813	0.17323	0.79219	0.38812	0.59030	0.18879	0.79789
1992	83	14	0.169	0.54643	0.35673	0.27347	1.09182	0.48268	0.36164	0.30407	0.76619	0.52724	0.35999	0.33281	0.83527
1993	83	6	0.072	0.60475	0.61681	0.19426	1.88264	0.43803	0.71828	0.18720	1.02496	0.49838	0.67040	0.22327	1.11249
1994	84	12	0.143	0.68083	0.35395	0.34247	1.35348	0.44160	0.32879	0.28949	0.67363	0.48730	0.35232	0.31045	0.76489
1995	97	8	0.082	0.27069	0.49437	0.10625	0.68965	0.32663	0.57263	0.16189	0.65901	0.34775	0.55772	0.17514	0.69049
1996	79	10	0.127	1.04968	0.54303	0.37976	2.90136	0.88729	0.56328	0.44420	1.77236	0.96553	0.51640	0.50870	1.83261
1997	74	11	0.149	0.44175	0.40089	0.20411	0.95609	0.37605	0.42453	0.21991	0.64307	0.40791	0.41243	0.24193	0.68776
1998	59	5	0.085	0.19614	0.50735	0.07531	0.51082	0.10883	0.52836	0.05659	0.20930	0.11741	0.55261	0.05946	0.23185
1999	71	8	0.113	0.70526	0.53686	0.25777	1.92960	0.48626	0.51581	0.25636	0.92234	0.51233	0.53118	0.26557	0.98837
2000	74	7	0.095	0.33973	0.49138	0.13403	0.86116	0.31220	0.52015	0.16381	0.59503	0.34367	0.54500	0.17548	0.67306
2001	71	11	0.15493	0.49223	0.37274	0.23926	1.01264	0.38708	0.35117	0.24695	0.60673	0.38711	0.38281	0.23777	0.63025
2002	71	4	0.05634	0.34091	0.60208	0.11209	1.03684	0.28438	0.56782	0.14168	0.57082	0.30437	0.65984	0.13781	0.67225
2003	38	10	0.26316	1.12451	0.35692	0.56258	2.24770	0.71051	0.41340	0.42093	1.19932	0.73696	0.40952	0.43859	1.23832
2004	32	6	0.18750	1.06810	0.63096	0.33557	3.39965	0.50400	0.67690	0.22432	1.13236	0.54127	0.68054	0.24004	1.22051
2005	74	13	0.17568	0.27384	0.31648	0.14762	0.50799	0.22057	0.36171	0.13894	0.35016	0.23045	0.32653	0.15149	0.35057
2006	75	16	0.21053	0.81568	0.35560	0.40907	1.62646	0.58389	0.38907	0.35598	0.95772	0.60532	0.35779	0.38311	0.95643
2007	48	10	0.20833	0.59244	0.36027	0.29459	1.19146	0.32591	0.41029	0.19378	0.54812	0.35488	0.40516	0.21228	0.59326

Table 10. Indices of larval bluefin tuna (number per 10-minute tow) collected in neuston tows developed from the Pennington delta-distribution method, the delta-lognormal model and zero-inflated delta-lognormal 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.

				delta-distribution method				*delta-lognormal model*				*zero-inflated delta-lognormal model*			
Survey Year	*n*	*m*	*f*	$I_{\Delta,y}$	*CV*	*LCL*	*UCL*	I_y	*CV*	*LCL*	*UCL*	$I_{Z,y}$	*CV*	*LCL*	*UCL*
1982	98	32	0.32653	3.71800	0.28384	2.13072	6.4877	3.83574	0.27670	2.68149	5.48685	3.85156	0.26441	2.73423	5.42547
1983	92	12	0.11957	1.60143	0.47662	0.64792	3.9582	1.64839	0.50944	0.87519	3.10469	1.69672	0.51044	0.89985	3.19926
1984	70	1	0.01429	.	.	.	.	0.02295	3.69537	0.00265	0.19893	0.02516	3.24411	0.00320	0.19754
1985	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1986	72	9	0.12500	1.95075	0.53455	0.71572	5.3169	2.02665	0.57794	0.99882	4.11215	2.03334	0.54126	1.04247	3.96604
1987	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1988	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1989	143	29	0.20280	1.68966	0.31124	0.91978	3.1039	1.57215	0.32022	1.04148	2.37321	1.66795	0.29950	1.13348	2.45443
1990	147	11	0.07483	0.28847	0.35626	0.14450	0.5759	0.26616	0.49229	0.14404	0.49180	0.28679	0.44173	0.16440	0.50030
1991	145	12	0.08276	0.60853	0.45493	0.25560	1.4488	0.73534	0.48625	0.40067	1.34956	0.78006	0.49532	0.42073	1.44628
1992	145	9	0.06207	0.14194	0.38541	0.06743	0.2988	0.11196	0.65495	0.05094	0.24606	0.12580	0.54844	0.06400	0.24729
1993	144	11	0.07639	0.33933	0.35133	0.17151	0.6714	0.20503	0.46543	0.11438	0.36752	0.24274	0.43680	0.13994	0.42105
1994	132	9	0.06818	0.57876	0.56863	0.20080	1.6682	0.45864	0.60226	0.22031	0.95479	0.53853	0.63946	0.24892	1.16509
1995	175	13	0.07429	0.26959	0.32233	0.14376	0.5056	0.24667	0.34858	0.15786	0.38544	0.27432	0.39489	0.16610	0.45306
1996	142	9	0.06338	0.70182	0.50481	0.27064	1.8200	0.57978	0.52495	0.30260	1.11087	0.67400	0.56407	0.33714	1.34745
1997	131	5	0.03817	0.14663	0.57445	0.05039	0.4266	0.10311	0.78976	0.04119	0.25812	0.12110	0.85799	0.04550	0.32233
1998	117	15	0.12821	2.34295	0.40834	1.06823	5.1388	1.79849	0.39191	1.09280	2.95990	2.02025	0.41478	1.19492	3.41563
1999	136	9	0.06618	0.71656	0.57054	0.24784	2.0718	0.58612	0.67835	0.26050	1.31876	0.66982	0.62601	0.31391	1.42926
2000	144	13	0.09028	0.39585	0.37875	0.19033	0.8233	0.32112	0.46768	0.17868	0.57710	0.36819	0.44365	0.21059	0.64373
2001	133	18	0.13534	0.45076	0.30927	0.24628	0.8250	0.35646	0.37717	0.22042	0.57646	0.39193	0.35494	0.24891	0.61714
2002	123	6	0.04878	0.59838	0.59228	0.19984	1.7917	0.45749	0.59406	0.22166	0.94423	0.50718	0.68057	0.22492	1.14367
2003	72	8	0.11111	3.09962	0.64049	0.95952	10.0130	1.72807	0.65829	0.78363	3.81076	2.02381	0.65296	0.92270	4.43896
2004	66	6	0.09091	0.38180	0.43935	0.16479	0.8846	0.19275	0.60010	0.09280	0.40036	0.23157	0.55902	0.11646	0.46045
2005	143	8	0.05594	0.24666	0.41231	0.11167	0.5448	0.17351	0.45642	0.09780	0.30784	0.19930	0.52697	0.10379	0.38271
2006	126	18	0.14286	1.37174	0.37437	0.66482	2.8303	1.11752	0.44902	0.63524	1.96594	1.23807	0.37458	0.76795	1.99600
2007	79	9	0.11392	0.29165	0.35360	0.14680	0.5794	0.15908	0.45382	0.08993	0.28140	0.06766	0.57390	0.03349	0.13670

Table 11. Indices of larval bluefin tuna collected in bongo and neuston tows combined developed from the delta-lognormal model. The number of samples included in analyses per year represented by *n*.

		delta-lognormal model			
Survey Year	*n*	I_y	*CV*	*LCL*	*UCL*
1977	20	8.9133	0.32711	5.85512	13.56880
1978	69	14.5433	0.12183	12.39319	17.06644
1979	0	.	.	.	.
1980	0	.	.	.	.
1981	35	1.8686	0.42264	1.09512	3.18838
1982	91	7.1249	0.25073	5.14565	9.86545
1983	93	7.9362	0.32636	5.21804	12.07029
1984	70	0.3549	0.75778	0.14606	0.86237
1985	0	.	.	.	.
1986	67	3.0657	0.44669	1.74734	5.37875
1987	78	0.9975	0.38484	0.61121	1.62794
1988	77	3.9025	0.17245	3.11425	4.89027
1989	84	7.4188	0.33349	4.83561	11.38194
1990	82	0.6424	0.31779	0.42683	0.96684
1991	69	1.2094	0.55520	0.61075	2.39485
1992	76	1.2015	0.42549	0.70182	2.05693
1993	80	2.4345	0.66654	1.09485	5.41334
1994	78	2.5336	0.41035	1.50635	4.26137
1995	97	0.6673	0.38793	0.40738	1.09305
1996	79	1.7450	0.56271	0.87413	3.48350
1997	73	0.5779	0.37269	0.35927	0.92958
1998	59	1.9818	0.49568	1.06847	3.67585
1999	69	1.1508	0.50999	0.61063	2.16882
2000	74	0.6784	0.38681	0.41471	1.10976
2001	63	0.8365	0.29054	0.57480	1.21735
2002	67	1.9870	0.67243	0.88834	4.44441
2003	37	2.4675	0.42917	1.43517	4.24240
2004	32	0.7420	0.58162	0.36426	1.51144
2005	74	0.3549	0.33121	0.23197	0.54298
2006	74	2.5144	0.34195	1.62213	3.89748
2007	47	0.4906	0.27600	0.34327	0.70117

Table 12. Indices of larval bluefin tuna collected in bongo and neuston tows developed from the multivariate delta-lognormal model. The number of samples included in analyses per year represented by *n*.

		multivariate delta-lognormal model			
Survey Year	*n*	$I_{MV,y}$	*CV*	*LCL*	*UCL*
1982	91	3.28523	0.47757	1.32698	8.13329
1983	93	2.90796	0.61001	0.94417	8.95629
1984	70	0.73574	1.16070	0.11599	4.66709
1985	0	.	.	.	.
1986	67	2.36769	0.71480	0.65510	8.55736
1987	0	.	.	.	.
1988	0	.	.	.	.
1989	84	1.83604	0.71573	0.50731	6.64499
1990	82	0.38035	0.73738	0.10182	1.42079
1991	69	0.59597	0.87260	0.13234	2.68384
1992	76	0.61045	0.57341	0.21015	1.77320
1993	80	0.57912	0.87619	0.12799	2.62037
1994	78	1.95863	0.64327	0.60371	6.35443
1995	97	0.45343	0.86018	0.10236	2.00870
1996	79	1.15357	0.77124	0.29419	4.52333
1997	73	0.35373	0.92758	0.07316	1.71015
1998	59	0.66361	0.80799	0.16077	2.73928
1999	69	0.62536	0.70011	0.17683	2.21159
2000	74	0.34859	0.68843	0.10030	1.21145
2001	63	0.90345	0.80812	0.21883	3.72997
2002	67	0.97398	0.76916	0.24912	3.80788
2003	37	1.03215	0.81577	0.24739	4.30635
2004	32	0.76625	1.40526	0.09494	6.18399
2005	74	0.55860	0.90039	0.11963	2.60841
2006	74	1.99008	0.56735	0.69188	5.72413
2007	47	0.37579	0.85866	0.08500	1.66139

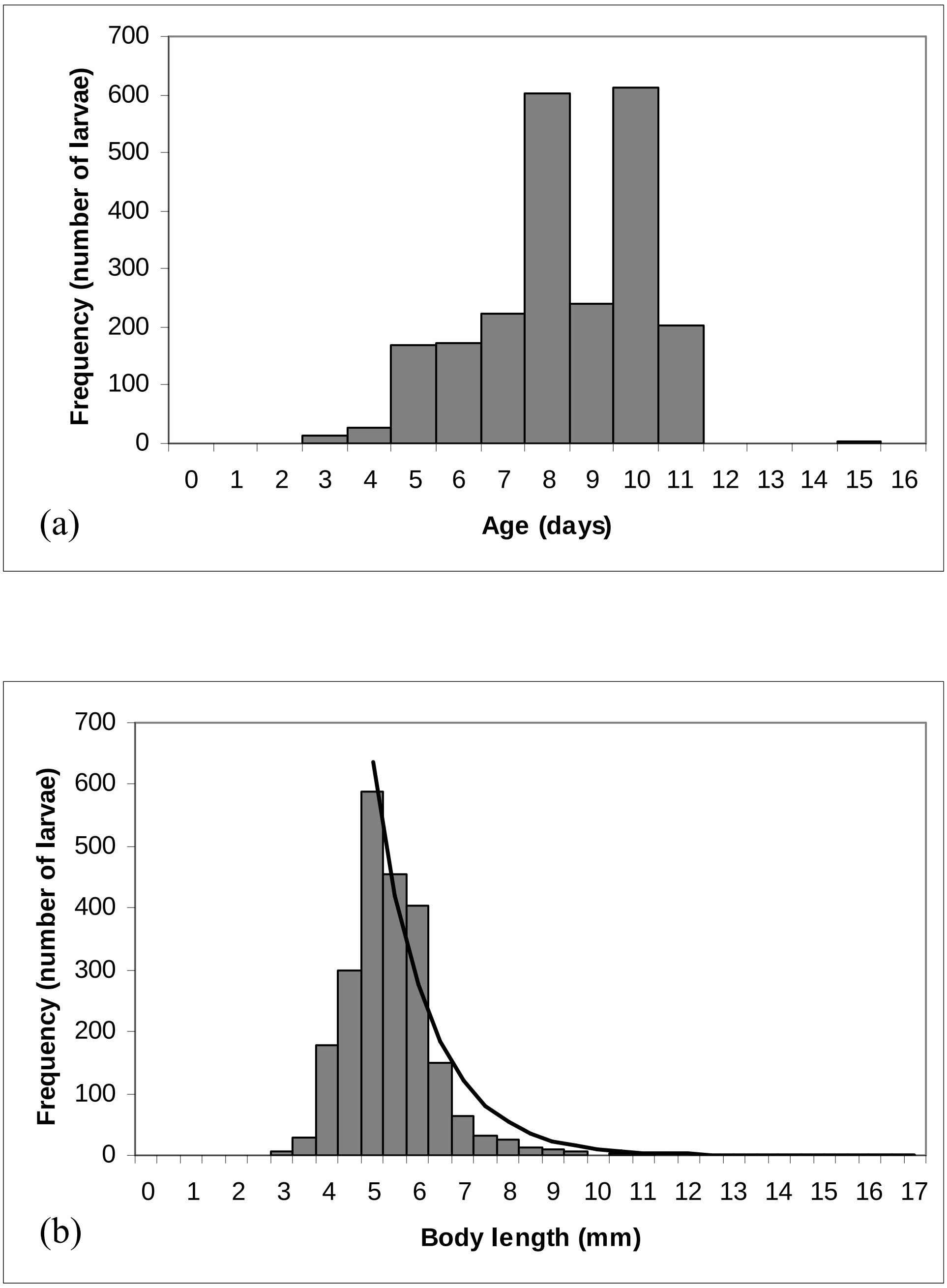

Figure 1. Age frequency (**a**) and length frequency (**b**) histograms of Atlantic bluefin tuna larvae collected in neuston tows (n=2270). Figure (**b**) illustrates the nonlinear regression by which the standardization factor was calculated.

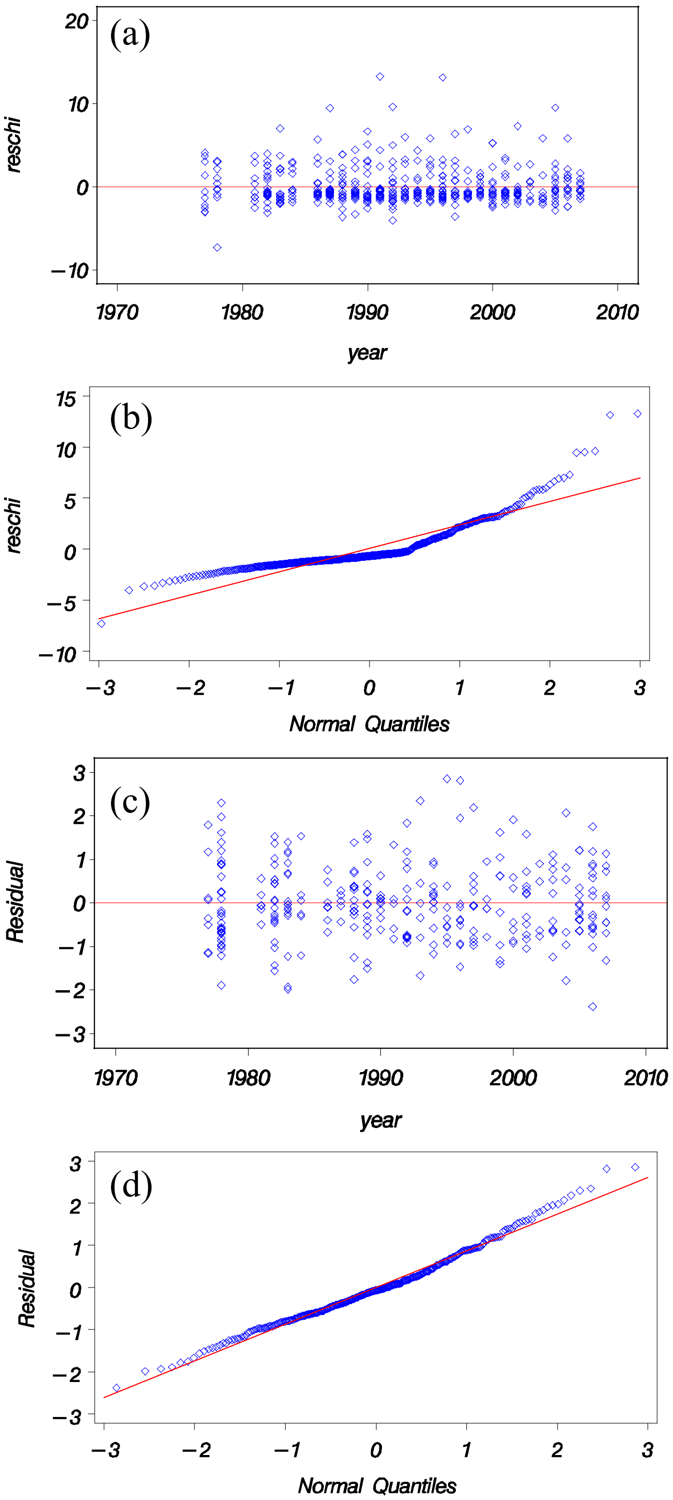

Figure 2. Residual plots of the binomial (**a** and **b**) and lognormal (**c** and **d**) submodels of the delta-lognomal model for larvae collected in bongo tows. Plots **a** and **c** are of residuals versus survey year, and plots **b** and **d** are QQ plots of the residuals.

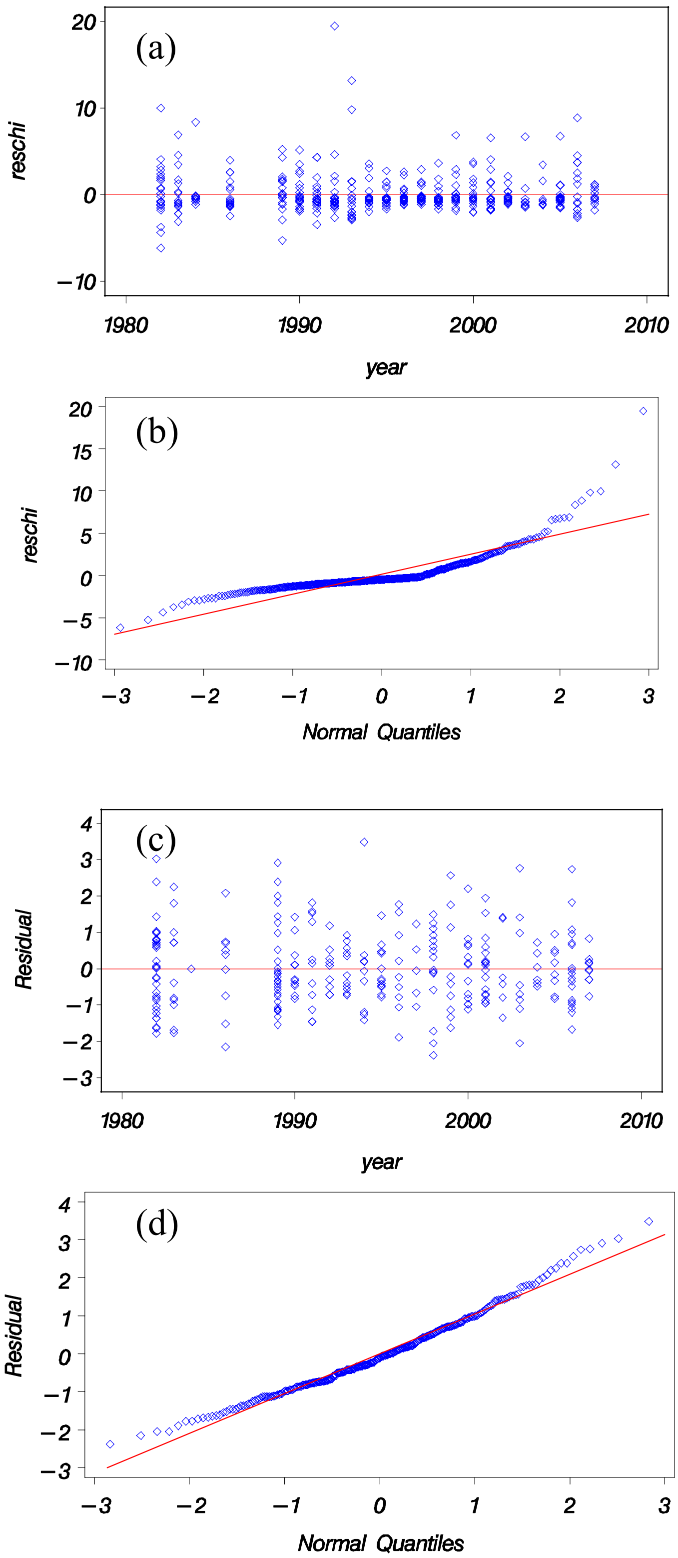

Figure 3. Residual plots of the binomial (**a** and **b**) and lognormal (**c** and **d**) submodels of the delta-lognormal model for larvae collected in neuston tows. Plots **a** and **c** are of residuals versus survey year, and plots **b** and **d** are QQ plots of the residuals.

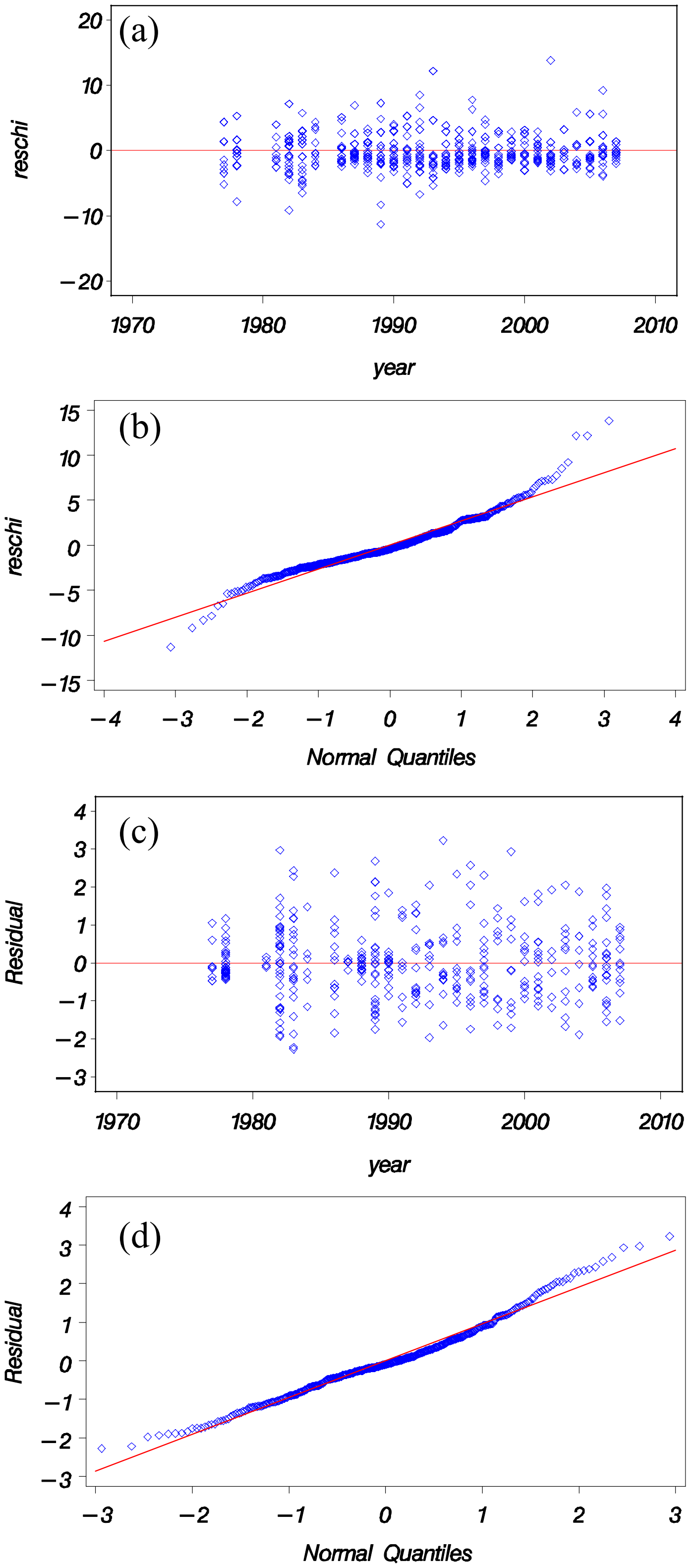

Figure 4. Residual plots of the binomial (**a** and **b**) and lognormal (**c** and **d**) submodels of the delta-lognomal model for larvae collected in bongo and neuston tows combined. Plots **a** and **c** are of residuals versus survey year, and plots **b** and **d** are QQ plots of the residuals.

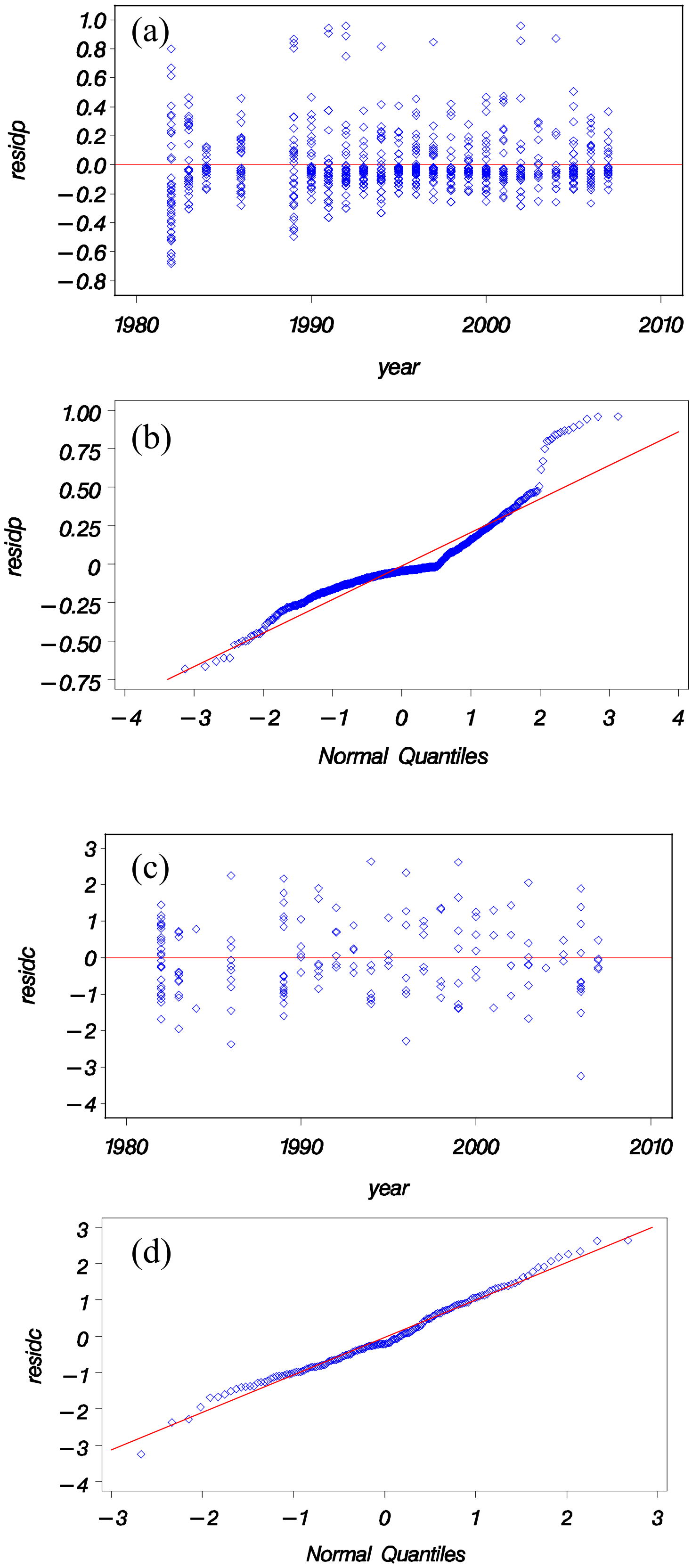

Figure 5. Residual plots of the binomial (**a** and **b**) and lognormal (**c** and **d**) submodels of the multivariate delta-lognormal model for larvae collected in bongo and neuston tows. Plots **a** and **c** are of residuals versus survey year, and plots **b** and **d** are QQ plots of the residuals.

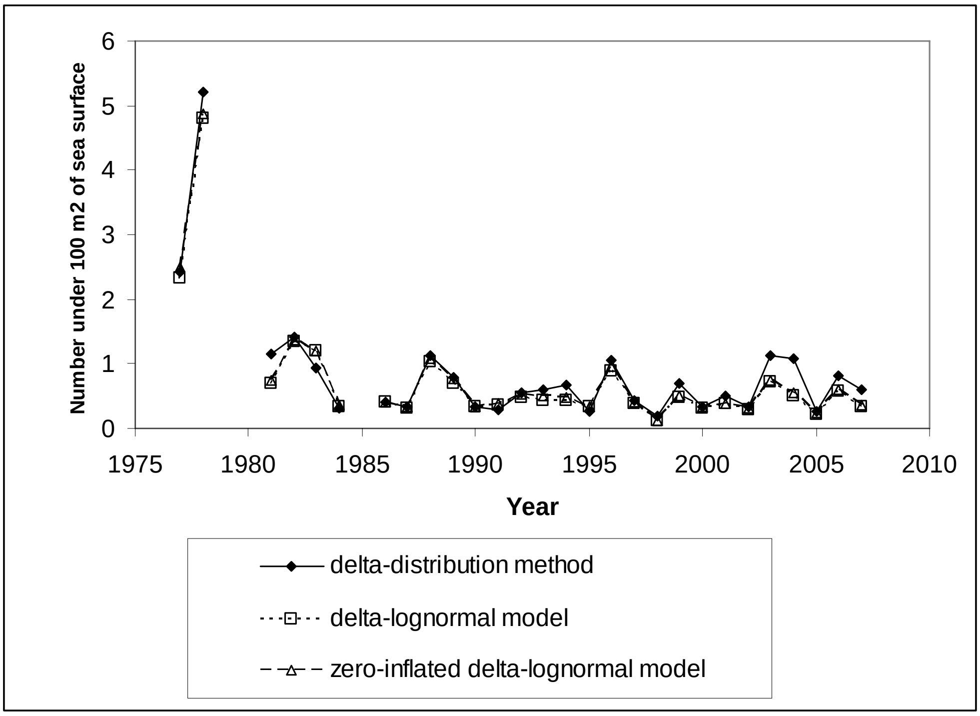

Figure 6. Annual indices of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the Pennington delta-distribution method, the delta-lognormal model and zero-inflated delta-lognormal model.

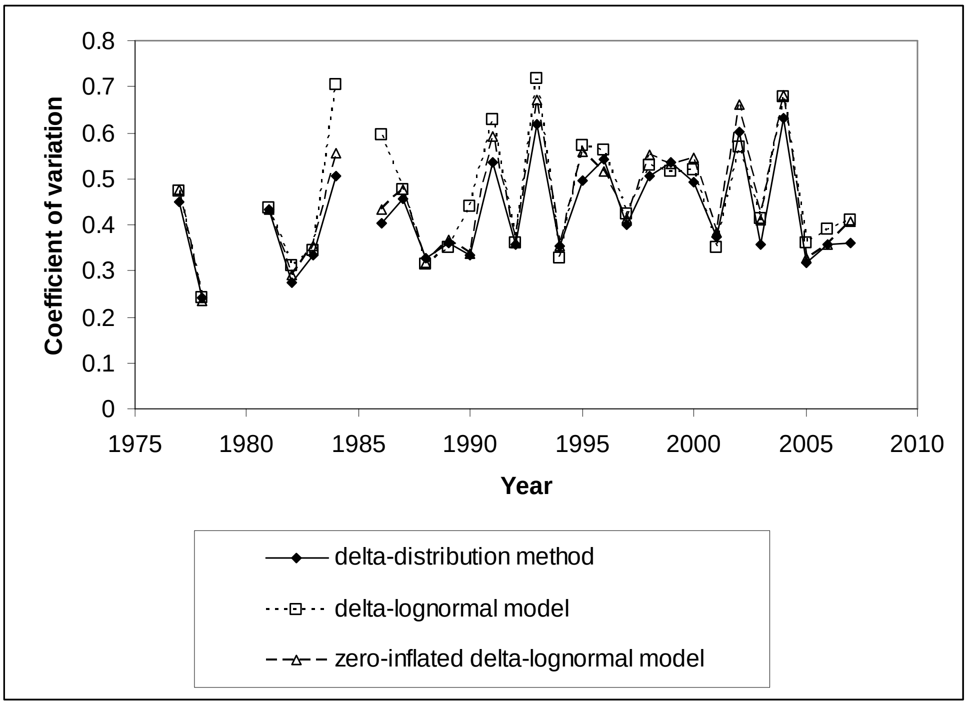

Figure 7. Coefficients of variation (i.e. standard error/mean) annual indices of larval bluefin tuna (number under 100 m^2 of sea surface) collected in bongo tows developed from the Pennington delta-distribution method, the delta-lognormal model and zero-inflated delta-lognormal model.

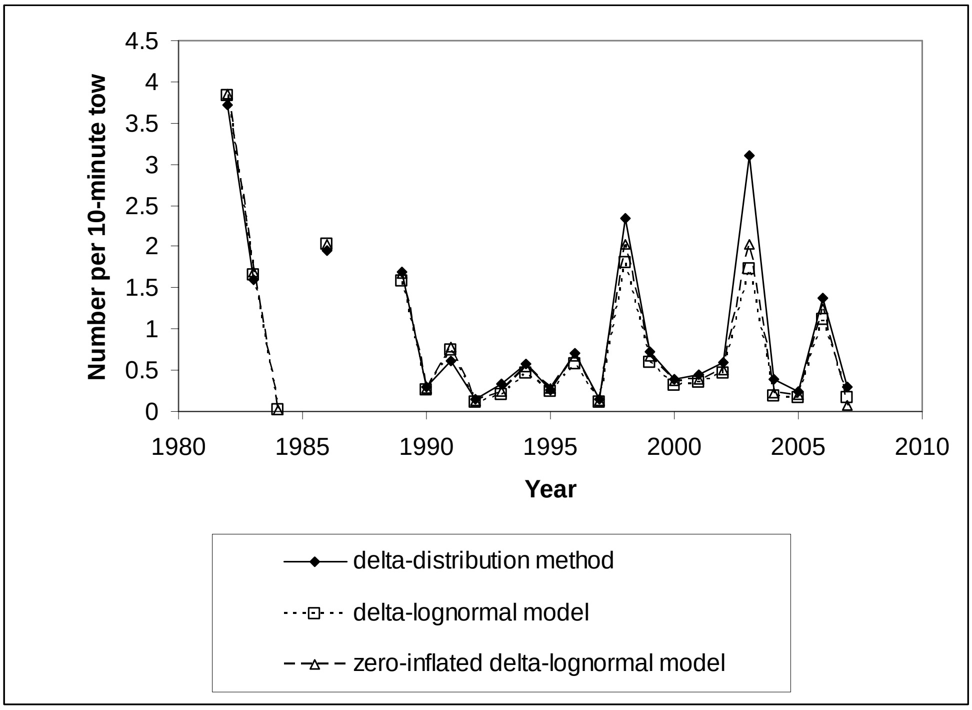

Figure 8. Annual indices of larval bluefin tuna (number per 10-minute tow) collected in neuston tows developed from the Pennington delta-distribution method, the delta-lognormal model and zero-inflated delta-lognormal model.

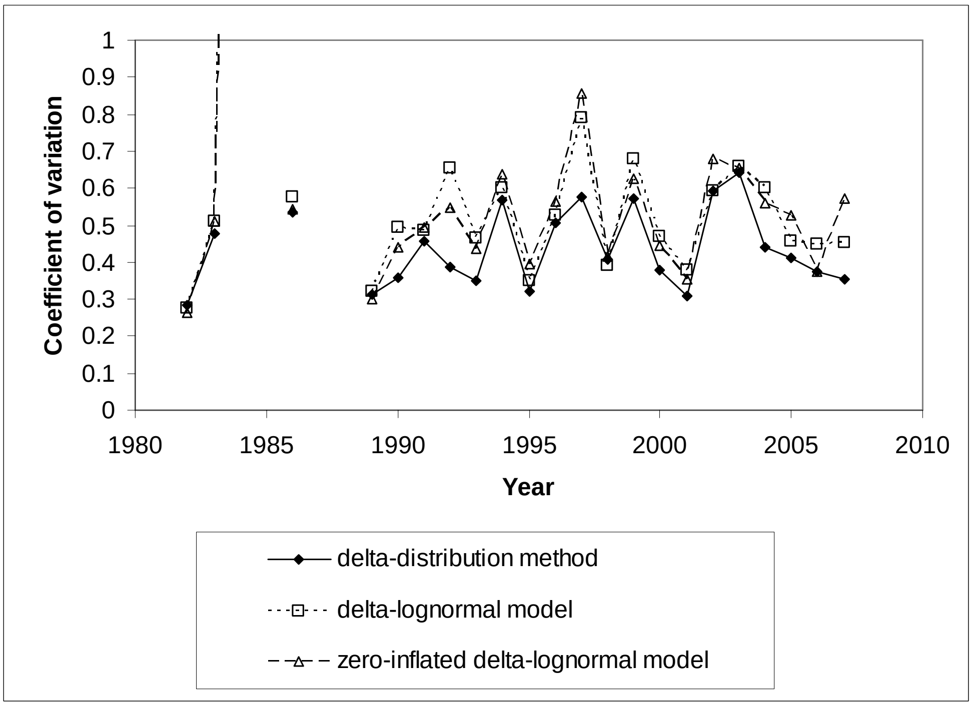

Figure 9. Coefficients of variation (i.e. standard error/mean) annual indices of larval bluefin tuna (number per 10-minute tow) collected in neuston tows developed from the Pennington delta-distribution method, the delta-lognormal model and zero-inflated delta-lognormal model.

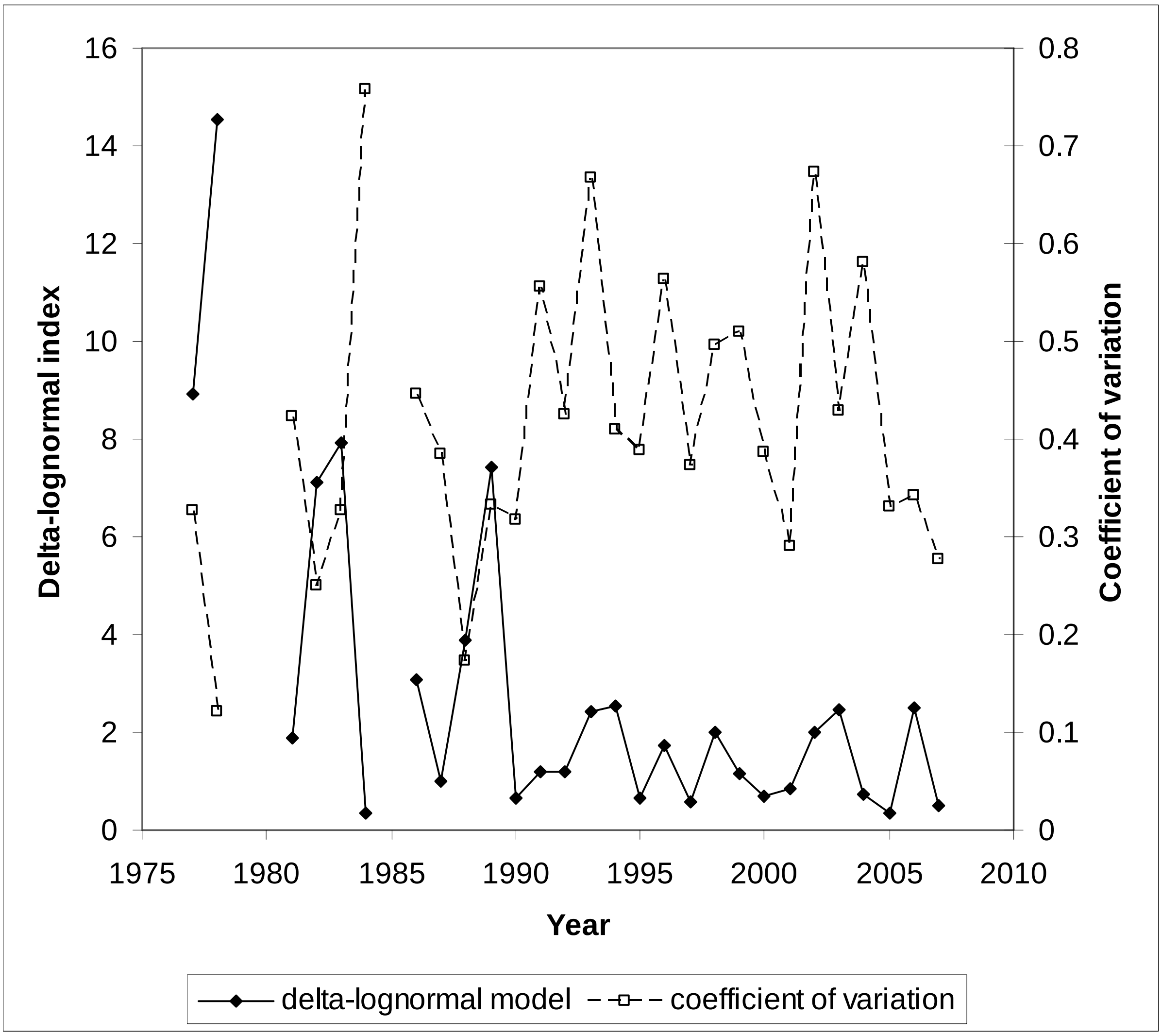

Figure 10. Annual indices of larval bluefin tuna collected in bongo and neuston tows developed from combined catch data using the delta-lognormal model and corresponding coefficients of variation.

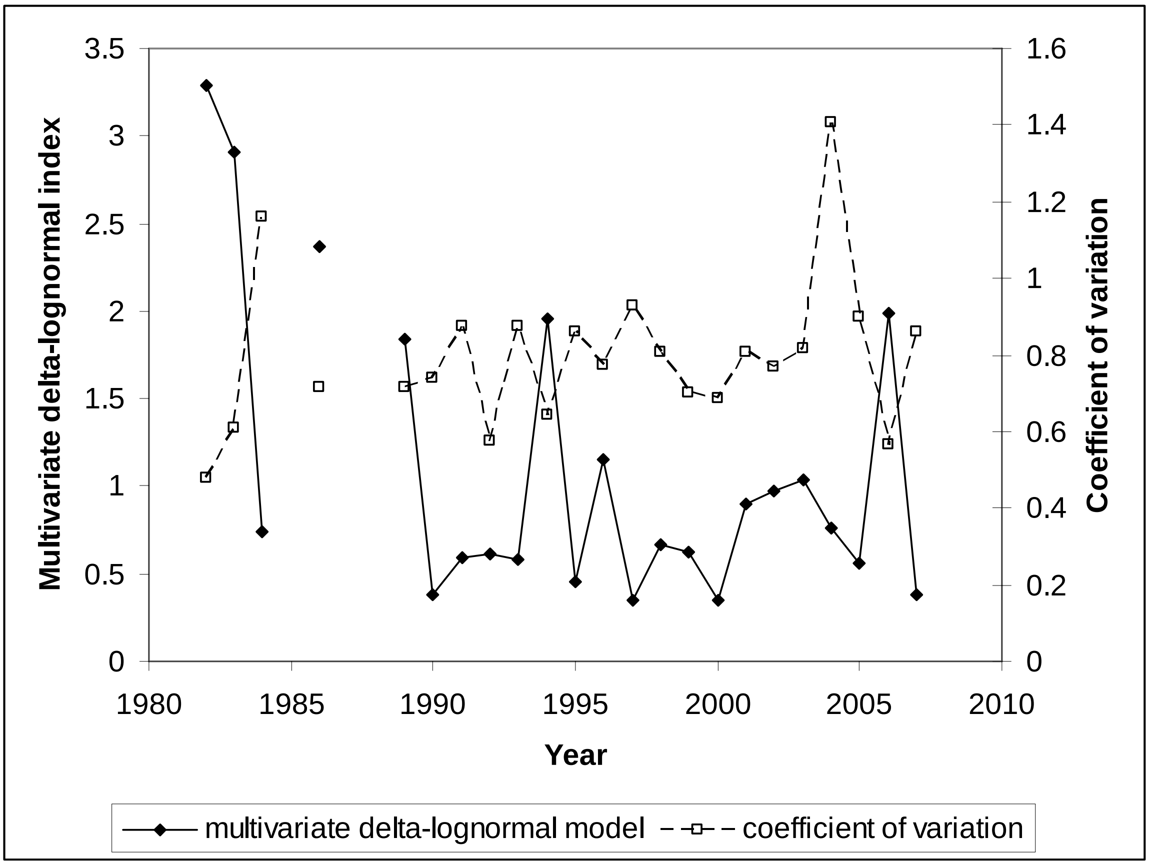

Figure 11. Annual indices of larval bluefin tuna collected in bongo and neuston tows developed from the multivariate delta-lognormal model and corresponding coefficients of variation.

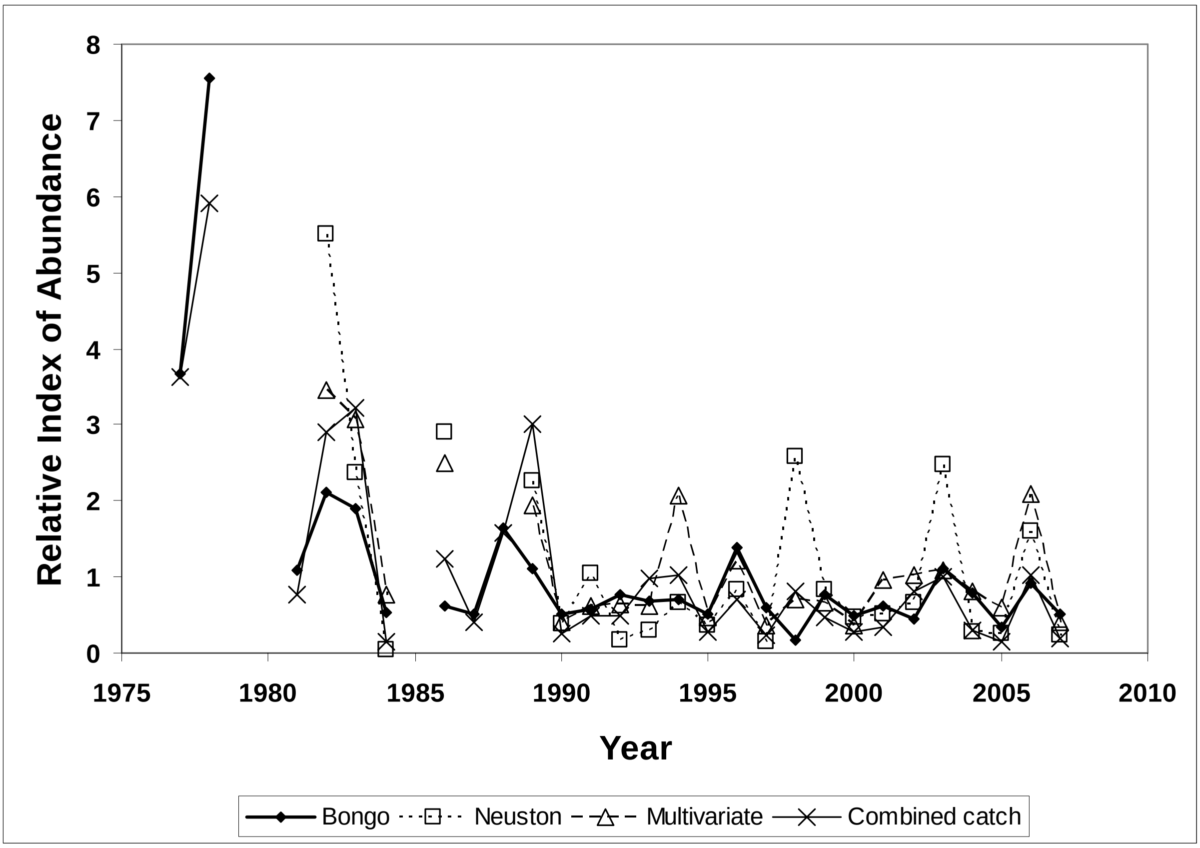

Figure 12. Comparison of annual indices of larval bluefin tuna collected in bongo and neuston tows.