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# Estimating mortality for the assessment of a small-scale fishery: Lane snapper (*Lutjanus synagris*) in Honduras

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ABSTRACT

Gillnets are very common in small-scale fisheries. However, data obtained using gillnets are biased because of their size selectivity, making accurate estimation of mortality difficult. This study applied various methods to estimate total, natural, and fishing mortality, using data for Lane Snapper (*Lutjanus synagris*) collected in Tela, Honduras. Total mortality was estimated using a catch-curve analysis with and without accounting for size-selectivity using fitted selectivity curves, the Chapman and Robson method, and Heincke's method. Gillnet selectivity of Lane Snapper was best characterized by a skewed normal selectivity curve. The catch-curve method in the absence of correction for gear selectivity produced greater total mortality estimates than the Chapman and Robson and Heincke's methods, with substantial variation among the three methods. Natural mortality estimates were consistent among five methods: Lorenzen, Peterson and Wroblewski, Sekharan, "FishLife" R package and Pauly's method. Consequently, variation among fishing mortality estimates was primarily the result of variation in estimates of total mortality. Our results suggest that accounting for gear selectivity is critically important when assessing and managing small-scale fisheries.

## 1. Introduction

Small-scale fisheries are important for millions of people around the world as a source of both food and income (Andrew et al., 2007; Delgado et al., 2003). However, a lack of adequate data has largely prevented effective assessment and management of small-scale fisheries (Andrew et al., 2007; Canales et al., 2018; Delgado et al., 2003; Worm et al., 2009). Small-scale fisheries are often characterized as being data-poor, meaning that they suffer from both a general lack of data and variability in the available data (Freitas et al., 2014; Hilborn and Walters, 1992; Martell and Froese, 2013; Pilling et al., 2008; Richards and Maguire, 1998; Sparre and Venema, 1992).

Despite the difficulties associated with the analysis of fishery-dependent catch data in small-scale fisheries, these are often the only data that can feasibly be obtained. Adding to this, common statistical models for the assessment and management of fisheries are typically developed for large-scale fisheries and require a large amount of data, which are often not available for small-scale fisheries. This makes the use of the fishery models difficult in small-scale fisheries (Mahon, 1997; Pilling et al., 2008). Therefore, determining the most effective methods for assessing a stock using available data in small-scale fisheries is critically important.

Gillnets are widely used, and data collected by surveying fishermen are often the only available data for the assessment of stocks, in small-scale fisheries in the tropics (Acosta and Appeldoorn, 1995; FAO, 2001; Reis and Pawson, 1992). During these surveys, the number of fish caught (catch), length of fish, type of gear used, and the duration of time fishermen spent catching fish (effort) are often recorded. This information is usually converted into length-specific catch per unit effort (CPUE) for a given gear type. If the length distribution of fish in the catch is assumed to be representative of the length distribution of fish in the ocean, the information can be used directly to estimate parameters for assessment purposes. However, gillnets are one of the most size-selective fishing gears, leading to bias in the observed length distribution of catch data (Doll et al., 2014; Gulland, 1987; Hamley, 1975), which must be accounted for before using the catch data in assessments (Acosta, 1994; Doll et al., 2014; Hamley, 1975; Márquez-Farias, 2005; Minns and Hurley, 1988; Reis and Pawson, 1992).

The bias associated with gear selectivity can be corrected by fitting selectivity curves (distribution curves) to catch data and adjusting the length distribution accordingly. Gillnet selectivity curves are typically dome-shaped, but they can have different mean, variance, and skew according to the characteristics of the fish and net (Hamley, 1975). Therefore, it is important to fit various selectivity curves to the catch

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data and choose the curve that best fits the data. Once the best-fit curve is determined, it can be used to correct the size distribution of the catch data such that it is representative of the size distribution of fish in the ocean (Hamley, 1975; Millar, 1992).

One common method for estimating the total mortality of a fish stock is regression catch-curve analysis (Chapman and Robson, 1960). For this method, obtaining the modified length distribution of the CPUE (hereafter “corrected CPUE”), which results after correcting for the selectivity bias, is important for the unbiased estimation of mortality (Hamley, 1975; Hovgård, 1996; Pet et al., 1995; Regier and Robson, 1966; Ricker, 1975). Furthermore, a regression catch-curve analysis is affected by the selection of a threshold for data inclusion (the length or age above which data are included in the analysis). Several methods have been suggested to determine the threshold, leading to increased uncertainty in the estimation of total mortality (Pauly, 1984; Smith et al., 2012).

Although catch-curve analysis is a practical method, it may not be adequate when working with limited data from fisheries with dome-shaped selectivity (Branch, 2009; Chapman and Robson, 1960; Hoenig, 1983; Jensen, 1996; Ricker, 1975; Smith et al., 2012) because catch-curve analysis makes various assumptions such as the age distribution in the data representing that in the population, constant recruitment, no net gain or loss of individuals due to immigration and emigration from the fishing area, normally distributed natural log abundance, and homoscedasticity of the log abundance with age. When some of these assumptions are violated, alternative methods for the estimation of total mortality may be necessary (Murphy, 1997). These methods are based on the relationship between the age of recruitment, mean age, and sample size (Murphy, 1997; Smith et al., 2012; Robson and Chapman, 1961).

In addition to estimating total mortality $Z$, estimating natural mortality $M$ is also important for fisheries management. However, natural mortality is difficult to estimate even for data-rich fisheries (Gaertner, 2015; Windsland, 2014). Therefore, methods that use the relationship between natural mortality $M$ and life history parameters (such as growth) have been suggested for estimating natural mortality $M$ in data-poor fisheries (Gaertner, 2015; Windsland, 2014). The use of several estimators for natural mortality is recommended to capture model uncertainty (Gaertner, 2015; Kenchington, 2014; Lee et al., 2011; Lorenzen, 1996).

Once total and natural mortality have been estimated, fishing mortality and exploitation rates ($F(1-e^{-Z})/Z$) can be estimated. Exploitation rates can inform fishery managers of the level of fishing pressure and are used to determine the sustainability of a given fishery. An exploitation rate equal to 0.5 is sometimes considered optimal based on the assumption that sustainable yield is optimum when $F = M$, and thus an exploitation rate above 0.5 is considered to be overexploited (Pauly, 1983; Walters and Parma, 1996). Understanding the uncertainty associated with the estimated exploitation rate requires understanding the uncertainties associated with the estimates of total and natural mortality.

The objectives of this study were to evaluate various methods for estimating total mortality, natural mortality, fishing mortality, and exploitation rates using available information from a small-scale fishery in Honduras. First, we determined the types of gear-selectivity curves that best fit the data for Lane Snapper (*Lutjanus synagris*) collected with gillnets. We used these results to analyze the effects of selectivity curves on the estimation of total mortality, $Z$, using a regression catch-curve analysis. Next, for comparison, alternative methods were employed to estimate $Z$. Then, five methods for estimating $M$ were used and using the different values of $Z$ and $M$, the fishing mortality rate F was estimated. Finally, the exploitation rates were estimated to evaluate the stock.

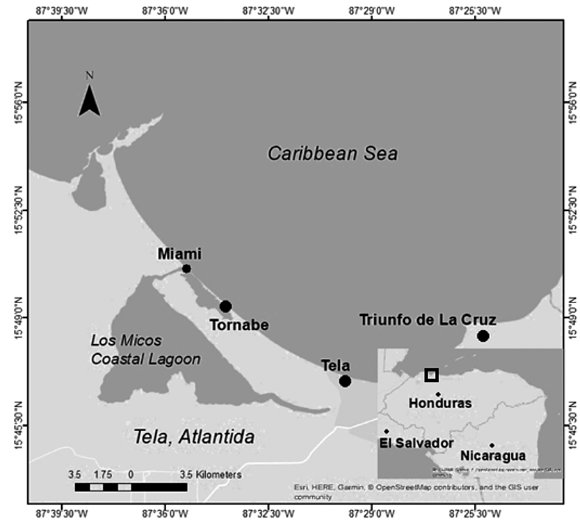


**Fig. 1.** Map of Tela on the northern coast of Honduras and the different villages surveyed: Miami, Tornabe, Tela Town and Triunfo de La Cruz.

## 2. Methods

### 2.1. Fisheries data

This study was based on data collected in Tela, Honduras (Fig. 1) by the Coral Reef Alliance, the World Wildlife Fund (WWF), and the National University of Honduras (UNAH). Tela is a coastal town located on the northern coast of Honduras, and is on the Caribbean Sea. Data for this study were collected by surveying fishers from the villages of Tornabe, Triunfo de la Cruz, Tela Town, and Miami from 2015–2017. These towns were selected because there were greater numbers of fishers compared to other towns and they were more accessible.

For each survey, fishers were chosen by order of arrival to the coast or port in each village. The surveys in each village were completed after all available fishers had participated. In some cases, multiple fishers arrived very closely together in time, leading to some fishers departing before being surveyed. In these cases, the fishers who arrived later were not included in the surveys. The total number of surveys depended on the number of fishers available and thus was not consistent between days and villages. There was also seasonal variability in fishing effort among the different towns. Because the data were corrected for varying efforts, the limitations in surveying and fishing effort are not expected to affect the size distribution in our sample.

In each survey, species, fork length (centimeters), and weight (grams) of every fish caught as well as the duration of the fishing trip (minutes) and fishing gear characteristics (gear type and size, including specific mesh size in the case of gillnets) were recorded. Based on this information, catch (number of fish) per unit effort (minutes) for each gear category (gillnet mesh size 2″ or 3″) was calculated. These calculations assume catchability remained constant, and that the fishing area did not change over time. For this study, we selected Lane Snapper (*Lujtanus synagris*) caught with gillnets of 2″ and 3″ mesh sizes because of the importance of this species for local economies in the area (Carbajal et al., 2017). However, we note that other fishing gears as well as gillnets of other mesh sizes were also used in the fishery. Therefore, the fishing mortality is not coming solely from gillnets of 2″ and 3″ mesh sizes in the area, since not all fishing gears were considered.

### 2.2. Selectivity of gillnets

First, distribution curves (a.k.a. selectivity curves) were fitted to the length-specific CPUE to correct for the bias from gear selectivity on the length distribution of the catches. The selectivity curves were estimated using a maximum likelihood method (described below). The parameters specifying the shape of the selectivity curve can be estimated when data from gillnets of different mesh sizes are available and it is assumed that the shape (but not necessarily the height) of the selectivity curves are the same for different mesh-sizes (Hamley, 1975; Hovgård, 1996; Kirkwood and Walker, 1986; Regier and Robson, 1966; Reis and Pawson, 1992). Once the selectivity curves were fitted, the length-specific the CPUE of each length class was divided by the respective value of the selectivity function to correct for the selectivity bias, thus resulting in the corrected CPUE.

The gear selectivity of gillnets is typically described by unimodal dome-shaped curves. Previously, it was often assumed that a normal distribution shape best represents a selectivity curve for gillnets (Hamley, 1975; Jensen, 1995; Millar, 2000). However, many authors tested other shapes such as lognormal and skewed normal distributions and found that the shape of the selectivity curve depended on the shape of targeted fish and quality of the gillnet material (Doll et al., 2014; Fujimori and Tokai, 2001; Hamley, 1975; Holt, 1963; Kawamura, 1972; Lobyrev and Hoffman, 2018). In this study, three dome-shaped selectivity curves were fitted and compared:

normal,

$$S_N(R_{ij}) = \exp\left(-\frac{(R_{ij} - R_0)^2}{2\sigma^2}\right)$$

log-normal,

$$S_L(R_{ij}) = \exp\left(-\frac{((\ln(R_{ij}) - \ln(R_0))^2}{2\sigma^2}\right)$$

and skewed normal,

$$S_k(R_{ij}) = \frac{\exp\frac{-X^2}{2}}{\sigma} * \left[1 + \operatorname{erf}\frac{(K_{ske} * X)}{\sqrt{2}}\right]$$

where $\operatorname{erf}(x) = \frac{1}{\sqrt{\pi}}\int_{-x}^{x} e^{-t^2}dt$ and $X = R_{ij} - R_0$. $R_0$, and $K_{ske}$ are the parameters to be estimated, and they represent the location, width, and skewness of the selectivity curves, respectively. $R_{ij}$ is associated with the data, $j$ is an index associated with a bin for length of fish (in this study, each bin was 1 cm), and $i$ denotes mesh size ($i$ = 1 or 2 for 2″ or 3″ mesh sizes, respectively).

The curves were fitted to length-specific CPUE data using a maximum likelihood method (Fujimori and Tokai, 2001). Where $C_{ij}$ denotes the CPUE of fish in length bin $j$ captured with gillnet of mesh-size $i$, $R_{ij} = \frac{l_j}{M_i}$, $l_j$ is the length of fish, and $M_i$ is the mesh-size (cm). The likelihood ($lik$) is:

$$lik = \prod_{j=1}^{n}\left[\frac{C_j!}{\prod_{i=1}^{k} C_{ij}!}\prod_{i=1}^{k}\left(p_i S(R_{ij}) / \sum_{i=1}^{k} p_i S(R_{ij})\right)^{C_{ij}}\right]$$

where $p_i$ is the fishing intensity (fishing effort of mesh size $i$), $k$ is the total of mesh sizes used, $n$ is the number of length classes, and $C_j$ is the total number of fish in length bin $j$ that were caught with all gillnets (consisting of both mesh sizes). The likelihood was maximized using an optimization routine "fminunc.m" in MATLAB (MATLAB, 2017). The Akaike information criterion (AIC) was used to determine the best model.

### 2.3. Estimation of total mortality Z

#### 2.3.1. Regression catch-curve analysis

To estimate Z, we divided the length-specific CPUE by the estimated selectivity function to correct for the selectivity, and then converted length into age using the following function (Cope and Punt, 2009):

$$Age = -\frac{1}{k_{gw}} * \log(1 - \frac{L}{L_\infty})$$

where $L$ is the length of the fish caught, $L_\infty$ is the length that the fish of a population would reach if they were to grow indefinitely and $k_{gw}$ is the growth parameter. This function was derived by solving the von Bertalanffy equation for age. It is important to consider that converting lengths to ages will always have an associated bias. For this study, $L_\infty$ = 516 mm and $k_{gw}$ = 0.23 for Lane Snapper (*Lutjanus synagris*) in Puerto Rico (Acosta and Appeldoorn, 1992), under the assumption that these parameters were applicable to our population.

The catch curve analyses were performed by regressing the natural log of the corrected age-specific CPUE against age. The slope of the fitted line gave the estimated total mortality $Z$ (Pauly, 1984; Robson and Chapman, 1961). Catch-curve analyses were repeated using the data from the gillnet of 2″ mesh size only, 3″ mesh size only, and both mesh sizes combined. For each of the gillnet type scenarios, total mortality $Z$ was estimated using each of the gear selectivity curves and without selectivity correction to determine the effect of selectivity correction on mortality estimates.

In addition to testing the effects of selectivity curves and mesh sizes on the estimates of total mortality Z (year $^{-1}$), two thresholds for data inclusion A and B) were used in the catch curve analysis. Threshold A was defined as the age immediately to the right of the highest point on the catch curve (Acosta and Appeldoorn, 1992), and threshold B was defined as the age of 3 years and older (because Lane Snapper is considered to be in full recruitment to the fishery at this age) (Aschenbrenner et al., 2017). The points after both thresholds were used to estimate the slope and thus $Z$ for each catch curve analysis. Fig. 2 shows the steps followed to obtain the total mortality estimates.

#### 2.3.2. Alternative methods for estimating total mortality

We applied two alternative methods to estimate $Z$. One of the alternative methods was proposed by Chapman and Robson (1960):

$$\widehat{Z} = log_e\left(\frac{1 + \overline{T} - T_C - 1/N}{\overline{T} - T_C}\right)$$

where $\overline{T}$ is the mean age of the fish in the sample that are greater or equal to age $T_C$, $T_C$ is the minimum age of fish in the sample that is considered to be fully recruited (considered to have reached sexual maturity) for the fishery, and $N$ is the number of fish that are greater or equal to age $T_C$. This method assumes that survivorship after recruitment follows a geometric distribution and assumes recruitment to be constant. For this study, $T_C$ was obtained by plotting the frequency of catches at different ages for each gillnet, and the age with the highest frequency was considered to be the age of full recruitment $T_C$. Similarly, $\overline{T}$ and $N$ were estimated from the frequency of catches at different ages. The associated variance estimator was:

$$VAR\,[(\widehat{Z})] = \frac{[1 - e^{-(\widehat{Z})}]^2}{Ne^{-(\widehat{Z})}}$$

The equation proposed by Heincke (Smith et al., 2012) was also used to estimate the survival rate $s$ as $\widehat{s} = \frac{N - N_0}{N}$, where $N$ is the number of fish at recruitment and greater than recruitment age (i.e., total number of fish at equal and greater than recruitment age) and $N_0$ is the number of fish at recruitment age (i.e., number of fish in the age with the highest frequency in an age frequency plot). The total mortality Z (year $^{-1}$) was then estimated using the equation: $-\log_e(\widehat{s})$. The variance was:

$$VAR(\widehat{Z}) = \frac{1 - \widehat{S}}{N\widehat{S}}$$

Total mortality values estimated with these methods were compared with the estimates from the catch curve analysis and with the values estimated in other studies for the same species.

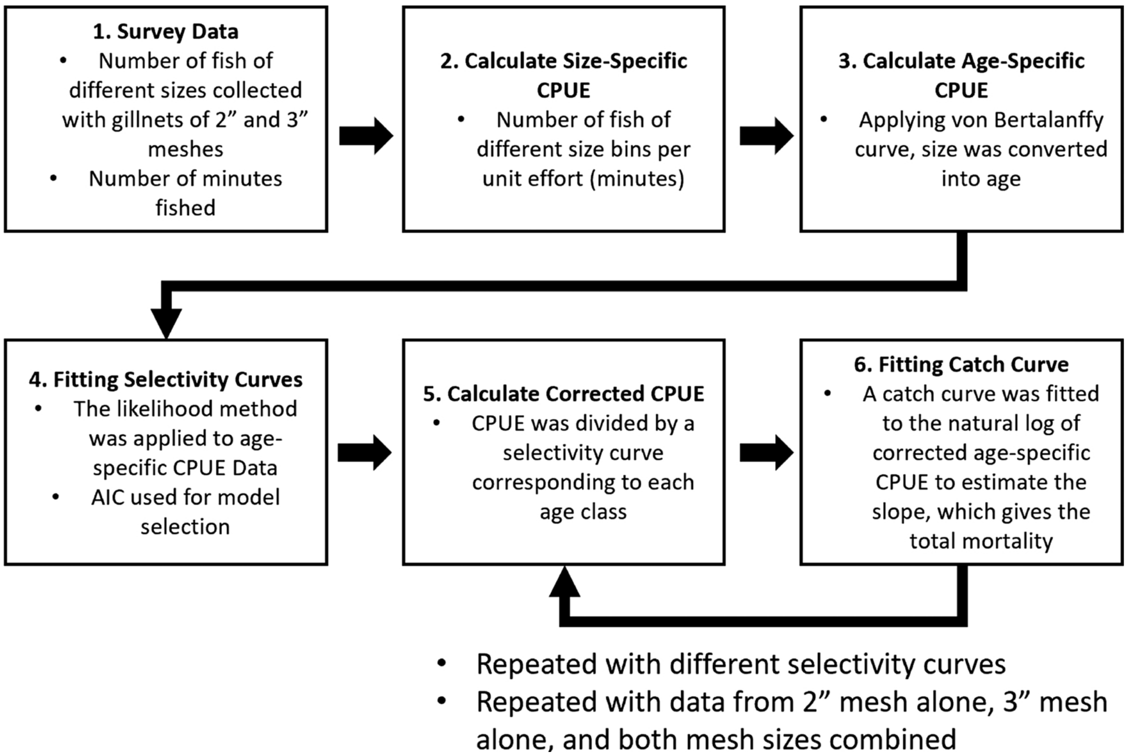


**Fig. 2.** Steps for the estimation of total mortality.

### 2.4. Estimation of natural mortality M (year $^{-1}$)

When estimating *M* for data-poor fisheries, it is recommended to use several estimators to assess model uncertainty (Kenchington, 2014; Pascual and Iribarne, 1993). For this study, five estimators for *M* were used: the Peterson and Wroblewski (1984) estimator, the Lorenzen (1996) estimator, the Sekharan (1975) estimator, the method in the R package "FishLife" (Thorson, 2017), and the Pauly estimator (Pauly, 1980).

#### 2.4.1. Peterson and Wroblewski estimator

Peterson and Wroblewski (1984) used an allometric relationship to model *M* based on wet weight (Kenchington, 2014; Peterson and Wroblewski, 1984). The method was developed based on the idea that there is a close connection between the *M* and growth parameters across a wide variety of pelagic organisms (Gulland, 1987; Kenchington, 2014; Post and Evans, 1989; Siegfried and Sansó, 2009). For estimating natural mortality, the following equation was used:

$$M_W = 1.28w^{-0.25}$$

where $M_W$ is the estimation of natural mortality, and $w$ is the wet weight in grams.

Depending on the type of available data, the estimation of $w$ might require different approaches. Lorenzen (1996) recommended taking the average among multiple individuals to estimate $w$. However, in many cases, the data might include outliers. For these cases, it is recommended to use the median or the midpoint of a weight-age relationship. For this study, the average and median of the weights and the midpoint of the von Bertalanffy growth curve fitted to weight-at-age reported by Aschenbrenner et al. (2017) were used for the estimation of $w$.

#### 2.4.2. Lorenzen estimator

Lorenzen (1996) used a regression approach to model *M* as a function of weight. Similar to Peterson and Wroblewski (1984), the Lorenzen estimator is based on the idea that *M* is highly correlated with growth parameters. However, while the Peterson and Wroblewski estimator uses all pelagic taxa combined, the Lorenzen estimator is based solely on juvenile and adult freshwater and marine fishes (Andrews and Mangel, 2012; Kenchington, 2014; Lorenzen, 1996, 2000). He proposed the following relationship between natural mortality and weight:

$$M_L = 3.00w^{-0.288}$$

where $M_L$ is the estimated natural mortality, and $w$ is the weight in grams.

#### 2.4.3. Sekharan estimator

Sekharan (1975) argued that for many fisheries in the tropics, the methods for estimating *M* based on allometric growth relationships were not adequate because many of these fisheries were composed of fish that have short and sometimes determinate lifespans. For this reason, he proposed that the *M* was closely related to the maximum observed age of a species. The updated version of this estimator (Then et al., 2015) is:

$$M_S = \frac{5.109}{T_{max}}$$

where $M$ is the estimate of natural mortality, and $T_{max}$ is the maximum age in years. To estimate $T_{max}$, two approaches were used: 1) the maximum age observed in our data and 2) the maximum age observed in the length-age curve for Lane Snapper according to Aschenbrenner et al. (2017). Because this method is simple, it has been widely used in assessing data-poor fisheries around the world (Kenchington, 2014).

#### 2.4.4. Estimation of natural mortality using "FishLife" R package

Natural mortality for the Lane Snapper (*Lutjanus synagris*) was also estimated using the R package "FishLife" (Thorson, 2017). In this package, information on a species is collected from databases such as Fishbase (Froese and Pauly, 2019). It applies a multivariate random-walk model for the evolution of life history parameters to a database of variables such as growth, size, mortality and temperature of different fish species. The package predicts *M* based on the assumption that it is possible to factor the probability distribution for life history parameters (such as *M*) within a certain taxon by specifying a series of probabilities for a given taxon. More details of the package can be found in FishLife R package version 1.0.2 (http://github.com/James-Thorson/FishLife).

#### 2.4.5. Pauly estimator

Pauly (1980) showed that temperature, the growth parameter, and the maximum length of fish are associated with their natural mortality. Using multiple regression, he developed the following estimator for *M*:

$$M = 0.9849\, L_{\infty}^{-0.279}\, k_{gw}^{0.6543} \tau^{0.4634}$$

where $L_{\infty}$ is the maximum length (cm) that the fish in a particular population would reach if they were to grow indefinitely, $k_{gw}$ is the growth parameter, and $\tau$ is the mean water temperature in Celsius (°C). For this study $L_{\infty}$ = 51.6 cm, $k_{gw}$ = 0.23 and $\tau$ = 26 °C was used. The mean water temperature was obtained from a study in the western Caribbean by Muniz-Castillo et al. (2019).

### 2.5. Estimation of fishing mortality F

Fishing mortality *F* was estimated by subtracting *M* from Z, using all of the combinations of natural and total mortality estimates. Fishing mortality estimates were rounded to two decimal points and were used for further analysis and interpretations.

### 2.6. Exploitation rate

To understand if the fishery is at a sustainable level, the exploitation rate was estimated. The fishery was considered to be overexploited if exploitation rate was above 0.5 (Pauly, 1983).

## 3. Results

### 3.1. Selectivity curves

Fig. 3 shows the fit of the various selectivity curves to the length-frequency data. According to the AIC (Table 1), the skewed normal curve had the best fit. The estimated parameters ($R_0$, $\sigma^2$ and $K_{ske}$) are also shown in Table 1.

**Table 1**
Estimation of parameters for the selectivity functions using combined data from mesh size 2″ and 3″ with the maximum likelihood function. $R_0$, $\sigma^2$, and $K_{ske}$ are parameters specifying the location, width, and skewness of the selectivity curves.

| Selectivity function | Parameter | Estimation of parameters with likelihood function (Standard Error) | AIC values |
|---|---|---|---|
| **Normal** | $R_0$ | 4.19 (0.002) | 1455 |
| | $\sigma^2$ | 0.71 | |
| **Lognormal** | $R_0$ | 4.05 (0.002) | 1420 |
| | $\sigma^2$ | 0.05 | |
| **Skewed normal** | $R_0$ | 3.27 (0.001) | 1418 |
| | $\sigma^2$ | 1.49 | |
| | $K_{ske}$ | 2.65 | |

### 3.2. Total mortality Z with catch curve-analysis

#### 3.2.1. Total mortality Z with different thresholds without correction for selectivity

Table 2 shows the estimated total mortality *Z* obtained without correction for selectivity. Overall, the estimated *Z* without correction for selectivity was from 1.69–2.09. Similarly, all the estimated $R^2$ were above 0.9.

#### 3.2.2. Total mortality Z with various thresholds with selectivity correction

With the skewed normal selectivity curve (Fig. 4), the estimated *Z* with the data from 2″ mesh and threshold A was 0.94 $year^{-1}$ (SE = 0.19). When using threshold B, the estimated *Z* was reduced to 0.79 $year^{-1}$ (SE = 0.38). Compared with the estimated *Z* values without correction of selectivity (1.93 and 2.05), the estimated *Z*'s with selectivity correction are lower. This is true regardless of the threshold

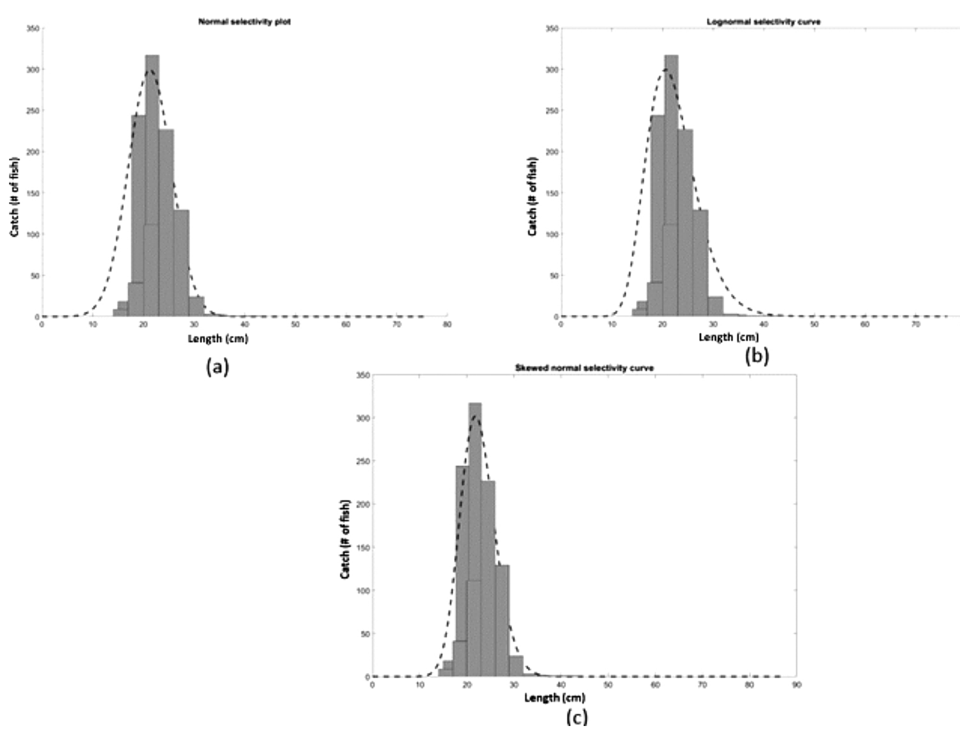


**Fig. 3.** (a) Normal selectivity curve fitted to length-specific catch data, (b) lognormal selectivity curve fitted to length-specific catch data and (c) skewed normal selectivity curve fitted to length-specific catch data correction of selectivity, the total mortality was between 0.77–1.93 $year^{-1}$.

**Table 2**
Estimated total mortality, Z, without correction for selectivity. The estimation was performed using different thresholds in the catch curve analysis with data collected using different mesh sizes of gillnets.

| Threshold | Mesh size | Sample size *n* | Z (year $^{-1}$) estimates and Standard error |
|---|---|---|---|
| A | 2″ | 714 | 1.93 (0.99) |
| A | 3″ | 547 | 2.09 (0.95) |
| A | 2″ and 3″ | 1261 | 1.79 (0.97) |
| B | 2″ | 714 | 2.05 (0.99) |
| B | 3″ | 547 | 1.69 (0.97) |
| B | 2″ and 3″ | 1261 | 2.07 (0.98) |

used. When using data from 3″ mesh size, the estimated *Z* with threshold A was 1.82 year$^{-1}$ (SE = 0.25) and with threshold B was 1.93 year$^{-1}$ (SE = 0.42). When data from both mesh sizes were combined, the estimated *Z* with threshold A was 0.86 year$^{-1}$ (SE = 0.36) and with threshold B was 0.77 (SE = 0.50). Using the skewed normal curve for the correction of selectivity, the total mortality *Z* was between 0.77–1.93 year$^{-1}$.

### 3.3. Total mortality using alternative methods

Total mortality estimates obtained using the Chapman and Robson method were 0.84 and 0.91 year$^{-1}$ for mesh size 2″ and 3″, respectively (with standard errors of 0.002 and 0.004, respectively). The estimated *Z* with the Heincke method was 0.28 year$^{-1}$ for mesh size 2″ and 0.18 year$^{-1}$ for mesh size 3″ with the standard errors of 0.002 and 0.003, respectively. Both estimators provided *Z* estimates that were lower than those estimated with regression catch-curve analysis without selectivity correction. Those obtained using the Chapman and Robson estimator were similar to those obtained with regression catch-curve analysis using the skewed normal function with selectivity correction.

### 3.4. Natural mortality M

Fig. 5 shows the *M* estimates from the five methods described above. The estimates ranged between 0.23–0.61 year$^{-1}$. The Lorenzen estimator using the average and median weight (average = 267.119 g and median = 252 g) provided the highest values of *M* (*M* = 0.60 year$^{-1}$, *M* = 0.61 year$^{-1}$, and *M* = 0.44 year$^{-1}$ with average weights, median weights, and the midpoint, respectively). The Peterson and Wroblewski method resulted in much lower values of estimated natural mortality using the average weight (*M* = 0.32 year$^{-1}$), the median weight (*M* = 0.32 year$^{-1}$), and the midpoint (*M* = 0.24 year$^{-1}$).

The Sekahran estimator (*M* = 0.64 year$^{-1}$ and *M* = 0.52 year$^{-1}$) and Pauly estimator (*M* = 0.57 year$^{-1}$) gave values similar to the Lorenzen estimator. The estimated natural mortality was 0.41 year$^{-1}$ when using the R-package "FishLife".

### 3.5. Fishing mortality F and exploitation rates

All the combinations of *Z* and *natural mortality M* were used for calculating *F* (Supplementary Appendix A) (Fig. 6). Fig. 7 shows the exploitation rates obtained when using the different values for *Z* and *F*. The values greater than 0.5 are overexploited.

## 4. Discussion

Uncertainties are inherent in small-scale fisheries data, and it is important to choose the correct analytical methods to reduce the bias in the estimation of mortality. The selectivity of fishing gears, especially gillnets, affects length-specific catch data (Acosta, 1994; Hamley, 1975; Reis and Pawson, 1992). Gear selectivity will bias the size distribution within a sample, such that it is no longer representative of the size distribution in the population. We fitted a selectivity curve to correct for the gear selectivity. The method assumes the geometrical similarity

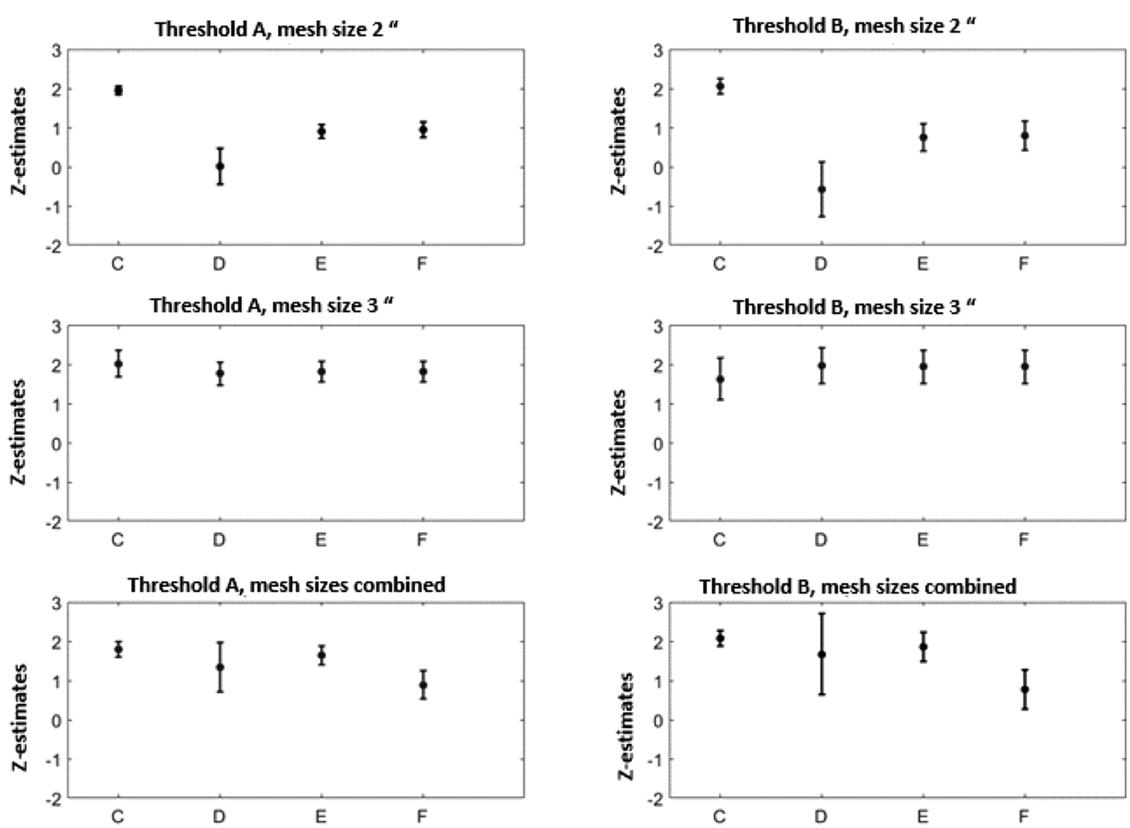


**Fig. 4.** Estimated Z (year$^{-1}$) for different mesh sizes, different thresholds and different selectivity curves: C = No selectivity correction, D = Normal selectivity curve, E = Lognormal selectivity curve and F = Skewed normal selectivity curve.

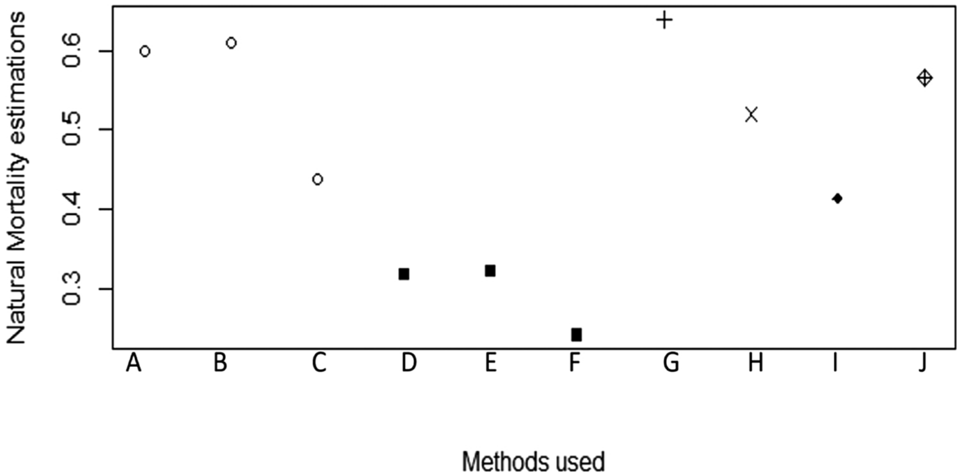


**Fig. 5.** Estimated natural mortality M (year$^{-1}$) using different methods; A: Lorenzen estimator using average of weights, B: Lorenzen estimator using median of weights, C: Lorenzen estimator using midpoint 8 years, D: Peterson & Wroblewski estimator using average of weights, E: Peterson & Wroblewski estimator using median of weights, F: Peterson & Wroblewski estimator using midpoint 8 years, G: Sekahran estimator T = 8 years, H: Sekahran T = 10 years, I: FishLife Package, and J: Pauly estimator.

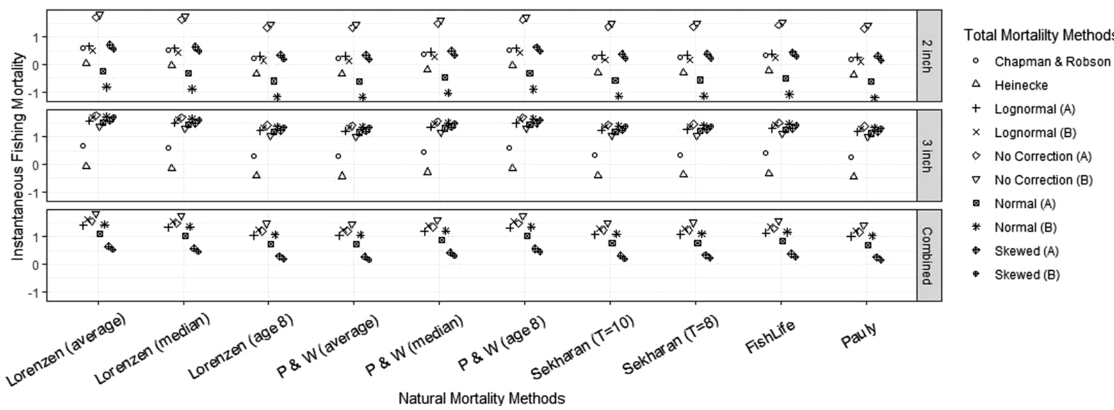


**Fig. 6.** Estimated instantaneous fishing mortality corresponding to the different total mortality and natural mortality methods used. The different symbols indicate the different methods used for the estimation of total mortality with different thresholds (A and B) and with and without the correction of selectivity. The horizontal axes show the natural mortality estimations used (see Fig. 5). Each panel represents the mesh size used.

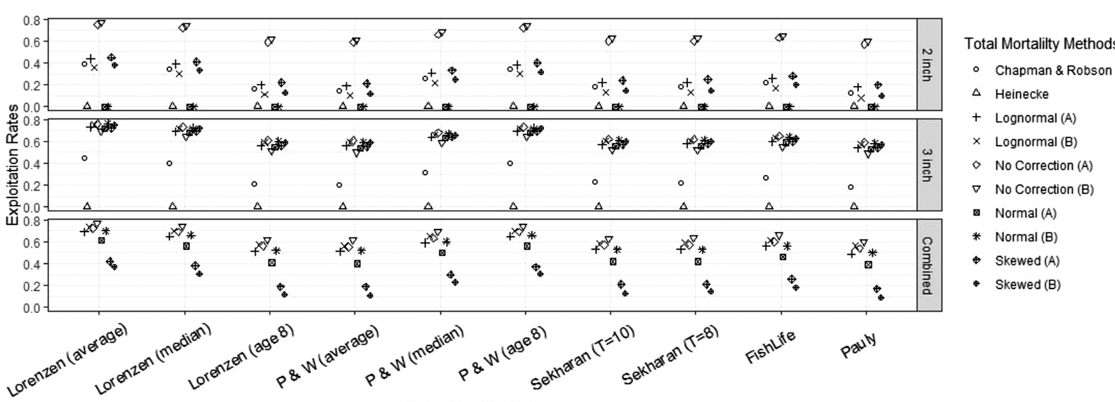


**Fig. 7.** Estimated exploitation rates corresponding to the different total mortality and natural mortality methods used. The different symbols indicate the different methods used for the estimation of total mortality with different thresholds (A and B) and with and without the correction of selectivity. The horizontal axes show the natural mortality estimations used (see Fig. 5). Each panel represents the mesh size used. F values were set to 0 when estimated total mortality was less than natural mortality to avoid getting negative exploitation rates.

theory of Baranov, which assumes selection is a function of the ratio between length and mesh size, rather than absolute length (Millar and Fryer, 1999). Then, we estimated total mortality. The estimated total mortality with selectivity correction was smaller than those without selectivity correction (Fig. 3).

Our total mortality estimates (with and without selectivity correction) fall within the range of total mortality values from other studies (Table 3). Some differences might be a result of ecological differences (i.e., natural mortality), the level and type of fishing pressure, selectivity differences among fishing gears, sample size, and potential bias associated with the methods used for estimating mortality. It is important to note that other studies did not correct for gear selectivity.

In our study, various methods were used for estimating total mortality. When using regression catch-curve analysis, the variation among the scenarios might be due to insufficient data for older age classes, which can be a result of not having constant mortality across ages and

**Table 3**
Estimated total mortality and natural mortality of *Lutjanus synagris* from different areas.

| Location | Fishing gear used | Length measurement used | $L_\infty$ (mm) | $k_{gw}$ | Z (year $^{-1}$) | M (year $^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|
| Puerto Rico | Hook & line | Fork length | 450 | 0.23 | 1.48 – 1.65 | 0.527 | (Acosta and Appeldoorn, 1992) |
| Florida | Not specified | Total length | 501 | 0.1337 | 0.68 | 0.4 | (Manooch and Mason, 1984) |
| Brazil | Gillnets and Hook & line | Total length | 560 | 0.22 | 0.58 | 0.17 – 0.36 | (Aschenbrenner et al., 2017) |
| Honduras | Hook & line | Fork length | 410 | 0.25 | 0.72 – 2.06 | N/A | (Berthou et al., 2001) |
| Honduras | Gillnets | Fork length | 450 | 0.23 | 0.006 – 2.07 | 0.24 – 0.61 | This study |

different levels of vulnerability among different sizes of fish (Hamley, 1975; Jensen, 1996). In addition, the estimated total mortality rates with the data obtained with 3″ mesh gillnets were consistently greater than those of 2″ mesh. This might indicate that older individuals are experiencing higher fishing pressure. Of the three methods (regression catch-curve analysis, Chapman and Robson estimator, and the Heincke estimator), the Heincke method resulted in the lowest estimated total mortality. The Heincke method is very sensitive to recruitment variability. When the fully recruited age class is highly abundant, the estimator will tend to underestimate total mortality. Similarly, if the abundance of this age group is less, then it will tend to overestimate mortality. We suggest the Heincke method should be avoided for assessment in data-poor fisheries because available data rarely demonstrate similar catchability among age.

On the other hand, the estimated natural mortality was more consistent among the methods employed in our study (Fig. 4), with the exception of the Peterson and Wroblewski estimator, which led substantially lower estimates. According to Gulland (1987) and McGurk (1987), the Peterson and Wroblewski method results provide a biased estimate of *M* because the estimator is based on the relationship of weight and natural mortality of all pelagic taxa (i.e., not specific for fish). Furthermore, Lorenzen (1996) found a stronger relationship between weight and natural mortality in his estimator than Peterson and Wroblewski (1984), and this might explain why the Peterson and Wrobleweski estimator gave different results (Andrews and Mangel, 2012). The variation in the estimated total mortality had a greater effect on the fishing mortality estimates than variation in estimated natural mortality. Many methods should be used when estimating natural mortality to obtain a range of values to account for model uncertainty (i.e., possible violation of model assumptions) (Hewitt et al., 2011; Vetter, 1988). The Lorenzen estimator, the Sekharan estimator, and the FishLife R package are relatively easy to implement. The Pauly method is also easy to implement if the temperature of the water and growth parameters can be obtained. Therefore, we recommend using these four methods.

The Lane Snapper fishery in Honduras is of great importance for coastal towns (both in the Atlantic Ocean and the Caribbean Sea), mainly because of its high economic value compared to other species (e.g., jacks) and because they are relatively easy to capture. Traditionally, this species has been targeted by different fishing gears (e.g., gillnets, traps, and hook-and-line) with little or no catch restrictions. Currently, the fishery is more regulated, and fishers target the species for its economic value. Consequently, they use more selective fishing gear (i.e., gillnets) with more fishing effort (Carbajal et al., 2017; Gobert et al., 2005; Lopez et al., 2018). We found the estimated fishing mortality was greater than the estimated natural mortality for this species (Supplementary Appendix A). Furthermore, the exploitation rate was higher than 0.5 under most of the methods employed in this study, which can be interpreted as the population being overexploited

We have demonstrated that selectivity has an impact on the estimation of total mortality using catch curve methods, and that total mortality estimates affect the variability in the fishing mortality estimates more than natural mortality estimates among the methods we compared. However, data in small-scale fisheries have additional uncertainty. For example, because the intensity of fishing in Honduras (and in most small-scale fisheries around the world) varies substantially among seasons, scattered surveys over a prolonged period result in inaccurate data by having insufficient sampling during a fishing season. This may be overcome by surveying more intensively during fishing seasons. Also, sampling suffers from the fact that fishers sometimes hide a part or all of their catch. This may occur when their catch includes some species that are illegal to keep. Many fishers also have their preferred fishing areas so that the sample may not be representative of the entire population. Small-scale fisheries data will likely always suffer from these and other types of uncertainty in addition to potentially violating the assumptions required by statistical models. Although our study does not overcome all of these problems, we accounted for gillnet size-selectivity and incorporated various approaches to estimate total, natural, and fishing mortality. We consider the approach presented in this study to be a step toward developing improved methods for obtaining useful information in the management of small-scale fisheries.

## CRediT authorship contribution statement

**Liliana Sierra Castillo:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Methodology, Writing - original draft, Writing - review & editing. **Michaela Pawluk:** Methodology, Writing - original draft, Writing - review & editing. **Masami Fujiwara:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing, Investigation.

## Declaration of Competing Interest

None.

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## Appendix A

| Method used for estimating M | Lorenzen average weight | Lorenzen median weight | Lorenzen mid-point weight age 8 years | Peterson & Wroblewski average weight | Peterson & Wroblewski median weight | Peterson & Wroblewski mid-point weight age 8 years | Sekharan T = 8 | Sekharan T = 10 | FishLife | Pauly |
|---|---|---|---|---|---|---|---|---|---|---|
| **Method used for estimating Z** | | | | | | | | | | |
| **Without selectivity Threshold A mesh size 2** | 1.34 | 1.33 | 1.62 | 1.62 | 1.36 | 1.48 | 1.30 | 1.43 | 1.70 | 1.37 |
| **With selectivity Normal distribution Threshold A mesh size 2** | −0.59 | −0.60 | −0.31 | −0.32 | −0.57 | −0.45 | −0.63 | −0.50 | −0.23 | −0.56 |
| **With selectivity Lognormal distribution Threshold A mesh size 2** | 0.30 | 0.29 | 0.59 | 0.58 | 0.33 | 0.44 | 0.27 | 0.39 | 0.66 | 0.34 |
| **With selectivity Skewed normal distribution Threshold A mesh size 2** | 0.34 | 0.33 | 0.63 | 0.62 | 0.37 | 0.48 | 0.31 | 0.43 | 0.70 | 0.38 |
| **Without selectivity Threshold B mesh size 2** | 1.45 | 1.44 | 1.73 | 1.73 | 1.48 | 1.59 | 1.41 | 1.54 | 1.81 | 1.48 |
| **With selectivity Normal distribution Threshold B mesh size 2** | −1.17 | −1.18 | −0.89 | −0.90 | −1.15 | −1.03 | −1.21 | −1.08 | −0.81 | −1.14 |
| **With selectivity Lognormal distribution Threshold B mesh size 2** | 0.15 | 0.14 | 0.43 | 0.43 | 0.18 | 0.29 | 0.11 | 0.24 | 0.51 | 0.18 |
| **With selectivity Skewed normal distribution Threshold B mesh size 2** | 0.19 | 0.18 | 0.48 | 0.47 | 0.22 | 0.33 | 0.15 | 0.29 | 0.55 | 0.22 |
| **Without selectivity Threshold A mesh size 3** | 1.42 | 1.41 | 1.70 | 1.70 | 1.44 | 1.56 | 1.38 | 1.51 | 1.78 | 1.45 |
| **With selectivity Normal distribution Threshold A mesh size 3** | 1.16 | 1.15 | 1.45 | 1.44 | 1.19 | 1.30 | 1.12 | 1.25 | 1.52 | 1.20 |
| **With selectivity Lognormal distribution Threshold A mesh size 3** | 1.22 | 1.21 | 1.50 | 1.50 | 1.24 | 1.36 | 1.18 | 1.31 | 1.58 | 1.25 |
| **With selectivity Skewed normal distribution Threshold A mesh size 3** | 1.21 | 1.20 | 1.50 | 1.49 | 1.24 | 1.36 | 1.18 | 1.30 | 1.57 | 1.25 |
| **Without selectivity Threshold B mesh size 3** | 1.03 | 1.02 | 1.31 | 1.31 | 1.05 | 1.17 | 0.99 | 1.12 | 1.39 | 1.06 |
| **With selectivity Normal distribution Threshold B mesh size 3** | 1.37 | 1.36 | 1.65 | 1.65 | 1.39 | 1.51 | 1.33 | 1.46 | 1.73 | 1.40 |
| **With selectivity Lognormal distribution Threshold B mesh size 3** | 1.34 | 1.33 | 1.62 | 1.62 | 1.36 | 1.48 | 1.30 | 1.43 | 1.70 | 1.37 |
| **With selectivity Skewed normal distribution Threshold B mesh size 3** | 1.34 | 1.33 | 1.62 | 1.62 | 1.36 | 1.48 | 1.30 | 1.43 | 1.70 | 1.37 |
| **Without selectivity Threshold A mesh sizes combined** | 1.20 | 1.19 | 1.48 | 1.48 | 1.22 | 1.34 | 1.16 | 1.29 | 1.56 | 1.23 |
| **With selectivity Normal distribution Threshold A mesh sizes combined** | 0.74 | 0.73 | 1.02 | 1.02 | 0.76 | 0.88 | 0.70 | 0.83 | 1.10 | 0.77 |
| **With selectivity Lognormal distribution Threshold A mesh sizes combined** | 1.04 | 1.03 | 1.33 | 1.32 | 1.07 | 1.18 | 1.00 | 1.13 | 1.40 | 1.08 |
| **With selectivity Skewed normal distribution Threshold A mesh sizes combined** | 0.29 | 0.28 | 0.57 | 0.56 | 0.31 | 0.43 | 0.25 | 0.37 | 0.64 | 0.32 |
| **Without selectivity Threshold B mesh sizes combined** | 1.47 | 1.46 | 1.76 | 1.75 | 1.50 | 1.61 | 1.43 | 1.56 | 1.83 | 1.51 |
| **With selectivity Normal distribution Threshold B mesh sizes combined** | 1.07 | 1.06 | 1.35 | 1.35 | 1.09 | 1.21 | 1.03 | 1.16 | 1.43 | 1.10 |
| **With selectivity Lognormal distribution Threshold B mesh sizes combined** | 1.25 | 1.24 | 1.54 | 1.53 | 1.28 | 1.39 | 1.22 | 1.34 | 1.61 | 1.29 |
| **With selectivity Skewed normal distribution Threshold B mesh sizes combined** | 0.17 | 0.16 | 0.45 | 0.45 | 0.19 | 0.31 | 0.13 | 0.26 | 0.53 | 0.21 |
| **Heincke method mesh size 2** | −0.60 | −0.61 | −0.31 | −0.32 | −0.57 | −0.46 | −0.36 | −0.23 | −0.24 | −0.29 |
| **Heincke method mesh size 3** | −0.59 | −0.60 | −0.31 | −0.31 | −0.57 | −0.45 | −0.46 | −0.33 | −0.23 | −0.39 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Chapman and Robson mesh size 2** | 0.24 | 0.23 | 0.52 | 0.52 | 0.27 | 0.38 | 0.20 | 0.33 | 0.60 | 0.27 |
| **Chapman and Robson mesh size 3** | 0.31 | 0.30 | 0.59 | 0.59 | 0.34 | 0.45 | 0.27 | 0.40 | 0.67 | 0.33 |

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