Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

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1 Executive Summary

The production foregone model estimates the lost future somatic growth (production) that killed organisms would have produced had they otherwise lived their normal lifespan. The biomass of organisms directly killed as the result of the Deepwater Horizon (DWH) spill represents pre-spill production; the production foregone model determines the biomass these organisms would have accrued until they died naturally or of fishing. Production foregone is calculated by simultaneously considering stage-specific growth rates and survival rates of individuals. Assessment of production foregone allows for a more thorough representation of the biological injuries to water column organisms resulting from the spill than would be captured by the direct kill alone. Results of the production foregone model are measured in biomass, which can be used to address biological concerns, as well as provide units that can be translated into a consideration of restoration needs.

The production foregone population model as described by the U.S. Environmental Protection Agency in its 316(b) rule (USEPA 2014) is used. This model employs life history information, growth rates, and natural and fishing mortality rates of water column biota. These values are developed from published literature, stock assessment analyses, technical reports, and newly-collected NRDA data sets for use as model input. The time that water column biota directly injured would have otherwise lived, and the production (growth) they would have undergone had there not been a spill, are evaluated using production foregone modeling.

Parameters required for the production foregone model include estimates of:

- stage durations for eggs, larvae, and juvenile stages over the first year of life;
- size of eggs (diameter) and larvae (length) at hatching;
- natural and fishing mortality rates by stage or age class;
- age of recruitment to the fishery (which is implied by the youngest stage where fishing mortality occurs);
- age-specific growth rates, estimated from length- and weight-at-age data; and
- size (length) of individuals directly killed.

These data sets were reviewed and evaluated to determine the best data inputs for the modeling calculations. Life tables were constructed using these life history parameter estimates. The results of the taxa-specific models are the total biomass that would be produced by an individual from the size at which it was killed had it lived its natural lifespan, expressed as grams per individual killed.

As is practice for NRDA (NOAA, 1997), the production foregone results quantified as grams per individual are expressed in 2010 values; i.e., future losses are discounted to their value as if the losses all occurred in 2010 using a 3% annual discount rate. Note that such discounting is not always practiced in 316(b) rule applications and other contexts. When discounting is included, consideration of compensatory restoration for these injuries would typically inflate project size(s) to account for 3% interest for each year in delay after 2010 before the restoration is realized.

These analyses, data inputs and results are described in this report. The objectives of this report are to:

- Describe the modeling approach and algorithms used for calculations of production foregone;
- Describe how the production foregone model may be used to evaluate production gained from restoration that increases numbers of individuals at particular sizes;
- Document available life history information and data inputs used in the modeling; and
- Tabulate the results of the model calculations (i.e., g of production per individual, along with life table data) for sizes of individuals typifying baseline densities of organisms in the Northern Gulf of Mexico.

Production foregone was calculated for larvae of 29 fish taxa which have or include species with growth models reported in state, federal, or international stock assessments, including snappers, tunas, mackerels, sea trout, croakers, and billfish (Appendix B.2.1). As part of their stock assessment development, the needed growth and mortality rates have been well studied and reviewed by fisheries managers, such that the production models based on these inputs are relatively robust. Invertebrate production foregone was calculated using the growth models of three species: blue crab (*Callinectes sapidus*), white shrimp (*Litopenaeus setiferus*), and spiny lobster (*Panulirus argus*). Each of these invertebrate species either has an available stock assessment and/or is extensively studied (Appendix B.2.2). The white shrimp growth model was applied to shrimp taxa that grow to similar size (~100-200mm in length maturing in ~1yr, which includes these superfamilies: Penaeoidea, Oplophoroidea, Pandaloidea and Pasiphaeoidea). This does not include these superfamilies: Sergestoidea, Palaemonoidea, Alpheoidea, Bresilioidea, and Nematocarcinoidea. For crabs, the blue crab growth model was applied to all crabs in the family Portunidae. The spiny lobster growth model was applied to spiny lobsters (i.e., in the family, superfamily and genus: Palinuridae, Palinuroidea and Panulirus), but not to other types of lobsters (which grow at differing rates).

Fish life history values calculated by the life table model were compared to empirical data available in published literature. Mortality rates at specific sizes and stages were compared to literature values. For two species, red snapper and red drum, detailed comparisons to literature estimates were made for stage duration, size range, daily and stage mortality rates, and growth rates for early life history stages. Results from these analyses indicate that values for the evaluated parameters generated by the life history model fall within the range of available empirical data. Additionally, the model-predicted first year cumulative survival rates were an order of 10^{-7} for most fish species, a rate that is compatible with populations at or near stationary abundance (Caswell 1989). A notable exception was the Gulf menhaden, where current adult mortality rates indicate a population in decline.

The model estimates of production foregone (g per individual over the remaining lifespan) for fish are lowest for eggs and larvae, and increase rapidly by the juvenile stage because of the rapid increase in survival rate with increasing body size. Results are summarized as follows:

- Fish embryos: 5×10^{-5} g/individual.
- Newly-hatched larval fish: 5×10^{-5} – 0.1 g/individual.
- Older larvae: 5×10^{-3} – 35 g/individual, the highest values resulting for fast-growing taxa with large adult body size, such as billfish, large tunas, and mahi mahi.
- Juvenile fish: ~1 to several thousand g/individual, again the larger fast-growing species have the most production foregone per individual.
- Adult fish: The production foregone results for small adult fish with short life spans (e.g., Engraulidae, the anchovies) are similar to the values for juvenile fish. However, for large

fish species where stock assessments have been developed, size-at-age estimates could be made. The modeled production foregone for these large fish ranged from 1 to 135 kg/individual.

Production foregone of larval decapods ranges from ~5 x 10^{-5} – 1 g/individual. Production foregone of late stage and adult shrimp is on the order of 1 g/individual.

It should be noted that uncertainties are inherent to this modeling approach and these uncertainties are likely higher for the smallest and the largest species. Each of the mortality models used herein are based on regressions of empirical data for a range of species of varying size. As with all regression models, utilization of the regression for inputs outside of the original regression data range is highly uncertain as these results are extrapolations from the original relationship.

In a subsequent technical report by French McCay et al. (2015b) describing injury quantification for water column biota, direct injuries resulting from acute exposure and mortality were calculated by combining estimates of water volumes affected by lethal concentrations of oil hydrocarbons with spatially- and time-varying volumetric density (# m-3) estimates for fish and invertebrate early life history stages. Injuries were estimated for planktonic fish eggs and larvae (ichthyoplankton) and planktonic invertebrates, including larval stages of decapods. For fish and invertebrate taxa with production foregone models developed herein, the injury quantification also included future loss of biomass production (i.e., production foregone), which was calculated from the estimated number killed times production foregone (g per individual) over its expected lifetime. See French McCay et al. (2015b) for further details.

2 Introduction and Objectives

Direct injuries to water column biota may be calculated by combining estimates of water volumes affected by lethal concentrations of oil hydrocarbons with spatially- and time-varying density estimates for fish and invertebrate species and life stages. Analyses of data from plankton samples, net tows, trawls, information gleaned from stock assessments by the National Marine Fisheries Service (NMFS), and related information were used to develop baseline density and individual size estimates for assessing injuries. The data sets used, density estimation methods, and results of these calculations comprise the Gulf of Mexico Fish and Invertebrate 2010 Baseline Density Dataset, described in French McCay et al. (2015a).

The injury quantification may also include consideration of the growth and (natural plus fishing) mortality the affected organisms would have undergone if they had not been killed in projecting future losses of biomass production (i.e., production foregone). The production foregone model estimates the lost future somatic growth (production) that killed organisms would have produced had they otherwise lived their normal lifespan. Assessment of production foregone allows for a more thorough representation of the biological injuries to water column organisms resulting from the spill than would be captured by the direct kill alone.

Results of the production foregone model, which are measured in biomass, can be used to address biological concerns, as well as provide units that can be translated into a consideration of restoration needs. The results are quantified as grams per individual, expressed in 2010 values; i.e., future losses are discounted to their value as if the losses all occurred in 2010 using a 3% annual discount rate (based on guidance from NOAA 1997). Scaling of compensatory restoration would inflate the project size to account for 3% interest for each year in delay after 2010 before the restoration is realized.

These analyses, data inputs and results are described in this report. The objectives of this report are to:

- Describe the modeling approach and algorithms used for calculations of production foregone;
- Describe how the production foregone model may be used to evaluate production gained from restoration that increases numbers of individuals at particular sizes;
- Document available life history information and data inputs used in the modeling; and
- Tabulate the results of the model calculations (i.e., g of production per individual, along with life table data) for sizes of individuals typifying baseline densities of organisms in the Northern Gulf of Mexico.

Section 3 provides a description of the approach and algorithms for the production foregone model. Appendix A.1 provides a literature review of mortality models considered for use in developing the life table and production foregone model. Section 4 contains literature reviews and data analyses used to define the model inputs. Results are in Section 5 and appendices to the report. Section 5 evaluates the overall life table for well-studied species, where the balance of growth, survival and fecundity by stage is quantifiable. Appendix A.2 evaluates and compares literature data to the modeled first-year mortality and cumulative survival rates, as well as age 1+ mortality models. Appendices B through D document the life history parameters reviewed and used as model input. Appendices E and F provide the results, which include (by taxa, season and biological density data set) full life tables, cumulative survival to age 1, age-equivalency data derived from the life table, weights and lengths per individual by age, and production foregone (or gained) per individual by age. Appendix G provides a roadmap for navigating the production foregone model results presented in the Excel workbooks for each of the modeled taxa that are included with Appendix E.

3 Production Foregone Model

3.1 Description of Production Foregone Model

3.1.1 Approach

The biomass (kg) of fish and invertebrates directly killed by the spill represents biomass produced before their death. If the spill had not occurred, those organisms directly killed would have continued to grow until they died naturally (e.g., predation) or to fishing. This lost future (somatic) production is estimated and added to the direct kill to calculate the total production foregone. The loss is expressed in "present day" (i.e., year of the spill) values using a 3% annual discount rate for future losses, based on NRDA guidance (NOAA 1997). In the model described herein, losses are discounted to the year of the spill, i.e., 2010.

Interim losses are sustained in future years (pending recovery to baseline abundance) resulting from the direct kill at the time of the spill. Interim losses potentially include:

- Lost future uses (ecological and human services) of the killed organisms themselves;
- Lost future (somatic) growth of the killed organisms (i.e., production foregone, which provides additional services); and
- Lost future reproduction, which would otherwise recruit to the next generation.

The approach followed here is that the total loss includes the direct kill and its future services, plus the lost somatic growth of the killed organisms, which would have provided additional services. It is assumed that density-dependent changes in survival rate are negligible, i.e., changes in natural and fishing mortality of surviving animals do not compensate for the killed animals during the natural lifespan of the animals killed.

In the model described herein, it is also assumed that the impacts were not large enough to significantly affect long-term future reproduction and recruitment; i.e., that the numbers of organisms affected are relatively small portions of the total reproductive stock. Therefore it is assumed that sufficient eggs will be produced to replace the lost animals in the next generation. Given the reproductive strategy of the majority of species involved to produce large numbers of eggs, of which only a few survive, it is assumed that density-dependent compensation for lost reproduction occurs naturally.

The services provided by the injured organisms are measured in terms of production, i.e., biomass (kg wet weight) directly lost or not produced. Among other factors, services of biological systems are related to the productivity of the resources, i.e., to the amount of food produced, the usage of other resources (as food and nutrients), the production and recycling of wastes, etc. Particularly in aquatic ecosystems, the rate of turnover (production) is a better measure of ecological services than standing biomass (Odum 1971). Thus, the sum of the standing stock killed (which resulted from production previous to the spill) plus lost future production (as number of individuals or kg) is a more appropriate scalar, as opposed to standing stock alone, for measuring lost ecological services.

This injury estimation approach was developed and used previously in the injury quantification for the *North Cape* spill of January 1996 (French McCay 2003; French McCay and Rowe 2003) and many other spill cases (e.g., French McCay et al. 2003; French McCay 2009). Injuries are calculated in three steps:

1. The direct kill is quantified by age class. Age class is based on size distribution data and application of a standard population model (Ricker 1975) used by fisheries scientists.
2. The net (somatic) growth normally to be expected of the killed organisms is computed and summed over the remainder of their lifespans (termed production foregone).
3. Future interim losses are calculated in “present day” (year of the spill) values using discounting at a 3% annual rate.

Survival rates, growth rates, and length-weight by age relationships are used to construct a life table of numbers and kg for each annual age class. Daily survival and growth rates are used to construct a daily life table for the first year of life. Production foregone is then estimated using the model of Jensen et al. (1988)(eq. 8), which is commonly used in fisheries science.

3.1.2 Model Equations

The production foregone population model as described by the U.S. Environmental Protection Agency in its 316(b) rule (USEPA 2014) is used. This approach is recommended by fisheries scientists and the models are those typically used for entrainment and impingement fisheries impact evaluations (EPRI 2004). The equations are based on fisheries model development described in Ricker (1975).

The production foregone population model makes use of survival rates from one stage to the next. The modeling includes estimation of survival rates for eggs, larvae, and juveniles up to age 1 year (365 days old). The number of individuals remaining after τ days from an initial number at $\tau = 0$ is calculated over a time interval where the daily (instantaneous) mortality rate M_d is considered constant:

$$N_\tau = N_o\, e^{(-M_d\, \tau)} \qquad \text{eq. 1}$$

The survival rate for the period of τ days (S_τ) is thus:

$$S_\tau = N_o / N_\tau \;=\; e^{(-M_d\, \tau)} \qquad \text{eq. 2}$$

For animals living more than one year, annual age classes from age 1 up are defined in the model. Natural and fishing mortality rates for annual age classes are used to estimate numbers that would remain alive by each annual age class. The number remaining alive at age t (years), N_t, is:

$$N_t = N_1\, e^{(-Z_a\,(t-1))} \qquad \text{eq. 3}$$

$$Z_a = M_a + F_a \qquad \text{eq. 4}$$

where N_1 denotes number at age one, Z_a is the annual instantaneous total mortality rate for age class *a,* M_a is the annual instantaneous natural mortality rate, and F_a is the annual instantaneous fishing mortality rate.

The annual survival rate for age t (S_t) is thus:

$$S_t = e^{(-Z_t)} \qquad \text{eq. 5}$$

The proportion dying in a year is 1-S_t.

If survival of a life stage over its entire duration is known, to account for the mix of ages within the stage present at any given time, survival to age one for eggs (S_{e1}) of mixed ages (in days) is calculated as:

$$S_{e1} = 2\, S_e\, e^{-\ln(1+Se)}\, S_L\, S_j \qquad \text{eq. 6}$$

where S_e is survival rate during egg stage, S_L is survival rate during larval stage, and S_j is survival rate during juvenile stage (EPRI 2004).

For larvae of a mix of ages (days), survival to age one (S_{L1}) is calculated as:

$$S_{L1} = 2\, S_L\, e^{-\ln(1+S_L)}\, S_j \qquad \text{eq. 7}$$

Survival from a single age class (such as a larva of a specific size) until age one is calculated using eq. 1, segmenting the calculations for intervals of constant M_d. Survival to end of life is calculated from the size killed using eq. 2 (if <1year old) and eq. 3, where *t* in eq. 3 is set at the maximum age.

Production foregone (P_k, USEPA 2014, Chapter A-5; based on Rago 1984 and Jensen et al. 1988; see also EPRI 2004) which includes yield (harvest) and the production consumed in the food web, is estimated for losses (kills) in the year *k* (i.e., 2010) for a mix of annual age classes (*j*) using:

$$P_k = \sum_j \sum_a [K_{jk}\, G_a\, W_a\, (e^{Ga-Za} - 1)\,]/[\, G_a - Z_a\,] \qquad \text{eq. 8}$$

where P_k is foregone production (g) in year *k*, K_{jk} is loss (kill) of individual of stage *j* in the year *k*, G_a is the instantaneous annual growth rate for individuals of age a, W_a *is* average weight (g) at the beginning of age *a*, and Z_a is the instantaneous annual total mortality rate for individuals of age *a*. The age counter *a* is summed from the age of stage *j* to the maximum age for the species modeled.

Total natural mortality (TM_k) (which would be lost to the food web) is calculated using an analogous model:

$$TM_k = \sum_j \sum_a K_{jk}\, S_{ja}\, W_a\, (M_a/Z_a)(1-e^{-Za}) \qquad \text{eq. 9}$$

where M_a is instantaneous natural mortality rate (yr^{-1}) for individuals of age *a*.

In order to populate the parameters of the production foregone equation (eq. 8) for a given species or taxonomy, basic growth and size equations/relationships are required. Length and weight of annual age classes are estimated using the von Bertalanffy growth equation and a power curve of weight versus length following methods in Ricker (1975). The equations used are as follows. To calculate length (mm) at age *t* (years):

$$L_t = L_\infty\, [1 - e^{(-K\,(t - t_o))}] \qquad \text{eq. 10}$$

where L_∞ is the asymptotic maximum length (mm), K is the Brody growth coefficient, and t_o is a constant. Weight as a function of length (mm) is:

$$W_t = \alpha\, L_t^{\,\beta} \qquad \text{eq. 11}$$

where W_t is wet weight (g) at age *t* and α and β are constants.

Growth rate is considered constant over each of the annual age classes (age 1+), such that:

$$W_{a+1} = W_a\, e^{Ga} \qquad \text{eq. 12}$$

$$G_a = \ln(W_{a+1} / W_a) \qquad \text{eq. 13}$$

where G_a is the annual instantaneous growth rate at age *a*.

Similarly, for invertebrates and larval and juvenile fish less than one year old, daily instantaneous growth rates (G_d) are calculated from weight ($W\tau$) at age τ (days) to weight at age $\tau+1$ ($W\tau_{+1}$):

$$W\tau_{+1} = W\tau\, e^{Gd} \qquad \text{eq. 14}$$

$$G_d = \ln(W\tau_{+1} / W\tau) \qquad \text{eq. 15}$$

Growth (i.e., the determination of $W\tau$) and mortality models for individuals less than one year old are described in Section 3.2.1.1 and Section 3.2.1.2, for fish and for invertebrates, respectively.

Production foregone through the first year of life for a mix of *i* stages (e.g., size classes or daily age classes) of young-of-the-year (YOY) killed in the year of the spill is calculated from:

$$P_1 = \sum_i \sum_d [K_i\, G_d\, W_d\, (e^{Gd\text{-}Zd} - 1)\,]/[\, G_d - Z_d\,] \qquad \text{eq. 16}$$

where P_1 is foregone production (g) from individuals <1 year of age when killed up to age 1 year (365 days old), K_i is loss (kill) of individuals of stage *i*, G_d is the instantaneous daily growth rate at age *d* (days) for individuals < 1 year old (day^{-1}), W_d is the average weight (g) of individuals at the beginning of age *d*, and Z_d is instantaneous daily total mortality rate for age *d.* The age counter *d* is summed from the age of stage *i* to 365 days of age. Eq. 8 is used to calculate production foregone from age-one equivalents of the YOY killed (N_1, which is calculated using eq. 1) and added to P_1 to estimate total production foregone from YOY losses.

Discounting at 3% per year (NOAA 1997) is included to translate production losses of the age 1+ age classes in future years (interim loss) backwards to present-day values. The discounting multiplier for translating value *n* years after the spill to present value (i.e., for the year of the spill, 2010) is calculated as:

$$(1+d)^{-n} = 1/(1+d)^n \qquad \text{eq. 17}$$

where d=0.03. Thus, the losses in future years have a discounted value at the time of the spill. In this analysis, all discounting is calculated based on the number of years from the year of the spill.

3.2 Mortality and Growth Models

3.2.1 First Year Growth and Mortality Models

A review of available mortality models that have been developed for calculating stage-based mortality is presented in Appendix A, Section A.1. Each mortality model was assessed based on the information (location, temperature, sample size) used to build the model, agreement of model estimates with available empirical data, the degree to which the model is widely used by other researchers, the scientific theory behind the model, and the availability and quality of the requisite input parameters. For each respective life history stage (egg, larvae, juvenile) a single model was selected to be used in the first year mortality model within the production foregone model. Additionally, subject experts were consulted for further review on these selections. Section 3.2.1 outlines the first year mortality models used to build the production foregone model.

Production foregone is calculated from the egg stage until the end of an individual's life and may be calculated from any in-between starting age. The first year mortality model calculates the survival per individual fish or invertebrate from the egg stage to age one year (365 days). The first year mortality model is developed using a life table-based approach, calculating growth and mortality from the egg stage through the end of the first year at daily increments to allow calculation of production foregone from any sized individual to the size it would reach at one year of age. The model framework of the first year survival model provides a series of linked empirical models which result in species (or analysis taxon)-specific data demonstrating realistic population dynamics (see Appendix A, Section A.2 for model examples and tests on population stability). Although the model framework is general at its base, using empirical models of growth and mortality, it is highly modular insofar as available species (or analysis taxon)-specific life history information may be incorporated (as a replacement to general empirical relationships) to refine each species first year survival calculations.

Stage-based, size-dependent mortality models are used for the estimation of first year survival based on the theory that vulnerability to predation is the major driver of early life history mortality and that predation rates are primarily driven by organism size (Bailey and Houde 1989, Pepin 1993). For fish species, the McGurk (1986) egg mortality model is used to calculate the cumulative survival until the end of the egg stage. Subsequently, the Pepin (1991) larval mortality model is used to calculate the daily survival rate through the larval stage as a function of larval size and temperature. And finally, the Lorenzen (1996) mortality model is used to calculate daily mortality rates from the end of the larval stage until the individual reaches 365 days in age. For invertebrate species where life tables were developed, the McGurk (1986) egg mortality model is used to calculate the cumulative survival until the end of the egg stage. The McGurk (1987) mortality model for marine animals of all sizes is used to calculate the daily survival rate from hatching until the individual reaches 365 days of age.

Invertebrate species with more detailed life history information available (e.g., penaeid shrimp), utilize species specific growth and mortality models (Section 3.2.1.2.2) during the first year of life. Invertebrate species with limited or no available life history data do not have life tables created to calculate production foregone.

3.2.1.1 Models used for Fish

The McGurk (1986), Pepin (1991), and Lorenzen (1996) mortality models are used to calculate cumulative survival of fish during the egg, larval, and juvenile stages respectively. The McGurk (1986) egg mortality model was selected for use within the first year mortality model based on input studies/data used to develop the model (including data from the Gulf of Mexico and egg sizes within the range of species being modeled for production foregone). Estimates produced by this model for mean egg sizes are well within the range of other available empirical data on egg mortality estimates.

The Pepin (1991) larval mortality model was selected for use based on the large dataset used to build the model which included many ecosystems similar to the Gulf of Mexico. The incorporation of temperature-based scaling within the Pepin model allows for seasonal distinction in mortality estimations. Estimates produced by this model for larval sizes are within the range of other available empirical data on larval mortality estimates.

The Lorenzen (1996) juvenile mortality model, which is based on a regression against body weight, is a well-cited model (>225) and is used by the Southeast Fisheries Science Center for several SEDAR stock assessments where species specific mortality information is not available. Estimates produced by this model for juvenile sizes are well within the range of available empirical data on juvenile mortality estimates (see Appendix A). Several other mortality models available in the literature are based on maximum age (T_{max}). However, T_{max} based mortality equations are difficult to implement, as maximum age is often unknown or uncertain. Other mortality models are based on von Bertalanffy growth equation parameters (e.g., Pauly 1980; Gislason 2010), and as such are highly sensitive to those parameters. Thus, the Lorenzen model was selected as providing the most generally applicable (to the range of species modeled here) and reliable empirical-based estimates of mortality rate with quantifiable variance (see Appendix A for more detailed information on each mortality model reviewed).

A final contributing factor to the selection of all three mortality models is that each of the models selected are founded in size-based mortality theory, which suggests larger individuals are less susceptible to predation, resulting in higher survival rates (Pepin 1993, Cowan et al. 1996). By basing each step within the first year mortality model on the same, well researched, scientific theory the model is cohesive and methodical. Separate spring and summer production foregone values are calculated for each analysis taxon in order to assess individuals that were present in each respective season.

Each of the mortality models are regressions based on empirical data. As with all deterministic regression models, the fit of the regression may be tenuous at data points at either end of the modeling range (in this case, very small and very large size fish) depending on the distribution of the model input data distribution. Utilization of the regression for values outside of the original regression data inputs is highly uncertain as these results are extrapolations from the original relationship.

3.2.1.1.1 Fish - Life Table Equations

The first year survival life table used in the calculation of production foregone begins at the egg stage and employs the McGurk (1986) equation for calculating mortality rate based on egg dry weight.

$$M = 0.00022W^{-0.85} \qquad \text{eq. 18}$$

where W is dry weight in grams. This equation returns M (day^{-1}).

The mean dry weight of eggs (0.000296 g) presented in the McGurk (1986) study is used in the life table model as the weight input to the mortality equation presented above (eq. 18). No egg stage growth equation is applied, thus egg weight is fixed through its stage duration.

Stage duration of the egg stage is estimated by the Pepin (1991) equation.

$$D_e = 16.1e^{-0.099T}\Phi^{0.44} \qquad \text{eq. 19}$$

where D_e is egg stage duration (days), T is water temperature (C), and Φ is egg diameter (mm).

Each of the above model inputs and model calculated variables (egg mortality rate, egg weight, egg diameter, egg stage duration) may be overwritten in the model if taxon-specific empirical data are available. Egg stage mortality rates are applied through the calculated egg stage duration.

A larval size at hatch is used as the starting point for application of the larval stage mortality model. Mortality rate during the larval stage (both yolk-sac stage and post-larval stage) is calculated by the Pepin (1991) length- and temperature-based model:

$$M = 0.25e^{0.067T}L^{-0.68} \qquad \text{eq. 20}$$

($n=32$, $r^2=0.59$, $p<0.001$)

where T is water temperature (C) and L is length (mm). The model returns M in day^{-1}.

The water temperature used in this calculation is dependent on the season for which production foregone is calculated. Mean seasonal temperature data were calculated using data acquired from the National Oceanographic Data Center (NODC) Ocean Climate Laboratory's monthly climatology data for the Gulf of Mexico (Boyer et al. 2001). Temperature from the upper mixed layer (0-30m) was taken from the one degree monthly climatology grid (http://www.nodc.noaa.gov/cgi-bin/OC5/GOMclimatology/gomregcl.pl?parameter=t) for the grid cell where the wellhead was found (28:29°N, 88:89°W). Spring (May-June) mean temperature was 26°C and summer (July-August) mean temperature was 29°C for this area.

Larval length begins on the first day of the larval stage as size at hatch (2 mm default, or a data input). The fish is then grown at daily increments according to the Pepin (1991) daily growth rate equation.

$$G_l = 0.031e^{0.073T}L^{0.54} \quad \text{eq. 21}$$

where G_l gives the daily growth increment of the larval individual (mm/day), T is water temperature (C), and L is larval length (mm). (Note that $G_l = (W_{\tau+1} - W_{\tau})$ in eq. 14).

Age-based larval fish weights of individuals are not generally available. In addition to larval length, weight at age is calculated according to the following length-weight (Wiebe and Davis 1985) and weight-weight (Nixon and Oviatt 1973) conversion equations:

$$W = 0.0069L^{2.886} \quad \text{eq. 22}$$

where W is wet weight (mg), and L is length (mm).

$$W_{wet} = W_{dry}/0.22 \quad \text{eq. 23}$$

where W_{wet} is wet weight (g) and W_{dry} is dry weight (g).

The duration of the larval stage is determined by the Houde (1989) equation:

$$D_L = 952.5T^{-1.0752} \quad \text{eq. 24}$$

where D_L is larval stage duration (days) and T is water temperature (C).

Each of the above variables (larval mortality rate, larval weight/length/growth, larval stage duration) may be overwritten in the model if taxon-specific empirical data are available.

The larval mortality rate is applied through the duration of the larval stage. At the end of the larval stage duration, the juvenile stage survival model is triggered. The Lorenzen (1996) model for oceanic fish species is used for calculating mortality rates during the juvenile stage and is a size based mortality model.

$$M = 3.69W^{-0.305} \quad \text{eq. 25}$$

where W is wet weight (g). This equation returns M (year^{-1}).

Age-based juvenile fish weights of individuals are not generally available for most taxa. Therefore an instantaneous exponential growth rate is calculated for the juvenile stage based on the size at the end of the larval stage (W_L) and the size at age 1 (W_1, derived from the age 1+ von Bertalanffy growth curve). This growth is applied at daily increments to allow calculation of survival at this same interval. Juvenile stage duration is determined by the following equation:

$$D_j = 365 - D_L - D_e \quad \text{eq. 26}$$

where D_j is juvenile stage duration (days), D_L is larval stage duration (days), and D_e is egg stage duration (days).

The growth equation for the juvenile stage up to age 1 year is:

$$G_j = ln(W_1 / W_L) / D_j \quad \text{eq. 27}$$

$$W_\tau = W_L \exp(G_j (\tau - D_L)) \quad \text{eq. 28}$$

where G_j is growth rate (instantaneous per day) from the end of the larval stage to age 1 year, W_τ is wet weight at age τ, and W_L is wet weight at the end of the larval stage.

Each of the above variables (juvenile mortality rate, juvenile weight/length/growth, juvenile stage duration) may be overwritten in the model if taxon-specific empirical data are available. The juvenile mortality rate is applied until the end of the juvenile stage, at which point the age 1+ mortality model is triggered (Section 3.2.2.1).

The final result of the first year mortality model is a cumulative survival for an individual from egg to each day of age up to 365 days in age (summarized as percent survival and a rate as 1 in *n* survive to age 1). Production foregone may then be calculated starting at any point during this first year ('initial length').

3.2.1.1.2 Fish – Initial Lengths

The calculation of production foregone for the first year of life is calculated based on the size of larvae present in the Gulf of Mexico at the time of the spill (referred to hereafter as 'initial length'). Due to the unique characteristics of each density database (see report on the Gulf of Mexico Fish and Invertebrate 2010 Baseline Density Dataset (French McCay et al. 2015a), representative lengths from each database are extracted in a manner appropriate to the data available. The section below outlines the methodology for calculating the representative initial length for fish used in production foregone calculations. The initial length is used as the size at which the production foregone model begins calculating cumulative survival per individual.

SEAMAP Bongo - The median length (mm) of larval fish was extracted from SEAMAP bongo database (November 25, 2013 database) to represent the 50th percentile size individual larva that was present during the time period when injury may have occurred. Length data used to calculate initial length were filtered based on the following:

- Bongo catches only
- Years: 1999 – 2009
- Latitude: 25 to 31º N
- Longitude: <81.5º W
- Excluded data when there were 0 specimens measured and only 2 were measured (the 2 measured are minimum and maximum lengths, thus would weight a length-frequency distribution inappropriately).
- Length data was trimmed to get most accurate estimate of median lengths in the trawl and drop outliers: lengths included those ≤97.5 percentile.
- All times of day (day, night, and twilights) were included

Samples were divided into spring and summer seasons (Spring = April, May and June; Summer = July, August and September). After compilation of all available lengths from the above protocol, ages corresponding to each respective length were calculated using the larval and juvenile fish life table calculations described above. These ages were then split into larval and juvenile specimens based on age (seasonally dependent). Medians were then calculated separately for the larval set of lengths and the juvenile set of lengths. Each of these median seasonal initial lengths was then used as inputs for the spring production foregone calculation and the summer production foregone calculations respectively.

NRDA MOC10 – All available lengths by taxa were extracted from the Meg Skansi 7 cruise database (March 24, 2014 release). Median lengths were calculated by taxa to represent initial lengths. No data trimming was implemented.

NRDA MOC1 (Below 200m) – Samples from the Walton Smith IV MOC1 database (September 26, 2014 release) were included. After compilation of all available lengths, ages corresponding to each individual length were calculated using the larval and juvenile fish growth curves described above. These ages were then split into larval and juvenile specimens. Medians were then calculated for the larval set of lengths to represent initial lengths. Juvenile specimens were not included in production foregone calculations.

3.2.1.2 Models used for Invertebrates

For invertebrate species, mortality models applied by life stage in the calculation of life tables include the McGurk (1986) (eq. 20) mortality model for the egg stage and the McGurk (1987) mortality model based on data for marine animals of all sizes for the larval and juvenile stages. As described in Section 3.2.1, each of these models are based on size-based mortality theory, which suggests larger individuals are less susceptible to predation, resulting in higher survival rates (Pepin 1993, Cowan et al. 1996). Although the McGurk (1986) mortality model for the egg stage was based on data for fish eggs, it is assumed the relationship would hold true for similarly sized invertebrate eggs. The invertebrate life table is designed to be applied to all species with adequate requisite life history parameters (e.g., growth curve, weight-length relationship). See Table 3-1 for a list of species for which this life table has been calculated.

Table 3-1. Taxonomies employing the life table production foregone approach described in Section 3.2.1.2.1

Taxonomy
Callinectes sapidus
Callinectes similis
Callinectes spp.
Portunidae
Palinuridae
Panulirus

For invertebrate species with more detailed life history information available (i.e., penaeid shrimp), species-specific life tables were constructed (Section 3.2.1.2.2). Conversely, invertebrate species with little to no life history information available, particularly those with lifespans less than two years, are not effectively modeled by the life table described in Section 3.2.1.2.1.

3.2.1.2.1 Invertebrate – Life Table Equations

Refer to eq. 18 for a description of the McGurk (1986) mortality model for the egg stage.

The McGurk (1987) regression model applied to the larval and juvenile stages of invertebrates is based on input data from a wide variety and sizes of marine animals.

$$M = 0.00713W^{-0.301} \quad \text{eq. 29}$$

where *W* is dry weight *(g) and* M is natural mortality (day^{-1}). This model is applied through the entirety of the larval and juvenile stages up to age 1 year.

Initial lengths for invertebrates were derived using the same methodologies as were fish (Section 3.2.1.1.2). Wet weight (*W*) at initial length is calculated from a respective Wiebe and Davis (1985) weight-length equation for the invertebrate order or family of interest (Table 3-2).

Table 3-2. Available taxon-specific weight-length parameters (eq. 11) for larval invertebrates (from Wiebe and Davis 1985). Units are mm for length and mg wet weight for mass.

Taxonomic Group	a	b
Copepod	0.0860	2.809
Copepod nauplii	0.0024	1.790
Euphausiid	0.0138	3.071
Decapod	0.0100	3.097
Amphipod	0.0466	2.619
Ostracod	0.0906	3.047
Crustacean Larvae/Cumacean	0.0172	2.546
Pteropod (Limacina)	0.5236	3.000
Pteropod (Styliola)	0.3770	3.000
Pteropod (Clio)	0.2152	2.293
Bivalve	0.224	3.353
Cephalopod	0.2152	2.293
Chaetognath	0.0005	3.498
Polychaete	0.0088	2.909
Medusae	0.0924	3.138
Siphonophore	0.4634	1.101
Ctenophore	0.0834	2.546
Larvacean	0.0015	2.986
Cyphanautes	0.0500	3.000
Tintinnid	0.3770	3.000
Thaliacean	0.0052	3.260
Phaeodarian	0.2618	3.000

Taxonomic Group	a	b
Medusozoa	0.1257	3.000

For species that live for multiple years, daily wet weights from hatch size to age one year are calculated using an exponential growth model derived from the wet weight at the start of the larval stage (i.e., using data for larval hatch size and the larval weight-length relationship) through to the wet weight at the end of the first year (365 days) based on age 1+ von Bertalanffy equation and weight-length relationship (species- or taxon-specific). An instantaneous daily growth rate is calculated and used to grow the individual from the weight at the beginning of the larval stage to the weight at the end of the first year (age 1). The growth equation applied for hatch to age 1 year is:

$$G_i = ln(W_1 / W_h) / D_j \qquad \text{eq. 30}$$

$$W_\tau = W_h \, exp(G_i \, (\tau - D_e)) \qquad \text{eq. 31}$$

where G_i is growth rate (instantaneous day^{-1}) from hatch to age 1 year, W_τ is wet weight at age 1 year, W_h is wet weight at hatch, τ is age (days), D_j is the duration of the larval and juvenile stages to age 1 (days) and D_e gives egg stage duration (days)

The invertebrate growth model is used to estimate age at size (eq. 31). Invertebrate larval duration is manually set within the model (no general empirical model is available for invertebrates) and is derived from published literature. If the invertebrate's early life history is not staged, larval duration is set to 365 days (i.e., the first year is treated as a single stage). However, the stage duration information is not used in the calculations since the growth model is not stage-specific between hatch and age 1 year.

The mortality model is then applied from the age at initial length until 365 days of age. The daily growth rates are applied from day of hatch to 365 days of age. Daily mortality is then estimated based on the daily weights derived through the growth rates. The final result of the first year mortality model is a cumulative survival for an individual to 365 days in age (i.e., 1 in *n* survive). At the completion of the first year, the age 1+ mortality model is triggered at which point yearly (as opposed to daily) survival rates are calculated.

For invertebrates that live less than or approximately one year, the daily growth model is derived from sizes at two known ages (eq. 30, with D_j set equal to the difference in ages), and applied up to the maximum age (< 365 days). Due to limited availability of life history parameters for invertebrate taxonomies, only a select few species have life tables constructed through this methodology (Table 3-2).

3.2.1.2.2 Penaeid Shrimp

In the production foregone model Penaeid shrimp do not use the generic growth and mortality models for invertebrates presented in Section 3.2.1.2.1. Because more specific, recent data is available for these taxa, more directed growth and mortality are applied. The growth and mortality model used for the first year of life for Penaeid shrimp (*Farfantepenaeus aztecus*, *Farfantepenaeus duorarum*, *Litopenaeus setiferus*) is based on work from Baker et al. (2014). The authors developed a population model that incorporated available information on vital rates for each life stage. Stage-based growth and mortality rates are applied in the production foregone model (Table 3-3).

Table 3-3. Life table values for Penaeid shrimp used in production foregone model.

Stage	Ages (Days)	Growth rate (mm/day)	Instantaneous Z (day^{-1})
Egg/Larvae	1-16	Exponential	0.373
Early Juvenile	17-42	0.815	0.0821
Late Juvenile	43-95	0.815	0.0312
Subadult	96-128	0.91	0.0275
Adult (<365 Days)	129-365	Logarithmic	0.0104

Exponential growth during the egg/larval stage is calculated as

$$L_t = L_{t-1} * e^{(0.009*(t-t_0))} \quad \text{eq. 32}$$

where L_t is length at day *t.*

Logarithmic growth during the adult (<365 day) stage is calculated from the size at 129 days old (100mm) to the size at age 1 (species dependent).

White Shrimp $$L_t = 107.88 * ln(t) - 423.86 \quad \text{eq. 33}$$

Brown Shrimp $$L_t = 86.30 * ln(t) - 319.00 \quad \text{eq. 34}$$

Pink Shrimp $$L_t = 71.98 * ln(t) - 249.41 \quad \text{eq. 35}$$

where L_t is length at day *t*.

After 365 days in age, each taxon is modeled by the invertebrate age 1+ growth and mortality models. All other life table calculations (e.g., weight at length) outlined in above sections required to compute production foregone are applied.

3.2.2 Age 1+ Mortality Model

The Age 1+ mortality model utilizes yearly, age structured mortality rates to calculate cumulative survival for individuals >365 days in age. When available, species specific age structured mortality rates are derived from published literature (most frequently stock assessments). When published age structured mortality rates are not available for a species or analysis taxon of interest, a natural mortality model is used to calculate the requisite values.

3.2.2.1 Fish

Published literature, including stock assessments and government reports were reviewed to determine age 1+, annual age-structured natural mortality rates for analysis taxa. If published values were not available for an analysis taxon, the Lorenzen (1996) mortality model (eq. 25) is used to calculate age 1+ natural mortality rates as a function of body weight. The Lorenzen (1996) mortality model is a frequently cited model (>225) and is used by the Southeast Fisheries Science Center within several SEDAR stock assessments. Estimates produced by this model for adult sizes are well within the range of available empirical data on adult fish mortality estimates. The input data used to develop the model is extensive and includes estimates for species in the Gulf of Mexico and similar ecosystems. Additionally, by continuing the use of size-based mortality models, wet weight is the input variable, model continuity is preserved.

Length at each age class is calculated from a species/taxon-specific von Bertalanffy growth curve (eq. 10). Length at each age class is converted to wet weight at age using a species/taxon-specific weight-length relationship (eq. 11). Von Bertalanffy growth curves and weight-length relationships for each species and analysis taxon of interest may be found in Appendices B and C. See Section 3.1.2 for more detailed information on the age 1+ growth model and production foregone methodology.

Depending on the taxonomy of interest, and data availability, one of three methodologies is used to assign fishing mortality (*F*) rates to analysis taxon at ages 1+. For taxonomies well known to not be actively commercially fished, or to be only incidentally taken by other fisheries (e.g., many small deep-sea fish, small, commercially unimportant forage fish), professional judgment was used to assign an annual fishing mortality rate of 0 for all age classes. Published literature, including stock assessments and government reports were reviewed to determine age 1+, annual age-structured fishing mortality rates for well-studied, commercially fished analysis taxa. Fishing mortality rates are generally only available for heavily managed or heavily fished stocks. Additionally, fishing mortality rates of a species differ greatly among geographic regions due to fishing fleet attributes, local species density, etc. such that using fishing mortality rates from a region outside of the Gulf of Mexico for this model application is not recommended. As a result, only a small set of species have reliable published fishing mortality rates available. If published values were not available for an analysis taxon that is actively fished, the Zhou et al. (2012) fishing mortality model (eq. 36 and eq. 37) was applied.

$$F_{tele} = 0.87M \qquad \text{eq. 36}$$

$$F_{chon} = 0.41M \qquad \text{eq. 37}$$

where F_{tele} is fishing mortality (yr^{-1}) for teleosts, F_{chon} is fishing mortality for chondrichthyans, and M is natural mortality (yr^{-1}). The input values for M in these equations may have been derived from published reports, or through application of the Lorenzen (1996) natural mortality model. Application of this fishing mortality model assumes that the species is being fished at the effort producing maximum sustainable yield. The NMFS commercial fisheries statistics database was queried for species reporting catch from the 'Gulf' region for the years 1999 to 2009. Species with reported landings greater than 0.5 metric tons for at least five of these years were considered to be actively fished, and have the Zhou et al. method applied. If a species had fishery mortality rates available from published literature, those rates were used in preference of the Zhou et al. values. Total mortality is calculated as the sum of natural mortality (M) and fishing mortality (F) at a given age (a).

$$Z_a = M_a + F_a \qquad \text{eq. 38}$$

3.2.2.2 Invertebrates

Published literature, including stock assessments and government reports were reviewed to determine age 1+, annual age-structured mortality rates for analysis taxa. For species that live for multiple years, the McGurk (1987) all-species mortality model (eq. 31) could be used to calculate age 1+ natural mortality values when direct values from published literature are not available; however, in practice this was not applied here. Length at each age class is calculated from a species/taxon-specific von Bertalanffy growth curve (eq. 10). Length at each age class is converted to wet weight at age using a species/taxon-specific weight-length relationship (eq.

11). If another growth model is more appropriate for a species than the von Bertalanffy growth model, the alternative growth model may be used to derive weights at each age (as is done in Section 3.2.1.2.2). Growth models and weight-length relationships for each species and analysis taxon of interest may be found in Appendices B and C.

3.2.3 Mortality Variance Estimates

Estimates of *M*, whether they are derived from catch data, ecosystem modeling, or empirical models, are known to be variable and uncertain. Quantifying this uncertainty is useful to aid in the understanding of the estimates that have been derived. However, sufficient data are not available to perform uncertainty analyses, as the input data used to develop the estimates of *M* for each taxon are not unbiased samples from a population of potential outcomes. Thus, to address uncertainty, proxy values for variance were developed as an approximation.

Bradford (1992) developed the following equation (eq. 39) for estimating variance around an estimate of *M* by examining multiple mortality estimates from all stages of marine and freshwater fishes. A significant relationship was found between mean stage specific natural mortality rates and inter-annual variation in stage specific mortality rates. The equation indicates that the variance is directly proportional to the mortality estimates (*M*); high variance with high mortality, low variance with low mortality.

$$\ln\{Var(M)\} = 2.231\ln(M) - 1.893 \qquad \text{eq. 39}$$

This relationship was found to be highly significant ($r^2 = 0.90$, $p<0.0001$, $n=97$). The Bradford estimator has been cited over 100 times in published literature.

The Bradford variance equation is used within the production foregone model to frame upper and lower bounds of the mortality point estimates, including those calculated by the natural mortality models used for fish and invertebrates and those rates provided directly from published literature. The Bradford variance estimator is calculated for each daily mortality rate derived in the first year survival model (within the production foregone model). These variance estimates were then used to calculate the standard deviation for each mortality value by taking the square root of the variance estimate. Two standard deviations above and below the mean mortality estimate was used to estimate a 95% confidence interval for cumulative survival through the end of the first year. These upper, lower, and center cumulative first year survival rates were input into the age 1+ production foregone calculations to produce upper, lower, and center estimates of production foregone per individual.

3.3 Development of Life Tables and Production Foregone Calculations

Life tables were produced for all fish species and fish analysis taxa where life history input data could be derived from a stock assessment. Life tables assess the survivorship of an individual by stage or age class. Two sets of life tables are constructed or calculated for each species or analysis taxon: a first year life table (larvae and juvenile stages) and an age 1+ life table. Each of these life tables is then applied in a consecutive, "back-to-back-to-back" fashion to determine survivorship of an individual over its lifetime.

Early life history mortality rates (larval and juvenile) calculated by the first year mortality model are used to calculate survivorship to age 365 days. Subsequently, annual mortality rates are applied for age 1+ age classes for each species or analysis taxon. Survivorship is then calculated to the end of each annual age class. For each age class in the life table a set of parameters are calculated which are used in the calculation of production foregone: length (mm), dry weight (g), wet weight (g), instantaneous mortality (day^{-1} for early life history model and $year^{-1}$ for age 1+ model), survival (day^{-1} for early life history model and $year^{-1}$ for age 1+ model), and cumulative survival to end of stage (1 in *n*). Cumulative survival to the end of each life stage is then applied in the production foregone equation (eq. 8) and biomass lost per stage is calculated.

4 Life History Parameter Model Inputs

4.1 Description of Parameters

Production foregone is calculated for each species or analysis taxon of interest based on respective life history parameters for each. (Refer to Section 3 for detailed implementation of each parameter within the production foregone model). This section outlines the model input parameters required for each analysis taxon for the calculation of production foregone. Section 4.2 provides information regarding data availability for each parameter.

The first year growth and survival model for fish described in Section 3.2.1 was developed to require a minimal number of inputs: the length of larvae at hatch, water temperature (where eggs and larvae develop), and weight at age 1. Weight at age 1 year is derived from the age 1+ growth model. Other requisite inputs, including egg diameter, are set to default values in the production foregone model, but may be edited where published data exists. Egg diameter is set at 1.5 mm (Pepin 1991).

The production foregone calculations require input of a representative length for the individuals killed (see Section 3.2.1.1.2 for description). The model calculates production foregone per individual for this input size. The production foregone model also calculates production foregone per individual egg, larva at hatch size, and from each annual age class. Lifetime production foregone is the sum of the remaining first-year production (from egg or the input initial larval size) and all subsequent annual size classes.

4.1.1 Early Life History Parameters

Table 4-1 summarizes the early life history parameters required as inputs to the first year survival model, as well as those that may be either calculated in the model or entered based on empirical data or other analyses.

Table 4-1. Early life history parameter inputs to first year survival model.

Parameter	Description	Units	Data Sources
Egg Diameter*	Mean diameter of egg	millimeters	Published literature, empirical equations
Egg Weight*	Mean weight of egg	grams	Published literature
Egg Stage Duration	Length of time between fertilization and hatch (incubation time)	days	Published literature, empirical equation
Egg Mortality Rate	Total mortality rate due to predation, disease, cannibalism, etc.	day^{-1} (instantaneous rate)	Published literature, empirical equation
Larval Size at Hatch*	Mean length of larvae at time of hatch	millimeters	Published literature
Larval Size in Sample*	Modal or other representative length of larvae in the sample	millimeters	SEAMAP ichthyoplankton data (see Section 3.1.2.1), published literature

Parameter	Description	Units	Data Sources
Age of Larvae at Size in Sample	Calculated from length of larvae	days	SEAMAP ichthyoplankton data (see Section 3.1.2.1), published literature
Water Temperature*	Water temperature where larvae develop	degrees Celsius	NODC (see Section 3.1.2.1)
Larval Stage Duration	Length of time between hatch and metamorphosis to juvenile stage	days	Published literature; or calculated (see Section 3.1.2.1 for calculation) from empirical equation
Larval Weight-Length Relationship	Equation relating weight to length of an analysis taxon: $W_t = \alpha\, L_t^{\,\beta}$	α – mg and mm β - unitless	Published literature, empirical equation
Median Spawning Month	Median time of spawning [not used in the calculations]	Month	Published literature, SEAMAP data
Days of age for “Age 1” annual age class	Days of age when recruited to what is evaluated as the first annual age class (age 1)	days	Default is 365 days, may vary based on what is included in “age 1” class

* Required inputs to the model that are not derived through model equations.

4.1.2 Age 1+ Life History Parameters

Table 4-2 lists the model inputs for the age 1+ annual age classes. All of the inputs in Table 4-2 are required, and may be based on other modeling analyses (such as growth or mortality models for animals older than age 1 year). In addition, fecundity data was compiled when possible to evaluate the first year survival model results against those needed to balance the life table, i.e., those inferred if the population or stock is steady state with respect to its age structure. Table 4-3 lists the needed parameters to perform such a life-table (“fecundity”) check.

Table 4-2. Requisite age 1+ life history parameter inputs to production foregone model

Parameter	Description	Units	Data Sources
von Bertalanffy Parameters	Equation relating age to length of an analysis taxon: $L_t = L_\infty\,[1 - e^{(-K\,(t - t_0))}]$ (Alternative growth models may be used for invertebrates, if appropriate.)	L_∞ – mm K – unitless t_0 – year^{-1}	Published literature (see Appendices B and C for data)
Weight-Length Relationship	Equation relating weight to length of an analysis taxon: $W_t = \alpha\, L_t^{\,\beta}$	α – mg and mm β - unitless	Published literature (see Appendices B and C for data)
Natural Mortality (age structured) (M_a)	The part of the total mortality rate that is due to causes other than fishing (e.g., predation, disease, cannibalism, etc.).	Year^{-1} (instantaneous rate)	Published literature (see Appendices B and C for data), stock assessments, calculated (see Section 3.1.3.1 for equation), empirical equation

Parameter	Description	Units	Data Sources
Fishing Mortality (age structured) (F_a)	The part of the total mortality rate that is due to fishing. Fishing mortality is usually expressed as an instantaneous rate, and can range from 0 per year (for no fishing) to high values such as 1.0 or more per year. Fishing mortality reflects all deaths in the stock that are due to fishing, not just those fish that are actually landed.	$Year^{-1}$ (instantaneous rate)	Published literature, stock assessments (see Appendices B and C for data)
Age at Recruitment to Fishery	The age when fish are considered to be recruited to the fishery. In stock assessments, this is usually the youngest age group considered in the analyses; typically age 0 or 1 (ICCAT Manual).(Note, this is inferred by the largest a (age) where F_a = 0.)	Years	Published literature, stock assessments (see Appendices B and C for data)

Table 4-3. Needed fecundity-related life history parameter inputs for completion of a life-table steady state analysis for comparison to the first year survival model included in the overall production foregone model.

Parameter	Description	Units	Data Sources
Fecundity (eggs per female)	Egg production per female (by annual age class or as a function of body weight)	eggs per individual or kg	Published literature; stock assessments
Fraction of females	Fraction in population of interest that is female (by annual age class or as a function of body weight)	Fraction	Published literature; stock assessments
Fraction of females mature	Fraction of females that are mature (by annual age class or as a function of body weight)	Fraction	Published literature; stock assessments

4.2 Life History Parameters Literature Review

4.2.1 Data Sources and Availability of Needed Information

Life history parameters were acquired through extensive literature searches and communication with fishery managers and experts who have studied Gulf of Mexico fish and invertebrates. The primary sources were peer reviewed journal articles sourced from various online databases including Aquatic Science and Fisheries Abstracts (ASFA), Web of Science, and Google Scholar among others. Aside from peer reviewed journals, government agency documents (e.g., FWS species profiles) were utilized when available. Stock assessments from the SouthEast Data, Assessment, and Review (SEDAR) program and The International Commission for the Conservation of Atlantic Tunas (ICCAT) were used to acquire life history parameters. When possible, fishery managers and Gulf of Mexico experts were consulted regarding particular species of interest. Specific agencies contacted include Southeast Fisheries Science Center (SEFSC), Gulf States Marine Fisheries Commission (GSMFC) and NOAA. Additionally, various biological experts from the trustee Aquatic TWG were consulted regarding life history parameters.

Data availability differs greatly among parameters and taxon. A summary of all available life history data is found in Appendix B.

4.2.2 Development of Life History Parameters for Model Input

For many analysis taxa, numerous published values are available for each requisite life history parameter, as summarized in Appendix B. Life history parameter values collected from the literature review come from studies which occurred in varied ecosystems, with differing sampling methodologies, and a wide range of sampling efforts. Additionally, parameters are published in a range of formats, from published journal articles and stock assessments to government documents and government and NGO websites (e.g., fishbase.org). Data quality differs considerably among each of these data sources. With these considerations in mind, in determining data included in Appendix B, fisheries biologists at RPS ASA selected the most appropriate parameter values. Due to the range in quality of data, only species with available stock assessments were considered for analysis. Data was collected primarily from state, federal, and international stock assessments. If these stock assessments did not provide the complete suite of requisite life history parameters, the remaining parameters were selected from all available data based on evaluation criteria. These criteria include scientific rigor of the study (quantitatively with sample size and qualitatively with methodology), gender of samples analyzed (preferentially using data for a mix of genders, then studies on females, and least preferentially studies on only males), relevance of sampling location (e.g., Gulf of Mexico given highest priority, followed by south Atlantic, subtropical North American ecosystems), general agreement with prior published value ranges, and that output of model with the fitted parameters would provide results which agree with empirical data. All available life history parameters for each species and analysis taxon may be found in Appendix B. References cited are in Appendix D.

Not all requisite model input parameters are available for all species or analysis taxon of interest. In the case of missing parameters, proxy values could be used in order to model the species of interest (see *species specific level*). Additionally, when analysis taxa are assessed for production foregone at taxonomies more general than the species level (e.g., genus, family, order) a single set of life history parameters is selected to represent this more general grouping (see *generalized grouping level*). Protocols for assigning these proxy parameters are outlined below.

Species specific level

A portion of injury assessment modeling is being done at the species specific level. Life history parameters are required to model production foregone for each species of interest. If all requisite life history parameters are not available for a species, proxies from other species are assigned. The following protocol is used to assign missing life history parameters based on known parameters from another species:

1. Assign requisite life history parameters from taxonomically related species.
    a. Identify species in the same genus as the species of interest.
    b. If multiple species in the same genus are available with life history parameters, choose species which has most similar body type, maximum size (typically in length) and maximum age. During this step, all three aspects are evaluated evenly. Body types were categorized into eight distinct forms, as described by Barton (2007):
        i. Fusiform (e.g., Scombridae)
        ii. Compressiform (e.g. Centarchidae)

iii. Depressiform (e.g. Rajidae)
iv. Anguilliform (e.g. Anguillidae)
v. Filiform (e.g. Nemichthyidae)
vi. Taeniform (e.g. Pholidae)
vii. Sagittiform (e.g. Esocidae)
viii. Globiform (e.g. Cyclopteridae)

c. If no species with life history parameters of same genus is available, move up to family level proxies and repeat steps a and b.

d. If no species with life history parameters of the same family is available, move up to order level proxies and repeat steps a and b.

2. If no order level proxies exist, assign requisite life history parameters from anatomically and ecologically similar species. Factors of interest in identifying a proxy species include, but are not limited to

    a. Habitat (e.g., reef, deep-pelagic)
    b. Body size
    c. Body shape
    d. Maximum age

Generalized grouping level (analysis taxon)

In some cases, broader taxonomic levels (genus, family and occasionally order) are used as a modeling group of interest in accordance with the taxonomic level of input data (e.g., density) available. When modeling production foregone for a grouping of species at broader taxonomic levels, life history parameters are required to effectively assess these groups of species. However, life history information is not available in published literature in a format generalized across groupings of species, rather it is at the species-specific level. As such, individual species must be used as proxies to represent these broader taxonomic groupings. The following protocol is used to assign life history parameters to analysis taxa consisting of groupings of species:

1. Identify species which make up the broader taxonomic grouping that occur within the density database of interest.
2. Select all species with stock assessments within the broader taxonomic grouping. These species (if available) should have multiple growth and length-weight studies available.
3. Assign all available life history parameters from that species to the larger grouping.
    a. If not all requisite life history parameters are available from this species, proceed to the second most abundant species to utilize needed parameters. Continue until are requisite parameters have been assigned to the larger grouping.

All selected model input parameters, data sources and proxy selections are found in Appendix C (with references cited in Appendix D).

4.3 Applied Life History Parameter Model Inputs

A compilation of all available life history parameter values for each species and taxon of interest is found in Appendix B. Appendix B includes all parameters collected during the literature review process. This includes parameters for which there were multiple values available. In these cases the most appropriate data have been indicated for use as modeling inputs. Additionally, the life history parameter summaries found in Appendix B include indicators where acceptable parameters are not available in literature (e.g., no calculated natural mortality is available for *Haemulidae spp.*). Data in Appendix B includes the following parameters: von Bertalanffy growth parameters, length-weight relationships, age structured natural and fishing mortality, and age at recruitment to fishery.

Appendix C summarizes model input parameters as actually used in the calculation of production foregone for each species or analysis taxon where a model was developed. Life history parameters presented in Appendix C include: von Bertalanffy growth parameters, length-weight relationships, age structured natural and fishing mortality, and age at recruitment to fishery. Proxy species parameters (e.g., where a higher taxonomic group was assigned data for a species within the category and where white shrimp data was applied to other shrimps) have been indicated where used. Appendix D provides the full list of references used.

5 Model Results

5.1 Evaluation of Life Table Model

In order to evaluate the life table results within the production foregone model, in particular the first year survival model, several unique model tests were employed. These tests were used to determine if the full life table population dynamics calculated by each species model is indicating populations in growth, decline, or near equilibrium. Additionally, we evaluated the results of the first year survival model against empirical data derived from species-specific studies.

5.1.1 Models

5.1.1.1 Fecundity Model I

A fecundity-based model was developed to effectively determine the requisite first year survival rate of a species/taxon for that population to be at equilibrium when considering adult stage survival and fecundity. The Fecundity Model I is based on the concept of calculating a replacement ratio of 1 for eggs to age-1 females. The cumulative survival rate from age 1 until maximum age is calculated. The cumulative egg production, corrected for cumulative survival rate during adult age classes is calculated.

$$S_{egg\ to\ age\ 1} = \left(\frac{1}{\sum S_a E_a}\right) \quad \text{eq. 40}$$

where *a* is year of age, starting from age 1 and proceeding through maximum age, S_a is cumulative survival at *a*, and E_a is eggs produced per female of age a.

For the population to be at equilibrium (replacement ratio of 1 for eggs to age-1 females) the survival during the first year of life is equal to the inverse of the survival-corrected cumulative egg production from age 1 to the end of life. Three potential first year survival rates are calculated based on spawning occurring at the beginning of an age class, the end of the age class, or the midpoint of the age class.

5.1.1.2 Fecundity Model II

A second fecundity based model was developed to determine the requisite first year survival rate of a species/taxon for that population to be at equilibrium when considering stage-specific survival and fecundity rates. The Fecundity Model II is based on the concept of calculating a replacement ratio of 1 for eggs hatched to eggs produced. This check is similar to Fecundity Model I. The Fecundity Model II calculates replacement ratio based on an initial number of eggs input to the model. Based on this initial "seed population", survival rates are applied through the end of life. At each age class, egg production is calculated based on the number of surviving egg equivalents and age-based fecundity. This life table results in a cumulative egg production based on the input number of eggs. Spawning is calculated to occur at the midpoint of each age class, with the mean number of individuals surviving to this time based on the exponential mean over each annual age class. A replacement ratio is calculated based on the initial input number of eggs to the cumulative egg production. Subsequently, the requisite first year survival rate for population equilibrium (replacement ratio = 1) is calculated.

5.1.1.3 Matrix Model (Lambda)

A Leslie Matrix Model was used to characterize population dynamics generated by the life table within the production foregone model. Matrix models have been utilized to examine population dynamics since the 1940s (Bernadelli 1941, Leslie 1945). The matrix model (Caswell 1989, Quinlan and Crowder 1999) used herein was designed to evaluate the relationship between stage-based survival rates and fecundity to determine if modeled populations exist in equilibrium, growth, or decline. An age structured matrix was developed with yearly age classes used as the basis of the matrix. This projection matrix allows analysis of population dynamics by examining the effect of first year survival rates on population growth. The key output of the matrix model is the calculation of λ (lamda), representing the population growth rate. Lambda values less than 1 indicates a population in decline, lambda values greater than 1 indicates a population in growth, and a lambda value of 1 is indicative of a population at with stationary abundance.

5.1.2 Results of Life Table Tests

Each of the above model tests of the life table model were conducted for five species of interest; red snapper (*Lutjanus campechanus*), red drum (*Sciaenops ocellatus*), red grouper (*Epinephelus morio*), king mackerel (*Scomberomorus cavalla*), and gulf menhaden (*Brevoortia patronus*). These species were chosen for analysis as they represent species of ecological, commercial, and conservation importance. There also are stock assessments available for these species, where fisheries managers have reviewed and developed appropriate life history parameters and vital rates. Additionally, each of the model checks conducted are highly dependent on annual fecundity data. Research on annual fecundity is limited, even for well-studied species. Each of the species used in this analysis have well documented annual fecundity rates, thus allowing for reliable fecundity-survival relationships. Results from the three analyses are presented below in Table 5-1.

The season column in Table 5-1 represents the season in which the production foregone life table model was run. Because growth rates are variable with temperature, and mortality is variable with size, seasonal fluctuations in temperature influence population dynamics. The Production Foregone Model's Survival column displays the cumulative first year survival rate of the species as calculated by the life table model within the production foregone model. The Fecundity I Requisite Survival for Equilibrium column displays the first year survival rate requisite for population equilibrium as calculated by the Fecundity I model. The Fecundity II Requisite Survival for Equilibrium column displays the first year survival rate requisite for population equilibrium as calculated by the Fecundity II model. The Lambda column displays the lambda value calculated by the matrix model analysis.

Table 5-1. Three Life Table Model checks for five species within the Gulf of Mexico. Survival is cumulative over the first year of life from egg stage.

Species	Season	Production Foregone Model's Survival	Fecundity I Requisite Survival for Equilibrium	Fecundity II Requisite Survival for Equilibrium	Lambda
Red Grouper	Summer	3.42×10^{-7}	4.62×10^{-7}	4.97×10^{-7}	0.98
King Mackerel	Summer	4.69×10^{-7}	4.33×10^{-7}	4.27×10^{-7}	1.03
Gulf Menhaden	Summer	1.75×10^{-7}	6.76×10^{-5}	5.77×10^{-5}	0.27
Red Drum	Summer	3.85×10^{-7}	3.71×10^{-7}	3.62×10^{-7}	1.03

Species	Season	Production Foregone Model's Survival	Fecundity I Requisite Survival for Equilibrium	Fecundity II Requisite Survival for Equilibrium	Lambda
Red Snapper	Summer	2.44×10^{-7}	2.37×10^{-7}	2.27×10^{-7}	1.04

Results from this analysis indicate the life table model is producing populations near equilibrium for four of the five species analyzed, i.e., for red snapper, red drum, red grouper, and king mackerel. The life table generated for gulf menhaden indicates a population in decline. Each of the three life table model checks are in agreement regarding which species are near equilibrium and which are in decline as well as the magnitude of these interpretations. Results from this analysis indicate the life table model within the production foregone model is producing biologically realistic representations of population dynamics.

5.1.3 Comparisons of Modeled Survival Rates to Empirical Data

In addition to the life table model checks presented above, life history values calculated by the life table model (within the production foregone model) were compared to empirical data available in published literature. A literature review was conducted including peer reviewed journal articles, government documents, and stock assessment reports. This was conducted for two species, red snapper and red drum. Parameters analyzed included stage duration, size range, daily and stage mortality rates, and growth rates for each respective early life history stage. Results from this analysis indicate that values for these parameters generated by the life history model fall within the range of empirical data available on the species of interest. Results are presented in Appendix A.2.

5.2 Production Foregone per Individual

The production foregone model calculations are performed in an Excel workbook set up with a single data input sheet for entry of the life history parameters. The model described in Section 3 is applied employing a number of worksheets of calculations in the workbook, and then summarized in tables on several sheets of the workbook. Results of these model applications, as production foregone (g) per individual, by taxon, size and season, are summarized in Appendix E. Copies of each application of the model to the taxa which have or include species with growth models reported in state, federal, or international stock assessments (Table 5-2) and the sizes found in the biological data bases used to quantify baseline (i.e., based on the planktonic fish and invertebrate 2010 Baseline Density Dataset described in French McCay et al. 2015a) are provided in Appendix F. Each of these model applications is an Excel workbook made from a template workbook that contains the entirety of the model. Appendix G provides guidance for navigating the production foregone model workbooks.

The model estimates of production foregone (g per individual over the remaining lifespan) for fish are lowest for eggs and larvae, and increase rapidly by the juvenile stage because of the rapid increase in survival rate with increasing body size. Detailed results may be found in Appendix E and F. Results are summarized as follows:

- Fish embryos: 5×10^{-5} g/individual.
- Newly-hatched larval fish: 5×10^{-5} – 0.1 g/individual.

- Larger larvae: 5×10^{-3} – 35 g/individual, the highest values resulting for fast-growing taxa with large adult body size, such as billfish, large tunas, and mahi mahi.
- Juvenile fish: ~1 to several thousand g/individual, again the larger fast-growing species have the most production foregone per individual.
- Adult fish: The production foregone results for small adult fish with short life spans (e.g., Engraulidae, the anchovies) are similar to the values for juvenile fish. However, for large fish species where stock assessments have been developed, size-at-age estimates could be made. The modeled production foregone for these large fish ranged from 1 to 135 kg/individual.

Table 5-2. List of 29 fish taxa for which production foregone models were applied.

Taxa	Common Name
Balistes	Triggerfish
Balistes capriscus	Grey triggerfish
Balistidae	Triggerfish
Brevoortia	Menhaden
Coryphaena	Mahi mahi (dolphinfish)
Cynoscion	Seatrout
Cynoscion nebulosus	Spotted seatrout
Engraulidae	Anchovy
Epinephelini	Epinephelini grouper
Haemulidae	Grunt
Istiophoridae	Billfish
Katsuwonus pelamis	Skipjack tuna
Leiostomus xanthurus	Spot
Lutjanidae	Snappers
Lutjanus	Lutjanus snapper
Lutjanus campechanus	Northern red snapper
Micropogonias undulatus	Atlantic croaker
Mugil	Mugil mullet
Pomatomus saltatrix	Bluefish
Rachycentron canadum	Cobia
Rhomboplites aurorubens	Vermilion snapper
Sciaenidae	Drums, croakers, and hardheads
Sciaenops ocellatus	Red drum
Scomberomorus cavalla	King mackerel
Scomberomorus maculatus	Spanish mackerel
Seriola	Amberjack
Thunnus	Tuna
Thunnus thynnus	Atlantic bluefin tuna
Xiphias gladius	Swordfish

For some species of fish that grow very large (such as amberjack, large tunas, and mahi-mahi), growth after the larval stage is very rapid and the production foregone represents the majority of the biomass lost (in comparison with direct injury). On the other hand, small fish (e.g., spot, anchovies) do not grow as rapidly and their mortality rates are much higher.

Ratios of production foregone to body weight were calculated for the 29 fish taxa where models were developed. The ratios are summarized for three groups of fish: prey, medium sized, and large pelagic fish (Table 5-3). Note that the ratio of production foregone to body weight of the animal increases the larger the fish size (at age 1 year or maturity), as these species grow faster and have higher cumulative survival rates per individual over their expected lifetime.

Table 5-3. Ratios of production foregone to body weight calculated for the 29 fish taxa where models were developed.

Statistic	Prey, Medium sized or Large Pelagic fish	Ratio Production Foregone (kg) / Body Weight (kg)
Mean	Prey fish	5
	Medium sized	55
	Prey & Medium	51
	Large pelagics	3,584
Maximum	Prey fish	9
	Medium sized	285
	Large pelagics	12,153
Minimum	Prey fish	2
	Medium sized	1
	Large pelagics	545
# of ratios	Prey fish	2
	Medium sized	22
	Large pelagics	5

Invertebrate production foregone was calculated using the growth models of three species: blue crab (*Callinectes sapidus*), white shrimp (*Litopenaeus setiferus*), and spiny lobster (*Panulirus argus*). Each of these invertebrate species either has an available stock assessment and/or is extensively studied. The white shrimp growth model was applied to shrimp taxa that grow to similar size (~100-200mm in length maturing in ~1yr, which includes these superfamilies: Penaeoidea, Oplophoroidea, Pandaloidea and Pasiphaeoidea). This does not include these superfamilies: Sergestoidea, Palaemonoidea, Alpheoidea, Bresilioidea, and Nematocarcinoidea. For crabs, the blue crab growth model was applied to all crabs in the family Portunidae. The spiny lobster growth model was applied to spiny lobsters (i.e., in the family, superfamily and genus: Palinuridae, Palinuroidea and Panulirus), but not to other types of lobsters (which grow at differing rates).

Production foregone of larval decapods ranges from ~5 x 10^{-5} – 1 g/individual. Production foregone of late stage and adult shrimp is on the order of 1 g/individual.

Appendix E lists the input size data used in calculating production foregone and results from the production foregone model. Based on the production foregone model, production foregone per individual increases with the body size of the species (i.e., at age 1 year and as adults). Thus, production foregone per individual is much higher for large pelagic fish than it is for prey fish. The reasons for this relationship are as follows.

The first year of life mortality model employed by the production foregone model is grounded in size-based mortality theory; the larger a marine organism is, the less likely it is to be predated upon. The greatest mortality rates occur during the larval stage when fish are least capable of avoiding predation. Thus, if the larvae are large at the size sampled (due to age of the individuals or to the species), their survival is higher and production foregone from the initial size to age 1 year or over the lifespan is higher.

The second most influential relationship exists between production foregone and weight at age 1 year. Species that grow to greater weights by age 1 year experience reduced mortality rates during the juvenile stage compared to smaller species, because they grow to larger sizes faster, reducing mortality, and resulting in greater production foregone per individual. Note that, in addition, these larger species also have higher survival rates after age 1 year due to larger size, at least until fishing mortality becomes substantial. Thus, the production per individual after age 1 year is also higher for larger species.

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Appendix A. Production Foregone: Comparison of Natural Mortality (M) Models

A.1 Literature Review of Available Natural Mortality Models

Natural mortality rates (M) are required to model production foregone for both early life history stages (<1 year of age) and age 1+ stages of fishes and invertebrates (Section 3.2.2). Natural mortality rates may be derived from published literature values, calculated through catch curves, or estimated via natural mortality models (often empirically derived relationships). A review of these options in consideration with the number and variety of taxa modeled for production foregone led to a decision to utilize available published values of natural mortality, as well as natural mortality estimation models when published values are not available. An extensive literature search was conducted to review available data and resources for estimations of natural mortality rates through mortality models.

Few mortality models have been developed for early life history stages of fish and invertebrates. Below are presented models for egg, larval and juvenile stages of fish and invertebrates.

A.1.1 Fish

A.1.1.1 Fish - Egg Natural Mortality Models

Model: Pepin 1991 for fish eggs

Description: Pepin (1991) developed an empirical model which estimates fish egg mortality based on water temperature. Mortality rates increase with increasing temperature but are independent of size.

Equation: $M = 0.030e^{0.18T}$

(n=32, r^2=0.72, p<0.001)

T – Temperature in Celsius

This model returns M (day^{-1}).

Development: Pepin developed his model from published literature mortality values in two stages. First a relationship was fitted describing the mortality rate as a function of temperature. Secondly, it was determined if the residuals from least squares fit regressions exhibited an isometric or an allometric relationship with egg size. The residuals from regression of the transformed equation were correlated with the log-transformed measure of organism size using both Pearson product moment and Kendall's rank measures of correlation. This is a well cited publication that includes 32 reported egg mortality rates (over a range of temperatures from 4 to 30°C) in the derivation of the above equation. This equation is specific to the egg stage.

Discussion: A limiting factor of this egg mortality model is that it suggests egg size is not a significant contributor to mortality. This concept is in contrast with size-based mortality (suggested for late life stages) as well as the author's own published work (Pepin 1993). However, because egg size data is so limited across a range of taxa, it is difficult to utilize as a model input. Additionally, because stage duration is typically about 1.5 days in the Gulf of Mexico (see Rabalais et al.1980 and Division of Aquatic Resources 2000), differences in duration with egg size among species may not be large. Therefore, this model's reliance on temperature as the only input makes it attractive, as compared to weight-based estimators.

Indeed, temperature is the parameter most closely tied to incubation length, indicating a strong relationship to mortality as a result (Barton 2007). However, surface water temperatures in the Gulf of Mexico in April to September are about 26-29°C, yielding M = 3.2 to 5.5 day^{-1}, which is much higher than many published estimates of egg mortality for Gulf of Mexico species (e.g., red snapper published values range from 0.37 day to 1.04 day^{-1}(e2M 2005); red drum have been estimated at 0.49 day^{-1} (Gallaway 2007). Given the inverse relationship between stage duration and daily mortality in relation to water temperature, total egg stage mortality will not differ greatly depending on season/water temperature. Although egg stage duration increases in cooler temperatures, mortality rates decrease at a similar rate. This leads to similar total stage mortality in comparison with the shorter stage duration but higher mortality rates associated with warmer water temperatures.

Model: McGurk 1986 for fish eggs and larvae

Description: McGurk (1986) published an empirically-derived model that estimates fish egg and larval stage mortality based on dry weight per individual. Mortality rates decrease with increasing egg size.

Equation: $M = 0.00022W^{-0.85}$

(n=74, r=0.58, p<0.001)

W – dry weight in grams

This equation returns M (day^{-1}).

Development: An empirical model developed through linear regression of observed (published literature) $\log_e M$ on $\log_e W$ for fish eggs and larvae.

Discussion: The McGurk (1986) model is based on the concept that size-dependent mortality is the major driver of early life history mortality. McGurk developed this model for both egg and larval stages. It is a well cited publication which includes 22 reported egg mortality rates (n=74 for larval data) based on a range of egg weights from 5×10^{-5} to 8.4×10^{-4} g per egg in the derivation of the above equation. The range of egg mortality rates (*M*) used in the derivation is 0.04 to 0.67 per day, and for an average egg size of 0.296 mg (McGurk 1986), *M* = 0.24 day^{-1}. Size-based mortality estimates are frequently used for later life stages (Pepin 1993). However, egg size availability is limited among a wide range of taxa, making species specific assessment difficult.

A.1.1.2 Fish - Larval Natural Mortality Models

Model: Lorenzen 1996

Description: An empirical model which estimates marine fish mortality based on wet weight. Mortality rates decrease with increasing larval size.

Equation: $M = 3.69W^{-0.305}$

W – wet weight in grams

This equation returns M ($year^{-1}$).

Development: An empirical model developed through nonparametric regression of observed (published literature) $\log_e M$ on $\log_e W$ for marine fish species. Parameter estimates were obtained using the complete Thiel estimator. The Thiel estimate of a parameter is the median of the parameter values obtained from all possible pairs of data points. Confidence limits for the Theil estimate were constructed on the basis of Kendall's tau at the 90% level.

Discussion: The Lorenzen (1996) model is based in size-dependent mortality being the major driver of marine fish mortality. It is a well cited publication which includes all marine fish data from McGurk (1986, 1987), as well as supplementary data on juveniles and small fish species. No significant latitudinal differences (0-30°; 30-60°; 60-90°) were found in the mortality-weight relationship.

Model: McGurk 1986 for fish eggs and larvae

Description: McGurk (1986) published an empirically-derived model that estimates fish egg and larval stage mortality based on dry weight per individual. Mortality rates decrease with increasing egg size. (see also Section A.1.1.1)

Equation: $M = 0.00022W^{-0.85}$

(n=74, r=0.58, p<0.001)

W – dry weight in grams

This equation returns M (day^{-1}).

Development: An empirical model developed through linear regression of observed (published literature) $\log_e M$ on $\log_e W$ for fish eggs and larvae.

Discussion: The McGurk (1986) model is based on the concept that size-dependent mortality is the major driver of early life history mortality. McGurk developed this model for both egg and larval stages. Section A.1.1.1 includes a description of the egg data used in developing the model. The model includes 52 reported larval mortality rates in the derivation of the above equation. The range of larval sizes used in the development was 0.06 – 7 mg, with a range of mortality rates of M = 0.02 to 0.69 day^{-1}. Studies were drawn from a variety of locations ranging from cool temperate ecosystems (e.g., Nova Scotia, Norway) to subtropical ecosystems (e.g., Gulf of Mexico).

The McGurk (1986) model predicts a more rapid decrease in mortality rate with increasing size than other models described herein (e.g., McGurk 1987, Lorenzen 1996 and Pepin 1991), due to the large magnitude of the negative exponent (-0.85, as compared to his 1987 exponent of -0.397 [see below] and the Lorenzen exponent of -0.305). It predicts very high mortality rates (higher than the other models) for newly-hatch larvae 2-3mm in length (0.01 to 0.05 mg, based on the weight-length relationship for fish larvae from Wiebe and Davis 1985, eq. 22). Mortality rates for older larvae (6 - 18mm, 0.3 – 7 mg) are much lower than predicted by the Pepin (1991) model. Mortality rates predicted by the McGurk (1986) model decrease much faster than those predicted by both the McGurk (1987) and the Lorenzen (1996) models that include McGurk's (1986) data and data for larger fish (where the McGurk 1986 model under-estimates the mortality rates). Thus, the exponent of the McGurk (1986) model seems to be too high, when including a larger range of fish sizes (and not including eggs).

Model: McGurk 1987 for fish

Description: In his 1986 paper McGurk developed a size-based mortality regression for all marine organisms. In a reply to this article, Gulland (1987) pointed out that some of the data points used were erroneous. Subsequently, McGurk (1987) published a reply with an updated data set and calculated a size-based regression for fish of all stages. Like his earlier models, this relationship is based in theory that predation rates are related to size.

Equation: $M = 0.00841W^{-0.397}$

(n=165, r^2 = 1.0 (functional regression), p<0.0001)

W – dry weight in grams

This model returns M (day^{-1})

Development: An empirical model developed through linear regression of observed (published literature) $\log_e$ *M* on $\log_e$ *W* for fish eggs, larvae, juveniles, and adults.

Discussion: The McGurk (1987) model is based in size-dependent mortality being the major driver of early life history mortality. This model has been developed for all life stages. It is a well cited publication which includes 165 mortality rates in the derivation of the above equation. The range of fish sizes used in the development was 6.0×10^{-5} to 1.1×10^{5}g, with a range of mortality rates of M = 0.02 to 1.5×10^{-4} day^{-1}. Studies were drawn from a variety of locations ranging from cool temperate ecosystems (e.g., Nova Scotia, Norway) to subtropical ecosystems (e.g., Gulf of Mexico).

Model: Pepin 1991

Description: An empirical model which estimates fish larval mortality based on water temperature and body length. Mortality rates increase with increasing temperature but decrease at a greater rate with increasing body length.

Equation: $M = 0.25e^{0.067T}L^{-0.68}$

(n=32, r^2=0.59, p<0.001)

T – temperature in Celsius

L – length in mm

Model returns M in day^{-1}.

Development: The Pepin (1991) model was developed from published literature mortality values in two stages. First a relationship was fitted describing the mortality rate as a function of temperature. Secondly, it was determined if the residuals from least squares fit regressions exhibited an isometric or an allometric relationship with egg size. The residuals from regression of the transformed equation were correlated with the log-transformed measure of organism size using both Pearson product moment and Kendall's rank measures of correlation. This is a well cited publication which includes 32 reported larval mortality rates in the derivation of the above equation. This equation is specific to the post-larval stage.

Discussion: This is a well-developed larval mortality model. This empirical model suggests much lower mortality rates for very small (<3 mm) sized larvae, and higher mortality rates for larger larvae, than does the McGurk (1986) model. The range of input data used by Pepin to calculate the empirical model was 1.6 – 57.5mm larvae, a broader range of sizes than used by McGurk (1986).

Model: Houde and Zastrow 1993

Description: There are strong relationships between temperature and vital rates of marine fish larvae, including mortality rates. Houde and Zastrow regressed temperature on published mortality rates to calculate an equation for this relationship.

Equation: $Z = 0.0149 + 0.0129T$

(n=33, r^2=0.38, p<0.0001)

T – temperature in Celsius

Model returns M in day^{-1}.

Development: Published sources of larval M and water temperature for marine fish species were obtained by the authors. The strong temperature dependencies of rates and properties for larvae were adjusted by analysis of covariance to allow mean values to be compared among taxa. A regression relationship between temperature and mortality rates was calculated.

Discussion: Houde and Zastrow acknowledge that mortality rates in early life history stages are dependent on body size (Peterson and Wroblewski 1984; McGurk 1986). However, they suggest temperature affects body size to such a degree that temperature may be used to estimate mortality. It is a well cited article which polls 33 marine fish larvae studies. However, the lack of dependence on larval size makes this model less desirable than the above-described models.

Model: Peterson and Wroblewski 1984

Description: The Peterson and Wroblewski (1984) model is an early attempt at a size-dependent mortality of fish sized organisms, derived using preexisting theory on the distribution of biomass as a function of size, assuming mortality is primarily due to predation.

Equation: $M = 0.00525W^{-0.25}$

W – dry weight in grams

This model returns M (day^{-1}).

Development: The Peterson and Wroblewski allometric relationship is derived by working through numerous equations representing the theory that organism size is the primary determinant in mortality. The model is not fit based on literature values, but is rather based in theory. The model represents an estimate of mortality for marine organisms of all sizes (microscopic plankton through whales). It is not specifically tailored to fish and invertebrate larvae.

Discussion: The general concept of size-based mortality has been confirmed in subsequent publications. However the intercept and power value have been honed using actual study values in succeeding years for fish species (McGurk 1986, 1987; Lorenzen, 1996).

A.1.1.3 Fish - Juvenile and Adult Natural Mortality Models

A detailed compilation and review of adult natural mortality estimators may be found in Kenchington (2014).

Model: Lorenzen 1996

Description: See description in Section A.1.1.2

Model: McGurk 1987 for fish

Description: See description in Section A.1.1.2

Model: Bayliff 1967

Description: Bayliff (1967) published a linear regression fitting the relationship between Z and T_{max} for six species of Engraulidae.

Equation: $Z = \frac{6.384}{T_{max}}$

T_{max} – maximum age

Development: Growth and mortality data for *Cetengraulis mysticetus, Anchoa naso, Engraulis mordax,* E. *ringens,* E. *anchoita,* E. *encraslcbolus,* E. *japonicus,* and E. *australis* were assembled and compared. A linear regression was fit to the data.

Discussion: The early empirical study is only relevant for Engraulidae species in the Pacific due to its input data. Additionally T_{max} is often unknown or uncertain, even for well-studied species.

Model: Hoenig 1983

Description: Hoenig (1983) published a geometric mean regression of T_{max} on natural mortality from 84 fish populations.

Equation: $Z = 2.214T_{max}^{-0.767}$

Development: This work built on the prior theories of Ohsumi (1979) and Bayliff (1967). Dr. Hoenig used a regression to explore the relationship between maximum age and natural mortality. /The presented equation is developed from a geometric mean regression.

Discussion: This equation is completely based on the highly uncertain maximum age parameter, making this estimator difficult to apply across a broad range of species and taxon.

Model: Hewitt and Hoenig 2005

Description: Building on Hoenig's earlier work, with an increased data set, Hewitt and Hoenig (2005) honed a maximum age-mortality relationship.

Equation: $M \approx \frac{4.22}{T_{max}}$

Development: Maximum age in this relationship is defined as when 1.5% of the population of a species is still alive.

Discussion: This research is based on decades of research and a large number of studies. It is often cited. As mentioned in other studies, T_{max} is often unknown or unreliable. Hewitt and Hoenig address this concern by defining T_{max} as the age when 1.5% of the population remains. However, this assumption may not be reliable, particularly among highly fished and non-fished species.

Model: Sekharan 1975
Description: Sekharan(1975) published a T_{max} based equation. Maximum age in this study is defined as when 1% of a species (small tropical fish in this study) population remains alive.
Equation: $M \approx 4.6 * T_{max}$
Development: Derived from an equation relating maximum age to natural mortality by forcing survival to maximum age to 1%.
Discussion: This equation is theoretical and is only applicable to small tropical fish. This equation was later expanded by Alagaraja (1984).

Model: Holt 1965
Description: Holt (1965) published a theoretical equation that estimates total mortality based on maximum age of a population, or sub-population, that corrects for sample size when approximating maximum age.
Equation: $Z = \frac{\ln(n)+0.577}{T_{max}-t_c}$
t_c – maximum observed age in sample
Development: Holt based this equation on the assumption of an exponential mortality model.
Discussion: Holt and Hoenig updated and expanded this relationship in later decades.

Model: Alverson and Carney 1975
Description: Alverson and Carney (1975) developed an equation to estimate yearly natural mortality rates in fish based on theoretical mortality and growth assumptions from Beverton and Holt (1956). Their equation includes assumptions of a von Bertalanffy growth curve with t_0=0, a traditional exponential natural mortality model, and an assumption of isometric growth.
Equation: $M = \frac{3K}{e^{K0.38T_{max}}-1}$
K – Brody coefficient from the von Bertalanffy equation
(n=63)
Development: Alverson and Carney developed an empirically derived equation fit on 63 adult fish populations. Their method includes a correction equation for accounting for sample size in determining T_{max}.
Discussion: As noted in other studies, T_{max} based mortality equations, even with sample size corrections, are difficult to implement, as maximum age is often unknown or uncertain.

Model: Zhang and Megrey 2006
Description: Zhang and Megrey (2006) revisited the Alverson and Carney (1975) empirically derived relationship, with the same model assumptions in place, but an increased sample size. This allowed for a more accurate derivation of an empirical model.
Equation: $M = \frac{\beta K}{e^{K(t_{mb}-t_0)}-1}$
T_{mb} = $0.44T_{max}$ for demersal fish and =$0.302T_{max}$ for pelagic fish
(n=91)
Development: Zhang and Megrey developed their model with a regression of T_{max} on natural mortality. The Brody coefficient from the von Bertalanffy equation is used as a scalar.

Discussion: As noted in other studies, T_{max} based mortality equations, even with sample size corrections, are difficult to implement, as maximum age is often unknown or uncertain.

Model: Rikhter and Efanov 1976
Description: Rikhter and Efanov (1976) developed a T_{max} based equation to calculate annual natural mortality for fish species with allometric growth.
Equation: $M = \frac{1.521}{t_m^{0.72}} - 0.155$
t_m – age at 50% maturity
Development: Rikhter and Efanov (1976) developed their model based on assumptions of the Alverson and Carney (1975) natural mortality estimation equation. The researchers removed the inclusion of the Brody coefficient by developing a standard numerator for all fish species with allometric growth.
Discussion: As noted in other studies, T_{max} based mortality equations, even with sample size corrections, are difficult to implement, as maximum age is often unknown or uncertain. The theory presented in this equation was further developed by Zhang and Megrey (2006)

Model: Chen and Watanabe 1989
Description: Chen and Watanabe (1989) developed an age based equation for the estimation of natural mortality in immature fish populations. The researchers sought to develop a relationship that captured high mortality at young age classes as well as high senescence in old age.
Equation: $M(t) = \frac{k}{1-e^{-k(t-t_0)}}$
This equation only applies for $t<t_m$
t_m – age at maturity
t_0 – from von Bertalanffy growth function
k – Brody coefficient from von Bertalanffy growth function
A second stage equation is used for mature ($t>t_m$) fish populations.
Development: Chen and Watanabe (1989) developed this model based in the concept that M is inversely proportional to their growth equation. This equation was not empirically derived, or based in evolutionary theory as many of the other natural mortality estimators that are presented in this review were.
Discussion: This model has seen little application by other researchers. It does produce the U-shaped curve the authors were attempting to capture for some parameter estimates (theoretical fish populations), but not for others.

Model: Jensen (first) 1996
Description: Jensen developed his "first" model to estimate natural mortality in fish populations based on earlier research into the relationship of maximum age and natural mortality by Charnov and Berrigan (1990). That research estimated that female t_m averaged 45% of T_{max} for both fish and shrimp.
Equation: $M = 1.65t_m$

Development: Jensen expanded upon the model presented by Charnov and Berrigan (1990) by suggesting that the age of reproductive maturity in a fish is about the age of the inflexion point in the von Bertalanffy curve as well as the age of maximum biomass of a year class in the absence of fishing.
Discussion: The Jensen 1996 method is occasionally cited in published articles. Age at maturity (50%) is generally available for fish species.

Model: Alagaraja 1984
Description: Alagaraja (1984) developed a model to estimate natural mortality in fish populations based on the age at which a fish species reaches its asymptotic length (from the von Bertalanffy equation). Alagaraja avoids using the T_{max} parameter because it is usually unknown, whereas von Bertalanffy equations are usually better understood for many fish populations.
Equation: $M \approx \frac{4.6}{T_\infty}$
T_∞ -Age at which fish reaches asymptotic length from the von Bertalanffy equation.
Development: Alagaraja assumed that T_∞ is found at 5mm < T_{max}. Additionally this relationship assumes that between 1 and 5% of individuals would survive to T_∞.
Discussion: The two assumptions presented by Alagaraja (1984) are questionable and based in general theory with little supporting evidence.

Model: Pauly and Binohlan 1996
Description: Pauly and Binohlan (1996) developed an empirical linear regression of natural mortality in fish populations on the Brody coefficient (*K*) for 29 populations of snappers and groupers. This equation and theory is an update of a publication from Ralston (1987).
Equation: $M = -0.1778 + 3.1687K$
Development: Pauly and Binohlan compiled von Bertalanffy parameters for 29 species of snappers and groupers from fishbase.org and computed a linear regression for M on K.
Discussion: This equation is dependent upon the reliability of the von Bertalanffy curves and mortality derived from fishbase. This relationship is only applicable for snappers and groupers.

Model: Jensen (second) 1996
Description: Jensen (1996) built upon his earlier relationship (Jensen's "first" 1996), but based this relationship on evolutionary theory instead of a regression equation.
Equation: $\frac{M}{k} = 1.5$
Development: Jensen confirmed this theoretical relationship and equation by calculating a similar regression relationship based on 175 species from Pauly (1980).
Discussion: Jensen's "second" equation has been used in various published articles. It is dependent on the reliability of the von Bertalanffy relationships of a species.

Model: Cubillos et al. 1999
Description: Cubillos et al. (1999) applied Hoenig's 1983 mortality estimator, but substituted a calculated age at 95% L_∞ for the observed T_{max}.

Equation: $M = 4.31 T_{95\%}^{-1.01}$

$$T_{95\%} = t_0 - \frac{\ln(0.05)}{K}$$

Development: Cubillos et al. built upon the Hoenig 1983 method, but substituted the age based parameter. The researchers developed a calculation to determine a generic estimate of $T_{95\%}$.
Discussion: This equation is highly dependent on K to determine the value of $T_{95\%}$. This equation is not frequently used in published research.

Model: Pauly 1980
Description: A multiple regression equation developed based on M, L_∞,K and temperature.
Equation: $M = L_\infty^{-0.28} K^{0.654} \tau^{0.463}$
L_∞ - from von Bertalanffy equation
K – Brody coefficient from von Bertalanffy coefficient
τ – mean environmental temperature (°C) at fish location
An alternative equation is offered based on asymptotic weight in grams
$M = 0.6156 W_\infty^{-0.0824} K^{0.6757} \tau^{0.4627}$
Development: Pauly developed a multiple regression equation based on data from 175 fish populations from arctic, temperate, and tropical environments. Pauly developed this relationship for both length and weight based sizes of fish.
Discussion: These equations are occasionally utilized in published literature. Like other von Bertalanffy based equations, this method is highly sensitive to those parameters. This method utilizes what could be considered a temperature correction factor which is a concept rarely accounted for in natural mortality studies.

Model: Gislason 2010
Description: Gislason (2010) explored the assumption that the natural mortality of exploited fish populations is a species-specific constant independent of body size (size dependent mortality is a concept generally accepted by many researchers and is the central concept of many of the models presented in this review). The researchers critically reviewed empirical estimates of natural mortality of marine and brackish water fish stocks and modeled them as a function of von Bertalanffy growth parameters, temperature and length (temperature was not found to be a significant contributor to M).
Equation: $\ln(M) = 0.55 - 1.61\ln(L) + 1.44\ln(L_\infty) + \ln(K)$
L – current length (cm)
L_∞ - from von Bertalanffy equation
K – Brody coefficient from von Bertalanffy equation
(r^2=0.62, p<0.0001, n=168)
Development: Gislason collected empirical estimates of M from available literature. These estimates were studied and many studies were rejected from inclusion based on a specific protocol. Numerous models were tested to find the significant relationship which explained the most variance in M estimates. This was accomplished using the Arrhenius equation.

Discussion: This recently developed model has seen little practical application. However, this study includes much increased sample sizes of empirical estimates of M from earlier studies. This study builds on the work of many earlier studies, including McGurk (1986) and Lorenzen (1996).

Model: McCoy and Gillooly 2008

Description: McCoy and Gillooly (2008) used newly-developed ecological theory and data to address the factors that control natural mortality rates across a diverse range of species, including marine fish. They test a model that yields predictions of rates of natural mortality, based on the body size and temperature dependence of individual metabolic rate. Two separate equations were developed, one a body-mass corrected mortality, and another temperature corrected mortality.

Equation A: $\ln\left(Zm^{\frac{1}{4}}\right) = -0.57 * \frac{1}{k}\left(\frac{1}{T} - \frac{1}{T_{20°C}}\right)$

This is developed for fish and invertebrates. It is the predicted temperature dependence of body mass corrected natural mortality rates.

Z – natural mortality

m – body mass (dry g)

k - Boltzman's contant ($8.62x10^{-5}$ eV K^{-1})

T – absolute temperature in degrees Kelvin

$T_{20°C}$ – standardization temperature (i.e. 293°)

(regression: $F_{1,430} = 368.69$, $p<0.0001$, $r^2 = 0.46$)

Equation B: $\ln\left(Ze^{\left(\frac{E}{k}\left[\frac{1}{T}-\frac{1}{T_{20°C}}\right]\right)}\right) = -0.27\ln(m) + 1.17$

This equation is developed for fish species only. It is for the predicted mass dependence of natural mortality rates.

E – average activation energy of heterotrophic respiration in animals (c. 0.6-0.7 eV)

(regression: $F_{1,210} = 2883$, $p<0.0001$, $r^2 = 0.58$)

Development: McCoy and Gillooly collected data on natural mortality rates, average adult body mass and body temperatures from published literature and available studies. ANCOVAs were used to test for differences in the slopes and intercepts of the relationships among groups. Secondly, ordinary least-squares regressions were used to determine how much of the variation in natural mortality rates within each group can be explained by body size and temperature dependence.

Discussion: This research has been praised by researchers from outside the fisheries realm, as it utilizes ecological concepts not usually implemented by fisheries ecologists. However, though recent, this relationship has seen little practical application. The use of "average adult body mass" as the mass unit of interest may not be the most appropriate method to test for body mass dependence.

Model: Gunderson and Dygert 1988

Description: Gunderson and Dygert (1988) developed their model based on earlier studies (Myers and Doyle 1983, Gunderson 1980) that related reproductive effort (gonadal somatic index) to natural mortality rates. The theory this model is based on suggests that species that assign greater effort to reproductive efforts experience greater rates of natural mortality such that populations may remain at or near equilibrium.

Equation: $M = 0.03 + 1.68GSI$

GSI – gonadal somatic index

Development: Gunderson and Dygert developed a simple multiple regression relating gonadal somatic index to natural mortality from available published rates.

Discussion: Gonadal somatic index across a wide range of taxa is not readily available. The authors found that the reproductive index was superior to any of the other life history parameters they assessed (these included von Bertalanffy parameters, age at maturity and maximum age).

Model: Peterson and Wroblewski 1984

Description: See description in Section A.1.1.2

A.1.2 Invertebrate – Natural Mortality Models

No distinctions are made by each of the models described below as to stage discretion.

Model: McGurk 1987 for small pelagic crustaceans

Description: An empirical model which estimates pelagic crustacean stage mortality based on dry weight. Mortality rates decrease with increasing organism size. This model is built on data from copepods and euphausiids and may not be accurate for larger or demersal crustaceans.

Equation: $M = 0.000142W^{-0.537}$

W – dry weight in grams

This model returns M (day^{-1})

(n=21, r^2=1 *functional regressions assume r=1*, p=0.0001)

Development: McGurk (1987) developed an empirical model through linear regression of observed (published literature) $\log_e$ *M* on $\log_e$ *W* for pelagic crustaceans. Size range of pelagic invertebrates used in the development model is 4.2×10^{-7} to 1.5×10^{-3} g, i.e., small zooplankton.

Discussion: The McGurk (1987) model is based in size-dependent mortality being the major driver of early life history mortality. This model has been developed for only small pelagic crustaceans. It is a well cited publication which includes 52 reported mortality rates in the derivation of the above equation.

Model: McGurk 1987 for marine organisms

Description: A size-based mortality model for all marine organisms based on dry weight. Mortality rates decrease with increasing organism size.

Equation: $M = 0.00713W^{-0.301}$

W – dry weight in grams

This model returns M (day^{-1})

Development: McGurk (1987) developed an allometric model for general application to marine organisms of all size, from plankton to whales. He utilized all available datasets, including those used in the fish and crustacean regressions. Regression includes 198 studies ($p<0.0001$).

Discussion: The McGurk (1987) marine organism model is based in size-dependent mortality being the major driver of early life history mortality. Majority of organisms used to build regression include bacteria, crustaceans, fish, and whales. The functional regression (assuming an $r = 1.0$) is presented here. Data was updated from McGurk 1986. The values presented here may be used to represent the daily natural mortality of all marine pelagic organisms.

Model: Peterson and Wroblewski 1984

Description: See description in Section A.1.1.2

Model: McCoy and Gillooly 2008

Description: See description is Section A.1.1.3

A.1.3 Catch Curve Analysis

In addition to the above literature review that examines published estimates and models of mortality rates, catch curve analysis was evaluated as a potential method to estimate mortality rates of early life history stages (i.e., over the first year of life) and older age classes. The conclusion of our evaluation was that sufficient data for the many fish and invertebrate taxa affected by the spill were not available to perform such analyses, and therefore catch curves are not directly utilized for the estimation of mortality rates in the production foregone model. However, the statistical models relating mortality to body size and other parameters utilize literature estimates, some of which are based on catch curve analyses. The sections below provide review of the approach and further discussion.

A.1.3.1 General Catch Curves

Catch curves, or frequency at age distributions, have been used to assess vital statistics of fish populations for over a century (Edser 1908; Ricker 1975; Pauly 1980). If age-frequency data are available, the estimation of mortality may be accomplished through the production and analysis of catch curves. The basic principle of catch curve mortality analysis is that the decrease in frequency/abundance from one age group to the next reflects the combined effect of mortality and the difference in initial class strength for the two age groups (Robson and Chapman 1961). Catch curve analysis is used to estimate total mortality by observing the regular decline of individuals in a cohort (see Vetter 1987 for review). This is generally accomplished by using growth equations to convert length frequency (available from catch data) to age frequency and then estimating the mortality rate from the decrease in abundance of successively older age classes (Robson and Chapman 1961; Comyns 1977; Houde 1987). This methodology requires extensive field efforts to adequately account for the significant spatiotemporal variability in the abundance of fish (Taggart and Legget 1987), to accomplish sampling with large enough geographical coverage to minimize the confounding effects of immigration and emigration within the study area, and to spatially average out the potential mosaic of localized spawning grounds or aggregations.

The basic premise behind catch curve analysis, using age-frequency distributions to estimate mortality rates, is that the decrease in abundance of successively older age classes is due to mortality. However, decreases in abundance of fish over time seen in field studies may also be affected by sample size, sample number, sample spatial configuration, spawning frequency, and spawning intensity prior to sampling. One of the assumptions of using catch curves is that the supply of fish to the study area is somewhat constant, and this assumption cannot be met if there are large fluctuations in spawning frequency, intensity or location prior to sampling. The assumptions for the Chapman-Robson survival estimate are constant survival for all age classes and all years (total mortality rate is independent of age and year), a stable age distribution, a stationary population (no emigration or immigration), equal catchability for all fully vulnerable age classes and an unbiased sample (not biased regarding any specific age-group). As might be expected, these assumptions are difficult to meet in most studies, either due to sampling design, or inherent characteristics of oceanography and fish populations.

The datasets used to develop the Gulf of Mexico Fish and Invertebrate 2010 Baseline Density Dataset (described in French McCay et al. 2015c) do not meet most of the requirements necessary to accurately calculate mortality from catch curves for fish populations from available data across a wide range of taxa. These surveys were not explicitly designed to address the research question of stage/age based mortality. Due to the inability to utilize species specific catch curve analyses to determine natural mortality of fish and invertebrate species from our available datasets, the literature-based mortality estimator equations are utilized in the production foregone model. A majority of the inputs used to calculate the mortality estimator equations were originally derived from well-designed catch curve based studies.

A.1.3.2 Larval Catch Curves

Among the concerns with the catch curve methodology as it relates to larval samples is the requisite age composition of the catch (either by direct aging methods or by application of a growth curve equation). As larval M is often estimated on a daily time scale, inaccuracies in the age of fish by as little as a day may adversely affect the results of the estimation. Other options for assigning age at length included a probability age-classification matrix (Scott et al. 1993) and discriminant analysis. However, these methods have been found to be ineffective in samples with few aged larvae (as is the case with the SEAMAP data). Any aging errors will be reflected in the catch curves and subsequently M estimate. Gledhill and Lyczkowski-Shultz (2000) note that "larval abundance has not been used in the past for stock assessments because larval catches had not been adjusted for age. Inter-annual differences in age composition of sampled larvae could contribute a large amount of variation in estimates of mean annual abundance because of the exponential decline in numbers of larvae with age."

Another catch curve analysis concern is related to the difficulty in obtaining representative samples from the population (even for only the larval stage). Bongo and MOCNESS nets are to some degree size/age selective. Each species' vulnerability (to catch) changes rapidly as larvae age, making a representative sample difficult to establish. Comyns (1977) suggests that smaller size classes may not be fully represented in each sample due to a lack of availability (due to spatiotemporally-explicit spawning locations). Additionally, larger fish larvae are capable of behavioral avoidance of gears causing reduced catchability at post-flexion lengths (Comyns 1977). Morse (1989), as well as others, have noted that when the whole water column is fished with a bongo net, catches at the same site during the night are typically higher than during the day. This indicates that larval fish use visual cues to sense the approaching net and will then avoid it if possible, hence vulnerability due to behavioral avoidance (V_B) < 1. Morse (1989) also found that the degree to which ichthyoplankton can sense the approaching net depends more specifically on the amount of light available; catches were highest during the darkest hours of the night. Somarakis et al. (1998) had similar findings: night catches were greater than day catches. However, they noted that this trend didn't appear until larvae are capable of notochord flexion (for the European anchovy in the study, flexion starts at ~ 6.5 mm). Underestimating the large larval size classes will affect M calculations by over-estimating mortality rates. Ensuring this representative sample is critical for the accurate estimation of M based on catch curves.

Comyns (1977) suggests that the most precise overall estimate of average mortality rate from catch curves of a species is probably obtained by combining catch data from large amounts of data from numerous cruises, when ambient conditions are somewhat similar. It is most important to account for water temperature (he used cruises where the sampled water was 28-30 C), because in order to estimate an overall mortality rate, the same overall growth equation is needed to convert size-frequency abundance to age-frequency.

Catch curves would effectively provide the most accurate calculation of larval stage mortality if these data limitations could be addressed. Given the lack of sufficient data within the SEAMAP dataset used in the density and production foregone models for fish and invertebrate taxa, larval catch curves are not utilized for the estimation of mortality rates. Published models of mortality rates related to body size are utilized (as discussed in the main report, Section 3.2). The mortality inputs used for the derivation of the larval mortality estimator equations in the published literature reviewed above (Sections A.1.1. and A.1.2) are primarily drawn from catch curve analyses.

A.2 Evaluation of Life Table and First Year Survival Models used in Production Foregone Calculations

A.2.1 Fish – First Year Survival Model Comparisons

Available larval and juvenile mortality models were evaluated by comparing estimates of cumulative survival through the first year. "Back-to-back" (i.e., larval, followed by juvenile) models assessed are listed in Table A-1. The models selected for analysis were based on the model selection criteria outlined in Section 3.2.1.1. The models presented here represent those that best satisfied those selection criteria and required further testing to confirm their efficacy and accuracy.

Table A-1. "Back-to-back" first year survival models that were compared. See Section A.1 for more in-depth discussion of each model.

ID	Larval Model	Juvenile Model
I	Lorenzen (1996)	Lorenzen (1996)
II	McGurk (All Stages) (1987)	McGurk (All Stages) (1987)
III	Peterson and Wroblewski (1984)	Peterson and Wroblewski (1984)
IV	McGurk (Larval) (1986)	Lorenzen (1996)
V	McGurk (Larval) (1986)	McGurk (All Stages) (1987)
VI	McGurk (Larval) (1986)	Peterson and Wroblewski (1984)
VII	Pepin (1991)	Lorenzen (1996)
VIII	Pepin(1991)	McGurk (All Stages) (1987)
IX	Pepin(1991)	Peterson and Wroblewski (1984)

Examples in this section are drawn from several species and season combinations:

- red snapper (*Lutjanus campechanus*) — spring season;
- red snapper (*Lutjanus campechanus*) — summer season;
- red drum (*Sciaenops ocellatus*) — summer season;
- skipjack tuna (*Katsuwonus pelamis*) — spring season.

Relationships among the back-to-back models presented here are representative of other fish species. The magnitude of difference in stage-based cumulative survival rates is similar among a wide range of species. Results for all taxa are available in the Excel workbooks in Appendix F. Cumulative survival rates to age 1 year are summarized in Appendix E for the back-to-back model selected for the production foregone model: the Pepin (1991) larval mortality model, followed by the Lorenzen (1996) model for juvenile fish.

Cumulative survival is presented in both graphical and tabular format. Table A-2 summarizes the cumulative survival to age 1 year predicted by each back-to-back model for the example species. Figures A-1 and A-2 display comparative cumulative survival rates for red snapper (spring) using various back-to-back models for the first year of life (Figure A-1) and for the first fifty days of life (Figure A-2). Each back-to-back model produces an exponential decrease in cumulative survival over time. It is the magnitude of this decrease that distinguishes each respective model.

Table A-2. Cumulative survival rates through the first year of life (from hatch to 365 days of age) for various first year survival models.

ID	Model (Larval-Juvenile)	Red Snapper (spring)	Red Snapper (summer)	Red Drum (summer)	Skipjack Tuna (spring)
I	Lorenzen – Lorenzen	3.80×10^{-3}	6.87×10^{-3}	1.09×10^{-2}	5.28×10^{-3}
II	McGurk (all fish) – McGurk (all fish)	5.45×10^{-6}	2.81×10^{-5}	6.29×10^{-5}	9.90×10^{-6}
III	Peterson – Peterson	2.70×10^{-2}	3.68×10^{-2}	5.02×10^{-2}	3.36×10^{-2}
IV	McGurk (larvae) – Lorenzen	2.88×10^{-8}	3.49×10^{-7}	5.52×10^{-7}	4.00×10^{-8}
V	McGurk (larvae) – McGurk (all fish)	3.29×10^{-9}	5.43×10^{-8}	1.22×10^{-7}	5.99×10^{-9}
VI	McGurk (larvae) – Peterson	7.02×10^{-8}	7.68×10^{-7}	1.05×10^{-6}	8.74×10^{-8}
VII	Pepin – Lorenzen	3.03×10^{-7}	3.09×10^{-7}	4.89×10^{-7}	4.58×10^{-7}
VIII	Pepin – McGurk (all fish)	3.77×10^{-8}	4.80×10^{-8}	1.08×10^{-7}	6.85×10^{-8}
IX	Pepin – Peterson	8.03×10^{-7}	6.80×10^{-7}	9.29×10^{-7}	9.99×10^{-7}

The Peterson and Wroblewski (1984) mortality model, when applied for both the larval and juvenile stages produces the most outlying cumulative survival results presented in this analysis, ~3-5% survival from hatching to age 1, Table A-2). The Lorenzen model used for both larval and juvenile fish results in cumulative survival rates to age 1 of 0.4-1%. Both these models, used from hatch, predict cumulative survival rates to age 1 that are several orders of magnitude greater than predicted by other models examined and required to maintain populations near equilibrium (See Section 5.1.2). The high cumulative survival rates are in large part due to the weight exponent (-0.25 for Peterson and Wroblewski model, -0.305 for the Lorenzen model) used which results in greater survival rates during the larval stage. Since the Peterson and Wroblewski model is a general size-dependent mortality model for a variety of organisms, derived using theory on the distribution of biomass as a function of size, whereas the other models are empirical, based on data for fish larvae, juveniles, and adults, the Peterson and Wroblewski model was not considered further or used in the production foregone model.

Among the other three models used in this analysis for the larval period (McGurk 1986 larval, McGurk 1987 all fish, Pepin 1991 larval), distinct differences exist in survival rates during the first fifteen days of life (Figure A-2) with the McGurk 1987 all-fish model producing the greatest survival rates, the McGurk 1986 larval model producing the lowest survival rates and the Pepin model falling between these other two but close to the McGurk 1987 all-fish model. Because survival rates estimated by each of these models are so low, by day fifteen (Figure A-2), cumulative survival rates become close in magnitude for each of the three models analyzed. When the larval phase models are combined with any of the juvenile phase models, the cumulative survival falls within an order of magnitude of each other by the end of the first year of life (Table A-2). However, the McGurk 1987 all-fish model run from hatch to age 1 year results in slightly higher cumulative survival rates, which would suggest the populations are increasing (Section 5.1.2), an unlikely result given the fishing rates on these species.

The juvenile model has much less influence on the final first year cumulative survival rates than does the larval model. This is due to the greater mortality rates during the larval stage, as well as the low cumulative survival rates produced by the end of the larval stage which feed into the juvenile model.

As noted, most back-to back models produce results for the first year (Table A-2) that generally fall within an order of magnitude or so of each other (excepting the Peterson-Peterson and Lorenzen-Lorenzen models, as previously discussed). Additionally, the results produced by each of these models falls generally within the range of available estimates of mortality during the first year of life (Tables A-3 to A-5). First year life mortality rates and sizes at specific ages calculated by the life table in the production foregone model were compared with data available in published literature and government documentations. An in depth literature review on this topic was conducted for red snapper and red drum. Results are presented in Tables A-3 and A-4.

With these considerations in mind, model selection for the first year survival model was made based on the original model selection criteria. From these selection criteria, the most thorough (sample size, scientific rigor), recent, and relevant (sample species and locations) models were selected for implementation in the production foregone model: the Pepin (1991) model for the larval stage, combined with the Lorenzen (1996) model for the juveniles up to age 1 year. This back-to-back model results in cumulative first year survival rates from hatch of 3-5 x 10^{-7} for the species listed in Table A-2, which is consistent with populations with near-stationary abundances (Section 5.1.2). Appendix E contains tables listing cumulative first year survival rates from hatch for all the species examined; the results are generally 0.5-5 x 10^{-7}.

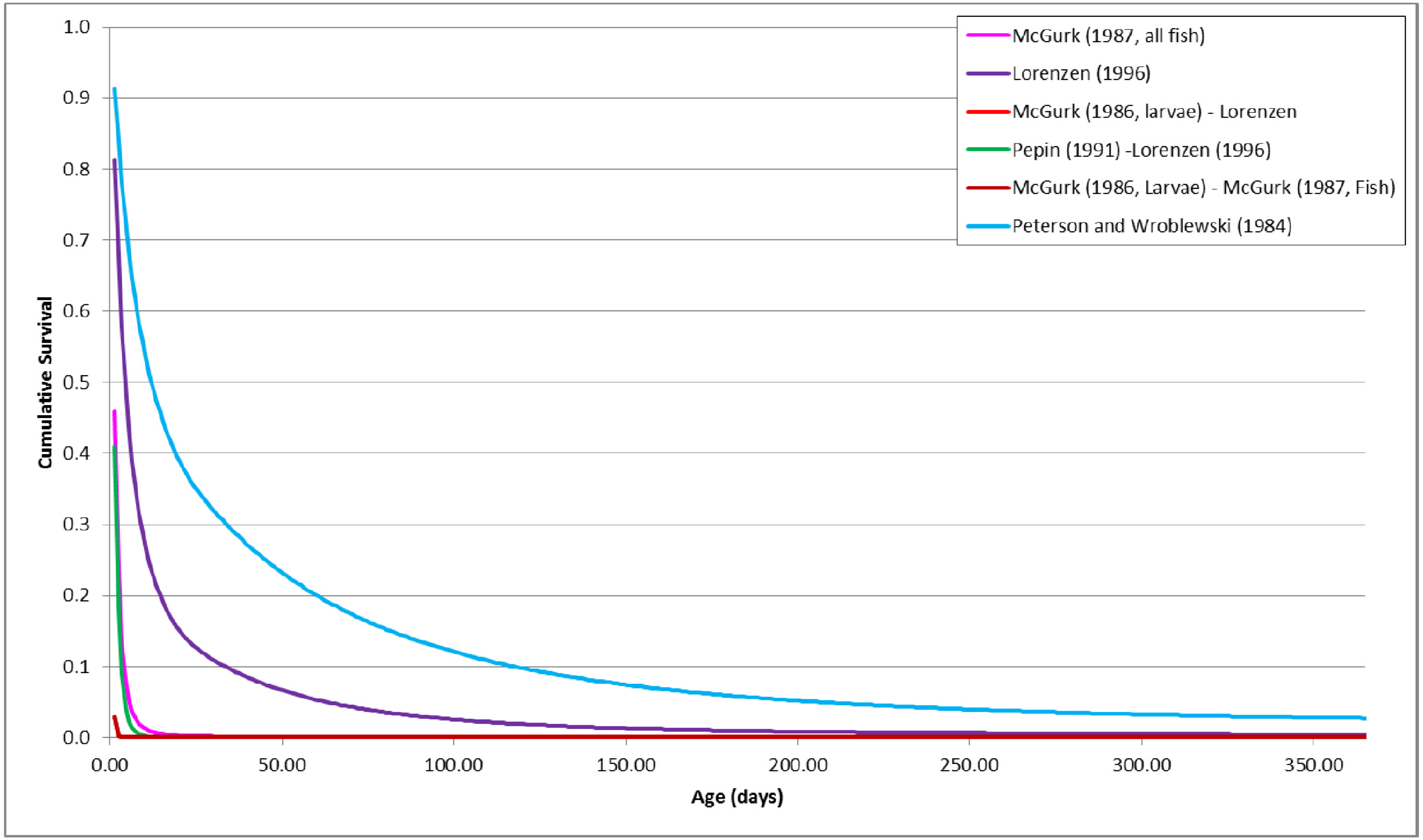

Figure A-1. Comparison of first year mortality models for red snapper (spring) with hatch length of 2 mm. Each model is plotted from hatch to 365 days. (McGurk 1986 larvae-Lorenzen 1996 is indistinguishable from McGurk 1986 larvae-McGurk 1987 fish).

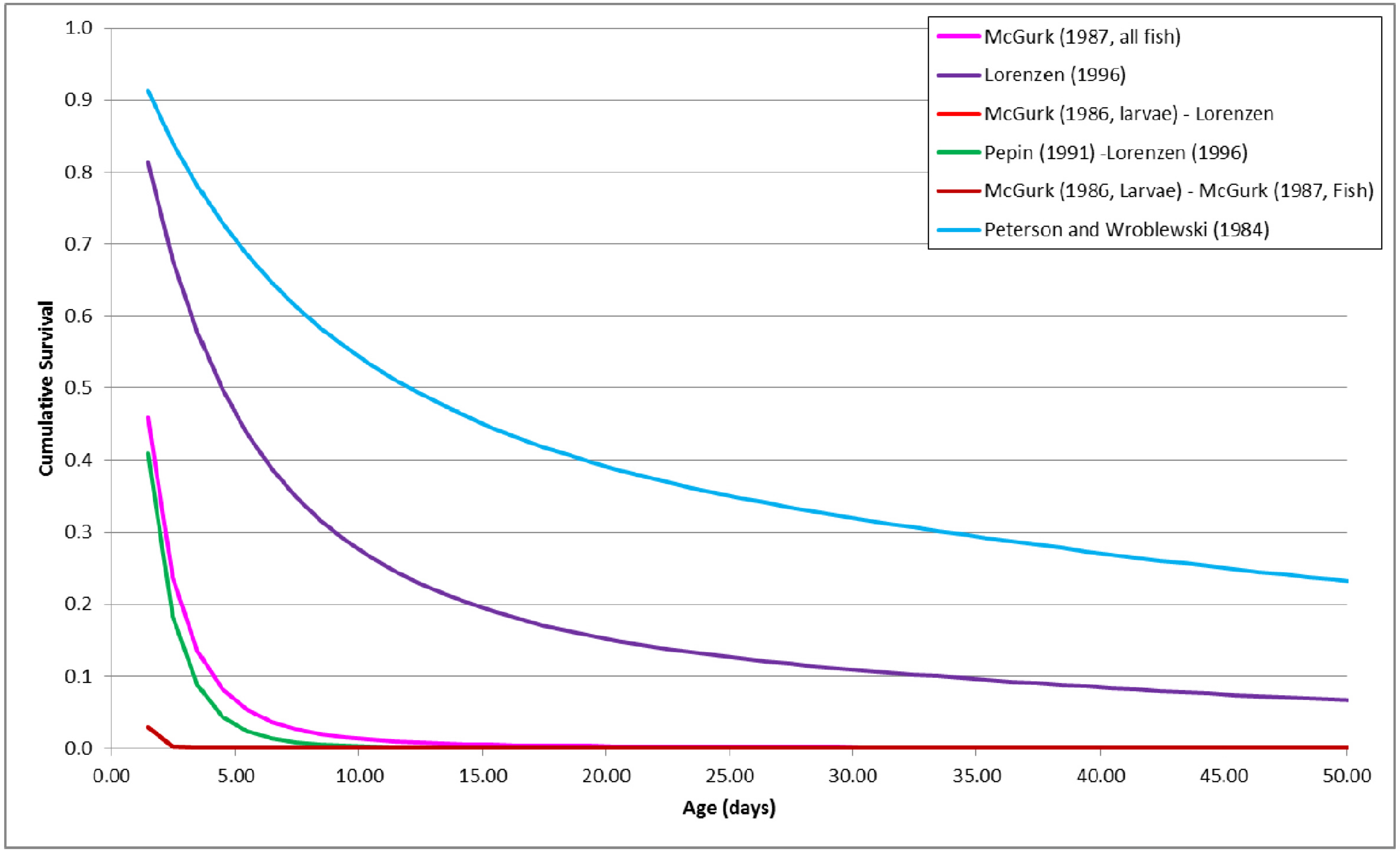

Figure A-2. Comparison of first year mortality models for red snapper (spring) with hatch length of 2.0 mm. Each model is plotted from hatch to 50 days. (McGurk 1986 larvae-Lorenzen 1996 is indistinguishable from McGurk 1986 larvae-McGurk 1987 fish).

Table A-3. Comparison of red snapper early life history model results with published values. The first two rows in each section (Production Foregone Model reference) are derived from the life table within the production foregone model. All other data references are from publications as listed in the reference column. [ND = no data]

Stage	Duration (days)	Lengths (mm)	Mortality (day^{-1})	Total Stage Mortality (day^{-1})	Growth Rate (mm/day)	Reference
Egg	**1.47**	**1.5**	**0.218**	**0.32**	**0**	**Production Foregone Model Spring**
	1.09	**1.5**	**0.220**	**0.24**	**0**	**Production Foregone Model Summer**
	0.94	0.82	ND	ND	ND	FWS Species Profile (Rabalais et al. 1980)
	0.9775	ND	0.3700	0.3617	0	e2M (Pearl Crossing/Beacon Port)
	1	ND	1.0440	1.0440	ND	e2M (Gulf Landing)
	0.75-1.13	ND	ND	ND	ND	Gallaway et al. (1999)
	1	ND	0.4984	0.4984	0	Gallaway et al. (2007)
	1	ND	0.4984	0.4984	0	Gallaway et al. (2009)
	1	ND	ND	ND	ND	Williams et al. (2004)
	ND	0.80	ND	ND	ND	Phelps et al. (2009)
	1	0.74	ND	ND	ND	Drass et al. (2000)
Larvae	**29**	**2-19**	**0.192-0.890**	**11.37**	**0.607**	**Production Foregone Model Spring**
	26	**2-17**	**0.214-1.09**	**11.63**	**0.798**	**Production Foregone Model Summer**
	28.5	2.2-ND	ND	ND	ND	FWS Species Profile (from Rabalais et al. 1980)
	27	ND	0.2721	7.3465	ND	e2M (Pearl Crossing/Beacon Port)
	22	ND	0.2494	5.4860	ND	e2M (Gulf Landing)
	28	2.2-17	0.3014	8.1378	ND	Gallaway et al. (2007)
	27	ND	0.2413	6.7564	ND	SEDAR 31
	ND	ND-35	ND	ND	ND	FAO Species Catalogue
	ND	1.9-ND	ND	ND	ND	Drass et al. (2000)
	25-47	ND-17	ND	ND	ND	Gallaway et al. (1999)
	28	2.2-17.5	0.2413	6.7564	ND	Gallaway et al. (2009)
Juvenile	**334.5**	**19-114**	**0.002-0.027**	**3.43**	**0.543**	**Production Foregone Model Spring**
	338.9	**17-114**	**0.002-0.024**	**3.55**	**0.544**	**Production Foregone Model Summer**
	337	ND	0.0036202	1.22	ND	e2M (Pearl Crossing/Beacon Port)
	343	ND	0.021	7.203	ND	e2M (Gulf Landing)
	ND	17-~130	ND	ND	ND	Gallaway et al. (1999)
	336	ND	ND	5.2699	ND	Gallaway et al. (2007)
	ND	ND	ND	ND	0.8	Szedlmayer (2007)
	336	ND	0.01831	6.154	ND	Gallaway et al. (2009)

Table A-4. Comparison of red drum early life history model results with published values. The first two rows in each section (Production Foregone Model reference) are derived from the life table within the production foregone model. All other data references are from publications as listed in the reference column. [ND = no data]

Stage	Duration (days)	Lengths (mm)	Mortality (day^{-1})	Total Stage Mortality (day^{-1})	Growth Rate (mm/day)	Reference
Egg	**1.47**	**1.5**	**0.218**	**0.32**	**0**	**Production Foregone Model Spring**
	1.09	**1.5**	**0.220**	**0.24**	**0**	**Production Foregone Model Summer**
	ND	ND	ND	2.27	ND	316b Final Rule
	ND	0.89	ND	ND	ND	FWS Species Profile
	1	0.775	0.4984	0.4984	0	Gallaway 2005
	2	ND	0.4984	0.9968	ND	e2M (Gulf Landing) Croaker Proxy
	1	0.775	0.4984	0.4984	0	Gallaway et al. (2007)
Larvae	**29**	**2-19**	**0.192-0.890**	**11.37**	**0.607 (mean)**	**Production Foregone Model Spring**
	25	**2-16**	**0.214-1.09**	**11.63**	**0.798 (mean)**	**Production Foregone Model Summer**
	ND	ND	ND	6.12	ND	316b Final Rule
	23.5	ND	0.1849	4.345	ND	Gallaway 2005
	103	ND	0.0660	6.82	ND	e2M (Gulf Landing) Croaker Proxy
	ND	ND	ND	ND	0.24-0.46	Rooker and Holt (1996)
	22	1.5-8	0.3009	6.6198	ND	Gallaway et al. (2007)
	ND	hatch-8	ND	ND	0.12-0.42	Stunz et al. (2002)
	ND	ND	ND	ND	0.075-0.4075	Brightman et al. (1997)
	ND	ND	ND	ND	0.093-0.393	Holt et al. (1981)
	ND	ND	ND	ND	0.22-0.26	Rooker and Holt (1997)
	ND	ND	0.33 (for 2-5mm)	ND	0.3 for <3mm; 0.5 for 4-6mm	Comyns et al.(1989)
Juvenile	**334.5**	**19-399**	**0.001-0.027**	**2.89**	**1.127 (mean)**	**Production Foregone Model Spring**
	338.9	**16-395**	**0.001-0.024**	**2.68**	**1.123 (mean)**	**Production Foregone Model Summer**
	ND	ND	ND	1.15	ND	316b Final Rule
	340.5	ND	0.00875	2.98	ND	Gallaway 2005
	254	ND	0.00987	2.52	ND	e2M (Gulf Landing) Croaker Proxy
	342	ND	0.01281	4.38	ND	Gallaway et al. (2007)
	ND	ND	0.1365	ND	ND	Rooker (1999)
	ND	50+	ND	2.15	ND	Gazey et al. (2014)
	ND	ND	ND	ND	0.50-0.82 (early juvenile)	Rooker and Holt (1997)
	ND	ND	0.504-3.984 (early juvenile)	ND	ND	Rooker et al. (1998)
	ND	ND	0.005-0.020	ND	0.6 mean, exponential relationship	Scharf (2000)
	ND	ND	0.129-0.141 (early juvenile)	ND	0.049-0.051 inst. Growth coefficient (g) (early juvenile)	Rooker et al. (1999)

Table A-5. Comparison of reported mortality rates from published literature with modeled mortality rates from production foregone model for first year mortality model. Reported mortalities from the literature are primarily derived from catch curve analysis.

Species	Stage	Age/Size	Reported Mortality (M)	Modeled Mortality Rate Range (M)	Sampling Location
Chloroscombrus chrysurus[1]	Larvae		0.17/day-0.62/day	0.19-0.89/day	GoM
Cynoscion arenarius[2]	Larvae	12-46 days	0.17/day	0.025-0.393/day	Southern GoM
Cynoscion nothus[2]	Larvae	10-20 days	0.25/day	0.263-0.443/day	Southern GoM
Euthynnus alletteratus[3]	Larvae		0.72/day	0.19-0.89/day	GoM
Euthynnus alletteratus[3]	Larvae		0.95/day	0.19-0.89/day	GoM
Istiophorus albicans[4]	Larvae	2.0-24.3mm	0.228-0.381/day	0.0223-0.891/day	North GoM
Opisthonema oglinum[5]	Larvae		4.6/stage	11.56/stage	GoM
Opisthonema oglinum[5]	Larvae		3.9/stage	11.56/stage	GoM
Rhomboplites aurorubens[6]	Larvae/Juvenile	19-30mm	0.245/day	0.0175-0.192/day	GoM
Scomberomorus cavalla[7]	Larvae		0.53/day	0.19-0.89/day	GoM
Stellifer lanceolatus[2]	Larvae	10-27 days	0.2/day	0.199-0.443/day	Southern GoM
Thunnus albacares[8]	Larvae		0.33/day	0.19-0.89/day	GoM
Thunnus thynus[8]	Larvae		0.2/day	0.19-0.89/day	Western Stock
Cynoscion nebulosus[9]	Juvenile		5.12/yr	3.65/yr	Florida Bay
Lagodon rhomboides[10]	Juvenile		0.06/day	0.003-0.023/day	GoM Florida
Leiostomus xanthurus[10]	Juvenile		0.066/day	0.004-0.028/day	GoM Florida
Leiostomus xanthurus[11]	Juvenile		0.04/day	0.004-0.028/day	North Carolina
Leiostomus xanthurus[11]	Juvenile		0.023/day	0.004-0.028/day	North Carolina
Leiostomus xanthurus[11]	Juvenile		0.03/day	0.004-0.028/day	North Carolina
Lutjanus griseus[9]	Juvenile		6.21/yr	4.14/yr	Florida Bay
Seriola dumerili[12]	Juvenile	40-130 days	0.0045/day	0.0125-0.025/day	GoM

References: 1-Leffler and Shaw. 1992. 2-Flores-Coto et al. 1998 3-Allman and Grimes 1998 4 – Simms et al. 2010 5 - Houde 1977 6 - Comyns 1977 7 – Gledhill and Lyczkowski-Shultz 2000 8 – Scott et al. 1993 9 – Rutherford et al. 1989 10 – Purtlebaugh and Allen 2010 11 – Currin et al. 1984 12 – SEDAR 9 2006

A.2.2 Fish – Age 1+ Mortality Models

A selection of adult stage natural mortality model estimates was compared for five fish species of interest. From among the numerous estimators available in the literature (Appendix A.1) the model selection criteria were broadly applied to narrow the list of potential adult models for use in the production foregone model. Adult stage natural mortality estimates are needed where no published values are available for a species of interest. A comparison of results for five species and eight mortality estimators is presented in Tables A-6 through A-10.

Table A-6. Comparison of adult instantaneous annual mortality rate (yr^{-1}) estimates for red snapper.

Age	Lorenzen (1996)	Pauly and Binohlan (1996)	Hewitt and Hoenig (2005)	Jensen's Second (1996)	Pauly (1980)	Gislason (2010)	McGurk (1987)	Peterson and Wroblewski (1984)	Stock Assess-ment
1	0.68	0.42	0.07	0.29	0.46	1.05	0.62	0.70	0.59
2	0.50	0.42	0.07	0.29	0.46	0.61	0.42	0.55	0.10
3	0.42	0.42	0.07	0.29	0.46	0.43	0.33	0.47	0.10
4	0.36	0.42	0.07	0.29	0.46	0.34	0.28	0.42	0.10
5	0.33	0.42	0.07	0.29	0.46	0.29	0.24	0.39	0.10
6	0.31	0.42	0.07	0.29	0.46	0.25	0.22	0.37	0.10
7	0.29	0.42	0.07	0.29	0.46	0.23	0.21	0.35	0.10
8	0.28	0.42	0.07	0.29	0.46	0.21	0.19	0.34	0.10
9	0.27	0.42	0.07	0.29	0.46	0.20	0.19	0.33	0.10
10	0.26	0.42	0.07	0.29	0.46	0.19	0.18	0.32	0.10
15	0.24	0.42	0.07	0.29	0.46	0.17	0.16	0.30	0.10
20	0.24	0.42	0.07	0.29	0.46	0.16	0.16	0.30	0.10
25	0.23	0.42	0.07	0.29	0.46	0.16	0.16	0.29	0.10

Table A-7. Comparison of adult instantaneous annual mortality rate (yr^{-1}) estimates for red drum.

Age	Lorenzen (1996)	Pauly and Binohlan (1996)	Hewitt and Hoenig (2005)	Jensen's Second (1996)	Pauly (1980)	Gislason (2010)	McGurk (1987)	Peterson and Wroblewski (1984)	Stock Assess-ment
1	0.43	0.84	0.11	0.48	0.63	0.78	0.34	0.48	0.16
2	0.34	0.84	0.11	0.48	0.63	0.53	0.25	0.40	0.13
3	0.30	0.84	0.11	0.48	0.63	0.42	0.21	0.36	0.11
4	0.27	0.84	0.11	0.48	0.63	0.36	0.19	0.33	0.09
5	0.26	0.84	0.11	0.48	0.63	0.32	0.18	0.32	0.09
6	0.25	0.84	0.11	0.48	0.63	0.30	0.17	0.31	0.06
7	0.24	0.84	0.11	0.48	0.63	0.29	0.16	0.30	0.06
8	0.24	0.84	0.11	0.48	0.63	0.28	0.16	0.29	0.06
9	0.23	0.84	0.11	0.48	0.63	0.27	0.15	0.29	0.06
10	0.23	0.84	0.11	0.48	0.63	0.27	0.15	0.29	0.06
15	0.23	0.84	0.11	0.48	0.63	0.26	0.15	0.28	0.06
20	0.23	0.84	0.11	0.48	0.63	0.26	0.15	0.28	0.06
25	0.22	0.84	0.11	0.48	0.63	0.26	0.15	0.28	0.06

Table A-8. Comparison of adult instantaneous annual mortality rate (yr^{-1}) estimates for red grouper.

Age	Lorenzen (1996)	Pauly and Binohlan (1996)	Hewitt and Hoenig (2005)	Jensen's Second (1996)	Pauly (1980)	Gislason (2010)	McGurk (1987)	Peterson and Wroblewski (1984)	Stock Assess-ment
1	0.44	0.33	0.15	0.24	0.41	1.32	0.35	0.49	0.37
2	0.30	0.33	0.15	0.24	0.41	0.71	0.22	0.36	0.37
3	0.24	0.33	0.15	0.24	0.41	0.48	0.16	0.30	0.37
4	0.21	0.33	0.15	0.24	0.41	0.36	0.13	0.26	0.15
5	0.18	0.33	0.15	0.24	0.41	0.30	0.11	0.24	0.15
6	0.17	0.33	0.15	0.24	0.41	0.26	0.10	0.22	0.15
7	0.16	0.33	0.15	0.24	0.41	0.23	0.09	0.21	0.15
8	0.15	0.33	0.15	0.24	0.41	0.21	0.08	0.20	0.15
9	0.14	0.33	0.15	0.24	0.41	0.19	0.08	0.19	0.15
10	0.13	0.33	0.15	0.24	0.41	0.18	0.08	0.19	0.15
15	0.12	0.33	0.15	0.24	0.41	0.15	0.07	0.17	0.15
20	0.12	0.33	0.15	0.24	0.41	0.14	0.06	0.16	0.15
25	0.11	0.33	0.15	0.24	0.41	0.13	0.06	0.16	0.15

Table A-9. Comparison of adult instantaneous annual mortality rate (yr^{-1}) estimates for gulf menhaden.

Age	Lorenzen (1996)	Pauly and Binohlan (1996)	Hewitt and Hoenig (2005)	Jensen's Second (1996)	Pauly (1980)	Gislason (2010)	McGurk (1987)	Peterson and Wroblewski (1984)	Stock Assess-ment
1	1.02	1.22	0.70	0.66	1.14	0.92	1.04	0.97	0.90
2	0.86	1.22	0.70	0.66	1.14	0.68	0.84	0.85	0.77
3	0.78	1.22	0.70	0.66	1.14	0.58	0.74	0.78	0.70
4	0.74	1.22	0.70	0.66	1.14	0.52	0.69	0.75	0.66
5	0.71	1.22	0.70	0.66	1.14	0.49	0.66	0.73	0.64
6	0.70	1.22	0.70	0.66	1.14	0.48	0.64	0.71	0.62

Table A-10. Comparison of adult instantaneous annual mortality rate (yr^{-1}) estimates for king mackerel.

Age	Lorenzen (1996)	Pauly and Binohlan (1996)	Hewitt and Hoenig (2005)	Jensen's Second (1996)	Pauly (1980)	Gislason (2010)	McGurk (1987)	Peterson and Wroblewski (1984)	Stock Assess-ment
1	0.36	0.39	0.18	0.27	0.40	0.39	0.27	0.42	0.20
2	0.32	0.39	0.18	0.27	0.40	0.31	0.23	0.38	0.20
3	0.29	0.39	0.18	0.27	0.40	0.26	0.21	0.35	0.20
4	0.27	0.39	0.18	0.27	0.40	0.23	0.19	0.33	0.20
5	0.26	0.39	0.18	0.27	0.40	0.21	0.17	0.31	0.20
6	0.24	0.39	0.18	0.27	0.40	0.19	0.16	0.30	0.20
7	0.24	0.39	0.18	0.27	0.40	0.18	0.16	0.29	0.20
8	0.23	0.39	0.18	0.27	0.40	0.17	0.15	0.29	0.20
9	0.22	0.39	0.18	0.27	0.40	0.17	0.15	0.28	0.20
10	0.22	0.39	0.18	0.27	0.40	0.16	0.14	0.28	0.20
15	0.21	0.39	0.18	0.27	0.40	0.14	0.13	0.26	0.20
20	0.20	0.39	0.18	0.27	0.40	0.14	0.13	0.26	0.20

Differences exist among the estimates produced by the mortality models compared above (Tables A-6 through A-10). Several of the models are not age structured (e.g., Pauly 1980, Jensen 1996) as they rely solely on fixed parameters such as von Bertalanffy equation parameters or maximum age, while other models are age structured (e.g., Lorenzen 1996, McGurk 1987) insofar as they are based in size at age measurements. The age/size structured models are preferable for implementation in the production foregone model as natural mortality rates of fish have been found to be tied directly to their body size. This concept has been shown to exist through several different methods including empirically within populations, comparisons between populations and between species, and theoretically based on energy flow and particle size distribution theory (see Lorenzen 1996 for overview). The concept of size-based natural mortality has continued to grow in support in recent years (McCoy and Gillooly 2008, Gislason 2010). Based on evidence and results from the numerous studies supporting particle size theory, the most recent published size-based models are preferable for use in the production foregone model: Lorenzen (1996, 2006) and Gislason (2010). These two models alternately produce rather disparate estimations of M (Table A-8) or very similar estimations of M (Table A-10). In the interest of model cohesiveness Lorenzen (1996) is used for the juvenile portion of the first year mortality model), institutional agreement (SEFSC utilizes the Lorenzen 1996 model), agreement with empirically available data, and reducing model over-parameterization (Lorenzen 1996 has one input, Gislason 2010 has four inputs), all while remaining within the bounds of the model selection criteria, the Lorenzen 1996 model was selected as the preferred model for generating natural mortality estimates for age 1+ fish populations. Table A-11 provides comparisons of the Lorenzen (1996) model predictions to literature mortality estimates for other species in the Gulf of Mexico region.

Table A-11. Comparison of reported mortality rates from published literature with modeled mortality rates based on Lorenzen (1996) used in the production foregone model for Age 1+ age classes.

Species	Stage	Age/Size	Reported Mortality (M or Z)	Modeled Mortality Rate Range (M or Z)	Location
Balistes capriscus[1]	Adult	Age 5-10	z = 0.88/yr	z = 0.42-0.52/yr	South Atlantic
Balistes capriscus[1]	Adult	Age 6-10	z = 1.09 /yr	z = 0.42-0.49/yr	South Atlantic
Brevoortia patronus[2]	Adult	Age 1	0.9/yr	1.02/yr	GoM
Brevoortia patronus[2]	Adult	Age 2	0.77/yr	0.86/yr	GoM
Brevoortia patronus[2]	Adult	Age 3	0.7/yr	0.78/yr	GoM
Brevoortia patronus[2]	Adult	Age 4	0.66/yr	0.74/yr	GoM
Brevoortia patronus[2]	Adult	Age 5	0.64/yr	0.71/yr	GoM
Brevoortia patronus[2]	Adult	Age 6	0.62/yr	0.70/yr	GoM
Cynoscion nebulosus[3]	Adult		0.69/yr	0.31-0.61/yr	Florida Bay
Lagodon rhomboides[4]	Adult		1.08/yr	0.62-1.01/yr	GoM
Lagodon rhomboides[4]	Adult		0.88/yr	0.62-1.01/yr	GoM
Lutjanus griseus[3]	Adult		1.27/yr	0.33-0.92/yr	Florida Bay
Lutjanus synagris[5]	Adult		z = 0.38/yr	z = 0.56-0.69/yr	GoM
Rhomboplites aurorubens[6]	Adult		z = 0.48/yr	z = 0.54-0.71/yr	GoM
Rhomboplites aurorubens[6]	Adult		z = 0.49/yr	z = 0.54-0.71/yr	GoM
Seriola dumerili[7]	Adult		z = 0.68/yr	z = 0.31-0.69/yr	GoM
Seriola dumerili[7]	Adult		z = 0.70/yr	z = 0.31-0.69/yr	GoM
Synodus foetens[8]	Adult	Age 3+	0.51/yr	1.03-1.20/yr	GoM
Synodus foetens[8]	Adult	Age 3+	0.57/yr	1.03-1.20/yr	GoM

References – 1 – Broome et al. 2 – SEDAR 27 2011 3 - Rutherford et al. 1989 4 - Nelson 2002. 5 – Johnson et al. 1995 6 - Hood & Johnson 1999 7 – Manooch & Potts 8 – Jeffers et al. 2008

A.2.3 Invertebrates

Only two invertebrate mortality estimator models were identified from the literature: McGurk (1987) for small pelagic crustaceans and McGurk (1987) for all marine organisms. The Peterson and Wroblewski (1984) and McCoy and Gillooly (2008) theoretical models were proposed by the authors to be applicable to all fish and invertebrates (See Section A.1.2). Table A-12 presents a comparison of the results of the four available models. Because the models are weight and temperature based, there are no species-specific interactions with mortality outside of their weight at age relationship.

Table A-12. Comparison of annual instantaneous mortality rate estimates (day^{-1}) for invertebrates.

Dry Weight (grams)	Peterson and Wroblewski (1984)	McGurk (1987) for small pelagic crustaceans	McGurk (1987) for all marine organisms	McCoy and Gillooly (2008)
0.0000001	0.30	0.82	0.91	0.31
0.000001	0.17	0.24	0.46	0.17
0.00001	0.093	0.069	0.23	0.097
0.0001	0.053	0.020	0.11	0.054
0.001	0.030	0.0058	0.057	0.031
0.01	0.017	0.0017	0.029	0.017
0.1	0.0093	4.9×10^{-4}	0.014	0.0097
1	0.0053	1.4×10^{-4}	0.0071	0.0053
10	0.0030	4.1×10^{-5}	0.0036	0.0031

The McGurk (1987) model for small pelagic crustaceans predicts the steepest survival curve, with comparatively high mortality rates at low weights and comparatively low mortality rates at greater weights. Most interestingly, the Peterson and Wroblewski model developed in 1984 and based off of particle size theory returns extremely similar results to the more recently developed McCoy and Gillooly model based on the body size and temperature dependence of metabolic rate. Figures A-3 and A-4 show cumulative survival for blue crab (*Callinectes sapidus*) for the first year of life. The Lorenzen (1996) and McGurk (1987) fish models are shown for comparison. (The McCoy and Gillooly model is not shown, as it is coincident with the Peterson and Wroblewski model.)

Data inputs for the McGurk crustacean model do not span the breadth of weights needed for this production foregone analysis. The McGurk (1987) model for all marine organisms is used in the production foregone model for invertebrates, as it is based on data analysis as opposed to theoretical. McGurk (1987) model for all marine organisms gives very similar results to the Lorenzen (1996) model (Figures A-3 and A-4).

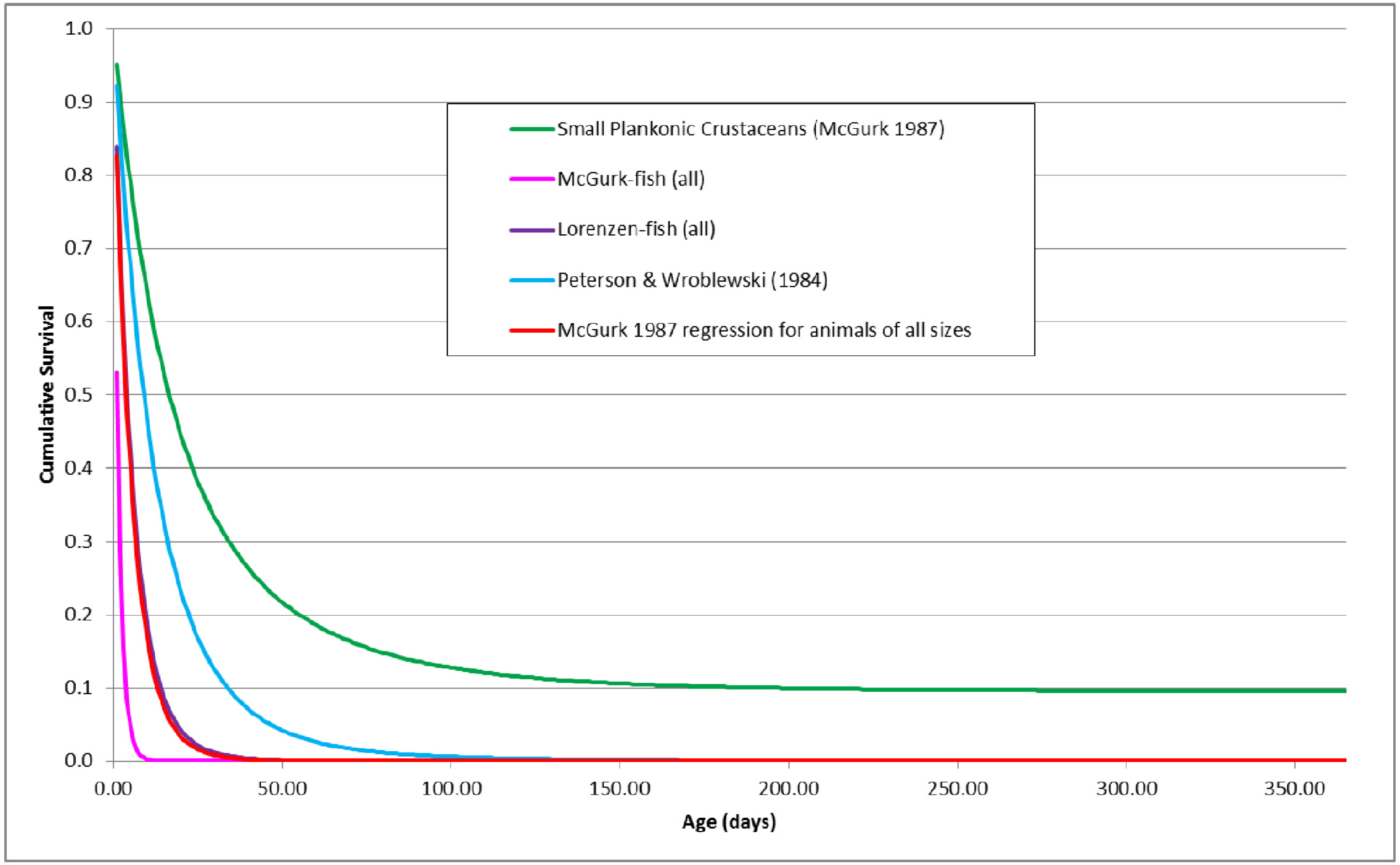

Figure A-3. Comparison of first year mortality models for blue crab (spring) with hatch length of 2.0 mm. Each model is plotted from hatch to 365 days.

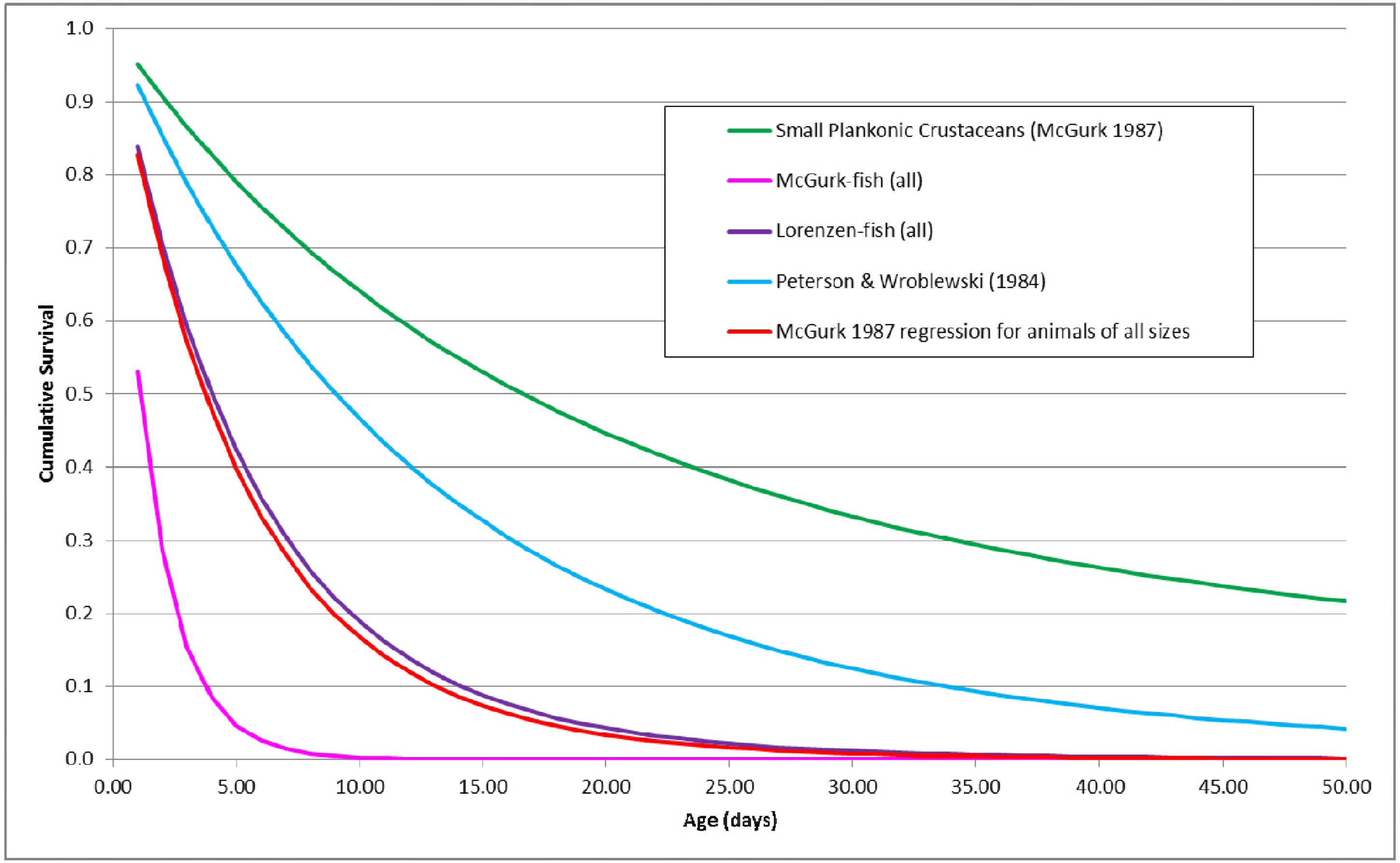

Figure A-4. Comparison of first year mortality models for blue crab (spring) with hatch length of 2.0 mm. Each model is plotted from hatch to 50 days.

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Appendix B. Production Foregone: Life History Parameters by Taxonomic Group – Available Data

[Summary of life history data available by taxonomic group. This is tabulated in a separate file.]

Appendix C. Production Foregone: Life History Parameters by Taxonomic Group – Model Input Data

[Summary of life history data used in the life table and production foregone model calculations, by taxonomic group. This is tabulated in a separate file.]

Appendix D. Production Foregone: Life History Parameters by Taxonomic Group – References

[References for life history data used in the life table and production foregone model calculations. This is in a separate file.]

Appendix E. Summary of Model Results – Life Table and Production Foregone per Individual by Species Group

[Summary of results by taxonomic group of survival rates and production foregone per individual. This is tabulated in a separate file.]

Appendix F. Model Results – Production Foregone Model Workbooks by Taxon, Season and Size

Model inputs, intermediate model calculations and results are provided in copies of the template Production Foregone Model Excel Workbook. One workbook is provided for each taxon, size in the gear, and season for the density data sets used to prepare the Gulf of Mexico Fish and Invertebrate 2010 Baseline Density Dataset (described in French McCay et al., 2015).

Appendix G. Guidance for Navigating the Production Foregone Model Workbooks

[This appendix provides a roadmap for navigating the production foregone model results presented in the Excel workbooks for each of the modeled taxa that are included with Appendix F.]

Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

Appendix B. Production Foregone: Life History Parameters by Taxonomic Group – Available Data

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Project Number: 2011-144
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B.1 Summary of Available Data

Appendix B.1 presents life history characteristics available in the literature that may be used to inform production foregone modeling. The following tables in this section (B.1) summarize life history data found in the literature for fish and invertebrates: von Bertalanffy growth parameters (Table B-1-1 for fish and B-1-4 for invertebrates), weight-length relationships (Table B-1-1 for fish and B-1-4 for invertebrates), maximum lifespan (Table B-1-1 for fish and B-1-4 for invertebrates), adult age structured natural (Table B-1-2 for fish and B-1-5 for invertebrates) and fishing mortality (Table B-1-3 for fish and B-1-6 for invertebrates), and age at recruitment to fishery (Table B-1-3 for fish and B-1-6 for invertebrates). Life history data presented within this appendix represents what is available from published literature (not necessarily what was used to model production foregone). This information was collected as part of a broad literature review on all life history aspects of fish and invertebrates in areas of the GOM potentially exposed to water column contamination from the DWH oil spill. The tables are organized by species in alphabetical order within subsections by order and family. Blank cells indicate where no information was found for the species or taxon. References listed by code in Appendix B are available in Appendix D.

Appendix Tables B-2-1 and B.2-2 in Section B.2 list the species which have growth models reported in state, federal, or international stock assessments, including snappers, tunas, mackerels, sea trout, croakers, billfish, blue crab, and spiny lobster. As part of their stock assessment development, the needed growth and mortality rates have been well studied and reviewed by fisheries managers, such that the production models based on these inputs are robust. In addition, growth of a few ecologically important or fishery species have been well studied: mahi mahi, engraulids (anchovies), and penaeid (white) shrimp. Appendix C within this report presents the life history parameters that were used as input to the production foregone model.

B.1.1 Fish – Size and Age Parameters

Table B-1-1. Available von Bertalanffy (L_{inf} in cm, t_0 in years), weight-length (cm, kg), and maximum age (years) parameter values and references for fish species. Reference codes are found in Appendix D.

			Von Bertalanffy				Weight-Length			Maximum Age	
Taxonomy	Order	Family	Linf	K	t_0	Reference	a	b	Reference	Maximum Age	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	46.6	0.36	0.19	RB358	0.0214	3.02	EB90	16	EB90
Balistes capriscus	Tetraodontiformes	Balistidae	53.1	0.18	-0.23	RB465					
Balistes capriscus	Tetraodontiformes	Balistidae	40.8	0.43	0	RB463					
Balistes capriscus	Tetraodontiformes	Balistidae	43.8	0.38	0.15	RB464					
Balistes capriscus	Tetraodontiformes	Balistidae	49.2	0.38	0.23	RB464					
Balistes capriscus	Tetraodontiformes	Balistidae	90.5	0.07	-2.38	EB90					
Balistes capriscus	Tetraodontiformes	Balistidae	39.0	0.26	-0.83	RB462					
Balistes capriscus	Tetraodontiformes	Balistidae	36.7	0.27	-0.75	RB462					
Cynoscion nebulosus	Perciformes	Sciaenidae	75.3	0.26	0	RGB22	0.0050	3.22	EB75	12	EB70
Cynoscion nebulosus	Perciformes	Sciaenidae	55.8	0.36	0	RGB21					
Cynoscion nebulosus	Perciformes	Sciaenidae	56.8	0.32	0	RGB22					
Cynoscion nebulosus	Perciformes	Sciaenidae	57.0	0.22	0	RGB23					
Cynoscion nebulosus	Perciformes	Sciaenidae	60.4	0.22	-0.28	RGB24					
Cynoscion nebulosus	Perciformes	Sciaenidae	60.6	0.27	-0.02	RGB24					
Cynoscion nebulosus	Perciformes	Sciaenidae	63.8	0.19	-0.34	RGB25					
Cynoscion nebulosus	Perciformes	Sciaenidae	70.6	0.17	0	RGB23					
Cynoscion nebulosus	Perciformes	Sciaenidae	85.5	0.13	-0.74	RGB27					
Cynoscion nebulosus	Perciformes	Sciaenidae	79.4	0.15	-0.47	RGB25					
Cynoscion nebulosus	Perciformes	Sciaenidae	83.6	0.16	0	RGB26					
Cynoscion nebulosus	Perciformes	Sciaenidae	70.0	0.22	-1.37	EB75					
Cynoscion nebulosus	Perciformes	Sciaenidae	70.1	0.17	-0.44	RGB24					
Katsuwonus pelamis	Perciformes	Scombridae	87.1	0.22	-2.09	RB80	0.007	3.25	RB80	12	RB145
Katsuwonus pelamis	Perciformes	Scombridae	94.9	0.34	0	RB80					
Katsuwonus pelamis	Perciformes	Scombridae	97.9	0.34	0	RB80					
Katsuwonus pelamis	Perciformes	Scombridae	80.0	0.32	0	RB80					
Leiostomus xanthurus	Perciformes	Sciaenidae	24.1	0.73	0.43	RGB46	0.009	3.07	RGB94	4	EB115
Leiostomus xanthurus	Perciformes	Sciaenidae	23.8	0.94	0	EB115					
Leiostomus xanthurus	Perciformes	Sciaenidae	34.0	0.43	0	RGB47					
Leiostomus xanthurus	Perciformes	Sciaenidae	23.9	0.89	-0.04	EB115					
Lutjanus campechanus	Perciformes	Lutjanidae	80.4	0.25	0	RB306	0.167	2.95	RB447	57	EB136
Lutjanus campechanus	Perciformes	Lutjanidae	87.6	0.22	0.37	EB138					
Lutjanus campechanus	Perciformes	Lutjanidae	85.6	0.19	-0.39	RB447					

			Von Bertalanffy				Weight-Length			Maximum Age	
Taxonomy	Order	Family	Linf	K	t_0	Reference	a	b	Reference	Maximum Age	Reference
Micropogonias undulatus	Perciformes	Sciaenidae	31.2	0.36	-3.26	RGB54	0.005	3.15	RGB94	8	EB92
Micropogonias undulatus	Perciformes	Sciaenidae	18.2	1.45	0.18	RGB55	0.007	3.13	EB92		
Micropogonias undulatus	Perciformes	Sciaenidae	41.9	0.27	-1.405	EB92					
Micropogonias undulatus	Perciformes	Sciaenidae	39.0	0.35	0	RGB56					
Pomatomus saltatrix	Perciformes	Pomatomidae	94.4	0.18	-1.03	RGB64	0.100	2.86	RB122	12	RB120
Pomatomus saltatrix	Perciformes	Pomatomidae	94.6	0.24	-0.13	RGB65	0.595	2.51	RGB91		
Pomatomus saltatrix	Perciformes	Pomatomidae	87.2	0.26	-0.93	RB120	0.014	2.90	MS8		
Pomatomus saltatrix	Perciformes	Pomatomidae	51.0	0.21	-1.41	RB119	0.052	3.06	RGB159		
Pomatomus saltatrix	Perciformes	Pomatomidae	48.0	0.26	-1.10	RB119	0.028	2.80	RGB158		
Rachycentron canadum	Perciformes	Rachycentridae	117.0	0.23	-3.85	RGB71	0.003	3.09	RGB163	15	RB123
Rachycentron canadum	Perciformes	Rachycentridae	133.0	0.18	-4.66	RGB70	0.002	3.43	RB123		
Rachycentron canadum	Perciformes	Rachycentridae	155.5	0.27	-1.25	RB123					
Rachycentron canadum	Perciformes	Rachycentridae	117.1	0.43	-1.15	RB123					
Rachycentron canadum	Perciformes	Rachycentridae	113.0	0.55	-0.76	RGB70					
Rachycentron canadum	Perciformes	Rachycentridae	113.0	0.49	-0.49	RGB69					
Rachycentron canadum	Perciformes	Rachycentridae	129.0	0.56	0.11	RGB69					
Rachycentron canadum	Perciformes	Rachycentridae	130.0	0.46	-0.97	RGB70					
Rachycentron canadum	Perciformes	Rachycentridae	156.0	0.27	-1.25	RB123					
Rhomboplites aurorubens	Perciformes	Lutjanidae	43.15	0.2	-3.9	EB86	0.047	2.59	RGB166	26	EB86
Rhomboplites aurorubens	Perciformes	Lutjanidae	63.0	0.2	0.13	RB303	0.017	2.90	RGB91		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.023	2.89	RGB91		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.017	3.00	RGB168		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.049	2.79	RGB106		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.033	3.04	RGB87		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.019	2.98	EB86		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.108	2.33	RGB165		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.019	2.95	RGB87		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.023	2.94	RGB167		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.011	3.12	RGB87		
Rhomboplites aurorubens	Perciformes	Lutjanidae					0.090	2.52	RGB87		
Sciaenops ocellatus	Perciformes	Sciaenidae	95.8	0.32	-0.65	EB83	0.010	3.03	RGB177	40	EB82
Sciaenops ocellatus	Perciformes	Sciaenidae	104.2	0.23	0	RGB77	0.008	3.06	EB82		
Sciaenops ocellatus	Perciformes	Sciaenidae					0.008	3.10	RGB177		
Scomberomorus cavalla	Perciformes	Scombridae	98.7	0.26	-2.48	RB59	0.008	3.00	RB105	24	RB59
Scomberomorus cavalla	Perciformes	Scombridae	122.4	0.18	-2.65	RB59				23	RB59
Scomberomorus cavalla	Perciformes	Scombridae	132.4	0.17	-2.52	RB59					
Scomberomorus cavalla	Perciformes	Scombridae	130.3	0.14	-3.56	RB59					

			Von Bertalanffy				Weight-Length			Maximum Age	
Taxonomy	**Order**	**Family**	**Linf**	**K**	**t_0**	**Reference**	**a**	**b**	**Reference**	**Maximum Age**	**Reference**
Scomberomorus cavalla	Perciformes	Scombridae	127.1	0.13	-4.45	RB59					
Scomberomorus cavalla	Perciformes	Scombridae	147.8	0.12	-2.36	RB59					
Scomberomorus cavalla	Perciformes	Scombridae	87.6	0.51	-0.56	RB79					
Scomberomorus cavalla	Perciformes	Scombridae	125.2	0.19	-2.16	RB79					
Scomberomorus cavalla	Perciformes	Scombridae	115.4	0.19	-2.60	RB79					
Scomberomorus maculatus	Perciformes	Scombridae	64.5	0.45	-1.12	RB321	0.001	2.88	RB321	11	RB321
Scomberomorus maculatus	Perciformes	Scombridae	56.0	0.61	-0.5	RB321					
Scomberomorus maculatus	Perciformes	Scombridae	51.5	0.48	-0.78	RB321					
Thunnus thynnus	Perciformes	Scombridae	289.0	0.12	-0.09	RGB83	0.029	2.93	RB95	38	RB94
Thunnus thynnus	Perciformes	Scombridae	382.0	0.08	-0.71	RGB81	0.016	3.02	RGB191		
Thunnus thynnus	Perciformes	Scombridae	257.0	0.20	0.83	RGB82					
Thunnus thynnus	Perciformes	Scombridae	314.9	0.09	-1.13	RB94					
Xiphias gladius	Perciformes	Xiphiidae	238.6	0.19	-1.40	RB106	0.004	3.21	RB107	15	RB82
Xiphias gladius	Perciformes	Xiphiidae	277.0	0.07	-3.94	RGB86	0.001	3.55	RB107		
Xiphias gladius	Perciformes	Xiphiidae	267.0	0.12	-1.68	RGB86	0.005	3.14	RB107		

B.1.2 Fish – Natural Mortality Parameters

Table B-1-2. Available age class specific natural mortality rates (M yr^{-1}) and references for fish species. Reference codes are found in Appendix D.

			Natural Mortality at Age (Years)										
Taxonomy	**Order**	**Family**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Ref Code**
Balistes capriscus	Tetraodontiformes	Balistidae	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	EB90
Cynoscion nebulosus	Perciformes	Sciaenidae	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	EB97
Katsuwonus pelamis	Perciformes	Scombridae	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae											
Lutjanus campechanus	Perciformes	Lutjanidae	0.59	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	EB136
Micropogonias undulatus	Perciformes	Sciaenidae											
Pomatomus saltatrix	Perciformes	Pomatomidae	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	RB122
Rachycentron canadum	Perciformes	Rachycentridae	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	RB124
Rhomboplites aurorubens	Perciformes	Lutjanidae	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	EB86

Taxonomy	Order	Family	Natural Mortality at Age (Years) 1	2	3	4	5	6	7	8	9	10	Ref Code
Sciaenops ocellatus	Perciformes	Sciaenidae	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	EB68
Scomberomorus cavalla	Perciformes	Scombridae	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	RB59
Scomberomorus maculatus	Perciformes	Scombridae	0.41	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	RB63
Thunnus thynnus	Perciformes	Scombridae	0.49	0.24	0.24	0.24	0.24	0.2	0.18	0.18	0.15	0.13	RB97
Xiphias gladius	Perciformes	Xiphiidae	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	RB82

B.1.3 Fish – Fishing Mortality and Age at Recuitment

Table B-1-3. Available age class specific fishing mortality rates (F yr^{-1}), age at recruitment (years) and references for fish species. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Fishing Mortality at Age (Years) 1	2	3	4	5	6	7	8	9	10	Ref Code	Recruitment Age	Ref Code
Balistes capriscus	Tetraodontiformes	Balistidae	0	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	EB90	2	EB90
Cynoscion nebulosus	Perciformes	Sciaenidae	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	EB97	1	EB75
Katsuwonus pelamis	Perciformes	Scombridae	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	RB80	1	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae													
Lutjanus campechanus	Perciformes	Lutjanidae	0	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	EB146	2	EB146
Micropogonias undulatus	Perciformes	Sciaenidae	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	RB463	1	EB94
Pomatomus saltatrix	Perciformes	Pomatomidae	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	RB121	1	RB121
Rachycentron canadum	Perciformes	Rachycentridae	0	0	0	0.20	0.20	0.20	0.20	0.20	0.20	0.20	RB464	4	RB123
Rhomboplites aurorubens	Perciformes	Lutjanidae	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	EB86	1	EB86
Sciaenops ocellatus	Perciformes	Sciaenidae	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	EB68	1	EB68
Scomberomorus cavalla	Perciformes	Scombridae	0	0.06	0.29	0.16	0.11	0.08	0.16	0.07	0.12	0.07	RB59	2	RB59
Scomberomorus maculatus	Perciformes	Scombridae	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	RB63	1	RB63
Thunnus thynnus	Perciformes	Scombridae	0	0	0	0	0.20	0.20	0.20	0.20	0.20	0.20	RB97	5	RB97
Xiphias gladius	Perciformes	Xiphiidae	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	RB82	2	RB82

B.1.4 Invertebrate – Size and Age Parameters

Table B-1-4. Available von Bertalanffy (L_{inf} in cm, t_0 in years), weight-length (cm, kg), and maximum age (years) parameter values and references for invertebrate species. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Linf	K	t_0	Ref Code	a	b	Ref Code	Max Age	Ref Code
Panulirus argus	Decapoda	Palinuridae	18.5	0.23	0.44	RB441	0.09	2.48	CM41	1	CM41
Panulirus argus	Decapoda	Palinuridae	17.0	0.21	0.41	RB441					
Litopenaeus setiferus	Decapoda	Penaeidae	21.4	5.04	0.00	CM44	3.8E-03	3.25	EB2	1	RB457
Callinectes sapidus	Decapoda	Portunidae	16.6	2.16	0.17	CM40	2.3E-01	2.45	CM40	6	CM40

B.1.5 Invertebrate – Natural Mortality

Table B-1-5. Available age class specific natural mortality rates (M yr^{-1}) and references for fish species. Reference codes are found in Appendix D.

			Natural Mortality ($Years^{-1}$)										
Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Ref Code
Panulirus argus	Decapoda	Palinuridae	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	RB441
Litopenaeus setiferus	Decapoda	Penaeidae											
Callinectes sapidus	Decapoda	Portunidae	1	1	1	1	1	1	1	1	1	1	EB202

B.1.6 Invertebrate – Fishing Mortality and Age at Recruitment to Fishery

Table B-1-6. Available age class specific fishing mortality rates (F yr^{-1}), age at recruitment (years) and references for invertebrate species. Reference codes are found in Appendix D.

			Fishing Mortality ($Years^{-1}$)												
Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Ref Code	Age at Recruitment to Fishery	Ref Code
Panulirus argus	Decapoda	Palinuridae	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	RB441	1	RB441
Litopenaeus setiferus	Decapoda	Penaeidae													
Callinectes sapidus	Decapoda	Portunidae	1	1	1	1	1	1	1	1	1	1	EB202	1	EB202

B.2 Species for Which Stock Assessments are Available

B.2.1 Fish species with available stock assessments

Table B-2-1. List of fish species for which stock assessments are available. Organization column indicates the publisher of the assessment. SEDAR indicates NOAA NMFS SouthEast Data, Assessment, and Review group. ICCAT indicates the International Commission for the Conservation of Atlantic Tunas.

Stock Assessed Species	Organization
Acanthurus coeruleus	SEDAR
Balistes capriscus	SEDAR
Balistes vetula	SEDAR
Brevoortia patronus	SEDAR
Brevoortia tyrannus	SEDAR
Carcharhinus limbatus	SEDAR
Carcharhinus obscurus	SEDAR
Carcharhinus plumbeus	SEDAR
Caulolatilus microps	SEDAR
Centropomus undecimalis	Florida
Centropristis striata	SEDAR
Cynoscion nebulosus	Florida
Cynoscion regalis	Florida
Epinephelus guttatus	SEDAR
Epinephelus itajara	SEDAR
Epinephelus morio	SEDAR
Epinephelus niveatus	SEDAR
Etelis oculatus	SEDAR
Haemulon plumierii	Florida
Hemiramphus brasiliensis	Florida
Hyporthodus flavolimbatus	SEDAR
Istiophorus albicans	ICCAT
Isurus oxyrinchus	ICCAT
Katsuwonus pelamis	ICCAT
Lachnolaimus maximus	SEDAR
Lagodon rhomboides	Florida
Lamna nasus	ICCAT
Leiostomus xanthurus	Florida
Lobatus gigas	SEDAR
Lutjanus analis	SEDAR
Lutjanus campechanus	SEDAR
Lutjanus vivanus	SEDAR
Makaira nigricans	ICCAT
Micropogonias undulatus	SEDAR
Mugil cephalus	Florida
Mugil curema	Florida
Mycteroperca bonaci	SEDAR
Mycteroperca microlepis	SEDAR

Stock Assessed Species	Organization
Mycteroperca venenosa	SEDAR
Ocyurus chrysurus	SEDAR
Pagrus pagrus	SEDAR
Pogonias cromis	Louisiana
Pomatomus saltatrix	Florida
Prionace glauca	ICCAT
Rachycentron canadum	SEDAR
Rhizoprionodon terraenovae	SEDAR
Rhomboplites aurorubens	SEDAR
Sciaenops ocellatus	SEDAR
Scomberomorus cavalla	SEDAR
Scomberomorus maculatus	SEDAR
Seriola dumerili	SEDAR
Sparisoma chrysopterum	SEDAR
Sphyrna tiburo	SEDAR
Tetrapturus albidus	ICCAT
Thunnus alalunga	ICCAT
Thunnus albacares	ICCAT
Thunnus atlanticus	ICCAT
Thunnus maccoyii	ICCAT
Thunnus obesus	ICCAT
Thunnus thynnus	ICCAT
Trachinotus carolinus	Florida
Xiphias gladius	ICCAT

B.2.2 Invertebrate species with available stock assessments

Table B-2-2. List of invertebrate species for which stock assessments are available. Organization column indicates the publisher of the assessment. GSMFC indicates the Gulf States Marine Fisheries Commission.

Stock Assessed species	Organization
Panulirus argus	SEDAR
Callinectes sapidus	GSMFC
Litopenaeus setiferus	NOAA
Farfantepenaeus aztecus	GSMFC

Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

Appendix C. Production Foregone: Life History Parameters by Taxonomic Group – Model Input Data

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C.1 Summary of Model Input Data

Appendix C presents life history characteristics available in the literature that were used as inputs to production foregone modeling. The following tables summarize von Bertalanffy growth parameters (C.1.1.1 for fish, C.1.2.1 for invertebrates), weight-length relationships (C.1.1.2 for fish, C.1.2.2 for invertebrates), maximum age (C.1.1.3 for fish, C.1.2.3 for invertebrates) adult age structured natural (C.1.1.4 for fish, C.1.2.4 for invertebrates) and fishing mortality (C.1.1.5 for fish, C.1.2.5 for invertebrates), and age at recruitment to fishery (C.1.1.6 for fish, C.1.2.6 for invertebrates). Life history data presented within this appendix represents what data were used in the calculation of production foregone. This information was collected as part of a broad literature review on all life history aspects of fish and invertebrates in areas of the GOM potentially exposed to water column contamination from the DWH oil spill. All available life history data is presented in Appendix B. References cited by code in Appendix C are available in Appendix D.

C.1.1 Fish

C.1.1.1 Fish - Modeled - Von Bertalanffy Parameters

Table C-1.1.1 von Bertalanffy parameters (Linf in cm, t_0 in years) used in modeling fish taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Linf	k	t_0	Proxy Species	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	90.5	0.07	-2.38	Balistes capriscus	EB90
Balistes spp.	Tetraodontiformes	Balistidae	90.5	0.07	-2.38	Balistes capricus	EB90
Balistidae spp.	Tetraodontiformes	Balistidae	90.5	0.07	-2.38	Balistes capricus	EB90
Brevoortia spp.	Clupeiformes	Clupeidae	23.8	0.44	-0.81	Brevoortia patronus	RB148
Coryphaena spp.	Perciformes	Coryphaenidae	145.7	2.19	-0.05	Coryphaena hippurus	RB157
Cynoscion nebulosus	Perciformes	Sciaenidae	70.0	0.22	-1.37	Cynoscion nebulosus	EB75
Cynoscion spp.	Perciformes	Sciaenidae	70.0	0.22	-1.37	Cynoscion nebulosus	EB75
Engraulidae spp.	Clupeiformes	Engraulidae	10.7	0.36	-0.81	Anchoa mitchilli	CA7, CA51
Epinephelini spp.	Perciformes	Serranidae	85.4	0.16	-0.19	Epinephelus morio	EB87
Haemulidae spp.	Perciformes	Haemulidae	32.3	0.52	-0.58	Haemulon plumierii	EB125
Istiophoridae spp.	Perciformes	Istiophoridae	190.9	0.60	0.00	Istiphorus albicans	RB85
Katsuwonus pelamis	Perciformes	Scombridae	94.9	0.34	0.00	Katsuwonus pelamis	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae	23.8	0.94	0.00	Leiostomus xanthurus	EB115
Lutjanidae spp.	Perciformes	Lutjanidae	85.6	0.19	-0.39	Lutjanus campechanus	RB447
Lutjanus campechanus	Perciformes	Lutjanidae	85.6	0.19	-0.39	Lutjanus campechanus	RB447
Lutjanus spp.	Perciformes	Lutjanidae	85.6	0.19	-0.39	Lutjanus campechanus	RB447
Micropogonias undulatus	Perciformes	Sciaenidae	43.5	0.24	-1.96	Micropogonias undulatus	RB463
Mugil spp.	Mugiliformes	Mugilidae	36.1	0.85	-0.11	Mugil cephalus	EB156
Pomatomus saltatrix	Perciformes	Pomatomidae	87.2	0.26	-0.93	Pomatomus saltatrix	RB120
Rachycentron canadum	Perciformes	Rachycentridae	128.2	0.42	-0.53	Rachycentron canadum	RB464
Rhomboplites aurorubens	Perciformes	Lutjanidae	43.2	0.20	-3.90	Rhomboplites aurorubens	EB86
Sciaenidae spp.	Perciformes	Sciaenidae	95.8	0.32	-0.65	Sciaenops ocellatus	EB83
Sciaenops ocellatus	Perciformes	Sciaenidae	95.8	0.32	-0.65	Sciaenops ocellatus	EB83
Scomberomorus cavalla	Perciformes	Scombridae	122.4	0.18	-2.65	Scomberomorus cavalla	RB59, RB105
Scomberomorus maculatus	Perciformes	Scombridae	56.0	0.61	-0.50	Scomberomorus maculatus	RB321
Seriola spp.	Perciformes	Carangidae	143.6	0.14	0.00	Seriola dumerili	RB451
Thunnus spp.	Perciformes	Scombridae	230.7	0.27	-0.08	Thunnus albacares	RB153
Thunnus thynnus	Perciformes	Scombridae	314.9	0.09	-1.13	Thunnus thynnus	RB94
Xiphias gladius	Perciformes	Xiphiidae	238.6	0.19	-1.40	Xiphias gladius	RB106

C.1.1.2 Fish - Modeled - Weight Length Parameters

Table C.1.1.2 Weight-length parameters (cm, kg) used in modeling fish taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	a	b	Proxy Species	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	0.021	3.02	Balistes capriscus	EB90
Balistes spp.	Tetraodontiformes	Balistidae	0.021	3.02	Balistes capriscus	EB90
Balistidae spp.	Tetraodontiformes	Balistidae	0.021	3.02	Balistes capriscus	EB90
Brevoortia spp.	Clupeiformes	Clupeidae	0.019	3.01	Brevoortia patronus	RB148
Coryphaena spp.	Perciformes	Coryphaenidae	0.012	2.91	Coryphaena hippurus	RB86
Cynoscion nebulosus	Perciformes	Sciaenidae	0.005	3.22	Cynoscion nebulosus	EB75
Cynoscion spp.	Perciformes	Sciaenidae	0.005	3.22	Cynoscion nebulosus	EB75
Engraulidae spp.	Clupeiformes	Engraulidae	0.017	2.81	Anchoa mitchilli	CA7
Epinephelini spp.	Perciformes	Serranidae	0.083	3.14	Epinephelus morio	EB87
Haemulidae spp.	Perciformes	Haemulidae	0.010	3.21	Haemulon aurolineatum	EB124
Istiophoridae spp.	Perciformes	Istiophoridae	0.001	3.24	Istiophorus albicans	RB144
Katsuwonus pelamis	Perciformes	Scombridae	0.007	3.25	Katsuwonus pelamis	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae	0.007	3.13	Micropogonias undulatus	EB92
Lutjanidae spp.	Perciformes	Lutjanidae	0.017	2.95	Lutjanus campechanus	RB447
Lutjanus campechanus	Perciformes	Lutjanidae	0.017	2.95	Lutjanus campechanus	RB447
Lutjanus spp.	Perciformes	Lutjanidae	0.017	2.95	Lutjanus campechanus	RB447
Micropogonias undulatus	Perciformes	Sciaenidae	0.005	3.13	Micropogonias undulatus	RB463
Mugil spp.	Mugiliformes	Mugilidae	0.030	3.24	Mugil cephalus	EB156
Pomatomus saltatrix	Perciformes	Pomatomidae	0.014	2.90	Pomatomus saltatrix	MS8
Rachycentron canadum	Perciformes	Rachycentridae	0.001	3.03	Rachycentron canadum	RB464
Rhomboplites aurorubens	Perciformes	Lutjanidae	0.019	2.98	Rhomboplites aurorubens	EB86
Sciaenidae spp.	Perciformes	Sciaenidae	0.008	3.06	Sciaenops ocellatus	EB82
Sciaenops ocellatus	Perciformes	Sciaenidae	0.008	3.06	Sciaenops ocellatus	EB82
Scomberomorus cavalla	Perciformes	Scombridae	0.008	3.00	Scomberomorus cavalla	RB105, RB59
Scomberomorus maculatus	Perciformes	Scombridae	0.001	2.88	Scomberomorus maculatus	RB321,
Seriola spp.	Perciformes	Carangidae	0.070	2.98	Seriola dumerili	RB451
Thunnus spp.	Perciformes	Scombridae	0.022	2.98	Thunnus albacares	RB70
Thunnus thynnus	Perciformes	Scombridae	0.029	2.93	Thunnus thynnus	RB95,
Xiphias gladius	Perciformes	Xiphiidae	0.005	3.14	Xiphias gladius	RB107

C.1.1.3 Fish - Modeled - Maximum Age

Table C.1.1.3 Maximum age values (years) parameters used in modeling fish taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Max Age	Proxy Species	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	16	Balistes capriscus	EB90
Balistes spp.	Tetraodontiformes	Balistidae	16	Balistes capriscus	EB90
Balistidae spp.	Tetraodontiformes	Balistidae	16	Balistes capriscus	EB90
Brevoortia spp.	Clupeiformes	Clupeidae	6	Brevoortia patronus	RB148
Coryphaena spp.	Perciformes	Coryphaenidae	4	Coryphaena hippurus	RB54
Cynoscion nebulosus	Perciformes	Sciaenidae	12	Cynoscion nebulosus	EB70
Cynoscion spp.	Perciformes	Sciaenidae	12	Cynoscion nebulosus	EB70
Engraulidae spp.	Clupeiformes	Engraulidae	3	Anchoa mitchilli	CA16
Epinephelini spp.	Perciformes	Serranidae	29	Epinephelus morio	EB87
Haemulidae spp.	Perciformes	Haemulidae	17	Haemulon aurolineatum	EB123
Istiophoridae spp.	Perciformes	Istiophoridae	17	Istiophorus albicans	RB83
Katsuwonus pelamis	Perciformes	Scombridae	12	Katsuwonus pelamis	RB145
Leiostomus xanthurus	Perciformes	Sciaenidae	4	Leiostomus xanthurus	EB115
Lutjanidae spp.	Perciformes	Lutjanidae	28	Lutjanus griseus	EB77
Lutjanus campechanus	Perciformes	Lutjanidae	57	Lutjanus campechanus	EB136
Lutjanus spp.	Perciformes	Lutjanidae	28	Lutjanus griseus	EB77
Micropogonias undulatus	Perciformes	Sciaenidae	17	Micropogonias undulatus	RB463
Mugil spp.	Mugiliformes	Mugilidae	9	Mugil cephalus	EB156
Pomatomus saltatrix	Perciformes	Pomatomidae	12	Pomatomus saltatrix	RB120
Rachycentron canadum	Perciformes	Rachycentridae	15	Rachycentron canadum	RB123
Rhomboplites aurorubens	Perciformes	Lutjanidae	26	Rhomboplites aurorubens	EB86
Sciaenidae spp.	Perciformes	Sciaenidae	40	Sciaenops ocellatus	EB82
Sciaenops ocellatus	Perciformes	Sciaenidae	40	Sciaenops ocellatus	EB82
Scomberomorus cavalla	Perciformes	Scombridae	24	Scomberomorus cavalla	RB59
Scomberomorus maculatus	Perciformes	Scombridae	11	Scomberomorus maculatus	RB321
Seriola spp.	Perciformes	Carangidae	17	Seriola dumerili	RB65
Thunnus spp.	Perciformes	Scombridae	8	Thunnus albacares	RB70
Thunnus thynnus	Perciformes	Scombridae	38	Thunnus thynnus	RB94
Xiphias gladius	Perciformes	Xiphiidae	15	Xiphias gladius	RB82

C.1.1.4 Fish - Modeled - Natural Mortality Parameters

Table C.1.1.4 Natural mortality (M, years^{-1}) parameters used in modeling fish taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. 'Lorenzen' indicates the taxonomies uses the oceanic fish species model from Lorenzen (1996) to calculate natural mortality. Reference codes are found in Appendix D.

			Natural Mortality (Years^{-1})											
Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Modeled Proxy	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	Balistes capriscus	EB90
Balistes spp.	Tetraodontiformes	Balistidae	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	Balistes capricus	EB90
Balistidae spp.	Tetraodontiformes	Balistidae	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	Balistes capricus	EB90
Brevoortia spp.	Clupeiformes	Clupeidae	0.90	0.77	0.70	0.66	0.64	0.62	0.62	0.62	0.62	0.62	Brevoortia patronus	RB148
Coryphaena spp.	Perciformes	Coryphaenidae											Lorenzen	Lorenzen
Cynoscion nebulosus	Perciformes	Sciaenidae	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	Cynoscion nebulosus	EB70, EB79
Cynoscion spp.	Perciformes	Sciaenidae	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	Cynoscion nebulosus	EB70, EB79
Engraulidae spp.	Clupeiformes	Engraulidae											Lorenzen	Lorenzen
Epinephelini spp.	Perciformes	Serranidae	0.16	0.13	0.11	0.09	0.09	0.09	0.09	0.09	0.09	0.09	Epinephelus morio	EB88
Haemulidae spp.	Perciformes	Haemulidae											Lorenzen	Lorenzen
Istiophoridae spp.	Perciformes	Istiophoridae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Xiphias gladius	RB82
Katsuwonus pelamis	Perciformes	Scombridae	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	Katsuwonus pelamis	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae											Lorenzen	Lorenzen
Lutjanidae spp.	Perciformes	Lutjanidae	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Lutjanus campechanus	EB136, age 2+
Lutjanus campechanus	Perciformes	Lutjanidae	0.59	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Lutjanus campechanus	EB136, age 2+
Lutjanus spp.	Perciformes	Lutjanidae	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Lutjanus campechanus	EB136, age 2+
Micropogonias undulatus	Perciformes	Sciaenidae	0.374	0.324	0.293	0.272	0.257	0.246	0.238	0.232	0.227	0.223	Micropogonias undulatus	RB463
Mugil spp.	Mugiliformes	Mugilidae	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	Mugil cephalus	EB156
Pomatomus saltatrix	Perciformes	Pomatomidae	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	Pomatomus saltatrix	RB122
Rachycentron canadum	Perciformes	Rachycentridae											Rachycentron canadum	Lorenzen
Rhomboplites aurorubens	Perciformes	Lutjanidae	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	Rhomboplites aurorubens	EB86

			Natural Mortality (Years^{-1})										
Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Modeled Proxy	Reference
Sciaenidae spp.	Perciformes	Sciaenidae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Sciaenops ocellatus	EB68
Sciaenops ocellatus	Perciformes	Sciaenidae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Sciaenops ocellatus	EB68
Scomberomorus cavalla	Perciformes	Scombridae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Scomberomorus cavalla	RB59
Scomberomorus maculatus	Perciformes	Scombridae	0.41	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	Scomberomorus maculatus	RB63
Seriola spp.	Perciformes	Carangidae	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	Seriola dumerili	RB149
Thunnus spp.	Perciformes	Scombridae	0.8	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	Thunnus albacares	RB70
Thunnus thynnus	Perciformes	Scombridae	0.49	0.24	0.24	0.24	0.24	0.2	0.18	0.18	0.15	0.13	Thunnus thynnus	RB97
Xiphias gladius	Perciformes	Xiphiidae	0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Xiphias gladius	RB82

C.1.1.5 Fish - Modeled - Fishing Mortality

Table C.1.1.5 Fishing mortality parameters (F, years^{-1}) used in modeling fish taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. 'Zhou et al.' indicates species uses the teleost model form Zhou et al. 2012. Reference codes are found in Appendix D.

			Fishing Mortality (Years^{-1})										
Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Modeled Proxy	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	0	0.477	0.477	0.477	0.477	0.477	0.477	0.477	0.477	0.477	Balistes capriscus	EB90
Balistes spp.	Tetraodontiformes	Balistidae	0	0.477	0.477	0.477	0.477	0.477	0.477	0.477	0.477	0.477	Balistes capricus	EB90
Balistidae spp.	Tetraodontiformes	Balistidae	0	0.477	0.477	0.477	0.477	0.477	0.477	0.477	0.477	0.477	Balistes capricus	EB90
Brevoortia spp.	Clupeiformes	Clupeidae	0.10	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	Brevoortia patronus	RB148
Coryphaena spp.	Perciformes	Coryphaenidae	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	Coryphaena hippurus	RB167
Cynoscion nebulosus	Perciformes	Sciaenidae	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	Cynoscion nebulosus	EB97
Cynoscion spp.	Perciformes	Sciaenidae	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	Cynoscion nebulosus	EB97
Engraulidae spp.	Clupeiformes	Engraulidae											Zhou et al.	Zhou et al.
Epinephelini spp.	Perciformes	Serranidae	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Epinephelus morio	EB88
Haemulidae spp.	Perciformes	Haemulidae											Zhou et al.	Zhou et al.
Istiophoridae spp.	Perciformes	Istiophoridae	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	Xiphias gladius	RB82

			Fishing Mortality (Years^{-1})											
Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Modeled Proxy	Reference
Katsuwonus pelamis	Perciformes	Scombridae	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	Katsuwonus pelamis	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae											Zhou et al.	Zhou et al.
Lutjanidae spp.	Perciformes	Lutjanidae	0	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	Lutjanus campechanus	EB146
Lutjanus campechanus	Perciformes	Lutjanidae	0	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	Lutjanus campechanus	EB146
Lutjanus spp.	Perciformes	Lutjanidae	0	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	Lutjanus campechanus	EB146
Micropogonias undulatus	Perciformes	Sciaenidae	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	Micropogonias undulatus	RB463
Mugil spp.	Mugiliformes	Mugilidae	0	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	Mugil cephalus	EB156
Pomatomus saltatrix	Perciformes	Pomatomidae	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	Pomatomus saltatrix	RB121
Rachycentron canadum	Perciformes	Rachycentridae	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Rachycentron canadum	RB464
Rhomboplites aurorubens	Perciformes	Lutjanidae	0.614	0.614	0.614	0.614	0.614	0.614	0.614	0.614	0.614	0.614	Rhomboplites aurorubens	EB86
Sciaenidae spp.	Perciformes	Sciaenidae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Sciaenops ocellatus	EB68
Sciaenops ocellatus	Perciformes	Sciaenidae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Sciaenops ocellatus	EB68
Scomberomorus cavalla	Perciformes	Scombridae	0	0.056	0.287	0.159	0.107	0.075	0.155	0.068	0.124	0.072	Scomberomorus cavalla	RB59
Scomberomorus maculatus	Perciformes	Scombridae	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	0.323	Scomberomorus maculatus	RB63
Seriola spp.	Perciformes	Carangidae											Zhou et al.	Zhou et al.
Thunnus spp.	Perciformes	Scombridae	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	Thunnus albacares	RB71
Thunnus thynnus	Perciformes	Scombridae	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	Thunnus thynnus	RB97
Xiphias gladius	Perciformes	Xiphiidae	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	Xiphias gladius	RB82

C.1.1.6 Fish - Modeled - Age at Recruitment to Fishery

Table C.1.1.6 Age at recuitment parameters (years) used in modeling fish taxonomies. Value indicates first age at which taxonomy is suspectable to major fishing gear. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Modeled Age at Recruit to Fishery	Modeled Age at Recruitment to Fishery Proxy	Reference
Balistes capriscus	Tetraodontiformes	Balistidae	2	Balistes capriscus	EB90
Balistes spp.	Tetraodontiformes	Balistidae	2	Balistes capricus	EB90
Balistidae spp.	Tetraodontiformes	Balistidae	2	Balistes capricus	EB90
Brevoortia spp.	Clupeiformes	Clupeidae	1	Brevoortia patronus	RB148
Coryphaena spp.	Perciformes	Coryphaenidae	1	Coryphaena hippurus	RB167
Cynoscion nebulosus	Perciformes	Sciaenidae	1	Cynoscion nebulosus	EB97
Cynoscion spp.	Perciformes	Sciaenidae	1	Cynoscion nebulosus	EB97
Engraulidae spp.	Clupeiformes	Engraulidae	1	Zhou et al.	Zhou et al.
Epinephelini spp.	Perciformes	Serranidae	4	Epinephelus morio	EB88
Haemulidae spp.	Perciformes	Haemulidae	2	Zhou et al.	Zhou et al.
Istiophoridae spp.	Perciformes	Istiophoridae	2	Xiphias gladius	RB82
Katsuwonus pelamis	Perciformes	Scombridae	1	Katsuwonus pelamis	RB80
Leiostomus xanthurus	Perciformes	Sciaenidae	2	Zhou et al.	Zhou et al.
Lutjanidae spp.	Perciformes	Lutjanidae	2	Lutjanus campechanus	EB146
Lutjanus campechanus	Perciformes	Lutjanidae	2	Lutjanus campechanus	EB146
Lutjanus spp.	Perciformes	Lutjanidae	2	Lutjanus campechanus	EB146
Micropogonias undulatus	Perciformes	Sciaenidae	1	Micropogonias undulatus	RB463
Mugil spp.	Mugiliformes	Mugilidae	2	Mugil cephalus	EB156
Pomatomus saltatrix	Perciformes	Pomatomidae	1	Pomatomus saltatrix	RB121
Rachycentron canadum	Perciformes	Rachycentridae	4	Rachycentron canadum	RB464
Rhomboplites aurorubens	Perciformes	Lutjanidae	1	Rhomboplites aurorubens	EB86
Sciaenidae spp.	Perciformes	Sciaenidae	1	Sciaenops ocellatus	EB68
Sciaenops ocellatus	Perciformes	Sciaenidae	1	Sciaenops ocellatus	EB68
Scomberomorus cavalla	Perciformes	Scombridae	2	Scomberomorus cavalla	RB59
Scomberomorus maculatus	Perciformes	Scombridae	1	Scomberomorus maculatus	RB63
Seriola spp.	Perciformes	Carangidae	1	Zhou et al.	Zhou et al.
Thunnus spp.	Perciformes	Scombridae	2	Thunnus albacares	RB71
Thunnus thynnus	Perciformes	Scombridae	5	Thunnus thynnus	RB97
Xiphias gladius	Perciformes	Xiphiidae	2	Xiphias gladius	RB82

C.1.2 Invertebrates

C.1.2.1 Invertebrate - Modeled - Von Bertalanffy Parameters

Table C.1.2.1 von Bertalanffy parameters (L_{inf} in cm, t_0 in years) used in modeling invertebrate taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Linf	k	t_0	Proxy Species	Ref Code
Panulirus argus	Decapoda	Palinuridae	18.5	0.23	0.44	Panulirus argus	CM41
Litopenaeus setiferus	Decapoda	Penaeidae	21.4	5.04	0.00	Litopenaeus setiferus	CM44
Callinectes sapidus	Decapoda	Portunidae	16.6	2.16	0.17	Callinectes sapidus	CM40

C.1.2.2 Invertebrate - Modeled - Weight-Length Parameters

Table C.1.2.2 Weight-length parameters (cm, kg) used in modeling invertebrate taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	a	b	Proxy Species	Ref Code
Panulirus argus	Decapoda	Palinuridae	9.2E-02	2.48	Panulirus argus	CM41
Litopenaeus setiferus	Decapoda	Penaeidae	3.8E-03	3.25	Litopenaeus setiferus	EB2
Callinectes sapidus	Decapoda	Portunidae	2.3E-01	2.45	Callinectes sapidus	CM40

C.1.2.3 Invertebrate - Modeled - Maximum Age

Table C.1.2.3 Maximum age values (years) parameters used in modeling invertebrate taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Max Age	Proxy Species	Ref Code
Panulirus argus	Decapoda	Palinuridae	16	Panulirus argus	CM41
Litopenaeus setiferus	Decapoda	Penaeidae	1	Litopenaeus setiferus	RB457
Callinectes sapidus	Decapoda	Portunidae	6	Callinectes sapidus	CM40

C.1.2.4 Invertebrate - Mortality - Natural Mortality

Table C.1.2.4 Natural mortality (M, $years^{-1}$) parameters used in modeling invertebrate taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Proxy Species	Ref Code
Panulirus argus	Decapoda	Palinuridae	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	Panulirus argus	CM41
Litopenaeus setiferus	Decapoda	Penaeidae	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	Farfantepenaeus aztecus	EB192
Callinectes sapidus	Decapoda	Portunidae	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Callinectes sapidus	EB202

C.1.2.5 Invertebrate - Modeled - Fishing Mortality

Table C.1.2.5 Fishing mortality parameters (F, years^{-1}) used in modeling invertebrate taxonomies. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	1	2	3	4	5	6	7	8	9	10+	Proxy Species	Ref Code
Panulirus argus	Decapoda	Palinuridae	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	Panulirus argus	CM41
Litopenaeus setiferus	Decapoda	Penaeidae	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	Farfantepenaeus aztecus	EB192
Callinectes sapidus	Decapoda	Portunidae	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	Callinectes sapidus	EB202

C.1.2.6 Invertebrate - Modeled - Age at Recruitment

Table C.1.2.6 Age at recuitment parameters (years) used in modeling fish taxonomies. Value indicates first age at which taxonomy is suspectable to major fishing gear. 'Professional Judgement' indicates values selected by researches for which published values were unavailable. Proxy species indicates the taxonomy from which the parameter values are derived. Reference codes are found in Appendix D.

Taxonomy	Order	Family	Modeled Age at Recruit to Fishery	Proxy Species	Ref Code
Panulirus argus	Decapoda	Palinuridae	1	Panulirus argus	CM41
Litopenaeus setiferus	Decapoda	Penaeidae	1	Professional Judgement	Professional Judgement
Callinectes sapidus	Decapoda	Portunidae	1	Callinectes sapidus	EB202

Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

Appendix D. Production Foregone: Life History Parameters by Taxonomic Group – References

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Project Number: 2011-144
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D. References

Appendix D presents a list of references used to determine life history parameters used in the production foregone model. Parameters pulled from references includes von Bertalanffy growth curves, weight-length relationships, maximum ages, natural mortality rates, fishing mortality rates, and age at recruitment to fishery. Data from these references is presented in Appendix B and C. The reference codes (labeled alternately as 'Ref Code' and 'Reference') presented in Appendix B and C refer to the 'Ref Code' column presented in Appendix D.

Ref Code	Reference
CA16	Houde, E.D. and C.E. Zastrow. Bay Anchovy Anchoa mitchilli. In: Funderburk, S.L., J.A. Mihursky, S.J. Jordan, D. Riley (eds.). Habitat requirements for Chesapeake Bay living resources, 2nd edn. Living Resources Subcommittee, Chesapeake Bay Program. Annapolis, p. 8.1-8.14.
CA51	Newberger, T.A., and E.D. Houde. 1995. Population biology of bay anchovy Anchoa mitchilli in the mid Chesapeake Bay. Mar. Ecol. Prog Ser. 116: 25-37.
CA7	Froese, R. and D. Pauly. Editors. 2014. FishBase. World Wide Web electronic publication. www.fishbase.org, version (11/2014).
CM40	VanderKooy, S. 2013. GDAR 01 Stock Assessment Report: Guf of Mexico Blue Crab. Gulf States Marine Fisheries Commission. 291 pp.
CM41	Southeast Data, Assessment, and Review (SEDAR). 2005. Stock Assessment Report of SEDAR 8: Caribbean Spiny Lobster. Assessment Report 2.
CM44	Klima, E.F. 1974. A white shrimp mark- recapture study. Transactions of the American Fisheries Society. 103(1): 107-113.
EB115	Sundaraj, B. 1960. Age and growth of the spot, Leiostomus xanthurus Lacépède. Tulane Studies in Zoology. 8(2):41-62.
EB123	Broome, M., D. Claar, E. Hamman, T. Matthews, M. Salazar, K. Shugart-Schmidt, A. Tillman, M. Vicent, and J.Berkson. 2011. Exploratory assessment of four stocks in the U.S. South Atlantic: bank sea bass (Centropristis ocyurus) gray triggerfish (Balistes capriscus) sand perch (Diplectrum formosum) tomtate (Haemulon aurolineatum). NOAA Technical Memorandum NMFS-SEFSC-617. National Marine Fisheries Service, Southeast Fisheries Science Center, Miami, Florida, June 2011.
EB124	Bohnsack, J.A., and D.E. Harper. 1988. Length-weight relationships of selected marine reef fishes from the southeastern United States and the Caribbean. NOAA Technical Memorandum NMFS-SEFC-215, 31 p.
EB125	Murphy, M.D., D.J. Murie, and R.G. Muller. 1999. Stock assessment of white grunt from the west coast of Florida. Report to the Florida Fish and Wildlife Conservation Commission, October 12, 1999.
EB136	Southeast Data, Assessment, and Review (SEDAR). 2005. SEDAR 7 Stock Assessment Report Gulf of Mexico Red Snapper. Edited by P.L. Cordue for SEDAR 7, New Orleans, LA.
EB138	Gazey, W.J., B.J. Gallaway, J.G. Cole, and D.A. Fournier. 2008. Age composition, growth, and density-dependent mortality in juvenile red snapper estimated from observer data from the Gulf of Mexico Penaeid shrimp fishery. North American Journal of Fisheries Management. 28(6): 1828-1842.
EB146	Linton, Brian. Personal communication; March 21, 2012. Results of the CATCHEM, base run of the 2009 update assessment for red snapper.
EB156	Mahmoudi, B. 2000. Status and trends in the Florida mullet fishery and an updated stock assessment, IHR 2000-006. Florida Marine Research Institute, St. Petersburg, FL. September 2000.

Ref Code	Reference
EB192	Nance, J.M. 2011. Stock Assessment Report 2010: Gulf of Mexico Shrimp Fishery. Report for the Gulf of Mexico Fishery Management Council. October 2011.
EB2	U.S. Fish and Wildlife Service. 1983 - 19__. Species Profiles: life histories and environmental requirements of coastal fishes and invertebrates. U.S. Fish Wildl. Serv. Biol. Rep. 82(11). U.S. Army Corps of Engineers, TR EL-82-4
EB202	Murphy, M.D., C.A. Meyer, and A.L. McMillen-Jackson. 2001. A stock assessment for blue crab, Callinectes sapidus, in Florida waters. A report to the Florida Fish and Wildlife Commission Division of Marine Fisheries IHR 2001-008. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute. St. Petersburg, Florida.
EB68	Murphy, M.D. 2002. A stock assessment of red drum, Sciaenops ocellatus, in Florida: status of the stocks through 2000. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute, ST. Petersburg, FL.
EB70	Murphy, M.D. 2003. A stock assessment of spotted seatrout Cynoscion nebulosus in Florida: status of the stocks through 2001. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute, ST. Petersburg, FL.
EB75	Nieland, D.L., R.G. Thomas, and C.A. Wilson. 2002. Age, growth, and reproduction of spooted seatrout in Barataria Bay, Louisiana. Transactions of the American Fisheries Society. 131: 245-259.
EB77	Fischer, A.J., M.S. Baker Jr., C.A. Wilson, and D.L. Nieland. 2005. Age, growth, mortality, and radiometric age validation of gray snapper (Lutjanus griseus) from Louisiana. Fishery Bulletin. 103: 307-319.
EB79	Rutherford, E. S., T. W. Schmidt, and J. T. Tilmant. 1989. Early life history of spotted sea trout (Cynoscion nebulosus) and gray snapper (Lutjanus griseus) in Florida Bay, Everglades National Park, Florida. Bulletin of Marine Science. 44(1): 49−64.
EB82	Porch, C.E. 2000. Status of the red drum stocks of the Gulf of Mexico, Version 2.1. Sustainable Fisheries Division Contribution: SFD-99/00-85. Southeast Fisheries Science Center, Miami, FL.
EB83	Porch, C.E., C.A. Wilson, and D.L. Nieland. 2002. A new growth model for red drum (Sciaenops ocellatus) that accommodates seasonal and ontogenic changes in growth rates. Fishery Bulletin. 100: 149-152.
EB86	Southeast Data, Assessment, and Review (SEDAR). 2006. SEDAR 9 Stock Assessment Report Gulf of Mexico Vermillion Snapper. SEDAR, 1 Southpark Circle #306, Charleston, SC 29414.
EB87	Walter, John. Personal communication; January 30, 2012. Results of the ASAP red tide 2009 update assessment model runs, including new recent discards. March 5, 2010.
EB88	Southeast Data, Assessment, and Review (SEDAR). 2006. SEDAR 12 Stock Assessment Report Gulf of Mexico Red Grouper. SEDAR, 1 Southpark Circle #306, Charleston, SC 29414.
EB90	Southeast Data, Assessment, and Review (SEDAR). 2011. Stock Assessment of Gray Triggerfish in the Gulf of Mexico: [Preliminary] SEDAR Update Assessment, Miami Florida, October, 2011. Note: received from Jeff Isely January 27, 2012. He noted that "the assessment is preliminary. The report was presented to the SSC and will be presented to the GMFMC next week. The SSC selected the option that includes the new age-length key and varying shrimp effort, but requested new projections based on average recruitment from 2005-2010".
EB92	Barger, L.E. 1985. Age and growth of Atlantic croakers in the northern Gulf of Mexico, based on otolith sections. Transactions of the American Fisheries Society 114(6): 847-850.
EB94	Sheridan, P.F., D.L. Trimm, and B.M. Baker. 1984. Reproduction and food habits of seven species of northern Gulf of Mexico fishes. Contributions in Marine Science. 27: 175-204.
EB97	Alabama Marine Resources Division. 2007. 2007 spotted seatrout assessment. Draft 4. 11 pp.
Lorenzen	Lorenzen, K. (1996). The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture.Journal of fish biology, 49(4), 627-642.

Ref Code	Reference
MS8	Haimovici, M. and G. Velasco. 2000. Length-weight relationships of marine fishes from southern Brazil. Naga ICLARM Q. 23(1): 19-23.
RB105	Pers. Comm. Cass-Calay, S. reply to data request.
RB106	Tserpes, G. and N. Tsimenides. 1995. Determination of age and growth of swordfish, Xiphias gladius L., 1758, in the eastern Mediterranean using anal-fin spines. Fishery Bulletin. 93: 594-602.
RB107	Turner, S. Length to weight and weight to length conversions for swordfish in the western north Atlantic and Gulf of Mexico. SEFC Swordfish Assessment Workshop.
RB119	Ceyhan, T., O. Akyol, A. Ayaz, and F. Juanes. 2007. Age, growth, and reproductive season of bluefish (Pomatomus saltatrix) in the Marmara region, Turkey. ICES Journal of Marine Science. 64: 531–536.
RB120	Salerno, D.J., J. Burnett and R.M. Ibara. 2001. Age, growth, maturity, and spatial distribution of Bluefish, Pomatomus saltatrix (Linnaeus), off the northeast coast of the United states, 1985-96. Journal of Northwest Atlantic Fisheries Science. 29: 31-39.
RB121	MAFMC. 2014. Overview of Stock Status: Pomatomus saltatirx, Blufish. http://www.mafmc.org/fisheries/fmp/bluefish
RB122	Fishery Management Plan for the bluefish fishery. May 1989. Mid-Atlantic Fishery Management Council and Atlantic States Marine Fisheries Commission.
RB123	Franks, J.S., J.R. Warren and M.V. Buchanan. 1999. Age and growth of cobia, Rachycentron canadum, from the northeastern Gulf of Mexico. Fishery Bulletin. 97: 459-471.
RB124	Williams, E.H. 2001. Assessment of Cobia, Rachycentron canadum, in the waters of the U.S. Gulf of Mexico. NOAA TECHNICAL MEMORANDUM NMFS-SEFSC-469. U.S. Department of Commerce NOAA.
RB144	Prager M.H., D.W. Lee and E.D. Prince. 1995. Empirical length and weight conversion equations for blue marlin, white marlin, and sailfish from the North Atlantic. Bull. Mar. Sci. 56: 201-210.
RB145	ICCAT Manual: http://www.iccat.es/en/ICCATManual.asp?mId=4
RB148	Southeast Data, Assessment, and Review (SEDAR). 2011. SEDAR 27 Stock Assessment Report Gulf of Mexico Menhaden. SEDAR, 4055 Faber Place Drive, Suite 201, North Charleston, SC 29405.
RB149	Southeast Data, Assessment, and Review (SEDAR). 2006. SEDAR 9 Stock Assessment Report Gulf of Mexico Gray Triggerfish. SEDAR, 4055 Faber Place Drive, Suite 201, North Charleston, SC 29405.
RB153	Lessa, R. and P. Duarte-Neto. Age and growth of yellowfin tuna (Thunnus albacares) in the western equatorial Atlantic, using dorsal fin spines. Fisheries Research. 69: 157-170.
RB157	Rivera, G.A. and R.S. Appeldoorn. 2000. Age and growth of dolphinfish, Coryphaena hippurus, off Puerto Rico. Fishery Bulletin 98: 345-352.
RB167	Prager, H.M. Exploratory assessment of dolphinfish, Coryphaena hippurus, based on U.S. landings from the Atlantic Ocean and Gulf of Mexico. NMFS Report
RB303	Grimes, C.B. 1978. Age, growth and length-weight relationships of vermilion snapper, Rhomboplites aurorubens from North Carolina and South Carolina waters. Trans. Am. Fish. Soc. 107(3): 454-456.
RB306	Saari, C. R. 2011. Comparison of the age and growth of red snapper (Lutjanus campechanus) amongst habitats and regions in the Gulf of Mexico (Doctoral dissertation, Eckerd College).
RB321	Southeast Data, Assessment, and Review (SEDAR). 2012. SEDAR 28 Stock Assessment Report Gulf of Mexico and South Atlantic Spanish mackerel and cobia. SEDAR, 4055 Faber Place Drive, Suite 201, North Charleston, SC 29405.
RB358	Jarzhombek, A.A. 2007. Compilation of studies on the growth of Acanthopterygii. Russian Federal Research Institute of Fisheries and Oceanography (VNIRO). 86 p.
RB441	Southeast Data, Assessment, and Review (SEDAR). 2005. Stock Assessment Report of SEDAR 8: Caribbean Spiny Lobster. Assessment Report 2.

Ref Code	Reference
RB447	Southeast Data, Assessment, and Review (SEDAR). 2013. Stock Assessment Report of SEDAR 31: Gulf of Mexico Red Snapper. Assessment Report.
RB451	Southeast Data, Assessment, and Review (SEDAR). 2014. Stock Assessment Report of SEDAR 33: Gulf of Mexico Greater Amberjack. Assessment Report.
RB457	Baker, R., M. Fujiwara, and T.J. Minello. 2014. Juvenile growth and mortality effects on white shrimp Litopenaeus setiferus population dynamics in the northern Gulf of Mexico. Fisheries Research. 155: 74-82.
RB462	Southeast Data, Assessment, and Review (SEDAR). 2011. Stock Assessment Report of SEDAR 26: Caribbean Queen Snapper. Final Stock Assessment Report
RB463	Southeast Data, Assessment, and Review (SEDAR). 2010. Stock Assessment Report of SEDAR 20: Atlantic Croaker and Atlantic Menhaden. Final Stock Assessment Report
RB464	Southeast Data, Assessment, and Review (SEDAR). 2012. Stock Assessment Report of SEDAR 28: South Atlantic Cobia, South Atlantic Spanish Macerel, Gulf of Mexico Cobia, and Gulf of Mexico Spanish Mackerel. Final Stock Assessment Report
RB465	Southeast Data, Assessment, and Review (SEDAR). 2013. Stock Assessment Report of SEDAR 34: Atlantic Sharpnose Shark and Bonnethead Shark. Final Stock Assessment Report
RB54	IUCN 2014. The IUCN Red List of Threatened Species. Version 2014.3. <http://www.iucnredlist.org>.
RB59	Southeast Data, Assessment, and Review (SEDAR). 2008. SEDAR 16 Stock Assessment Report Gulf of Mexico King Mackerel. SEDAR, 4055 Faber Place Drive, Suite 201, North Charleston, SC 29405.
RB63	Southeast Data, Assessment, and Review (SEDAR). 2011. SEDAR 21 Stock Assessment Report HMS Sandbar, Dusky, and Blacknose sharks. SEDAR, 4055 Faber Place Drive, Suite 201, North Charleston, SC 29405.
RB65	Southeast Data, Assessment, and Review (SEDAR). 2007. SEDAR 15 Stock Assessment Report South Atlantic Red Snapper and Greater Amberjack. SEDAR, 4055 Faber Place Drive, Suite 201, North Charleston, SC 29405.
RB70	ICCAT. 2011. Report of the 2011 Yellowfin Tuna Stock Assessment Session. San Sebastián, Spain - September 5 to 12, 2011. https://www.iccat.int/Documents/Meetings/Docs/2011_YFT_ASSESS_REP.pdf
RB71	Amendment 1 to the consolidated HMS FMP. Chapter 5 June 2009 Essential Fish Habitat; http://www.nmfs.noaa.gov/sfa/hms/EFH/Final/FEIS_Amendment_1_Chapter5.pdf#page=13
RB79	Richards, W.J. and D.C. Simmons. 1971. Distribution of tuna larvae (Pisces, Scombridae) in the northwestern Gulf of Guinea and off Sierra Leone. Fishey Bulletin. 69: 555-568.
RB80	ICCAT. 2008. Report on the 2008 Skipjack Tuna Stock Assessment Session.
RB82	ICCAT. 2009. Report on the 2009 Swordfish Stock Assessment Session.
RB83	ICCAT. 2009. Report on the 2009 Sailfish Stock Assessment Session. Recife, Brazil, June 1-5, 2009. https://www.iccat.int/Documents/SCRS/DetRep/DET-SAI.pdf
RB85	Ehrhardt, N.M. and V.K.W. Deleveaux. 2006. Interpretation of tagging data to study growth of the Atlantic sailfish (Istiophorus platypterus). Bulletin of Marine Science. 79: 719-726.
RB86	Oxenford, H.A. 1999. Biology of the dolphinfish (Coryphaena hippurus) in the western central Atlantic: a review. Scientia Marina. 63: 277-301.
RB94	Restrepo, V.R., G.A. Diaz, J.F. Walter, J.D. Neilson, S.E. Campana, D. Secor and R.L. Wingate. 2010. Updated estimate of the growth curve of Western Atlantic bluefin tuna. Aquatic Living Resources. 23: 335-342.
RB95	Parrack, M.L. and Phares. 1979. Aspects of the growth of Atlantic bluefin tuna determined from mark recapture data. ICCAT 1979
RB97	ICCAT. 2010. Report on the 2010 Bluefin Tuna Stock Assessment Session.
RGB106	García, C.B., L.O. Duarte, N. Sandoval, D. von Schiller, G. Melo and P. Navajas, 1998. Length-weight relationships of demersal fishes form the Gulf of Salamanca, Colombia. Naga ICLARM Q.

Ref Code	Reference
RGB158	Barger, L.E., 1990. Age and growth of bluefish Pomatomus saltatrix from the northern Gulf of Mexico and U.S. south Atlantic coast. Fish. Bull. 88:805-809.
RGB159	Bluefish Species Account. 2010. http://myfwc.com/media/194512/bluefish.pdf
RGB163	Richards, C.E., 1967. Age, growth and fecundity of the cobia, Rachycentron canadum, from Chesapeake Bay and adjacent mid-Atlantic waters. Trans. Am. Fish. Soc. 96(3):343-350.
RGB165	Olaechea, A. and U. Sauskan, 1974. Cartas de pesca del Banco de Campeche, 1972, Parte 1. Centro de Investigaciones Pesqueras, La Habana. 67 p. [inédito].
RGB166	Leite, N.O. Jr., A.S. Martins and J.N., Araújo, 2005. Idade e crescimento de peixes recifais na região central da Zona Econômica Exclusiva entre Salvador-BA e o Cabo de São Tomé-RJ (13°S a 22°S). In COSTA, P.A.S.; MARTINS, A.S.; OLAVO, G. (Eds.) Pesca e potenciais de exploração de recursos vivos na região central da Zona Econômica Exclusiva brasileira. Rio de Janeiro: Museu Nacional. p.203-216 (Série Livros n.13).
RGB167	Boardman, C. and D. Weiler, 1980. Aspects of the life history of three deep water snappers around Puerto Rico. Proc. Gulf Caribb. Fish. Inst. 32:158-172.
RGB168	Grimes, C.B., 1978. Age, growth and length-weight relationships of vermilion snapper, Rhomboplites aurorubens from North Carolina and South Carolina waters. Trans. Am. Fish. Soc. 107(3):454-456.
RGB177	Murphy, M.D. and R.G. Taylor, 1990. Reproduction, growth, and mortality of red drum Sciaenops ocellatus in Florida waters. Fish. Bull. 88:531-542.
RGB191	ICCAT Bluefin Stock Assessment http://www.iccat.es/Documents/Meetings/Docs/2014_BFT_ASSESS-ENG.pdf
RGB21	Welsh, W. and G. Breder, 1924. Contribution to the life history of Sciaenidae of the U.S. East Coast. Fish. Bull. 39(945):141-201
RGB22	Maceina, M.J., D.N. Hata, T.L. Linton and A.M. Landry Jr., 1987. Age and growth analysis of spotted seatrout from Galveston Bay, Texas. Trans. Am. Fish. Soc. 116(1):54-59.
RGB23	Klima, E.F. and D.C. Tabb, 1959. A contribution to the biology of the spotted weakfish, Cynoscion nebulosus (Cuvier), from Northwest Florida, with a description of the fishes. Florida Board Conserv. Tech. Bull. (30):25 p.
RGB24	Moflett, A., 1961. Movements and growth of spotted sea trouts, Cynoscion nebulosus, Cuvier, in West Florida. Fla. St. Bd. Cons. Tech. Ser. (36):1-35.
RGB25	Tabb, D.C., 1961. A contribution to the biology of the spotted sea trout, Cynoscion nebulosus, in East Central Florida. Fla. St. Bd. Cons. Tech. Ser. (35):1-23.
RGB26	Matlock, G.C. and M.A. Garcia, 1983. Stomach contents of selected fishes from Texas bays. Contrib. Mar. Sci. 26:95-110.
RGB27	Pearson, J., 1929. Natural history and conservation of redfish and other commercial sciaenids on the Texas coast. Bull. U.S. Bur. Fish. Wash. 44:129-214.
RGB46	Pacheco, A., 1962. Age and growth of spot in lower Chesapeake Bay, with notes on distribution and abundance of juveniles in the York River system. Chesapeake Sci. 3(1):18-28.
RGB47	Pearson, J., 1929. Natural history and conservation of redfish and other commercial sciaenids on the Texas coast. Bull. U.S. Bur. Fish. Wash. 44:129-214.
RGB54	CHITTENDeN JR, M. E., & Jones, C. M. (1994). Age, growth, and mortality of Atlantic croaker, Micropogonias undulatus, in the Chesapeake Bay region, with a discussion of apparent geographic changes in population dynamics. Fish. Bull, 92, l-12.
RGB55	Hansen, D., 1970. Food, growth, migration, reproduction and abundance of pinfish, Lagodon rhomboides and Atlantic croaker, Micropogon undulatus, near Pensacola, Florida. U.S. Fish. Comm. Bull. 68(1):135-146.
RGB56	Pearson, J., 1929. Natural history and conservation of redfish and other commercial sciaenids on the Texas coast. Bull. U.S. Bur. Fish. Wash. 44:129-214.
RGB64	Barger, L.E., 1990. Age and growth of bluefish Pomatomus saltatrix from the northern Gulf of Mexico and U.S. south Atlantic coast. Fish. Bull. 88:805-809.

Ref Code	Reference
RGB65	Terceiro, M. and J.L. Ross, 1993. A comparison of alternative methods for the estimation of age from length data for Atlantic coast bluefish (Pomatomus saltatrix). Fish. Bull. 91:534-549.
RGB69	Thompson, B.A., C.A. Wilson, J.H. Render and M. Beasley, 1992. Age, growth and reproductive biology of greater amberjack and cobia from Louisiana waters. Year 1. Rep. To U.S. Dep. Commer., NOAA, NMFS, Coop. Agreement NA90AA-H-MF089, Marine Fisheries Initiative (MARFIN) Prog., Coastal Fish. Inst., Louisiana State University, Baton Rouge, Louisiana, USA. 55 p.
RGB70	Burns, K.M., C. Neidig, J.M. Lotz and R.M. Overstreet, 1998. Cobia (Rachycentron canadum) stock assessment study in the Gulf of Mexico and the South Atlantic. Final Rep. to U.S Dep. Commer., NOAA, NMF, Award No. NA57FF0294, Marine Fisheries Initiative (MARFIN) Prog., Mote Marine Laboratory, Sarasota, FL, var. pag.
RGB71	Franks, J.S. and N.J. Brown-Peterson, 2002. A review of age, growth, and reproduction of cobia, Rachycentron canadum, from U.S. waters of the Gulf of Mexico and atlantic ocean. p. 552-569. In R. LeRoy Creswell (eds.) Proc. 53rd Gulf and Caribbean Fisheries Institute, Biloxi, Mississippi, November 2000. Fort Pierce, Florida.
RGB77	SEDAR 18. http://sedarweb.org/sedar-18-stock-assessment-report-atlantic-red-drum
RGB81	TURNER, S. C. and V. R. Restrepo. 1994. A review of the growth rate of West Atlantic bluefin tuna, Thunnus thynnus, estimated from marked and recaptured fish. Collect. Vol. Sci. Pap. ICCAT, 42: 170-172.
RGB82	Secor D.H., Wingate R.L., Neilson J.D., Rooker J.R., Campana S.E.,2008, Growth of Atlantic bluefin tuna: direct age estimates.ICCAT, SCRS/2008/084.
RGB83	Neilson J.D., Campana S.E., 2008, A validated description of age and growth of western Atlantic bluefin tuna (Thunnus thynnus). Can.J. Fish. Aquat. Sci. 65, 1523-1527
RGB86	Radtke, R.L. and P.C. Hurley, 1983. Age estimation and growth of broadbill swordfish Xiphias gladius, from the North West Atlantic. NOAA Tech. Rep. NMFS 8:145-150.
RGB87	Bohnsack, J.A. and D.E. Harper, 1988. Length-weight relationships of selected marine reef fishes from the southeastern United States and the Caribbean. NOAA Tech. Mem. NMFS-SEFC-215:31 p.
RGB91	Frota, L.O., P.A.S. Costa and A.C. Braga, 2004. Length-weight relationships of marine fishes from the central Brazilian coast. NAGA WorldFish Center Q. 27(1&2):20-26.
RGB94	Dawson, C.E., 1965. Length-weight relationships of some Gulf of Mexico fishes. Trans. Am. Fish. Soc. 94:279-280.
Zhou et al.	Zhou, S., Yin, S., Thorson, J. T., Smith, A. D., & Fuller, M. (2012). Linking fishing mortality reference points to life history traits: an empirical study. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(8), 1292-1301.

Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

Appendix E. Summary of Model Results – Life Table and Production Foregone per Individual by Species Group

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E.1 Summary of Production Foregone Inputs and Results

Appendix E presents input size data used in calculating production foregone and results from the production foregone model. Length (mm) is used as the direct input to the model. Production foregone (g) per individual from input length is calculated using the methodology described within the main production foregone report. Complete results may be found in each individual production foregone workbook. A list of these workbooks may be found in Appendix F.

Summary

Based on the production foregone model, production foregone per individual increases with the body size of the species (i.e., at age 1 year and as adults). Thus, production foregone per individual is much higher for large pelagic fish than it is for prey fish. The reasons for this relationship are as follows.

The first year of life mortality model employed by the production foregone model is grounded in size-based mortality theory; the larger a marine organism is, the less likely it is to be predated upon. The greatest mortality rates occur during the larval stage when fish are least capable of avoiding predation. Thus, if the larvae are large at the size sampled (due to age of the individuals or to the species), their survival is higher and production foregone from the initial size to age 1 year or over the lifespan is higher.

The second most influential relationship exists between production foregone and weight at age 1 year. Species that grow to greater weights by age 1 year experience reduced mortality rates during the juvenile stage compared to smaller species, because they grow to larger sizes faster, reducing mortality, and resulting in greater production foregone per individual. Note that, in addition, these larger species also have higher survival rates after age 1 year due to larger size, at least until fishing mortality becomes substantial. Thus, the production per individual after age 1 year is also higher for larger species.

Results and Discussion

Table E.1 provides a comparison of input larval length with various model outputs by species and season. Larval survival rates and production foregone values are calculated from the larval length provided in the fourth column. Egg survival rates and production foregone are calculated from the beginning of the egg stage.

Table E-1. Input size and production foregone results for Historical SEAMAP Bongo Ichthyoplankton

Latin Name	Common Name	Season	Larvae length (mm)	Larval survival to age 1yr	Egg survival to age 1yr	Larval production foregone to age 1yr (g/indiv)	Egg production foregone to age 1yr (g/egg)	Larval production foregone to end of life (g/indiv)	Egg production foregone to end of life (g/egg)	Age 1yr wet weight (g/indiv)
Balistes capriscus	Gray triggerfish	Spring	3	4.4E-06	3.8E-07	1.1E-03	1.3E-04	3.0E-03	2.6E-04	184.4
Balistes capriscus	Gray triggerfish	Summer	3.2	2.8E-06	3.5E-07	7.5E-04	1.3E-04	1.9E-03	2.6E-04	184.4
Balistes spp.	Triggerfish	Spring	2.5	9.3E-07	3.8E-07	2.8E-04	1.3E-04	6.7E-04	2.6E-04	184.4
Balistes spp.	Triggerfish	Summer	2.5	1.1E-06	3.5E-07	3.2E-04	1.3E-04	7.6E-04	2.6E-04	184.4
Balistidae spp.	Triggerfish	Spring	3.5	8.6E-06	3.8E-07	2.2E-03	1.3E-04	5.8E-03	2.6E-04	184.4
Balistidae spp.	Triggerfish	Summer	3.4	6.6E-06	3.5E-07	1.7E-03	1.3E-04	4.5E-03	2.6E-04	184.4
Brevoortia spp.	Menhaden	Spring	5.8	8.1E-05	2.3E-07	6.3E-03	6.3E-05	9.8E-03	7.1E-05	43.8
Brevoortia spp.	Menhaden	Summer	3.6	4.2E-06	2.2E-07	5.1E-04	6.2E-05	6.9E-04	7.1E-05	43.8
Coryphaena spp.	Dolphin	Spring	3.6	2.4E-05	1.0E-06	4.3E-01	1.9E-02	5.4E-01	2.3E-02	17068.9
Coryphaena spp.	Dolphin	Summer	3.3	1.7E-05	9.1E-07	3.0E-01	1.6E-02	3.8E-01	2.0E-02	17068.9
Cynoscion nebulosus	Spotted seatrout	Spring	2.6	9.9E-07	4.1E-07	3.4E-04	1.6E-04	6.1E-04	2.5E-04	228.8
Cynoscion nebulosus	Spotted seatrout	Summer	2.5	1.1E-06	3.8E-07	3.8E-04	1.5E-04	6.9E-04	2.4E-04	228.8
Cynoscion spp.	seatrout unspecified	Spring	2.2	4.1E-07	4.1E-07	1.6E-04	1.6E-04	2.7E-04	2.5E-04	228.8
Cynoscion spp.	seatrout unspecified	Summer	2.5	1.1E-06	3.8E-07	3.8E-04	1.5E-04	6.9E-04	2.4E-04	228.8
Engraulidae spp.	Anchovy	Spring	5	5.8E-06	4.5E-08	8.7E-04	4.9E-05	8.7E-04	4.9E-05	1.7
Engraulidae spp.	Anchovy	Summer	4.3	3.8E-06	4.6E-08	6.8E-04	4.9E-05	6.8E-04	4.9E-05	1.7
Epinephelini spp.	Epinephelini	Spring	2.6	1.1E-06	4.7E-07	5.9E-04	2.6E-04	2.2E-02	7.5E-03	392.0
Epinephelini spp.	Epinephelini	Summer	2.6	1.3E-06	4.3E-07	6.6E-04	2.4E-04	2.4E-02	7.3E-03	392.0
Haemulidae spp.	Haemulidae spp.	Spring	3.6	7.3E-06	3.2E-07	1.2E-03	9.1E-05	2.3E-03	1.3E-04	108.0
Haemulidae spp.	Haemulidae spp.	Summer	3.1	2.4E-06	3.0E-07	4.7E-04	8.9E-05	8.1E-04	1.3E-04	108.0
Istiophoridae spp.	billfishes; sailfishes; marlins	Spring	4	3.1E-05	7.3E-07	8.3E-02	2.0E-03	5.1E-01	1.0E-02	2456.8
Istiophoridae spp.	billfishes; sailfishes; marlins	Summer	3.7	1.2E-05	6.5E-07	3.2E-02	1.8E-03	2.0E-01	9.6E-03	2456.8
Katsuwonus pelamis	Skipjack tuna	Spring	3.1	5.3E-06	4.6E-07	2.3E-03	2.3E-04	7.3E-03	6.0E-04	353.6
Katsuwonus pelamis	Skipjack tuna	Summer	3.1	3.3E-06	4.2E-07	1.5E-03	2.2E-04	4.6E-03	5.7E-04	353.6
Leiostomus xanthurus	Spot	Spring	2	2.0E-07	2.0E-07	5.8E-05	5.8E-05	6.5E-05	6.4E-05	31.2
Leiostomus xanthurus	Spot	Summer	2.1	2.0E-07	2.0E-07	5.8E-05	5.8E-05	6.5E-05	6.4E-05	31.2
Lutjanidae spp.	sea perches; snappers	Spring	2.2	3.3E-07	3.3E-07	9.6E-05	9.6E-05	5.1E-04	4.4E-04	118.0
Lutjanidae spp.	sea perches; snappers	Summer	2.2	3.1E-07	3.1E-07	9.3E-05	9.3E-05	4.8E-04	4.4E-04	118.0
Lutjanus campechanus	Red snapper	Spring	4.5	2.5E-05	3.3E-07	4.2E-03	9.6E-05	2.5E-02	3.2E-04	118.0
Lutjanus campechanus	Red snapper	Summer	4.6	2.6E-05	3.1E-07	4.4E-03	9.3E-05	2.5E-02	3.1E-04	118.0

Latin Name	Common Name	Season	Larvae length (mm)	Larval survival to age 1yr	Egg survival to age 1yr	Larval production foregone to age 1yr (g/indiv)	Egg production foregone to age 1yr (g/egg)	Larval production foregone to end of life (g/indiv)	Egg production foregone to end of life (g/egg)	Age 1yr wet weight (g/indiv)
Lutjanus spp.	Snappers	Spring	3.2	3.8E-06	3.3E-07	7.3E-04	9.6E-05	5.5E-03	4.4E-04	118.0
Lutjanus spp.	Snappers	Summer	3.1	2.4E-06	3.1E-07	5.0E-04	9.3E-05	3.5E-03	4.4E-04	118.0
Micropogonias undulatus	Atlantic croaker	Spring	2.1	3.0E-07	3.0E-07	8.3E-05	8.3E-05	1.3E-04	1.2E-04	90.8
Micropogonias undulatus	Atlantic croaker	Summer	2.1	2.9E-07	2.9E-07	8.1E-05	8.1E-05	1.2E-04	1.2E-04	90.8
Mugil spp.	Mullet	Spring	2.9	3.0E-06	5.4E-07	2.4E-03	4.6E-04	6.7E-03	1.1E-03	676.4
Mugil spp.	Mullet	Summer	2.2	5.0E-07	5.0E-07	4.2E-04	4.2E-04	1.1E-03	1.1E-03	676.4
Pomatomus saltatrix	Bluefish	Spring	2.5	1.1E-06	4.7E-07	5.8E-04	2.6E-04	1.8E-03	6.7E-04	387.5
Pomatomus saltatrix	Bluefish	Summer	2	4.3E-07	4.3E-07	2.4E-04	2.4E-04	6.9E-04	6.4E-04	387.5
Rachycentron canadum	Cobia	Spring	3.5	9.4E-06	4.1E-07	2.9E-03	1.7E-04	8.8E-03	3.8E-04	244.5
Rachycentron canadum	Cobia	Summer	4.1	1.6E-05	3.8E-07	4.8E-03	1.6E-04	1.5E-02	3.7E-04	244.5
Rhomboplites aurorubens	Vermilion snapper	Spring	4.4	3.5E-05	4.6E-07	1.4E-02	2.3E-04	1.9E-02	2.8E-04	350.2
Rhomboplites aurorubens	Vermilion snapper	Summer	4.1	1.7E-05	4.2E-07	7.3E-03	2.2E-04	9.5E-03	2.6E-04	350.2
Sciaenidae spp.	Drums and Croaker	Spring	2	5.4E-07	5.4E-07	4.3E-04	4.3E-04	1.8E-03	1.6E-03	639.0
Sciaenidae spp.	Drums and Croaker	Summer	2	4.9E-07	4.9E-07	3.9E-04	3.9E-04	1.6E-03	1.5E-03	639.0
Sciaenops ocellatus	Red drum	Spring	2	5.4E-07	5.4E-07	4.3E-04	4.3E-04	1.8E-03	1.6E-03	639.0
Sciaenops ocellatus	Red drum	Summer	2	4.9E-07	4.9E-07	3.9E-04	3.9E-04	1.6E-03	1.5E-03	639.0
Scomberomorus cavalla	King mackerel	Spring	3.1	7.6E-06	6.6E-07	1.3E-02	1.2E-03	3.6E-02	2.8E-03	1536.9
Scomberomorus cavalla	King mackerel	Summer	3	4.7E-06	6.0E-07	7.9E-03	1.0E-03	2.2E-02	2.6E-03	1536.9
Scomberomorus maculatus	Spanish mackerel	Spring	2.5	4.4E-07	1.8E-07	9.5E-05	5.5E-05	1.1E-04	5.9E-05	23.6
Scomberomorus maculatus	Spanish mackerel	Summer	2.7	5.2E-07	1.8E-07	1.1E-04	5.5E-05	1.2E-04	6.0E-05	23.6
Seriola spp.	Amberjacks	Spring	2.8	2.7E-06	5.0E-07	1.6E-03	3.2E-04	3.2E-02	4.9E-03	476.0
Seriola spp.	Amberjacks	Summer	2.5	1.4E-06	4.6E-07	8.1E-04	2.9E-04	1.6E-02	4.7E-03	476.0
Thunnus spp.	Tunas	Spring	2.6	1.9E-06	7.9E-07	8.0E-03	3.3E-03	4.2E-02	1.5E-02	3778.7
Thunnus spp.	Tunas	Summer	2.7	2.1E-06	7.1E-07	8.5E-03	2.9E-03	4.5E-02	1.4E-02	3778.7
Thunnus thynnus	Bluefin tuna	Spring	2.7	4.3E-06	7.8E-07	1.6E-02	3.0E-03	1.5E-01	2.3E-02	3464.1
Thunnus thynnus	Bluefin tuna	Summer	2.7	2.1E-06	7.0E-07	7.7E-03	2.6E-03	7.2E-02	2.2E-02	3464.1
Xiphias gladius	Swordfish	Spring	8	1.5E-03	8.5E-07	8.5E+00	4.9E-03	4.0E+01	2.0E-02	5306.6
Xiphias gladius	Swordfish	Summer	8	1.0E-03	7.5E-07	5.8E+00	4.3E-03	2.8E+01	1.8E-02	5306.601

Table E-2. Input size and production foregone results for NRDA Bongo decapod plankton samples from above 200m.

Latin Name	Family	Length (mm)	Wet Weight (g)	Production Foregone (g) per Individual from Input Size
Callinectes	Portunidae	2.0	8.6E-05	5.2E-05
Ovalipes floridanus	Portunidae	2.0	8.6E-05	5.2E-05
Portunidae	Portunidae	2.0	8.6E-05	5.2E-05
Portuninae	Portunidae	2.0	8.6E-05	5.2E-05
Palinuroidea		12.8	8.3E-02	2.2E+00
Scyllarides nodifer	Scyllaridae	6.3	5.8E-03	4.8E-02
Parapenaeus	Penaeidae	2.0	2.1E-05	1.0E-03
Penaeoidea		2.0	2.1E-05	1.0E-03
Rimapenaeus	Penaeidae	2.0	2.1E-05	1.0E-03
Sicyonia	Sicyoniidae	2.0	2.1E-05	1.0E-03
Solenocera	Solenoceridae	2.0	2.1E-05	1.0E-03
Penaeidae	Penaeidae	2.0	2.1E-05	1.0E-03
Penaeidae A	Penaeidae	2.0	2.1E-05	1.0E-03
Penaeidae B	Penaeidae	2.0	2.1E-05	1.0E-03
Penaeidae C	Penaeidae	2.0	2.1E-05	1.0E-03
Mesopenaeus	Penaeidae	2.0	2.1E-05	1.0E-03
Solenoceridae	Solenoceridae	2.0	2.1E-05	1.0E-03

Table E-3. Input size and production foregone results for NRDA 1m-MOCNESS plankton samples from below 200m.

Latin Name Bongo B200	Family	Length (mm)	Wet Weight (g)	Production Foregone (g) per Individual from Input Size
Portunidae	Portunidae	2.0	8.6E-05	5.2E-05
Portuninae		2.0	8.6E-05	5.2E-05
Palinuroidea		7.4	1.1E-02	1.6E-01
Panulirus	Panularidae	4.1	1.2E-03	7.2E-04
Parapenaeus	Penaeidae	2.1	2.2E-05	2.2E-03
Penaeoidea		2.0	2.1E-05	1.0E-03
Rimapenaeus	Penaeidae	2.7	4.7E-05	1.4E-02
Sicyonia	Sicyoniidae	2.0	2.1E-05	1.0E-03
Solenocera	Solenoceridae	2.3	3.2E-05	6.7E-03
Penaeidae	Penaeidae	3.0	7.6E-05	2.9E-02
Penaeidae A	Penaeidae	2.0	2.1E-05	1.0E-03
Penaeidae B	Penaeidae	2.0	2.1E-05	1.0E-03
Penaeidae C	Penaeidae	2.0	2.1E-05	1.0E-03
Mesopenaeus	Solenoceridae	2.0	2.1E-05	1.0E-03
Hymenopenaeus	Solenoceridae	5.7	4.4E-04	1.9E-01
Hymenopenaeus debilis	Solenoceridae	10.2	3.9E-03	6.0E-01
Solenoceridae	Solenoceridae	3.5	1.0E-04	4.3E-02
Oplophoridae	Oplophoridae	6.5	7.3E-04	4.0E-01

Table E-4. Input size and production foregone results for NRDA 10m-MOCNESS plankton samples.

Latin Name MOC10	Family	Length (mm)	Wet Weight (g)	Production Foregone (g) per Individual from Input Size
Decapoda		2.0	8.6E-05	5.2E-05
Acanthephyra	Acanthephyridae	5.8	4.4E-04	1.9E-01
Acanthephyra acutifrons	Acanthephyridae	10.3	3.9E-03	6.0E-01
Acanthephyra brevirostris	Acanthephyridae	4.9	2.9E-04	1.3E-01
Acanthephyra curtirostris	Acanthephyridae	9.9	3.0E-03	5.5E-01
Acanthephyra purpurea	Acanthephyridae	12.2	6.4E-03	7.0E-01
Acanthephyra stylorostratis	Acanthephyridae	8.3	1.6E-03	4.7E-01
Acanthephyridae	Acanthephyridae	6.3	7.3E-04	4.0E-01
Bentheogennema intermedia	Benthesicymidae	12.8	7.9E-03	7.6E-01
Benthesicymidae	Benthesicymidae	7.1	1.1E-03	4.3E-01
Caridea		6.6	7.3E-04	4.0E-01
Gennadas	Benthesicymidae	6.8	7.3E-04	4.0E-01
Gennadas capensis	Benthesicymidae	10.8	3.9E-03	6.0E-01
Gennadas valens	Benthesicymidae	10.9	5.0E-03	6.5E-01
Hymenodora gracilis	Acanthephyridae	7.1	1.1E-03	4.3E-01
Hymenopenaeus debilis	Solenoceridae	6.9	1.1E-03	4.3E-01
Janicella spinicauda	Oplophoridae	4.8	2.9E-04	1.3E-01
Meningodora mollis	Oplophoridae	11.8	6.4E-03	7.0E-01
Mesopenaeus tropicalis	Solenoceridae	6	7.3E-04	4.0E-01
Notostomus gibbosus	Acanthephyridae	19.2	3.1E-02	1.4E+00
Oplophoridae	Oplophoridae	12.5	6.4E-03	7.0E-01
Oplophorus gracilirostris	Oplophoridae	12.1	6.4E-03	7.0E-01
Oplophorus spinosus	Oplophoridae	5	2.9E-04	1.3E-01
Pandalidae	Pandalidae	11.1	5.0E-03	6.5E-01
Parapasiphae sulcatifrons	Pasiphaeidae	9.8	3.0E-03	5.5E-01
Pasiphaea merriami	Pasiphaeidae	11.7	5.0E-03	6.5E-01
Penaeidae	Penaeidae	12.7	7.9E-03	7.6E-01
Penaeoidea		6.1	7.3E-04	4.0E-01
Plesionika	Pandalidae	7.2	1.1E-03	4.3E-01
Solenoceridae	Solenoceridae	6	7.3E-04	4.0E-01
Stylopandalus richardi	Pandalidae	7.1	1.1E-03	4.3E-01
Systellaspis cristata	Oplophoridae	5.8	4.4E-04	1.9E-01
Systellaspis debilis	Oplophoridae	13	7.9E-03	7.6E-01

Table E.5 presents correlation coefficients (r^2) relating larval production foregone (g/individual) with several model inputs and model calculated values for fish species. These results suggest that, among the values analyzed, the length of the larvae from which production foregone is calculated is most strongly correlated with production foregone. Model results indicate that the less time spent in the larval stage (due to the length and weight of the larvae corresponding to older larvae) leads to greater production foregone per individual. The second most influential relationship (though not significant) exists between production foregone and weight at age 1 yr. Species which grow to greater weights by age 1 year experience reduced mortality rates during the juvenile stage than do smaller species, because they grow to larger sizes faster, reducing mortality and resulting in greater production foregone per individual for large species.

Table E-5. r^2 correlation coefficients for select production foregone model inputs and outputs. Significant relationships are in bold.

	Production Foregone from Larvae to End of Life (g/inidiv)	Input Larval Length (mm)	Brody Coefficient	Maximum Age	Weight at Age 1
Production Foregone from Larvae to End of Life (g/inidiv)	1				
Input Larval Length (mm)	**0.53**	1			
Brody Coefficient	0.01	0.00	1		
Maximum Age	0.00	0.00	**0.16**	1	
Weight at Age 1	0.06	0.05	**0.57**	0.04	1

The production foregone model also calculates grams lost per individual from the egg stage until the end of life. This value presents the potential production foregone per individual of a given species exclusive of a particular starting larval size (as is discussed above and shown in Table E.5). As such, production foregone from the egg stage serves as proxy for how life history model inputs affect the final production foregone values respectively. A strong, significant positive correlation exists between production foregone from the egg stage and weight at age 1. Species that exhibit fast growth during the first year of life receive reduced size-based mortality rates, resulting in greater survival until adult age classes and greater production foregone.

Table E-6. r^2 correlation coefficients relating egg production foregone (g/egg) with several model inputs and model calculated values for fish species. Significant relationships are in bold.

	Production Foregone from Egg to End of Life (g/inidiv)	Brody Coefficient	Maximum Age	Weight at Age 1
Production Foregone from Egg to End of Life (g/inidiv)	1			
Brody Coefficient	**0.33**	1		
Maximum Age	0.00	**-0.40**	1	
Weight at Age 1	**0.77**	**0.75**	-0.20	1

Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

Appendix F. Model Results – Production Foregone Model Workbooks by Taxon, Season and Size

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F.1 Introduction

Appendix F presents the full results of the production foregone modeling for species where production foregone is modeled. Model inputs, intermediate model calculations and results are provided in copies of the template Production Foregone Model Excel Workbook. One workbook is provided for each taxon, size in the gear, and season for the species' density data in the Gulf of Mexico Fish and Invertebrate 2010 Baseline Density Dataset.

F.2 List of Production Foregone Workbooks

Below is a list of the workbooks containing results of the production foregone modeling. The name of the workbook indicates the taxa and season modeled.

F.2.1 Fish Larvae (Ichthyoplankton)

Larvae fish for which production foregone was modeled occurred in the SEAMAP bongo sampling the upper 200m of the water column. Production foregone was not modeled for any of the fish larvae occurring in the 1m-MOCNESS below 200m.

Table F-1. Production foregone models for fish larvae in the SEAMAP Bongo data set.

SEAMAP Bongo - Larvae		
Latin Name	**Season**	**Filename**
Balistes capriscus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Balistes capriscus-Spring_20150828.xlsx
Balistes capriscus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Balistes capriscus-Summer_20150828.xlsx
Balistes spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Balistes spp.-Spring_20150828.xlsx
Balistes spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Balistes spp.-Summer_20150828.xlsx
Balistidae spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Balistidae spp.-Spring_20150828.xlsx
Balistidae spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Balistidae spp.-Summer_20150828.xlsx
Brevoortia spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Brevoortia spp.-Spring_20150828.xlsx
Brevoortia spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Brevoortia spp.-Summer_20150828.xlsx
Coryphaena spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Coryphaena spp.-Spring_20150828.xlsx
Coryphaena spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Coryphaena spp.-Summer_20150828.xlsx
Cynoscion nebulosus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Cynoscion nebulosus-Spring_20150828.xlsx

SEAMAP Bongo - Larvae		
Latin Name	**Season**	**Filename**
Cynoscion nebulosus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Cynoscion nebulosus-Summer_20150828.xlsx
Cynoscion spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Cynoscion spp.-Spring_20150828.xlsx
Cynoscion spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Cynoscion spp.-Summer_20150828.xlsx
Engraulidae spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Engraulidae spp.-Spring_20150828.xlsx
Engraulidae spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Engraulidae spp.-Summer_20150828.xlsx
Epinephelini spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Epinephelini spp.-Spring_20150828.xlsx
Epinephelini spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Epinephelini spp.-Summer_20150828.xlsx
Haemulidae spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Haemulidae spp.-Spring_20150828.xlsx
Haemulidae spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Haemulidae spp.-Summer_20150828.xlsx
Istiophoridae spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Istiophoridae spp.-Spring_20150828.xlsx
Istiophoridae spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Istiophoridae spp.-Summer_20150828.xlsx
Katsuwonus pelamis	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Katsuwonus pelamis-Spring_20150828.xlsx
Katsuwonus pelamis	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Katsuwonus pelamis-Summer_20150828.xlsx
Leiostomus xanthurus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Leiostomus xanthurus-Spring_20150828.xlsx
Leiostomus xanthurus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Leiostomus xanthurus-Summer_20150828.xlsx
Lutjanidae spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Lutjanidae spp.-Spring_20150828.xlsx
Lutjanidae spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Lutjanidae spp.-Summer_20150828.xlsx
Lutjanus campechanus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Lutjanus campechanus-Spring_20150828.xlsx
Lutjanus campechanus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Lutjanus campechanus-Summer_20150828.xlsx
Lutjanus spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Lutjanus spp.-Spring_20150828.xlsx
Lutjanus spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Lutjanus spp.-Summer_20150828.xlsx
Micropogonias undulatus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Micropogonias undulatus-Spring_20150828.xlsx
Micropogonias undulatus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Micropogonias undulatus-Summer_20150828.xlsx
Mugil spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Mugil spp.-Spring_20150828.xlsx
Mugil spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Mugil spp.-Summer_20150828.xlsx
Pomatomus saltatrix	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Pomatomus saltatrix-Spring_20150828.xlsx
Pomatomus saltatrix	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Pomatomus saltatrix-Summer_20150828.xlsx
Rachycentron canadum	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Rachycentron canadum-Spring_20150828.xlsx

SEAMAP Bongo - Larvae		
Latin Name	**Season**	**Filename**
Rachycentron canadum	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Rachycentron canadum-Summer_20150828.xlsx
Rhomboplites aurorubens	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Rhomboplites aurorubens-Spring_20150828.xlsx
Rhomboplites aurorubens	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Rhomboplites aurorubens-Summer_20150828.xlsx
Sciaenidae spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Sciaenidae spp.-Spring_20150828.xlsx
Sciaenidae spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Sciaenidae spp.-Summer_20150828.xlsx
Sciaenops ocellatus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Sciaenops ocellatus-Spring_20150828.xlsx
Sciaenops ocellatus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Sciaenops ocellatus-Summer_20150828.xlsx
Scomberomorus cavalla	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Scomberomorus cavalla-Spring_20150828.xlsx
Scomberomorus cavalla	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Scomberomorus cavalla-Summer_20150828.xlsx
Scomberomorus maculatus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Scomberomorus maculatus-Spring_20150828.xlsx
Scomberomorus maculatus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Scomberomorus maculatus-Summer_20150828.xlsx
Seriola spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Seriola spp.-Spring_20150828.xlsx
Seriola spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Seriola spp.-Summer_20150828.xlsx
Thunnus spp.	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Thunnus spp.-Spring_20150828.xlsx
Thunnus spp.	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Thunnus spp.-Summer_20150828.xlsx
Thunnus thynnus	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Thunnus thynnus-Spring_20150828.xlsx
Thunnus thynnus	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Thunnus thynnus-Summer_20150828.xlsx
Xiphias gladius	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Xiphias gladius-Spring_20150828.xlsx
Xiphias gladius	Summer	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl- Xiphias gladius -Summer_20150828.xlsx

F.2.2 Decapod Plankton

Production foregone was modeled for shrimp, portunid crabs and lobsters occurring in the NRDA bongo above 200m, the 1m-MOCNESS below 200m, and the 10m-MOCNESS.

Table F-2. Production foregone models for shrimp, portunid crabs and spiny lobster taxa.

Production foregone models for Decapods		
Latin Name	**Season**	**Filename**
Penaeidae	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Litopenaeus setiferus-Spring_20150828.xlsx
Callinectes	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Callinectes_sapidus-Spring_20150828.xlsx
Palinuridae	Spring	WC_TR.12_ProductionForegone-AppF-2015Aug30_Fish&InvertTempl-Panulirus_argus-Spring_20150828.xlsx

Table F-3. Decapod species where production foregone is applied in Bongos above 200m.

Latin Name	Length (mm)
Achelous	1.7
Benthesicymidae	3
Callinectes	2
Caridea	3
Funchalia	2.1
Gennadas	3
Mesopenaeus	1.1
Palinuridae	10
Palinuroidea	14.5
Panulirus	10
Parapenaeus	1.1
Penaeidae	0.5
Penaeidae A	0.6
Penaeidae B	2
Penaeidae C	1
Penaeoidea	1.9
Portunidae	0.7
Portuninae	1.3
Portuninae A	1.5
Portuninae B	2
Rimapenaeus	0.6
Sicyonia	0.8
Solenocera	1.7
Solenoceridae	0.7
Stylopandalus richardi	3
Xiphopenaeus	0.9

Table F-4. Decapod species where production foregone is applied in 1m-MOCNESS below 200m.

Latin Name	Length (mm)
Acanthephyra	3
Acanthephyra stylorostratis	3
Benthesicymidae	3
Gennadas	3
Hymenopenaeus	5.7
Hymenopenaeus debilis	10.2
Mesopenaeus	1.6
Oplophoridae	6.5
Pasiphaea	2.09
Pasiphaeidae	3
Penaeidae	3
Solenoceridae	3.5
Stylopandalus richardi	3
Systellaspis debilis	3

Table F-5. Decapod species where production foregone is applied in 10m-MOCNESS.

Latin Name	Length (mm)
Acanthephyra	5.8
Acanthephyra acutifrons	10.3
Acanthephyra brevirostris	4.9
Acanthephyra curtirostris	9.9
Acanthephyra purpurea	12.2
Acanthephyra stylorostratis	8.3
Acanthephyridae	6.3
Bentheogennema intermedia	12.8
Benthesicymidae	7.1
Caridea	6.6
Gennadas	6.8
Gennadas capensis	10.8
Gennadas valens	10.9
Hymenodora gracilis	7.1
Hymenopenaeus debilis	6.9
Janicella spinicauda	4.8
Meningodora mollis	11.8
Mesopenaeus tropicalis	6
Notostomus gibbosus	19.2
Oplophoridae	12.5
Oplophorus gracilirostris	12.1
Oplophorus spinosus	5
Pandalidae	11.1
Parapasiphae sulcatifrons	9.8
Pasiphaea merriami	11.7
Penaeidae	12.7
Penaeoidea	6.1
Plesionika	7.2
Solenoceridae	6
Stylopandalus richardi	7.1
Systellaspis cristata	5.8
Systellaspis debilis	13

Technical Reports for Deepwater Horizon Water Column Injury Assessment

WC_TR.12: Evaluation of Production Foregone as the Result of Direct Kill of Fish and Invertebrate Individuals

Appendix G. Guidance for Navigating the Production Foregone Model Workbooks

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Project Number: 2011-144
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Production Foregone Spreadsheet Walkthrough
Each workbook is a model of non-spill-related survival and growth-related production foregone for a single analysis taxon for larvae and age classes of specified sizes. This document presents a general walkthrough or user's guide to navigating the production foregone workbook. It works stepwise through the workbook, tab by tab, to explain how each part of the workbook fits together.

"Quick Start Guide"

Only three tabs are integral in the operation and calculation of the production foregone model workbook. Model inputs (e.g., life history, organism size, season of interest) are entered in the tabs **Load_LifeHist-Inputs** and **LifeHist-Inputs**. Once all requisite model parameters have been entered into these sheets, results of the production foregone model (including the first year survival model) are found in the tab **RptTabs-Summary**. All other tabs in the production foregone workbook contain various calculations, summaries, detailed results, sub-models, and model checks. It is not necessary to refer to these other tabs unless the user is interested in specific parts of the detailed model (refer to the "Full Walkthrough" section below for more detailed information of what is contained within these other tabs). Color-coding below matches the colors represented on tabs within the worksheet.

Load_LifeHist-Inputs – Species information is entered in this tab including taxonomy, life history characteristics, and larval size

- In column C, all blue highlighted cells should be filled in with species information as directed by column B.
- Original Unit codes for von Bertalanffy and length-weight equation parameters are found in cells E11:F25
- In the instantaneous annual natural mortality rate section (C28:C37) the user may enter known age-based mortality rates, or may refer to the adjacent cells (D28:D37), which provide the Lorenzen (1996) calculated mortality values based on organism size at age that would be used if no published natural mortality rates are available.
- The instantaneous annual fishing mortality rates are found in cells C43:C52. If species specific data are not available, proxy species data should be input here. If species is known to be commercially fished, but no fishing mortality data is available, users may refer to the adjacent cells (D43:D52), which provide the Zhou et al. 2012 calculated fishing mortality rates based on M. Additionally, the age at recruitment to the fishery is entered in cell C41.
- Initial larval length (mm) is entered in cell C63. To represent the SEAMAP larval data, the mean, median or other statistic may be entered to obtain production foregone for that size larvae.
- The season of interest (Spring or Summer) is chosen (C65). This affects temperature and therefore growth rates. We are currently modeling separate production foregone values for spring and summer seasons,

LifeHist-Inputs – Water temperature and larval stage duration are entered (if known) into this tab

- The mean water temperature (°C) at for the larval stage should be set in cell H93. Two defaults are available, the means for the upper 30m from NOAA's climatic atlas for spring and summer months in the northeast Gulf of Mexico. These default temperatures are linked from Cell C65 in the 'Load_LifeHist-Inputs' tab (Spring or Summer) and should not be changed unless another temperature is of particular interest.

- If larval stage duration for the species of interest is known it may be entered in cell C81. If duration is not known, this cell has a default value (C80) and may be left unedited.

RptTabs-Summary – All general model output is found in this tab including age 1 equivalents and production foregone mass by age

Results:

- A45:C49 – Cumulative survival rate from hatch to age 1, with upper and lower variance bounds
- A51:C55 – Cumulative survival rate from larvae to age 1, with upper and lower variance bounds
- A57:C61 – Results for production foregone per larvae, with upper and lower variance bounds
    - Loss per larvae - grams lost per larvae up to age 1
    - Production Foregone – grams lost per individual larvae over its entire lifetime
- A63:C67 – Mean results for production foregone per larvae
    - Loss per larvae - grams lost per larvae up to age 1
    - Loss per age 1 indiv – grams lost per age 1 fish
    - Survival to age 1 – fraction of those surviving from larvae to age 1
    - Production Foregone – grams lost per individual larvae over its entire lifetime
- A69:A73– Mean results for production foregone per larvae from egg stage
- E26:I30 – Age equivalents per larvae
- E76:I79 – Basic summary of production foregone model results for lost larvae
    - Species
    - Larval Length (mm) – larval length used as input to model
    - Survival to Age 1 – cumulative survival for an individual larvae from age at the input larval length to age 1
    - Production Foregone – Larvae to Age 1 - grams of production foregone per individual larvae from larval starting size to age 1
    - Production Foregone – Age 1 to End of Life - grams of production foregone per individual larvae from age 1 to end of life
    - Production Foregone – Larvae to End of Life - grams of production foregone per individual larvae from initial larval size until end of life
- E32:I65 – Age structured model output for adult (>age 1) age class production foregone calculations
    - # Age-1 Equiv. – The number per age-1 equivalents per individual at stage (age)
    - L (mm) – length at start of stage
    - Wet Weight (g) – weight at start of stage
    - Production Foregone (g/indiv.) – The production foregone (g) per individual killed at stage

Model Input Summaries (data imported from other worksheets):

- A4:G20 – Summarizes the basic life history which was input by the user
- A26:C30 – Stage durations used in the model for the first year of life
- A41:C43 – Median size of larvae (g) of larvae used as starting size in model

Full Walkthrough

Instructions -Tab provides general instructions for model use.

Load_LifeHist-Inputs -Tab is the base input sheet for the model. Users are prompted to enter basic life history characteristics and mortality data as inputs to the model.
Cells that require input information/data are highlighted in light blue. Requisite information/data inputs on this sheet include:

- Taxonomy
  - Common Name (C4)
  - Latin Name (C5)
  - Family Name (C6)
  - Fish or Invertebrate (C7)
    - If a fish, enter 1. If a invertebrate, enter 2.This affects which mortality and life history characteristics are used within the production foregone model
- Von Bertalanffy Parameters
  - L_{inf} (C11)
  - K (C13)
  - t_0 (C14)
  - Original units of von Bertalanffy (C12, C15)
- Length/Weight Equation Parameters (Power Law Growth Model)
  - alpha (C19)
  - beta (C21)
  - Original units of Length/Weight equation (C20, C22)
- Instantaneous Annual Natural Mortality Rate
  - Yearly age specific natural mortality rates (1 through 10+) (C28:C37)
    - Data may be drawn from any of the three following sources. The user should note which source is used (stating the specific taxonomy of the species used, whether it is the species of interest, or a proxy) (C39)
      - Species specific information
      - Proxy species
      - Lorenzen 1996 model
        - Spreadsheet calculates age specific Lorenzen M values (D28:D37) which may be copied and pasted into C28:C37 if the Lorenzen model mortality information is to be used for the species.
- Instantaneous Annual Fishing Mortality Rate
  - Age recruited to fishing (years) (C41)
  - Yearly age specific fishing mortality rates (1 through 10) (C43:52)
    - Data may be drawn from the species of interest, or a taxonomically close proxy species. The user should note which source is used (stating the specific taxonomy of the species used, whether it is the species of interest or a proxy) (C54). There are three possible options:
      - Species specific information
      - Proxy species
      - Zhou et al. 2012 model
        - Spreadsheet calculates age specific Zhou et al. F values (D43:D52) which may be copied and pasted into C43:C52 if the Zhou et al. model mortality information is to be used for the species. Note: this model only applies to teleosts.
      - Non-fished species assumed to have an F of 0

- Seasonality
  - Months present in Gulf of Mexico (C56)
  - Median month (of months present) (C57)
  - Days from fertilized egg until start of age 1 annual class (for starting of application of age class 1 mortality information) (C59)
- Larval Size Information
  - Range of sizes (mm) in dataset (C61)
  - Median Size (mm) of Larvae at Hatch (C62)
    - This is set at a default of 2mm
  - Mean Size (mm) of larvae in dataset, or desired user input (C63)
  - Species/Taxonomy used for length data (C64)
- Temperature conditions (C65) – choose the season of interest (Spring 1 or Summer 2) for modeling.
- Maximum Age information (C67:C69)

LifeHist-Inputs -This tab is the secondary data input tab to the production foregone model. It reads in some general species information from the Load_LifeHist-Inputs Tab as well. The LifeHist-Inputs tab may be considered an "optional" data input tab. There are a few cells which are set at model default values which can be overwritten if more specific information is available.

Model Inputs:

- Larval Stage Duration (C81)
  - Value is automatically calculated based on empirical equation, but may be overwritten if more accurate, taxon specific data is available.
- Median Age of Larvae (C90)
  - Value is automatically calculated based on input larval size, but may be overwritten if more accurate, taxon specific data is available. [Note that this information is not actually used in the calculations but may serve as a check on the model.]
- Water Temperature (H93)
  - This cell should be updated by the user with the appropriate temperature for which season production foregone is being calculated for. The current values are:
    - Spring (May-June) – 26°C
    - Summer (July-August) – 29°C
- Discounting Rate (J11:M13) – User may enter an annual discount rate in cell L12, but the default of 3% annually is typically used in NRDAs

Model Input Summaries (data imported from other worksheets):

- Instructions (1:8) – provides general information about this tab
- Taxonomy (A10:H17) – linked data from Load_LifeHist-Inputs
- Growth Curve (A19:L37) – von Bertalanffy parameters
- Weight-Length Relationship (A39:F56) – weight-length relationship parameters
- Adult Stage Mortality Rates (A58:M75) – mortality rates

Invert.W-L models – (*Not used in calculating fish species production foregone*) This tab provides a listing of various invertebrate weight-length relationships. If workbook is being completed for an invertebrate species the user pulls the appropriate code from column A and enters this code in worksheet LifeHist-Inputs, cell C86.

Fecundity (1) – Tab provides a "model check" relating cumulative egg production to cumulative survival rates. Results are found in cells E6:K10. For species at or near equilibrium, the survival value in J8 (value of first year survival rate required for population to be at equilibrium produced by this fecundity check) will nearly match the survival value in I10 (first year survival rate from the production foregone model).

Fecundity (2) – Tab provides a "model check" relating cumulative egg production to cumulative survival rates. Results are found in cells A5:H11. For species at or near equilibrium, the survival value in E8 (value of first year survival rate required for population to be at equilibrium produced by this fecundity check) will nearly match the survival value in E7 (first year survival rate from the production foregone model).

Fecundity Daily Calculator – Tab calculates mean population numbers for each year. Feeds into Fecundity (2) tab.

RptTabs-Summary – All general model output is found in this tab including age 1 equivalents and production foregone

Results:

- A45:C49 – Cumulative survival rate from hatch to age 1, with upper and lower variance bounds
- A51:C55 – Cumulative survival rate from larvae to age 1, with upper and lower variance bounds
- A57:C61 – Results for production foregone per larvae, with upper and lower variance bounds
    - Loss per larvae - grams lost per larvae up to age 1
    - Production Foregone – grams lost per individual larvae over its entire lifetime
- A63:C67 – Mean results for production foregone per larvae
    - Loss per larvae - grams lost per larvae up to age 1
    - Loss per age 1 indiv – grams lost per age 1 fish
    - Survival to age 1 – fraction of those surviving from larvae to age 1
    - Production Foregone – grams lost per individual larvae over its entire lifetime
- A69:A73– Mean results for production foregone per larvae from egg stage
- E26:I30 – Age equivalents per larvae
- E76:I79 – Basic summary of production foregone model results for lost larvae
    - Species
    - Larval Length (mm) – larval length used as input to model
    - Survival to Age 1 – cumulative survival for an individual larvae from age at the input larval length to age 1
    - Production Foregone – Larvae to Age 1 - grams of production foregone per individual larvae from larval starting size to age 1
    - Production Foregone – Age 1 to End of Life - grams of production foregone per individual larvae from age 1 to end of life
    - Production Foregone – Larvae to End of Life - grams of production foregone per individual larvae from initial larval size until end of life
- E32:I65 – Age structured model output for adult (>age 1) age class production foregone calculations
    - # Age-1 Equiv. – The number per age-1 equivalents per individual at stage (age)

- L (mm) – length at start of stage
- Wet Weight (g) – weight at start of stage
- Production Foregone (g/indiv.) – The production foregone (g) per individual killed at stage

Model Input Summaries (data imported from other worksheets):

- A4:G20 – Summarizes the basic life history which was input by the user
- A26:C30 – Stage durations used in the model for the first year of life
- A41:C43 – Median size of larvae (g) of larvae used as starting size in model

YOY # at Age – Calculates cumulative survival per daily YOY age class. Various plots of survival and cumulative survival (fractions and by numbers assuming a 1 million stating number) at age provided.

YOY Size at Age – Tabular and graphical representations of size at daily age classes for species being modeled, data pulled in from 'Life tab' sheet and model inputs.

Annual Size at Age – Tabular and graphical representations of size at yearly age classes for species being modeled, data pulled in from 'Life tab' sheet and model inputs.

YOY Size Freq #&kg - Used to calculate and plot age frequencies from size frequency data entered on that sheet from ichthyoplankton database. User manually enters numbers by size class into the blue cells. The size intervals are set up so the user may specify a size range for each using the selected length units in the yellow cells, to facilitate data entry. [These results are not used elsewhere.]

Annual Size Freq #&kg - Used to calculate and plot annual age frequencies from size frequency data entered on that sheet from shrimp trawl database. User manually enters numbers by size class into the blue cells. The size intervals are set up so the user may specify a size range for each using the selected length units in the yellow cells, to facilitate data entry. [These results are not used elsewhere.]

Age1+ Calc Biomass from # - Used to calculate the recruited biomass from total number of individuals > age 1 sampled; it assumes exponentially decreasing density distribution by size using total mortality rates (Z) by age class. User manually enters sample information into blue cells with red text. [These results are not used elsewhere.]

References – List of citations of equations and submodels used in production foregone model

Notes re Calculation Sheets – Provides notes on sheets to the right of this one that contain the calculations

Life Params – Summary of the life history parameters and stage-specific mortality rates

Prod Foregone per YOY – Summary of the production foregone results per individual larvae (at the size entered as input).

Fish Larv Growth – First year growth models for fish larvae and juveniles. This contains calculations for the size at age (daily) over the first year of life. The Fish 1st Yr SurvModel sheet draws from these data.

Fish 1st Yr Surv Model – Tab calculates first year survival for fish larvae. Multiple models are calculated, but results for select model are highlighted in results boxes near top of tab (green headings). All input data on this tab is from other sheets, no cells may be edited in this tab.

Model Input

- The larval growth rate used is controlled by cell C45. Model defaults to the Pepin Model (3)
    - 1 – Exponential Growth
    - 2 – Linear Growth
    - 3 – Pepin Growth Relationship
    - 4 – Houde Growth Relationship
- The survival model which results are presented for is selected in cell Q32. Model 1 is the default.
    - 1 – Pepin to Lorenzen
    - 2 – Lorenzen to Lorenzen

Model Input Summaries (data imported from other worksheets and/or simple calculations):

- Stage based duration and stage (A5:J15)
    - Stage duration used in model for egg, larval, and juvenile stages (B7:B11)
    - Age at size for egg, initial larval size, and end juvenile stage (C7:C11)
    - Length (mm), wet weight (mg), and dry weight (mg) at stage (D7:F11)
    - Instantaneous growth rate for first year of life in mm (D12), wet mg (E12), and dry mg (F12)
- First year mortality models (D34:M45) – equation parameters are presented here

Model Results:

- Cumulative Survival to age 1 and upper and lower variance of cumulative survival (L6:R10)
- Weight-Length Relationship and Initial Larval Size (A17:L20)
- Initial larval age calculations (A23:O30)
    - Results of calculations are found in column C. Columns D-G contain hard-coded equation parameters used in the calculation of initial larval age
- Cumulative Survival Larvae to Age 1 (All Models) (P34:V42)
    - Results are presented for several available mortality estimators
- Larval size (length, wet weight, dry weight) by day (A47:D415) – Presents larval size by day calculated through growth rate and weight-length relationship. These data are used in the calculation of daily mortality rates present in columns E-M.
- Instantaneous Daily Mortality Rate (M day^{-1}) (E47:H415) – Daily mortality rates for different mortality estimators are presented in each column. Each cell is the daily mortality rate for that age/size larvae
- Daily Survival Rates (I47:M415) – Daily survival rates based on instantaneous mortality rates. Data presented for 5 mortality models
- Cumulative Survival Rates (O47:X415) – Cumulative survival rates based on survival from columns to the left. Columns T:X display "back-to-back: survival models where one mortality model is used for the duration of the larval stage, then a second mortality model is used for the juvenile stage. Results from this section are summarized in cells P34:V42

- Bradford Mortality Variance Estimator (AC47:AC415) – Calculates the variance of the Lorenzen estimated daily mortality rate. Used in framing upper and lower cumulative survival.
- Graphical representations of the different estimators of daily mortality rates are found at cells B418:S448

Invert 1st Yr Surv Model – Tab calculates first year survival for invertebrate larvae. The growth model used is exponential from hatch to age 1. Multiple survival models are calculated, but results for select model are highlighted in results boxes near top of tab (green headings). All input data on this tab is from other sheets, no cells may be edited in this tab.

The remaining sheets perform the production foregone calculations for either the first year or age 1 + age classes, with and without discounting. Catch foregone is also calculated on so-named sheets. "LifeTab" and "Factors" contain life table data used in these calculations.