Supplementary Material

# Supplementary Model Descriptions

2.1 Ecopath with Ecosim (EwE) Model Description

Below we outline the basic structure and function of the EwE model. To garner more insight on the specific model used in this study, please reference De Mutsert et al. (2017).

EwE is an open source ecosystem modeling software, based on ECOPATH, which was originally developed by Polovina (1984) to model trophic interactions and to estimate mean annual biomass on a coral reef ecosystem. Since that time, the model has been greatly improved by including temporal and spatially dynamic modules (Ecosim and Ecospace), and is used to model ecosystems worldwide (Christensen & Pauly 1992; Walters et al. 1997; Walters et al. 1999; Walters et al. 2000). While a spatial application was added in 1999 by the name of Ecospace (Walters et al. 2000), the name for the software has remained ‘Ecopath with Ecosim’, or EwE for short. Since this aspect has been cause for some confusion, it deserves clarification that Ecospace is part of EwE, and has been included in all recent developments regarding this software.

Ecopath is a virtual representation of the food web of an ecosystem, including flows and pools of biomass within this food web. Ecosim then allows for temporal simulations of changes in biomass of groups in the model (which could be species or species guilds) in response to changes in environmental variables (such as nutrient loads and salinity) and fishing over time. Because of the trophic interactions represented with the initial foodweb, both direct and indirect effects of these drivers and forcing functions are made evident. Lastly, Ecospace allows for spatial and temporal simulations of biomass change of each of the groups in response to spatially and temporally explicit drivers, and habitat characteristics. This feature not only provides information on the spatial distribution of each group in the model, but it also improves estimates of total biomass changes of each group over the course of the model run because movement of consumers and fishing fleets, and spatially explicit habitat characteristics of the system are taken into consideration.

The first step in developing an EwE model is to create a mass-balanced foodweb that is representative of the ecosystem of interest. This virtual ‘snapshot’ of the ecosystem is the Ecopath model. For each group in the model, three of the following four parameters need to be provided in the model interface: the initial biomass (tonnes km-2 yr-1), the production to biomass ratio , the consumption to biomass ratio , and the ecotrophic efficiency . Two master equations must be satisfied to correctly parameterize the Ecopath model. The first equation describes the production of each functional group as a set of *n* linear equations for *n* groups:

(1)

where is the production to biomass ratio for group , is the ecotrophic efficiency (the proportion of production used in the system), and are the biomasses of the prey and predators respectively, is the consumption to biomass ratio, is the fraction of prey in predator ’s diet, is catch rate for the fishery for group , is the net migration rate, and is the biomass accumulation for group .

The Ecopath model assumes conservation of mass over a year. Energy balance within each group is ensured with the second master equation:

Consumption = production + respiration + unassimilated energy (2)

where production can be described as:

Production = predation mortality + catches + net migration +  
biomass accumulation + other mortality (3)

Species or groups in Ecopath can be divided into multiple life stages. This approach is referred to as the multistanza approach and can include a juvenile and adult for each group, or multiple life stages per group when ontogenetic shifts occur at several instances in the life cycle. Each stanza in Ecopath requires input for the production to biomass ratio , and time (in months) of stanza break, while biomass, the consumption to biomass ratio, and von Bertalanffy K values (von [Bertalanffy 1938](#_ENREF_7)) are required for the leading stanza (i.e. the life stage for which the initial biomass is entered) allowing for Ecopath to estimate those parameters for the other life stages based on the von Bertalanffy growth function. K is considered a curvature parameter and suggests how fast a fish will reach the asymptotic length, otherwise known as L∞ (Sparre & Venema 1998).

In addition to the above-mentioned parameters, a diet matrix is another essential component of the model. The matrix specifies the diet items of each group and stanza, and the relative proportion of each of these items in the diet of each stanza. A consumer can feed proportionally on any prey item ranging from 0 to 1, with a predator’s entire diet composition summing to a total of 1.

Lastly, fleets must be described if fishing occurs in the model. Fleets are defined here as specific fisheries responsible for biomass removal of the target species by which it is named. Fleets can also be responsible for bycatch of other non-target species and this bycatch can be explicitly modeled in EwE. For each fleet (e.g. brown shrimp fishery) we include the annual catch of each target species in weight per area fished (tonnes km-2), plus discards in tonnes km-2.

In order to move into either the Ecosim or the Ecospace module in EwE, the Ecopath model must achieve mass balance (which means that the Ecopath master equations are solved.) The EwE software enables the balancing process by not allowing higher consumption on a certain prey item than biomass of that prey item present in the system. If a group’s is > 1 during model parameterization, more biomass than present in the system is being consumed/removed (either by predation mortality or fishing mortality), and the model will not balance. Adjustments to the model will then need to be made to reduce this mortality. While Ecopath usually solves for when biomass, and is provided, it is also possible to have Ecopath solve for any other of these four parameters (biomass, , , and ) as long as three parameters are provided.

Applying the initial parameters derived from the first master equation in Ecopath, the Ecosim module of EwE can be invoked. Ecosim re-expresses the system of linear equations from Ecopath as a system of coupled differential equations to predict biomass outcomes over time integrated via a 4th order Runge-Kutta operation:

(4)

where is the net growth efficiency; is the biomass immigration rate; is the nonpredation mortality rate; is the fishing mortality rate; is the emigration rate; can be considered the “flow” from pool to pool organisms as a function of time—the consumption rate of type biomass pool by type biomass pool.

Environmental parameters can influence trophic interactions when included as forcing functions in Ecosim, which are used to alter the effective search rate of predators by applying a scaler on , the value of which is determined by species-specific response curves. The effective rate of search in Ecosim allows predators to spend more (or less) time foraging in arenas where prey are concentrated. To include forcing functions in the model, a dataset with monthly values of the environmental variables of interest is uploaded to the model. These data can be field observations or output of other models. In addition, response curves need to be created that represent the tolerance ranges of each group in the model for this specific environmental variable. Effective search rate of the group will be affected in sub-optimal conditions, which reduces energy derived from food, and thereby reduces the biomass of the affected group. The software provides other options as well to invoke effects of forcing functions in the ecosystem; for example, primary producers can respond to changes in nutrient levels with a multiplier instead of a response curve to simulate increases and decreases in primary production in response to changes in nutrient loading.

### Foraging Arena Theory

Within the dynamic components of the EwE modeling framework (Ecosim and Ecospace), each prey group is present in a vulnerable and invulnerable state. This characteristic represents a situation where prey groups seek refuge until they have to expose themselves to forage, at which point they become vulnerable to predation. This adjustment to predator-prey interactions that introduces prey behavior into the traditional equation of the predator-prey model is termed the Foraging Arena Theory (Walters & Juanes, 1993). In Ecosim, the rates of consumption can be limited at very small temporal scales, allowing for the flow of prey from (behaviorally or locationally) varying states of vulnerability to limit the rates of predation to levels that the traditional Lotka-Volterra mass-action models would not predict. Consumption rates (C in equation 4) in Ecosim can be described by:

(5)

where is the biomass of the prey; is the biomass of the predator/consumer; is the rate of effective search for prey by predator ; and are the behavioral exchange rates between prey pools, expressed as vulnerable and invulnerable. Equation (5) is based on the concept of the foraging arena theory, which regulates consumption rates by assuming predator-prey interactions take place in restricted arenas where prey vulnerability in terms of predation depends on a prey’s need for a particular resource (Ma et al. 2010; Walters et al. 1997) . Vulnerability in predator-prey interactions can also be influenced in Ecosim by the addition of mediation factors,, which allows for a third organism to affect a predator/prey pair’s interaction. The transfer rate values determine whether control within the ecosystem is top-down or bottom-up, where high values indicate top-down control and low values indicate bottom-up control (Christensen & Walters 2004) . Users can ‘turn off’ this improvement in representation of predator-prey interactions by simply setting vulnerabilities of each prey group to a high value (e.g. 100). This has not been turned off for this modeling effort, and the foraging arena theory is included in the simulations.

### 

### General Calibration and Validation Description in EwE

Prior to using models for future predictions and policy analysis, it is important to ensure they can reproduce historical patterns of abundance ([Shannon et al. 2004](#_ENREF_57)). Calibration is an important step in model development and allows for adjustments to input parameters within a plausible range of solutions. These adjustments provide the ‘best fit’ of model predictions to data collected in the field. The model parameterization process in Ecopath is the first calibration step a user employs when developing a model in EwE. During this procedure, the EwE program gives warnings if the model is unbalanced, which usually means that more of a certain group is consumed in the model than is present in the system, resulting in failure to achieve the assumption of a mass-balanced ecosystem. So, to achieve mass balance, the user adjusts, within plausible ranges, the diet matrix, the or values, the initial biomass of a group, or perhaps even the number of groups in the model. Once the model is balanced, Ecopath represents an ecosystem in which the energy flow is balanced over a certain time period (usually a year). This feature in Ecopath is a valuable component of the EwE software and is often used in other community model applications (e.g. Atlantis) to ensure that the model is based on a balanced foodweb.

A second important calibration step is the fitting to time series routine in Ecosim. During this routine, model runs are fitted to observed biomass and landings data, while the model is forced or driven with fishing mortality or effort data and/or environmental variables (e.g. salinity). The routine searches for the lowest Sum of Squares () by adjusting the vulnerabilities of groups to predation and fishing (see section 2.2.1 for more on vulnerability). Validation of the model is accomplished by comparing the final model run to a different set of observed data and noting the SS without fitting the model to this second set of time series.

### Specific Calibration Description for Models Used in This Study

All calibrations simulations were reported in De Mutsert et al. (2017). An Ecopath model (developed using v. 6.5.12658) was formulated using ecological data collected in the model area from 1995-2000 for the entire domain that included Barataria Bay, Breton Sound, and surrounding waters that comprise the Mississippi River Delta (Figure 1). The calibration started with a balanced Ecopath (base) model. Subsequently, this averaged snapshot of the ecosystem was simulated through time and calibrated using the Ecosim module. Ecosim in this application used fishing effort and mortality, environmental conditions (Figure 2A-C), and adjustments to the vulnerability to predation and fishing of the various species to fit model predictions to the observed fish monitoring data used by both models. Calibration was done on annual biomass values (by species) that were averaged across the entire model domain (i.e., Mississippi River Delta) from 1995 – 2013. The full-domain was used here because simulated and observed biomasses of species and the structure of the food web over the calibration time period showed similar dynamics to results for the Barataria portion from simulations using a spatially-explicit (Ecospace) version (De Mutsert et al. 2017).2.2

2.2 The Comprehensive Aquatic Systems Model (CASM) Model Description

The Dynamic Solutions (2016) final report describes the data and detailed methods used for the CASM model processes, inputs and parameters, and assumptions, the governing equations, as well as calibration and validation under simulated existing conditions for Barataria Basin used in this study.

The basic structure and function of the CASM are summarized below to provide readers with similar information outlined for the EwE model. The CASM source code is written in Fortran. The source code is continually updated, with code versions and datafiles used to run the model often very different between modeling studies. Therefore, the general CASM framework description also includes the added modeled processes and changes specific to the CASM version developed for this study.

The CASM is a generalized and flexible aquatic food web modeling platform originally developed by DeAngelis et al (1989). The CASM has been further developed and applied to freshwater and coastal ecosystems to evaluate food web responses to changes in seasonal salinity and temperature gradients, toxicant concentrations in the water column, changes in nutrient loading and suspended sediment concentrations, and effects of invasive species (Bartell et al. 1999, Naito et al. 2002, Bartell 2003. Bartell et al. 2010, Fulford et al. 2010, Dynamic Solutions 2012, Dynamic Solutions 2013). The CASM uses a series of coupled differential equations to describe the daily biomass pools and flows among its component taxa groups or populations (referred to populations from hereon) within the modeled food web, with one equation defined for each of the state variables. Daily production for each state variable is calculated using a differential equation solved with the Euler method using a time step (Δt) equal to 0.10 day. The daily food web dynamics are simulated over single or multiple years, and the CASM is also capable of simulating concentrations of water chemistry state variables including dissolved inorganic nitrogen and phosphorus, dissolved silica, dissolved oxygen, and dissolved and particulate organic matter.

The CASM used for this study simulates the daily food web dynamics for Barataria Basin from 1995-2010 using driving input variables generated by coupled hydrodynamic, water quality, and geomorphology models. The CASM simulates the food web for 20 spatial polygons in Barataria Basin, such that the daily conditions and food web interactions differ over the 20 spatial polygons, but the food webs do not mix among the polygons. The 20 spatial food web models use daily inputs for salinity and temperature, and the estimated percent area of marsh vegetation versus open water habitat (marsh:open water) averaged across each polygon, as driving input variables that differentially modify the food web populations. Chl-a concentrations are simulated additionally from an integrated hydrodynamic and water quality model for Barataria Basin (Meselhe et. al. 2013), and converted to base prey biomass pools that fuel the 20 polygon food webs; water chemistry variables are not simulated in this CASM version.

The modeled food web for Barataria Basin includes three sizes of phytoplankton, three sizes of benthic algae, bacterioplankton, particulate organic carbon (POC) in the water column and the sediments (i.e., detritus) as the base prey groups, and 32 consumer groups. The phytoplankton, benthic algae, bacterioplankton and POC pools are estimated directly from the daily Chl-a inputs, with daily consumption by the food web as a daily loss term. The consumer groups include a zooplankton group, a benthic infauna group, a small mollusk group, and several key fish and invertebrate groups. The zooplankton, benthic infauna, and small mollusk group are simulated using the logistic growth equation with consumption from the food web as a daily loss term. The remaining consumer groups represent the key fish and invertebrate populations of Barataria Basin. Some of the fish and invertebrate populations are divided into life stages (i.e., early young-of-year, late young-of-year, Age-1+). The fish and invertebrate consumer life stages or populations are described by input-output bioenergetics rates that affect the daily growth rate (i.e., production) of each modeled consumer group.

Daily production for the fish and invertebrate consumer groups is determined from consumption gains minus energetic losses to egestion, excretion, specific dynamic action and respiration, and population losses due to background mortality and consumption by its predator populations (Eqn 6, first through third lines, not including *hmod*). This is the primary governing equation used for consumer groups in the CASM framework originally developed in DeAngelis et al. 1989. For this CASM version (Dynamic Solutions 2016), the net change in daily biomass is additionally adjusted to account for salinity and marsh:open water habitat effects on growth (*hmod*), and also includes terms for the flux of biomass between life stages (*Fouti,j,DOY*) and out of the estuary (for migratory species, *Fini,j,DOY*). The daily value of production (g m-2 d-1) for each fish and invertebrate consumer (Bi,j) is determined by the following equation:

(6)

where

*hmod* habitat modifier on daily production (unitless)

*Bi,j* biomass of consumer species i and life stage j (g m-2)

*Cmi,j* maximum consumption rate of consumer i,j (d-1)

*h1(T)i,j* temperature modifier on consumption for consumer i,j (unitless)

*wi,j,pi,pj* fraction of prey type pi,pj available to consumer i,j (unitless)

*Bpi,pj* biomass of prey population pi,pj (g m-2)

*fi,j* egestion loss of consumer i,j (unitless)

*ui,j* excretion loss of consumer i,j (unitless)

*rsdai,j* specific dynamic action of consumer i,j (unitless)

*ri,j* standard respiration rate of consumer i,j (d-1)

*h2(T)i,j* temperature modifier on respiration for consumer i,j (unitless)

*mi,j* background mortality rate for consumer i,j (d-1)

*Bvi,vj* biomass of predator population vi,vj (g m-2)

*Cmvi,vj* maximum consumption rate of consumer vi,vj (d-1)

*h1(T)vi,vj* temperature modifier on consumption for consumer vi,vj (unitless)

*wvi,vj,i,j* fraction of consumer i,j available as prey for predator vi,vj (unitless)

*Δt* time step equal to 0.10 d

*Fouti,j,DOY* biomass leaving i,j to move up to the next life stage or offshore (g m-2 d-1)

*Fini,j,DOY* biomass entering i,j from the previous life stage or as recruits (g m-2 d-1)

The first and second lines of Eqn (6) describe the daily growth gained through consumption of all available prey items, minus the energetic and background mortality losses to the consumer population. Maximum consumption of consumer population i,j (*Cmi,j)* is modified by temperature (*h1(T)i,j*) using the Thornton and Lessem (1978) response, and the amount of prey pi,pj biomass available for consumption by consumer i,j is adjusted by the availability fraction (*wi,j,pi,pj*). A non-zero prey availability fraction, wi,j,pi,pj (or wi,j,vi,vj, in Eqn 6), is specified for each predator-prey interaction in the food web. The values of wi,j,pi,pj range from 0-1, with higher values indicating increased availability (or selectivity) of the prey biomass by the predator population. Realized consumption is a density-dependent function of all available prey and the consumer biomasses preying upon each of the prey (DeAngelis et al. 1989). Bioenergetic loss due to respiration (ri,j) of the consumer is also modified by an increasing temperature function (*h2(T)i,j*). All population-specific bioenergetics parameters, parameters for the salinity and habitat modifier functions on daily growth, fractions of prey biomass available for consumption for each predator, and parameters defining the flux of biomass between life stages were defined using available data and literature during the CASM development for the study (see Dynamic Solutions 2016).

**Calibration and Validation Description Specific to This Study**

Three steps for calibrating and validating the CASM for Barataria Basin were performed for the study (Dynamic Solutions 2016). First, daily consumer biomasses generated by the CASM were calibrated to monthly observed biomass data estimated from a combination of catch per unit effort and size (mass in grams, length in mm) data collected by the Louisiana Department of Wildlife and Fisheries marine sampling program and drop-sampler data from NMFS in Barataria Basin. The PEST calibration software (Doherty 2014) was used to iteratively adjust maximum consumption (*Cmi,j*), background mortality rates (*mi,j*), temperature modifier parameters in *h1(T)i,j* and *h2(T)i,j*, flux parameters in *Fini,j,DOY*, and prey availability fractions (*wi,j,pi,pj*) until the magnitude and seasonal pattern of simulated population biomasses matched the observed calibration data set for each species and life stage. PEST iteratively adjusts the calibration parameter set to best fit the model predicted biomasses to the observed biomasses. The best fit is determined when the sum of squared residuals (SSR) is minimized between the daily model predictions and observations. Additional changes were then made ad hoc to further improve the model fit to the biomass data, using the sum of squared residuals to find the best model fit.

The calibration run used single years of repeating averaged daily salinity, temperature, and chl-a, and annual marsh:open water inputs, for the 20 spatial polygons, estimated from the model-generated inputs from 1995-2010. The CASM biomass results were weighted by the area of each polygon in order to estimate a system-wide average biomass that was fit to the observed data during calibration. The biomass estimates from the field sampling period of 1995 to 2010 were also averaged for a repeating single year time series of the averaged observed population biomass. The repeating single climatic year was used for calibrating the species biomasses because the biomass data were too variable in magnitude among the field stations for any single month or peak season of abundance, and too variable by month when averaged across stations over years for Barataria Basin.

The model validation run used the calibrated CASM with varying daily salinity, temperature, and chl-a, and annual marsh:open water inputs, for the 20 polygons generated from 1995-2010. The CASM polygon results were weighted by the area of each polygon in order to estimate a system-wide average biomass that was compared to the observed biomass data from 1995 to 2010. The temporal validation run was used to demonstrate how well the calibrated CASM explained the observed biomass data for Barataria Basin based on the varying input driving variables from 1995-2010.

The biomass results from the validation run with varying inputs from 1995-2010 in the 20 CASM polygons were also evaluated by species and peak season of occurrence in Barataria Basin as a form of pattern-oriented validation (Grimm and Railsback 2012). The average seasonal biomass was estimated from the daily predicted biomasses, and plotted with the corresponding average salinity, temperature, vegetation:open water, and phytoplankton or periphyton biomasses (both driven directly by daily chl-a inputs). The scatter plots of the 20 polygons showed which driving input variables affected the CASM predicted biomasses the most and the least within the food web. The 2002 conditions were identified as a normal water year representation, so scatter plots of the polygon biomass by each driving variable in 2002 were used to demonstrate the spatial patterns in key species biomass with the differences in the driving variables (see Dynamic Solutions 2016).

REFERENCES

Bartell, S. M., S. K. Nair, and Y. Wu. 2010. Mississippi River-Gulf Outlet (MRGO) ecosystem restoration study: preliminary evaluation of proposed freshwater diversion in the vicinity of Violet, Louisiana. E2 Consulting Engineers, Inc. Prepared for the U. S. Army Corps of Engineers-New Orleans District, New Orleans, Louisiana

Canning, A. D., and R. G. Death. 2018. Relative ascendency predicts food web robustness. Ecological research **33**:873-878.

Christensen, V., and D. Pauly. 1992. Ecopath II—a software for balancing steady-state ecosystem models and calculating network characteristics. Ecological Modelling **61**:169-185.

Christensen, V., C. Walters, and D. Pauly. 2005. Ecopath with Ecosim: a user’s guide. Fisheries Centre, University of British Columbia, Vancouver **154**.

Christensen, V., and C. J. Walters. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling **172**:109-139.

De Mutsert, K., K. Lewis, S. Milroy, J. Buszowski, and J. Steenbeek. 2017. Using ecosystem modeling to evaluate trade-offs in coastal management: effects of large-scale river diversions on fish and fisheries. Ecological Modelling **360**:14-26.

Deng, L., S. Liu, S. Dong, N. An, H. Zhao, and Q. Liu. 2015. Application of Ecopath model on trophic interactions and energy flows of impounded Manwan reservoir ecosystem in Lancang River, southwest China. Journal of Freshwater Ecology **30**:281-297.

Doherty, J. 2014. PEST, Model-independent parameter estimation-User manual. 5th edition. Watermark Numerical Computing, Brisbane, Australia.

Fulford, R. S., D. L. Breitburg, M. Luckenbach, and R. I. Newell. 2010. Evaluating ecosystem response to oyster restoration and nutrient load reduction with a multispecies bioenergetics model. Ecological applications **20**:915-934.

Heymans, J., and D. Baird. 2000. Network analysis of the northern Benguela ecosystem by means of NETWRK and ECOPATH. Ecological Modelling **131**:97-119.

Levine, S. 1980. Several measures of trophic structure applicable to complex food webs. Journal of theoretical Biology **83**:195-207.

Ma, H., H. Townsend, X. Zhang, M. Sigrist, and V. Christensen. 2010. Using a fisheries ecosystem model with a water quality model to explore trophic and habitat impacts on a fisheries stock: a case study of the blue crab population in the Chesapeake Bay. Ecological Modelling **221**:997-1004.

Naito, W., K.-i. Miyamoto, J. Nakanishi, S. Masunaga, and S. M. Bartell. 2002. Application of an ecosystem model for aquatic ecological risk assessment of chemicals for a Japanese lake. Water Research **36**:1-14.

Polovina, J. J. 1984. Model of a coral reef ecosystem. Coral reefs **3**:1-11.

Shannon, C., and W. Weiner. 1948. A mathematical theory of communication. Publ. University of Illinois Press, Urbana.

Shannon, L., V. Christensen, and C. Walters. 2004. Modelling stock dynamics in the southern Benguela ecosystem for the period 1978–2002. African Journal of Marine Science **26**:179-196.

Sparre, P. 1998. Introduction to tropical fish stock assessment. Part 1. Manual. FAO Fish. Tech. Paper. **306**:1-407.

Ulanowicz, R. 1981. Economic input–output analysis.*in* T. Platt, Mann, K.H., and Ulanowicz, R.E., editor. Mathematical Models in Biological Oceanography. UNESCO Press, Paris, France.

Von Bertalanffy, L. 1933. Modern theories of development: An introduction to theoretical biology. Oxford University Press, New York.

Walters, C., V. Christensen, and D. Pauly. 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Reviews in Fish Biology and Fisheries **7**:139-172.

Walters, C., D. Pauly, and V. Christensen. 1999. Ecospace: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. Ecosystems **2**:539-554.

Walters, C., D. Pauly, V. Christensen, and J. F. Kitchell. 2000. Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. Ecosystems **3**:70-83.

Walters, C. J., and F. Juanes. 1993. Recruitment limitation as a consequence of natural selection for use of restricted feeding habitats and predation risk taking by juvenile fishes. Canadian Journal of Fisheries and Aquatic Sciences **50**:2058-2070.

Ware, D. M., and R. E. Thomson. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. Science **308**:1280-1284.