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Using ecosystem modeling to evaluate trade-offs in coastal management: Effects of large-scale river diversions on fish and fisheries

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ABSTRACT

A coupled ecosystem modeling approach was used to evaluate how select combinations of large-scale river diversions in the lower Mississippi River Deltaic Plain may affect the distribution, biomass, and landings of fish and shellfish over decades relative to a future without action. These river diversions are controlled openings in the riverbank of the Mississippi River designed to reintroduce sediment, water, and nutrients into hydrologically isolated coastal wetlands in order to mitigate wetland loss. We developed a spatial ecosystem model using Ecopath with Ecosim (EwE) software, and prepared it to receive output from a Delft3D hydrodynamic model coupled to primary production models. The Delft3D model provided environmental drivers including salinity, temperature, Chl *a*, total suspended solids, and change in wetland cover as a result of simulated river diversions over decadal model runs. Driver output was averaged either daily, monthly, or annually depending on the parameter. A novel oyster-specific subroutine is introduced in this paper to incorporate information at daily intervals in Ecospace, while Ecospace runs on a monthly time step. The ecosystem model simulates biomass and distribution of fish and shellfish species, and landings of targeted fisheries species, as a result of environmental changes projected for a preliminary set of management scenarios designed to evaluate and screen select combinations of river diversions. Abundant local field samples and landings data allowed for model calibration and validation. The results of simulations indicate that inflow of Mississippi River water in estuaries may cause local shifts in species assemblages. These changes were in some cases direct effects of decreased salinity, such as locally reduced Spotted Seatrout biomass. Changes in some other species in the affected areas resulted from indirect effects; for example, reduced Chl *a* (as a result of increased TSS) resulted in near-field reductions of Gulf Menhaden. The simulations also showed that local biomass reductions were mostly the result of redistribution, since the scenario with the proposed diversions open had minimal impact on the total biomass or landings of species simulated in the Mississippi River Delta as compared to a future without action. The model and its output were used as a decision support tool to help evaluate and compare alternative management actions. The results of this study played a role in the decision by the Coastal Protection and Restoration Authority to prioritize moving forward to conduct more detailed analyses through engineering and design of the two middle diversions but not the two lower diversions that were tested in this study.

1. Introduction

Louisiana is losing land at an alarming rate as a result of the subsidence and erosion of coastal wetlands (Boesch et al., 1994). Because the Mississippi River once built this Deltaic plain (Coleman et al., 1998), large-scale river diversions are a promising restoration measure (Kemp et al., 2014), since they mimic the natural processes that form deltas. River diversions are controlled openings in the levees of the Mississippi River that are used to divert freshwater containing nutrients and sediment into subsiding estu-

Abbreviations: CFS, cubic feet per second; Chl *a*, chlorophyll *a*; CPRA, Coastal Protection and Restoration Authority; CPUE, catch per unit effort; EwE, Ecopath with Ecosim software; FIMP, Fisheries Independent Monitoring Program; FWOA, future without action; LDWF, Louisiana Department of Wildlife and Fisheries; MRDM, Mississippi River Delta Management; NMFS, National Marine Fisheries Service; OECL, oyster environmental capacity layer.

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aries. The main objective of such an approach is to stimulate land building by delivering inorganic and organic sediments, as well as nutrients that stimulate wetland plant growth, resulting in accumulation of organic matter and land stabilization (Wang et al., 2014). Some of the concerns of this approach include the potential negative effects of eutrophication on wetland vegetation (Turner et al., 2002), and the potential negative effects of freshening the estuaries on fish and shellfish (Rose et al., 2014). Simulation models can serve as tools to evaluate the potential of success and trade-offs of planned restoration projects such as river diversions (Yang et al., 2010). Here we present a coupled modeling approach to evaluate effects of coastal restoration on fish and fisheries, and demonstrate the results from a preliminary set of simulations designed to evaluate select combinations of proposed river diversions. The models were developed as decision support tools under the framework of science-based restoration efforts of the Coastal Protection and Restoration Authority (CPRA) in partnership with the US Army Corps of Engineers (USACOE).

Output from a physical-biological model, namely the environmental variables that were expected to change under a diversion scenario and affect fish and shellfish, was used as environmental driver input of an ecosystem model. Using salinity, Chl *a*, percent wetland cover per km^2, total suspended solids, and temperature as environmental drivers, effects on fish and shellfish of proposed operation plans of four river diversions (Lower Breton, Lower Barataria, Mid-Breton, and Mid-Barataria) were compared to a future without action in 50-year simulations.

We describe the model developed for this purpose, and the results of one 50-year scenario compared to a future without action. The scenario simulated four large-scale sediment diversions opened for approximately 5 months each year based on a representative annual hydrograph and an on/off trigger of 600,000 CFS (cubic feet per second) in the Mississippi River. While we included 70 groups (species, life stages and functional groups) in the model to represent the biological community (Table 1), we focus on 6 species in this paper that are of ecological and economic importance: Blue Crab (*Callinectes sapidus*), Brown Shrimp (*Farfantepenaeus aztecus*), Eastern Oyster (*Crassostrea virginica*), Gulf Menhaden (*Brevoortia patronus*), Red Drum (*Sciaenops ocellatus*), and Spotted Seatrout (*Cynoscion nebulosus*). The potential effects on fish and shellfish described here are only one component in the decision-making process to determine how to prioritize further analyses of diversion operations and design, and it provides information needed to evaluate various trade-offs.

2. Methods

2.1. Study area

The study area covers the Lower Mississippi River Delta (Fig. 1). The proposed river diversion locations are indicated in the image. We have focused our research on Barataria Bay and Breton Sound, which are the two basins that directly receive freshwater and sediment flow from the proposed river diversions.

2.2. Modeling approach and simulation scenarios

A coupled modeling approach was used to first simulate the environmental response to a preliminary set of scenarios including select combinations of diversions, and then simulated effects of the changing environment on fish and fisheries (Fig. 2). Delft3D (Roelvink and Van Banning, 1995) was used for the physical-biological modeling, while the fish and shellfish modeling was performed in Ecopath with Ecosim software (EwE; www.ecopath.org). EwE was used to develop and run an Ecospace model, which allows for temporal and spatial simulations of fish biomass and fisheries yield response to environmental changes, predator-prey interactions, and fishing. The Delft model used was Version 1 of the Mississippi River Delta Management (MRDM) Delft3D, described in detail in Meselhe et al. (2015a).

The MRDM Delft3D model (Version 1) provided outputs used as environmental drivers in the Ecospace model, which included salinity, Chl *a*, percent wetland, total suspended solids, and temperature. The MRDM Delft3D model was calibrated to observed data for all parameters and details specific to the calibration can be found in Chapter 4 of Meselhe et al. (2015a). An additional habitat feature added in Ecospace was percent cultch (the area of stones, old shells and gravel that forms the basis of an oyster bed) based on information gathered by the CPRA. The simulation scenario examined here involved opening four proposed diversions from March to June each year based on a representative annual hydrograph for the river in order to capture effects of maximizing sediment capture from high Mississippi River flow during that time (Fig. 3). This simulation scenario is compared to one that represents a future without action (FWOA), which only has the existing Davis Pond and Caernarvon diversions open with the operational plan as shown in Fig. 3. These two existing diversions are operational during both the 'action' scenario and the FWOA scenario.

2.3. Ecopath model development

To simulate fish and shellfish response to this operational plan, first an Ecopath model was developed using the EwE open source software. An Ecopath model is a mass-balanced representation of the food web of the ecosystem of interest, in this case the Lower Mississippi River Delta. For each group in the model (which includes species, life stages, and functional groups; see Table 1), the initial biomass (g m^{-2}), the production to biomass ratio $\left(\frac{P}{B}\right)$, and the consumption to biomass ratio $\left(\frac{Q}{B}\right)$ were included as initial conditions. With these input parameters, the ecotrophic efficiency (*EE*) was calculated by EwE using the first Ecopath master equation (Christensen and Pauly, 1992). The relative proportion of prey items in the diet of each group was entered based on stomach content data collected in a Louisiana estuary when available (De Mutsert, 2010), published literature, and FishBase (www.fishbase.org), and adjusted based on prey availability under the asumption of opportunistic feeding. Fisheries were included with effort and yield of select groups (Table 2). The first master equation describes the production of each functional group as a set of *n* linear equations for *n* groups:

$$\left(\frac{P_i}{B_i}\right)\cdot B_i\cdot EE_i-\sum_{j=1}^{n}B_j\cdot\left(\frac{Q_j}{B_j}\right)\cdot DC_{ji}-Y_i-E_i-BA_i=0 \quad (1)$$

where $\left(\frac{P_i}{B_i}\right)$ is the production to biomass ratio for group *i*, EE_i is the ecotrophic efficiency (the proportion of production used in the system), B_i and B_j are the biomasses of the prey and predators respectively, $\left(\frac{Q_j}{B_j}\right)$ is the consumption to biomass ratio, DC_{ji} is the fraction of prey *i* in predator *j*'s diet, Y_i is catch rate for the fishery for group *i*, E_i is the net migration rate, and BA_i is the biomass accumulation for group *i*.

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

$$\text{Consumption} = \text{production} + \text{respiration} + \text{unassimilatedenergy} \quad (2)$$