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Use of the Connectivity Modeling System to estimate movements of gag grouper (*Mycteroperca microlepis*) recruits in the northern Gulf of Mexico

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Introduction

The purpose of this study is to understand how oceanographic factors affect the annual recruitment success of gag grouper. We use the Connectivity Modeling System (Paris et al. 2013), an individual-based model which estimates the movement of particles in a 3-D velocity field, and has the capacity to simulate complex behaviors such as those displayed by fish larvae. Simulated gag grouper larvae are tracked from their release sites in the northeastern Gulf of Mexico to suitable settlement habitat, given the specified biological parameters. The modeling effort presented here produces an index of annual recruitment deviations for the years 2003-2012, which can be directly input into the 2013 Stock Synthesis assessment model.

Methods

Connectivity Modeling System

The Connectivity Modeling System (CMS) is a biophysical modeling system based on a Lagrangian framework, and was developed to study complex larval migrations (Paris et al. 2013). The CMS uses outputs from hydrodynamic models and tracks the three-dimensional movements of advected particles through time, given a specified set of release points and particle behaviors. Optional modules are provided to allow for complex behaviors and movements, simulating observed biological phenomena such as egg buoyancy, ontogenetic vertical migration, and tidal stream transport. The specific model set up used for this study is outlined in detail below.

Ocean velocity fields

The hydrodynamic model we used was the HYCOM + NCODA Gulf of Mexico 1/25° Analysis, a freely available ocean model with daily velocity fields available from 2003 – 2012 (www.hycom.org). HYCOM is a hybrid isopycnal coordinate ocean model (i.e., isopycnal in the stratified open ocean, fixed-depth in the unstratified surface layers, and terrain-following in shallow coastal waters), while allows for optimal simulation of both coastal and open-ocean features simultaneously (Chassignet et al. 2007). The model is data-assimilative, using real-time observations of the ocean's surface via satellite altimetry, as well as vertical profile information from CTDs, the ARGO observation program, and other sources. This allows for a three-dimensional depiction of ocean currents in real time at a relatively high resolution.

Initial conditions of the biological model

The biological traits specified for simulated gag grouper larvae are outlined in the table below. The methods by which these traits are incorporated into the connectivity model are described following.

Biological trait	**Description of information used in model parameterization**	**Source**
Spawning time	Spawning occurs from December to April, with a peak in Feb and Mar; frequency of approximately every 4 days	Coleman et al. 1996 Fitzhugh et al. 2005 Hood and Schlieder 1992 Koenig et al. 1996 Koenig et al. 2000
Spawning location	High relief hardbottom along the shelf edge in the northeastern Gulf of Mexico. Currently, the only confirmed extant spawning sites in the northeast Gulf are in the Madison-Swanson Marine Reserve	Coleman et al. 2011 Fitzhugh et al. 2005 pers. comm., C. Koenig
Spawning depth	50-90m depth	Coleman et al. 2011
Egg diameter	Epinepheline grouper eggs are generally between 0.9 and 1.0 mm in size.	Colin et al. 1987 Colin et al. 1996 Powell and Tucker 1992 Richards 2006 pers. comm. C. Koenig
Egg buoyancy	Fertilized eggs (+4 hrs) of red grouper (*Epinephelus morio*) were neutrally buoyant in 28-30 ppt seawater at 22 degrees C. Fertilized eggs (+20 hrs) were neutrally buoyant at 32 ppt. Epinepheline grouper eggs are generally similar in density.	Colin et al. 1996 pers. comm. C. Koenig
Pelagic larval duration	33-60 days	Koenig and Coleman 1998 Lindeman et al. 2000
Settlement habitat	Settlement occurs in high-salinity estuaries and seagrass beds. Spatial seagrass habitat information used to define settlement habitat.	Fitzhugh et al. 2005 Koenig and Coleman 1998 http://ocean.floridamarine.org/mrgis/
Timing of hatching and flexion	Hatching occurs 45 hours after fertilization. Nassau grouper (*Epinephelus striatus*) reaches flexion ~15 day post fertilization and at ~6mm length.	Powell and Tucker 1992 Roberts and Schlieder 1983
Vertical migration	See Table 1; Appendix 1	Unpublished data, (G. Zapfe) Unpublished data, (C. Paris)

In the larval transport simulation, particles representing gametes are released from observed spawning sites, during the period of peak spawning activity at the observed frequency.

For these preliminary model runs, we released particles only from confirmed spawning sites in the area of the Madison-Swanson Marine Reserve. Further model refinements may include releases from alternate locations, based on general knowledge of spawning habitat and topography, and areas of high gag abundance from fishery-dependent data and independent surveys.

Particles are initially released from the average spawning depth (70 m), and their movements are then tracked in horizontal and vertical space. Because the simulated depth distributions of particles in the first few days can have significant effects on the ultimate dispersion patterns, the CMS includes a number of modules to more realistically parameterize vertical movements of eggs during this early period. For gag grouper, we used CMS's buoyancy module, which simulates the sinking or floating of particles based on their physical properties. Vertical particle movements are defined according to Stoke's Law, which relates vertical velocity to the diameter and density of the particle, along with the density and viscosity of the water. The latter two variables are calculated directly from the oceanographic data for the location of the particle. The diameter and density of the particles are defined based on values from the literature. The CMS also allows for some variation in the specification of the size and density parameters by incorporating these values as a distribution rather than a fixed value (Table 2).

After two days, at which point gag grouper eggs hatch into larvae, simulated particles are subject to a probabilistic vertical migration matrix based on empirical data (Table 1). Vertical distributions for preflexion larvae were calculated from winter SEAMAP surveys using the MOCNESS sampling (unpublished data, G. Zapfe; see Appendix 1 for sampling description). Because grouper larvae are rare in the samples, and cannot easily be identified to species level, we used all serranid larvae in our calculations. Only eight postflexion stage serranid larvae were available for the two winter surveys, so we combined these observations with MOCNESS samples from Barbados (unpublished data, C. Paris) to come up with a hypothesized vertical distribution for this stage. As samples from the 2012 spring MOCNESS sampling become available, we will increase our sample size of post-flexion larvae and adjust vertical migration specifications according to new data. Overall however, data on grouper larvae vertical distributions are scarce, and this is a large source of uncertainty in the model. Sensitivity analyses will be run to assess the effect of uncertainty in vertical movements on estimates of annual recruitment success.

Once the competency period is reached, simulated particles are allowed to settle, only when they reach appropriate settlement habitat as defined by the model (Fig. 1). Throughout the remainder of the competency period, particles are allowed to successfully settle or continue to move if they have not yet reached suitable habitat.

Other CMS specifications

We used the built-in turbulence module of the CMS, which adds a random component to the motion of the particles to represent turbulent diffusion. This component represents sub-grid turbulent processes not resolved by the resolution of the hydrodynamic model. We used a value of 10 $m^2 s^{-1}$ for horizontal diffusivity and 1 $m^2 s^{-1}$ for vertical diffusivity. We also used the ‘avoid coast’ algorithm built in the CMS, which helps to prevent particles from getting stranded on the land mask. Because fish larvae are not passive drifters, they can likely swim away from the coast to avoid being stranded. This module thus provides a more realistic estimate of the movements of fish larvae near coasts.

Results

Preliminary model runs estimate recruitment to be strongest in 2009 (Fig. 2). Other strong years of recruitment are estimated to be 2012, 2008, and 2004. Recruitment occurs primarily off the coast of northern Florida, to the west of the Big Bend region, and also in the Florida Bay region down to the Tortugas. Recruitment occurs more sporadically and to a lesser extent throughout the rest of the Florida West Shelf.

Discussion

The preliminary recruitment index presented here is based on knowledge that has been compiled to date on the reproductive and larval behaviors of gag grouper. Further model refinements, to be included as new data become available, are likely to alter the trends seen in the index. Initial sensitivity runs show that results are easily affected by changes in the vertical distribution patterns of post-flexion larvae, particularly during the long settlement competency window. Given that few empirical observations are available to inform the exact vertical distributions during this phase, this will be a major source of uncertainty in the model. Formal sensitivity runs will be completed to quantify the effect of this uncertainty on the results, and to construct a variance estimate for the recruitment index.

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Table 1. Vertical migration parameters applied to simulated gag grouper larvae. Columns are percentages of larvae to be distributed in each of the 20-m depth bins during the specified time periods.

	2-15 days	16-29 days	30 - 60 days
0-20 m	36	34	60
20-40 m	29	20	20
40-60 m	25	15	20
60-80 m	5	20	0
80-100 m	5	11	0

Table 2. Specifications of variability in the density and size of simulated particles.

percentage of particles in each category	25%	50%	25%
minimum density (kg m^{-3})	1018.7	1019.7	1020.7
maximum density (kg m^{-3})	1019.7	1020.7	1021.7
minimum particle diameter (mm)	0.900	0.925	0.950
maximum particle diameter (mm)	0.950	0.975	1.000

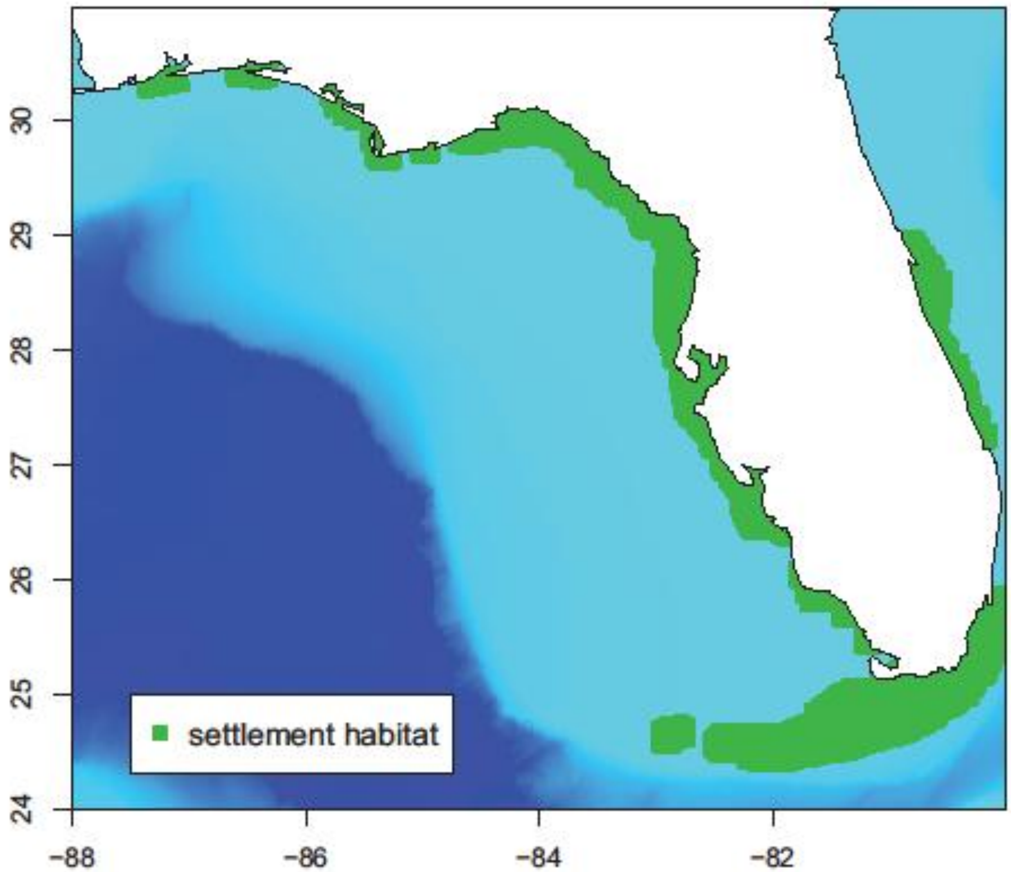

Figure 1. Map of assumed suitable recruitment habitat for gag grouper, based on spatially-explicit seagrass data. Data were downloaded from the Florida Fish and Wildlife Conservation Commission's Marine Resources GIS system (http://ocean.floridamarine.org/mrgis/).

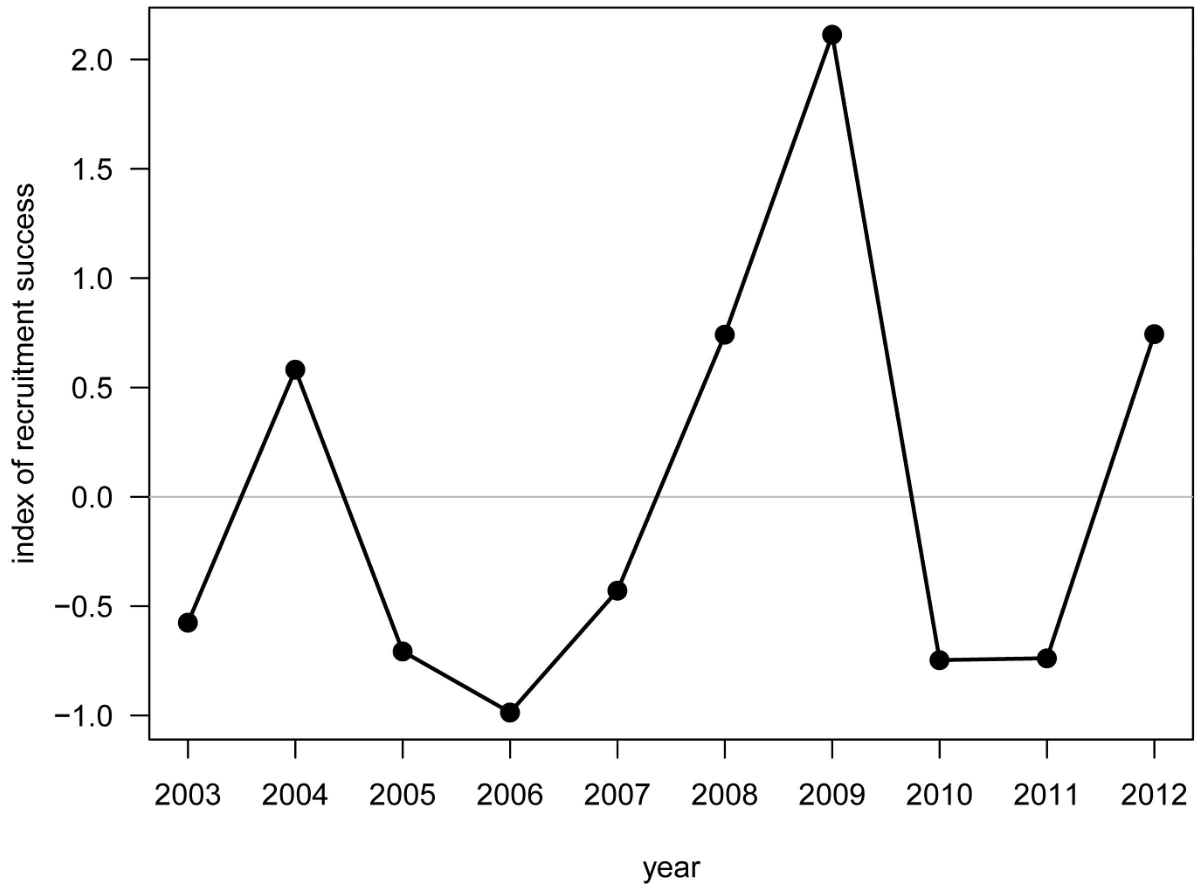

Figure 2. Index of recruitment success for northeastern GoM gag grouper, by year as estimated by the preliminary larval transport model runs.

Appendix 1. Description of SEAMAP MOCNESS sampling.

The National Oceanic and Atmospheric Administration conducts several ichthyoplankton surveys in the northern Gulf of Mexico (GOM) throughout the year as part of the Southeast Area Monitoring and Assessment Program (SEAMAP). A winter survey is set up to assess distribution, occurrence and abundance of the early life stages of a variety of winter spawning species of fishes. The survey covers the continental shelf break and deeper GOM waters where larvae of grouper, tilefish, and other species can be found. Standard sampling gears include bongo and neuston nets to determine distribution of fish larvae throughout the GOM. More recently, a 1 m Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS) has been used as supplemental sampling gear during the SEAMAP surveys.

The 1 m MOCNESS is a rectangular frame constructed to hold up to 9 nets with a 1 m mouth opening. Sensors attached to the frame measure depth, vertical velocity, horizontal velocity, salinity, temperature, angle of the instrument, and flowmeter counts. The system uses the angle and flowmeter count to calculate volume filtered and relay real-time data back to the shipboard computer. Net deployment is controlled through the MOCNESS software and allows scientists to choose the sample depth bin for each net during the actual tow. The MOCNESS is equipped with nine, 0.505 mm mesh nets and deployed from the stern with the port trawl winch using 1/2 in conducting wire and poded termination. One net is used in the oblique tow (Net 0) from the surface to the bottom or a maximum depth of 130 m. Each of the remaining 8 nets (Nets 1-8) samples a discrete 20m depth bin except for the bottom net (Net 1) which samples a 30m depth bin (130 to 100m). Due to productive GOM waters, a target volume of 250 - 300 m^3 of water filtered for each depth bin is set to ensure ample sampling. Currents frequently prevent the target volume from being reached, especially at the surface, but manipulation of ship and winch speed allow the actual volume filtered to approach the target volume.

Vertical distributions of larvae, as parameterized in the Connectivity Modeling System, are obtained by calculating the mean density of target species larvae (in number per volume filtered) by depth bin across all samples, and then converting these densities to percentages.