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Individual-based modeling of an artificial reef fish community: Effects of habitat quantity and degree of refuge

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ABSTRACT

Artificial reefs are often deployed as fishery management tools, and yet there is substantial lack of understanding and agreement on how reefs affect fish population and community dynamics. We developed and applied a multi-species, individual-based model to examine the long-term effects of increasing number of reefs on fish weight, abundance, and biomass. The model simulated the population dynamics of three fish species for 50 years on a 2-dimensional spatial grid. Growth, mortality, and movement were computed each hour for individuals of red snapper (*Lutjanus campechanus*), a croaker-like species (*Micropogonias chromis*), and a pinfish-like species (*Lagodon rhomboides*). We also included individuals of two other species (bluefish – *Pomatomus saltatrix* and a generic jack-like species), but only simulated their hourly movement and their effects on prey and predation of the focal species. The densities of five prey groups were simulated independently in each cell. Our results showed that increasing the number of reefs generally produced higher biomass, but at the cost of slower growth, and smaller individuals. Abundance was higher under fixed-AR recruitment and maximum refuge treatments. In all treatments there were diminishing returns on abundance and biomass with increasing number of artificial reefs. Experiment 2 showed that model results based on regularly spaced reefs were consistent with a real layout of reefs currently being sampled in the northern Gulf of Mexico. Management strategies for determining the habitat-value of reefs in the Gulf of Mexico should consider the number of reefs and the local spatial layout of the reefs to ensure they are optimally arranged. Field experiments performed should assist in resolving how fish recruit to artificial reefs and help determine their roles as fish refuges.

1. Introduction

Artificial reefs (AR) are often deployed as fishery management tools, and yet there is substantial lack of understanding and agreement on how reefs affect fish population and community dynamics. The extent to which artificial reef structures influence exploited fish stocks, either directly via increasing population production rates or indirectly through changes in fishing mortality rates, remains controversial. Many investigations of the effects of reefs ignore potential inter- and intra-specific interactions and focus on static metrics such as diversity indices, while other studies assume simple relationships between reef deployment and fish population responses (Szedlmayer and Shipp, 1994; Ponti et al., 2002; Sherman et al., 2002; Workman et al., 2002). At a local spatial scale, reefs generally support higher densities of less diverse fish and epibenthic fauna as compared to natural reefs (Fujita et al., 1996; Svane and Petersen, 2001; Badalamenti, 2002; Wilson et al., 2003; Sargent et al., 2006).

There is no clear relationship between reef deployment and sustained regional increases in fish abundance and production. One reason for the lack of definitive empirical evidence is that the relative importance of recruitment versus refuge limitation (which is enhanced by reefs) is often unknown and likely varies by species, location, and from year to year (Tolimieri, 1995; Grossman et al., 1997; Powers et al., 2003). Furthermore, the fish responses to reefs are often affected by site-specific factors related to the design and complexity of the reefs, features of the area (e.g., vertical relief), proximity to other reefs, and biological factors such as competition and density-dependent mortality (Charbonnel et al., 2002; Hanner et al., 2006; Strelcheck et al., 2005). This makes generalizations difficult and the measurements needed to isolate the effects of AR deployment within highly variable population dynamics for any single location impractical (Alevizon and Gorham, 1989; Bohnsack, 1989; Bohnsack et al., 1997; Grossman et al., 1997; Powers et al.,

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2003). In this paper, we explore the interaction among number of reefs and density-dependent competition for resources and predation using an individual-based simulation model of a simple fish community.

Questions that are inherently spatial in nature necessitate an evaluation of how population distributions are affected by the interaction between individual behaviors and spatial resource distributions (Mueller and Fagan, 2008). Modeling behavioral movement becomes especially important so that individuals in the model are responding to the appropriate cues (e.g., temperature, prey fields and predators), and doing so in a manner that results in realistic spatial distributions relative to changing environmental and biological conditions. Many studies on artificial reefs have exhibited a halo effect of low prey abundance near reefs, which is largely attributed to near-reef foraging behavior (Frazer and Lindberg, 1994; Galván et al., 2008). Other studies have shown inconsistent development of prey halo distributions around reefs in favor of non-descript, or patchy, prey distributions that are dependent upon local conditions (Ambrose and Anderson, 1990; Barros et al., 2001; Langlois et al., 2006; Smale, 2008). Finally, reefs are often cited as being beneficial refuge habitat; however, there is evidence that this assumption might be an oversimplification of spatially complex predator–prey interactions (Overholtzer-McLeod, 2004, 2006).

The Gulf of Mexico is an oceanic basin characterized by mud, silt, and sand substrates with sparse natural reef formations (Wilson et al., 2006). Parker et al. (1983) estimated that there was approximately 2800 km^2 of naturally occurring hard-bottom in the region in addition to approximately 4000 oil and gas structures. The paucity of natural reefs in the northern Gulf of Mexico has led to the argument that reef habitat is a limiting factor for populations of red snapper (*Lutjanus campechanus*) stocks. Further, the overfished status of red snapper stocks from the Gulf of Mexico (Schirripa and Legault, 1999), and the economic significance of their landings, has led to increased interest in studies pertaining to red snapper stock enhancement through artificial reef programs.

Individual-based models (IBMs) are important both for theory and management because they allow consideration of aspects usually ignored in analytical models such as individual variability, local interactions in spatially complex habitats, and complex behavior (Grimm et al., 2006). Therefore, our set of questions involving complex spatio-temporal interactions and competition for resources, are best modeled using a spatially explicit IBM. In this paper, we present a 2-dimensional, multi-species, individual-based model to explore how reef abundance affects long-term fish population production. We simulate the hourly growth, mortality, and movement of red snapper, and two major competitor species, across a spectrum of reef configurations under alternative assumptions of high and low recruitment (arrival of new age-1 fish to the reefs) and the level of refuge provided by the reefs. We conclude with a discussion of areas for improvement in the model and in data collection, and the ecological and management implications of our results.

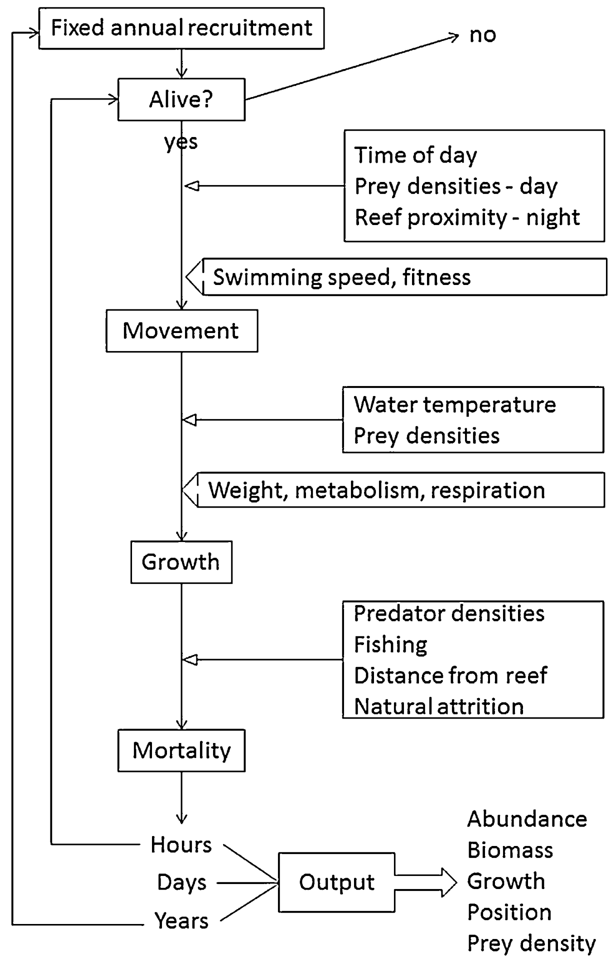

Fig. 1. Conceptual individual based model. Four sub-models determine annual recruitment, and hourly movement, growth, and mortality. At the beginning of each hour, survival in the previous hour is assessed, and mortalities excluded from processing. External influences on individuals are in the boxes with horizontal arrows. Major processes affecting each sub-model are in the pointed boxes. The model is simulated on an hourly time step however output can occur hourly, daily or annually.

2. Model description

2.1. Overview

The model simulated the population dynamics of three fish species for 50 years on a 2-dimensional spatial grid and are presented in brief in the conceptual model (Fig. 1), in detail in the sections below, and with detailed equations in an attached section (Appendix A). The model year was from July 1 to June 31. Growth, mortality, and movement were computed each hour for individuals of red snapper, a croaker-like species (*Micropoganias undulatus*), and a pinfish-like (*Lagodon rhomboides*) species. These three species, which we term the focal species, compete for prey resources. We also included individuals of two other species (bluefish – *Pomatomus saltatrix* and jack-like), but only simulated their hourly movement (not population dynamics) and their consumptive effects on the three focal species. Bluefish individuals acted to remove prey in their spatial cell based on their consumption rates, and both bluefish and jack biomass in each cell were used to adjust the mortality rates of the focal species to mimic spatially dynamic predation.

We used a super-individual approach whereby each model individual is treated like a cohort (Scheffer et al., 1995). Worth was initially assigned when the individuals were created and added to the population as newly recruited age-1 individuals; initial worth was computed as the total number of new recruits in a year divided by the number of model individuals allocated to the first age-class. For the focal species, worth was then reduced each hour by multiplying worth by the fraction surviving. For the two predator species, who did not grow or die, individuals maintained their initially assigned worth throughout the simulation. The worth of an individual was used to adjust consumption rate to compute predation effects on prey, and to compute population abundances and biomass.