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Simulated mark-recovery for spatial assessment of a spiny lobster (*Panulirus argus*) fishery

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ABSTRACT

Marine reserves are becoming widely implemented along with conventional fisheries controls as integrated approaches to fisheries management. The restricted spatial distribution of fishing effort, relative to the spatial distribution of fish stocks that may be partially protected by marine reserves, often necessitates spatial considerations in the design of monitoring and stock assessment. Simulation modeling was used to evaluate whether a mark-recovery design could be used to accurately estimate fishing mortality rates without information about movement rates being available to the assessment procedure. A spatially-explicit individual-based simulation was developed with environmental characteristics of Glover's Reef Marine Reserve, Belize and with biological characteristics of a fished population of Caribbean spiny lobster (*Panulirus argus*). Accuracy of fishing mortality estimates depended on whether these estimates were calculated for the fished area only or for the entire stock. Stock-wide fishing mortality estimates could usually be obtained that were robust to uncertainty about dispersive movement. We discuss results in the context of managing fisheries based on the status of fished areas alone or on the entire stock and discuss the necessity for information about fish movement for accurate assessment of stocks managed using marine reserves.

1. Introduction

Marine reserves have become globally popular as means to regulate fishing and non-fishing human activities within defined spatial boundaries (Lubchenco et al., 2003). In many instances, no-take marine reserves – where fishing is prohibited within reserve boundaries – are used as fisheries management tools (Botsford et al., 2003; DeMartini, 1993; Meester et al., 2004; Polacheck, 1990). This use is often coupled with other fisheries controls that together function as integrated spatial approaches to fisheries management (Hilborn et al., 2006; White et al., 2010). Stock assessment procedures are usually necessary to inform managers about how to adjust levels of fishing effort or acceptable yields in areas surrounding marine reserves. Problematically however, marine reserves complicate stock assessment and can obscure evaluations of whether fishery management objectives are being achieved (Field et al., 2006; Jennings, 2001). One reason for these complications is that marine reserves increase the spatial heterogeneity of fishing pressure by excluding harvesting over part of the fish stock's distribution. In contrast, many stock assessment procedures that are used to estimate abundance and fishing mortality rates are built upon the assumption that all areas are more-or-less equally subject to fishing pressure. Consequently, whenever part of a fish stock is not vulnerable to fishing, assessment inaccuracies will occur unless this complication is addressed in data collection and assessment procedures (Beverton and Holt, 1957; McGilliard et al., 2014; Punt and Methot, 2004).

Approaches have been developed that rely on the availability of fishery-independent monitoring of abundance or biomass within reserve boundaries to address spatial considerations related to assessing fisheries that are managed in conjunction with nearby marine reserves (Pincin and Wilberg, 2012; Punt and Methot, 2004). In addition, information about transfer rates between protected and fished areas are sometimes used to inform assessment models. However, assessment outcomes are known to be sensitive to the accuracy of this information (Punt et al., 2000; Punt and Methot, 2004; Quinn and Deriso, 1999). Here, we simulated a mark-recovery design not to investigate how to obtain information about movement; rather, to investigate the potential application of mark-recovery designs that are robust to fish movement uncertainty. Mark-recovery (fish tagging) has been generally useful in providing information for stock assessment, including estimation of fishing mortality rates (Hoenig et al., 1998a; Martell and Walters, 2002; Youngs and Robson, 1975). Our

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expectation was that since individuals carry markings with them when they move, marking individuals within and around a no-take marine reserve, and with subsequent recovery by the fishery, could lead to accurate estimates of stock-wide fishing mortality without explicitly requiring knowledge about movement patterns.

Simulations were constructed with spatial dimensions and environmental characteristics representative of Glover's Reef Marine Reserve, Belize and with biological characteristics representative of a fished population of Caribbean spiny lobster (*Panulirus argus*). Glover's Reef Marine Reserve includes a no-take area that covers approximately 20% of the atoll, while an economically important spiny lobster fishery occurs in the surrounding areas of the atoll (Belize Fisheries Department, 2013). Within Glover's Reef Marine Reserve, management proceeds without information about historical yield and with limited fishery-independent sampling of relative abundance within the no-take area (Babcock et al., 2013). In addition, this spiny lobster fishery has experienced increased entry in recent years, which has led to calls for restrictions on total yield (Babcock et al., 2013; Belize Fisheries Department, 2013; Gongora, 2010). This situation is not unique to Glover's Reef however, as fisheries for many invertebrate species, and lobster fisheries in particular, have developed rapidly in recent years (Anderson et al., 2011; FAO, 2001). Coinciding with calls for yield restriction, stock assessments of the spiny lobster fishery have already been performed without detailed information about lobster abundance within no-take areas and without information about movement between fished and no-take areas (Babcock et al., 2014; Gongora, 2010).

Thus, to compare a probable baseline of assessment bias associated with the current assessment procedure for spiny lobster at Glover's Reef with a mark-recovery-based alternative, our objectives were two-fold. We first evaluated the magnitude of bias in abundance and fishing mortality estimates that could be expected when only fishery yield and effort data were available to an assessment procedure, and the fishery operated in conjunction with a no-take marine reserve. We then evaluated whether more accurate estimates of fishing mortality could be obtained from a mark-recovery design without information about spiny lobster movement being available to the assessment procedure. Both evaluations were carried out across alternative scenarios about spiny lobster movement and spatial behavior of the fishery. Characteristics of Glover's Reef coral atoll and its spiny lobster fishery were utilized as a strategic representation of the kinds of places where marine reserves are used to manage fisheries targeting substrate-associated fishes and invertebrates. Our simulations were not intended to directly support management decisions at Glover's Reef. Rather, we used the simulations as a basis for discussing when information about fish movement is necessary for accurate assessment of stocks managed using marine reserves.

2. Methods

2.1. Spatially explicit simulation framework

2.1.1. Purpose

The simulation framework was constructed as an individual-based model (IBM). IBMs can be used to describe the ecological movement patterns of fishes relative to management boundaries, from which patterns of connectivity, spillover, and dispersal among areas can be quantified as emergent properties (Huse, 2001; Huse and Giske, 1998; Nathan et al., 2008; Railsback et al., 1999; Werner et al., 2001). Since IBMs simulate the independent actions of many individuals, their use is intuitive for evaluating mark-recovery designs where individuals carrying marks move across landscapes to be later recaptured in different locations. The simulation framework is presented below according to a protocol for communicating the construction of IBMs, which is known as overview, design concepts, and details (ODD; Grimm et al., 2006). Additional details are also provided in the Appendix.

2.1.2. State variable and scales

The simulation framework comprised three primary components: individual spiny lobster, the coral reef environment, and management boundaries and the fishery. All spiny lobster were considered to be adult sized and fully recruited to the fishery and comprise a single stock. In reality, whether spiny lobster at Glover's Reef can be considered a unique stock is currently unknown, owing to uncertainty about the relative importance of localized recruitment versus long-distance dispersal of larval spiny lobster (Ehrhardt, 2005; Kough et al., 2013; Truelove et al., 2012). Nevertheless, fishery management concerns for spiny lobster persist at local, national, and international scales (Babcock et al., 2013; FAO, 2001; Gongora, 2010). Simulated individuals were characterized by location, and by whether they were carrying a unique mark assigned during mark-recovery sampling. Movement of adult spiny lobster had two forms: dispersive and migratory. Dispersive movement consisted of relocations lacking strong directionality, which occurred among the actual configuration of contiguously distributed shallow reef habitats at Glover's Reef. Migratory movement consisted of directed relocations between shallow water and deep water habitats, which were specified in the model to occur seasonally (Childress and Jury, 2006; Herrnkind, 1980).

The coral reef environment was simulated based on the actual spatial dimensions and coarse substrate characteristics of Glover's Reef Marine Reserve, Belize. Glover's Reef is a coral atoll located 45 km east of the coast of Belize (lat 16.82°N, long 87.78°W; Fig. 1). The isolated lagoon is enclosed by emergent reef crest and the seaward sloping forereef descends 30° to 45° downward from the surface where it connects to the vertical wall reef, which continues to depths of 400 m to 2000 m (Acosta, 2002; Acosta and Robertson, 2003; Karnauskas et al., 2011). The simulated coral reef environment consisted of (1) shallow reef habitat and (2) deep wall reef habitat. Shallow reef habitat was represented using a grid of rectangular cells with dimensions of 25 m × 25 m. This grid was created from an existing GIS layer that described the benthic geomorphology distribution of coral reefs within the lagoon and fore reefs (Mumby et al., 1995; Mumby and Harborne, 1999a,b). Shallow reef habitat consisted of 63,426 cells (each grid cell 25 m resolution; area of 625 m^2; total area 3964 ha; Fig. 1). The deep wall reef habitat functioned as a natural refuge from fishing because its depths exceed those that are accessible by free-diving lobster fishers. The deep wall reef was not represented in a spatially explicit manner. Instead, individuals on the deep wall reef were simply aggregated separately from those in shallow habitats.

The spiny lobster fishery at Glover's Reef operates by free-diving from June 15 to February 14 of the following year, with peak fishing effort occurring at the beginning of the season (Fig. 2; Babcock et al., 2012). This temporal pattern of fishing effort was incorporated into the simulations as a representation of current fishery practices. Like other spiny lobster fisheries, catches tend to consist of newly recruited two and three year-olds, which are rapidly depleted through the fishing season (Cruz et al., 2001; Gongora, 2010; Medley and Ninnes, 1997). Commercial fishing at Glover's Reef occurs in shallow reef habitat of the general use zone and is excluded from the neighboring area known as the conservation zone (Fig. 1). A geo-referenced GIS layer of the management zones at Glover's Reef was provided by the Wildlife Conservation Society. Within zones, 79.8% (3164 ha) of shallow reef habitat was located within the general use zone, and 20.2% (800 ha) was located within the conservation zone. For simplicity, all shallow