Journal of Marine Systems 129 (2014) 248–258

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Dynamic connectivity patterns from an insular marine protected area in the Gulf of California

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ARTICLE INFO

Article history:
Received 5 February 2013
Received in revised form 20 June 2013
Accepted 24 June 2013
Available online 4 July 2013

Keywords:
Propagule dispersal
Connectivity
Marine Protected Areas
Gulf of California

ABSTRACT

We studied connectivity patterns from a small and isolated island in the Gulf of California (San Pedro Mártir Island Biosphere Reserve), as a source of propagules to surrounding Marine Protected Areas and fishing sites. We used a particle-tracking scheme based on the outputs of a three-dimensional numerical hydrodynamic model to assess the spatial domain to which the island exports larvae as well as larvae retention. We modeled the release of passive particles from locations around the island during the four release dates (May 15 and 31, and June 14 and 30), matching the lunar phases and the peak of the reproductive season for several commercial invertebrates and fish, at the time when currents in the Gulf typically reverse. For each simulation we analyzed the data at 15, 20 and 30 days after the release to represent different planktonic propagule durations. Particle dispersion was highly dynamic and spread over ~600 km along the coast over the study period. Overall, we observed potential ecological connectivity with a few key distant fishing sites that changed trough time, and potential genetic connectivity towards many near and distant sites, including all neighboring Marine Protected Areas, although not simultaneously. The percentages of particles remaining within the boundaries of the island tended to decline from May to June, and decreased with delayed planktonic propagule duration. The design of effective Marine Protected Areas should acknowledge the dynamic nature of connectivity patterns, for instance, by establishing adaptive network reserves to respond to changing ocean features that match reproductive patterns of target species and fisheries behavior.

1. Introduction

The Gulf of California (GC) is a semi-enclosed sea situated in Northwest Mexico with three marine faunal regions, the northern, central and southern (Brusca et al., 2005; Walker, 1960) (Fig. 1). Driven by low frequency currents and tides from the Pacific Ocean, and local winds, the circulation of the GC is seasonally-reversing; cyclonic in summer and anticyclonic in winter (Alvarez Borrego, 2010; Lavín and Marinone, 2003). The cyclonic phase lasts from June to September (Carrillo and Palacios-Hernández, 2002; Marinone, 2008; Palacios-Hernández et al., 2002) and includes a poleward coastal current over the mainland continental shelf in the southern Gulf. This coastal current starts in June and quickly intensifies. Part of this current continues northward across the constriction between the large islands to form the cyclonic eddy of the northern Gulf, and part turns cyclonically to return on the peninsula side of the Gulf. The anticyclonic phase lasts from November to April, and entails the reversal of the northern Gulf eddy and the coastal current in the southern Gulf (Marinone, 2008). In addition to the seasonal circulation, there are meso-scale eddies in the southern Gulf, which have been modeled by Zamudio et al. (2008) and described in detail by Lavín et al. (2013).

The northern GC has two different oceanographic subregions, the Upper Gulf of California and the Midriff Island Region (MIR, Fig. 1), characterized each by different marine landscapes (depth, currents, bottom types) (Brusca et al., 2005). One distinctive oceanographic feature is the presence of a tidal-mixing front in the southern end of the MIR (Argote et al., 1995) which affects the distribution and exchange of sea-water between the southern and the northern Gulf (Danell-Jiménez et al., 2009; Sánchez-Velasco et al., 2009). The MIR and the front are believed to play an important role molding dispersal

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http://dx.doi.org/10.1016/j.jmarsys.2013.06.012

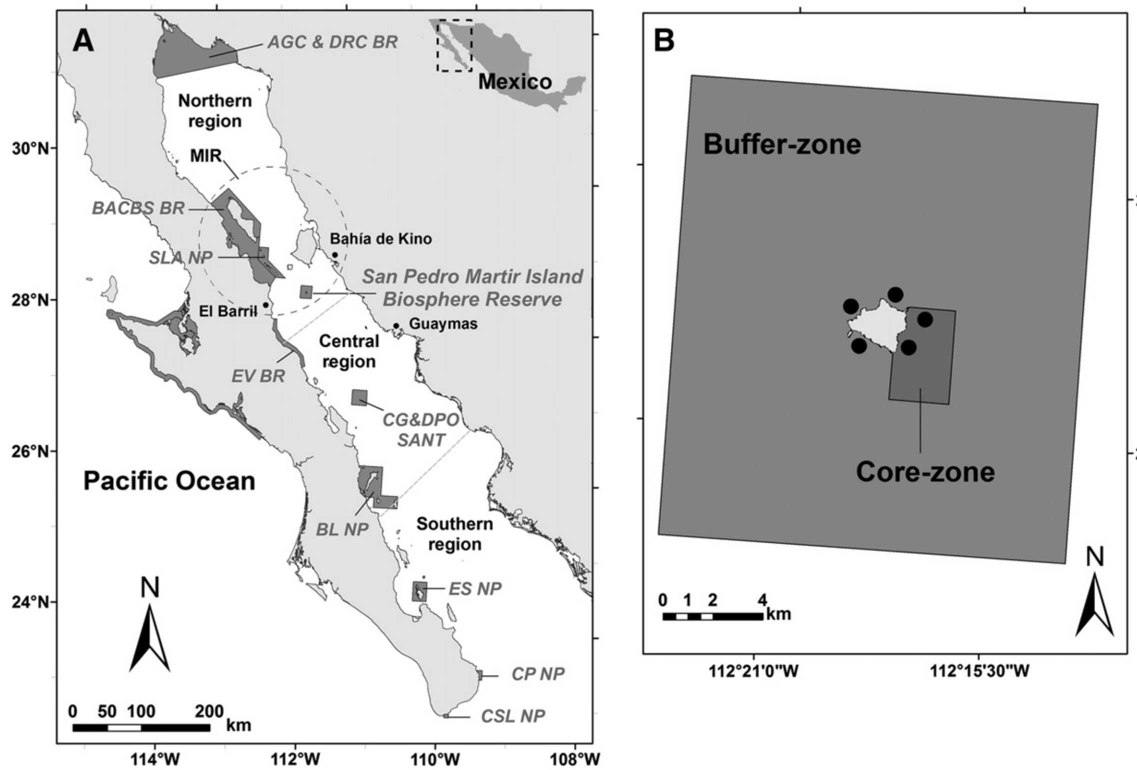

Fig. 1. Gulf of California. Panel A) Marine Protected Areas are indicated as follows: Alto Golfo de California y Delta del Rio Colorado (AGC & DRC BR), Bahía de los Ángeles, Canal de Ballenas y Salsipuedes (BACBS BR), San Lorenzo Archipelago National Park (SLA NP), El Vizcaíno (EV BR), Cuenca de Guaymas y Dorsal del Pacifico Oriental Sanctuary (CG & DPO SANT), Bahía de Loreto (BL NP), Espiritu Santo (ES NP), Cabo Pulmo (CP NP), and Cabo San Lucas (CSL NP). Midriff Islands Region (MIR). Panel B) San Pedro Mártir Island Biosphere Reserve (BR) and location of particle release sites in 3D oceanographic model.

pathways for nutrients, food and propagules (eggs, larvae, and spores), and thus connecting marine species populations (Danell-Jiménez et al., 2009; Lavín and Marinone, 2003; Sánchez-Velasco et al., 2009). The MIR contains islands of different sizes, islets, basins, sills and straits which promote a unique seascape distinguished by its species richness and biodiversity largely supported by surrounding nutrient-rich waters brought to the upper layer throughout the year by tidal mixing and convergence-induced upwelling (Alvarez Borrego, 2010; López et al., 2006, 2008).

San Pedro Mártir Island (SPMI) is the most remote island in the GC (*ca.* 60 km from each coast) (Murphy et al., 2002) located in the southern limit of the MIR and positioned within a transition zone between the northern and central (Lavín and Marinone, 2003). This 2.9 km-diameter island harbors large colonies of cacti (Wilder and Fleger, 2010), and its surrounding waters are rich in fish, invertebrates, seabirds, marine mammals and sea-turtles, (CONANP-SEMARNAT, 2007). Given the unique characteristics of the island, including small size and isolation, it was decreed a Marine Protected Area (MPA) with the status of Biosphere Reserve (BR) in 2002 (DOF, 2002). In total, the reserve has an area of 302 km^2, including the island and two islets and 8 km^2 of coastal waters as core zone (no-take) and 291 km^2 of buffer zone where extractive activities are permitted (Fig. 1) (DOF, 2002). The island has long been used by sport fishers from continental Sonora targeting rocky reef and pelagic fishes (*e.g.*, groupers, marlin, mahi-mahi) (Fujitani et al., 2012) and by small-scale commercial fishers from communities in both margins of the GC targeting mainly mollusk, lobsters, sea cucumbers and reef fishes (Erisman et al., 2011; Meza et al., 2008; Moreno-Báez et al., 2012). Currently, small-scale fishers within the buffer zone use three fishing gears: hookah diving, metallic traps, and hand lining. Although sport fishers are the most frequent visitors to the island, it is an important destination for small-scale commercial fishers when fish abundances in remote fishing sites are depressed (Fujitani et al., 2012; Meza et al., 2008).

A distinctive attribute of many benthic invertebrate species (bivalves, crustaceans, echinoderms) and rocky reef fishes (snappers, groupers) is that they are structured as metapopulations: an assemblage of geographically separate subpopulations of sedentary organisms that are interconnected by the exchange of planktonic propagules (Lipcius et al., 2005). The extent to which these subpopulations are linked by the exchange of planktonic propagules is termed connectivity and can have multiple and different patterns, and implications (Lowe and Allendorf, 2010; Palumbi, 2003; Soria et al., 2012). The design of management strategies that explicitly acknowledge the complexity and dynamics of metapopulation connectivity would be most appropriate. In this sense, MPA networks, including fully protected marine reserves or no-take zones, are a tool to overcome the loss of biodiversity and the over-exploitation of fisheries that can integrate the spatial structure of marine populations in the design of management strategies (Gaines et al., 2010). The process of selecting an area or several areas to be set as MPAs is inherently a challenging assignment that involves the consideration of biophysical and human dimensions (Pollnac et al., 2010; Soria et al., 2012; Ulloa et al., 2006). As for the design of effective MPAs in general, the determination of the geographical scale, direction and magnitude of propagule dispersal, for instance through the use of oceanographic models, and its demographic and genetic impacts on distant populations is a critical area of research (Cowen and Sponaugle, 2009; Lowe and Allendorf, 2010; Soria et al., 2012). On one hand, demographic connectivity is characterized by relatively large amounts of propagules that have measurable effects in fishing activities over ecological timescales, while genetic connectivity usually involves fewer propagules that are, however, key for biodiversity conservation over evolutionary time scales,