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An integrated stock assessment for red spiny lobster (*Panulirus penicillatus*) from the Galapagos Marine Reserve

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ABSTRACT

The population of red spiny lobster (*Panulirus penicillatus*) around the Galapagos Islands has supported a fishery since the 1960s. However, conservation concerns have been raised given signs of over-exploitation observed during the mid-2000s, including decreasing trends in catch per unit effort (CPUE), yield, and profitability. We developed an integrated, size-structured assessment method to estimate trends in fishing mortality, recruitment, and mature biomass. A posterior distribution of spawning potential ratio (SPR) in 2011 was calculated using Bayesian methods and had a median of 44%, which is higher than most commonly used reference points (e.g. SPR = 40%). However, there are uncertainties in our estimates and continued monitoring with standardized data collection protocols should be a priority for future work in this fishery. Management should work toward establishing science-based management strategies that consider both the needs of fishing communities and the imperative to conserve unique ecosystems such as the Galapagos Islands.

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1. Introduction

The Galapagos Islands are a UNESCO world heritage site owing in many respects to their high proportions of endemic species (Baine et al., 2007), including iconic species such as the Galapagos tortoise and Darwin's finches. They are also credited with contributing to the development of Darwin's theory of evolution (Darwin, 1859). The ecology of the archipelago has been largely preserved due to the late human colonization of the islands (officially initiated in 1832) and the declaration of ~97% of the land area as a National Park (González et al., 2008). However, the Islands do have a history of natural resource exploitation, beginning at the end of the eighteenth century with the capture of sperm whales (*Physeter macrocephalus*), fur seals (*Arctocephalus galapagoensis*), and Galapagos sea lions (*Zalophus wollebaeki*) (Castrejón et al., 2014; Schiller et al., 2014).

In March 1998, the Galapagos archipelago and its surrounding open ocean were enclosed in a multiple-use marine reserve of nearly 138,000 km^2, the Galapagos Marine Reserve, through the enacting of the Special Law for Galapagos by the government of Ecuador (Castrejón et al., 2014). A wide variety of marine species are commercially harvested by local small-scale fishing communities, including 68 finfish species from 27 families, and nine shellfish species, with red (*Panulirus penicillatus*) and green (*P. gracilis*) spiny lobsters being two of the most valuable species (Castrejón, 2011; Schiller et al., 2014). *P. penicillatus* is the most abundant spiny lobster species in the archipelago, often representing more than 75% of the annual total catch (Ramírez et al., 2012). Galapagos spiny lobsters are primarily exported to the United States and the European Union for a relatively high price per lobster (Ramírez et al., 2012). The spiny lobster fishery began in Galapagos during the early 1960s as an export-oriented business (Bustamante et al., 2000), primarily around the islands of Santa Cruz, Santiago, Floreana, and southern regions of Isabella (Reck, 1983; Fig. 1). Spiny lobsters were reported to be so abundant in the intertidal and upper tidal zones at that time that they were harvested exclusively by free-divers (Holthuis and Loesch, 1967). Fishermen transitioned to hookah diving in the 1970s (Reck, 1983), which remains the most common form of lobster fishing in the Galapagos to this day. Most divers transitioned to night fishing and the use of Hawaiian slings as the fishery developed and lobsters became less common (Bustamante et al., 2000). Fishing in the Galapagos expanded rapidly following the development, overexploitation, and collapse of a fishery for the sea cucumber *Isostichopus fuscus* beginning in 1992 (Castrejón et al., 2014). Licenses obtained for the sea cucumber industry were valid for all other fisheries in Galapagos, creating an influx of active and latent effort in

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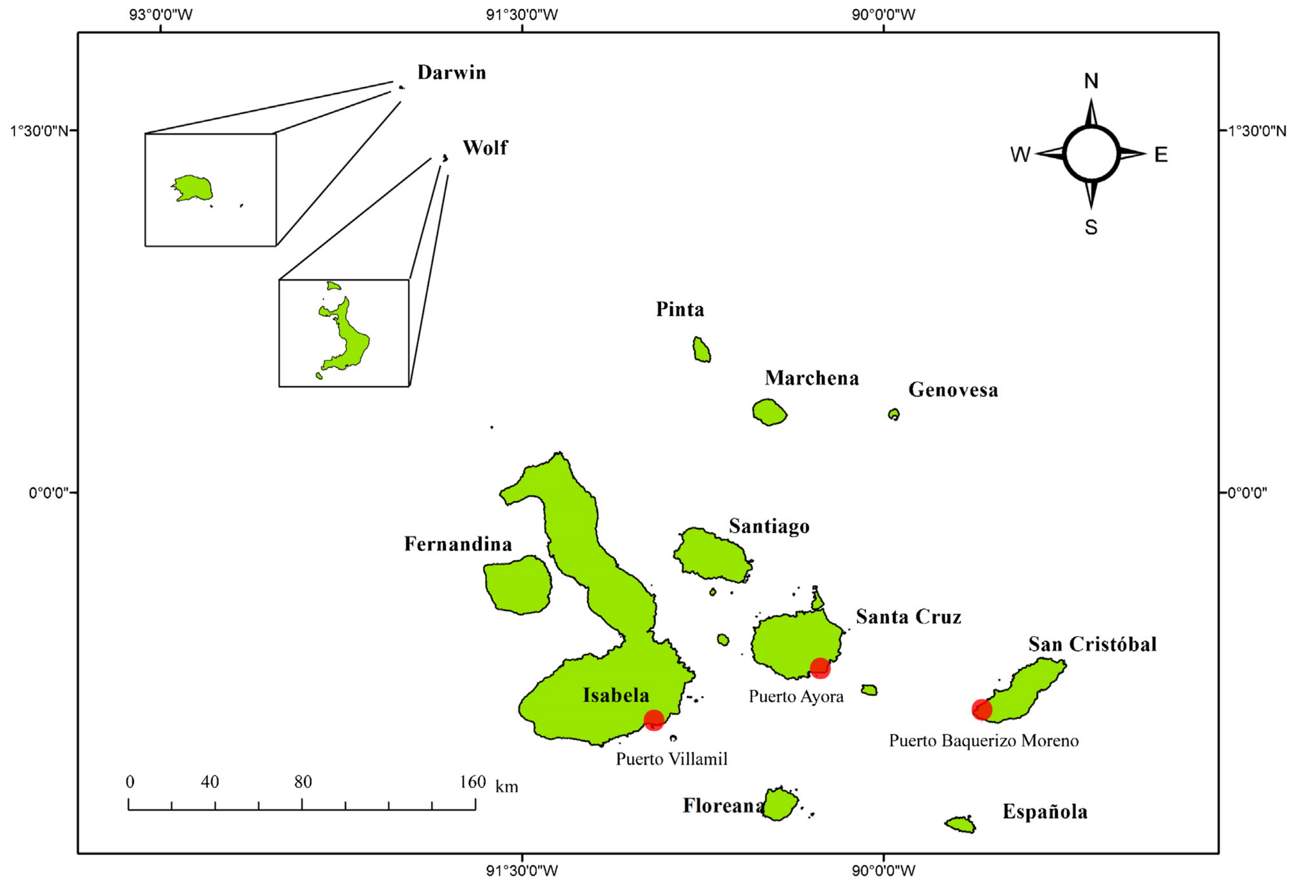

Fig. 1. A map of the Galapagos Islands with major ports indicated by red dots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the lobster fishery. This increase in effort was associated with a 'race to fish' within the fleet (Castrejón, 2011), and with declines in raw catch per unit effort (CPUE), catches, and economic profitability in the lobster fishery from 2000 to 2005 (Defeo et al., 2014).

The spiny lobster fishery appears to show signs of recovery in recent years, including a stabilization of fishing effort, increasing yields, and the highest raw CPUE and revenues per unit effort values observed since 1998. These outcomes are hypothesized to be the result of the combined effect of market forces, climate variability, and a moratorium on new entrants to fisheries implemented since 2003 (Defeo et al., 2014). However, little empirical evidence is available to assess the significance of these apparent increases, as the population lacks robust assessments of its current biological status.

The first analysis of Galapagos spiny lobsters was published by Reck (1983). Since then, only one empirical assessment has been conducted. Hearn (2004) used a length-based cohort analysis (Jones, 1981) in combination with a Thompson and Bell (1934) model, using commercial catch data from 2001–2003, to provides estimates of stock size (biomass and number of individuals) of *P. penicillatus*. According to his results, fishing effort was above optimal levels in 2004, and maximum sustainable yield (MSY) was equal to ~28 MT lobster tails (which was substantially lower than the average of ~40 MT taken from the fishery in the preceding four years). Given the lack of recurrent stock assessments, the annual management of the fishery (including sporadically implemented TACs, size limits, seasons, and marine protected areas; Ramírez et al., 2012), has been mostly based on descriptive summaries of catch statistics since 1997, size structure, and raw CPUE indices.

Science-based management is a critical component to conserving the marine resources of the Galapagos and ensuring the livelihood of the fishing community. We present an integrated assessment of the available fishery-dependent data to provide estimates of the recent stock status for the red spiny lobster population from the Galapagos Marine Reserve. An integrated assessment combines all available data into a single modeling framework, thereby providing more comprehensive estimates of model parameters as well as biological reference points (Maunder and Punt, 2013). Our goal is to demonstrate how systematically collected data could be used in an integrated framework to provide management advice for this fishery.

2. Methods

2.1. Study area and fishery statistics

The Galapagos Archipelago is located in the Eastern Tropical Pacific about 1240 km west of mainland Ecuador (DPNG, 2014; Fig. 1). It is formed by 234 islands, islets and rocks of volcanic origin, with a total emerged land area of 7,985 km^2, including 1,667 km of coastline (DPNG, 2014). This archipelago is located at the convergence of three major seasonally varying current systems: the Peru (from the southeast), the Cromwell (from the west), and the North Equatorial (from the northeast) currents (Baine et al., 2007). The abundance and distribution of marine species and habitats is strongly influenced by natural environmental variability such as "El Niño" (Defeo et al., 2013).

There are only four inhabited islands (Santa Cruz, San Cristóbal, Isabela, and Floreana) and three main fishing ports (Puerto Ayora,