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Forecasting the success of invasive marine species; lessons learned from purposeful reef fish releases in the Hawaiian Islands

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ABSTRACT

Eleven grouper, snapper, and emperor fish species were intentionally released in the Hawaiian Islands spanning the years 1955–1961 to produce new fisheries. Within 15 years, three of the introduced species established self-sustaining populations and eight did not. Two species, *Lutjanus kasmira* and *Cephalopholis argus*, are now considered invasive. We report on the results of a biophysical computer model which combines the life history traits of the inductees with prevailing oceanographic conditions in the Hawaiian Islands to hindcast the fate of the introduced fish. This comparative study is valuable in providing numeric insight into the characteristics that predispose fish introduced outside their native range to becoming invasive. Simulations created by the model spanning the years 1955–1970 succeeded to reproduce the establishment of the three species now found in the Hawaiian Islands and also replicated the failure of those fish that did not establish. Our results suggest that mortality rate, tolerance to water depth, age to maturity, and the quantity of individuals released are the best predictors of the establishment of the introduced fish in the Hawaiian Islands.

1. Introduction

Stocking non-native fish to bolster fisheries is common place in freshwater ecosystems and, even if environmentally risky, in some cases is economically advantageous to the fishing communities that they support (Copp et al., 2005). The State of Florida (USA), for instance, introduced the butterfly peacock bass (*Cichla ocellaris*, native to Brazil) in 1984 to create a robust recreational fishery (Shafland, 1995). Non-native salmonids are also regularly stocked as game fish in freshwater systems throughout the United States (Krueger and May, 1991). The purposeful introduction of marine fish outside of their native ranges is less common than in freshwater, though the literature is well-furnished with examples of mistaken marine introductions that have wrought disastrous environmental consequences (Boudouresque et al., 1995; Rudnick et al., 2003; Albins and Hixon, 2011). One of the most thoroughly documented cases of a purposeful marine introduction is from the Hawaiian Islands (Oda and Parrish, 1982; Randall, 1987). This introduction was affected in the 1950's–1960's when thousands of juvenile snappers, groupers, and emperors, comprising 11 different species, were released by the Hawai'i Division of Fish and Game (HDFG). The purpose of the releases was to enhance Hawaiian fisheries by introducing shallow-water game and food fishes to the Islands (Gaither et al., 2012). This experiment is now perceived as a failure, however, due to a lack of foresight in that some of the introduced fishes would later be viewed as invasive. Perhaps more importantly, the local Hawaiians did not take to these strange new inductees as either game or food fishes (Friedlander et al., 2002; Schumacher and Parrish, 2005).

Beginning in 1955, the fish were introduced into the wild over a period of six years. The locations where the fishes were released, the species names, and their quantities were documented by the HDFG (see Table S1 in Gaither et al., 2012). Though their natural ranges are vast, the introduced fish were sourced from the Marquesas, Society, and Phoenix Islands, with one species from Mexico (*L. guttatus*) (Gaither et al., 2012). Three species established reproductive populations in the waters surrounding the Main Hawaiian Islands (MHI – Fig. 1) within 15 years after their introduction; the blacktail snapper, *Lutjanus fulvus*, the peacock hind, *Cephalopholis argus*, and the bluestriped snapper, *Lutjanus kasmira*. Going forward in this paper,

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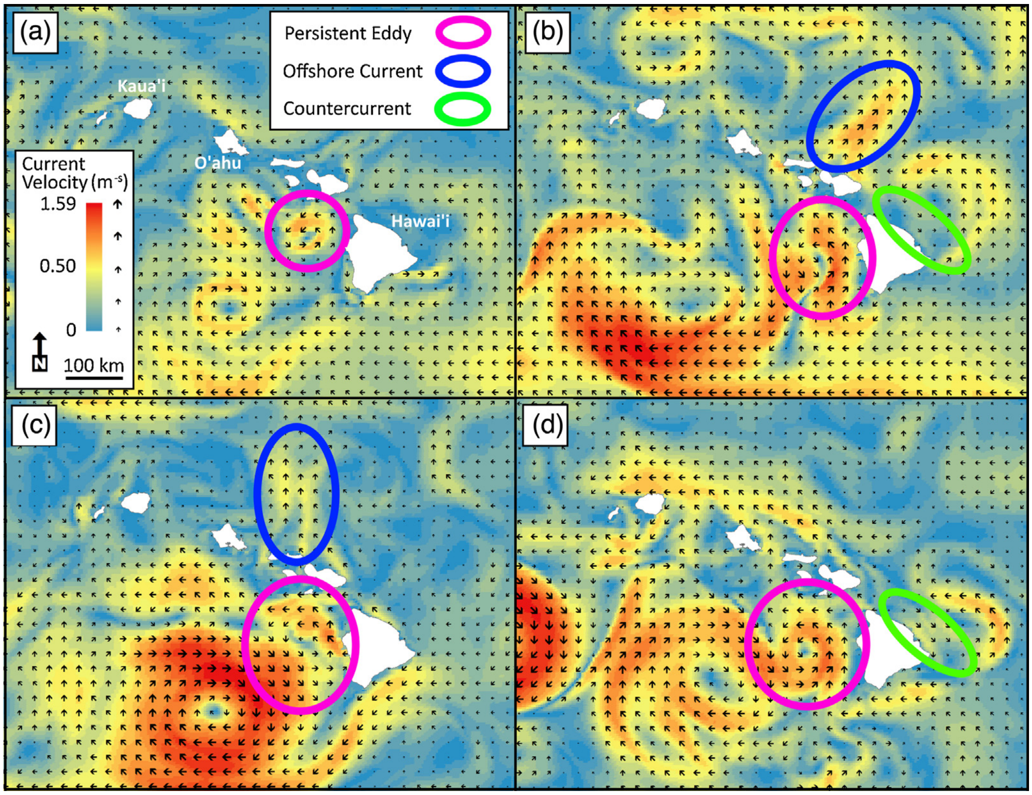

Fig. 1. Hawaiian ocean circulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Ocean currents in Hawai'i for a proxy year (2011 – Johnston and Purkis, 2014b), compiled for January 1st (a), April 1st (b), July 1st (c), and October 1st (d) at a scale of 4 km. Current velocities are indicated via a fast (red – maximum 1.59 m^{-s}) to slow (blue – minimum 0.00 m^{-s}) scale, and arrows represent water flow velocity and direction every 10 km. Pink ovals demark the 'Alenuihaha Channel Eddy west of the Island of Hawai'i. Blue ovals highlight an intermediate offshore current north of O'ahu. Green ovals show a countercurrent on the north shore of the Island of Hawai'i.

all three are deemed the 'successful species'. Historical abundance and distribution data of the successful species, though, are sparse. We therefore base the success of these three species (i.e., *L. fulvus*, *C. argus*, and *L. kasmira*) on contemporary distributions and anecdotal abundance data in the Hawaiian Islands. The Hawaiian introductions provide a rare case study to further our understanding as to why some marine species successfully colonize their introduced range and why others fail to establish.

The motivation for this study was to provide insight as to the ocean conditions surrounding the MHI, and also the biotic traits of the inductees, that could have predicted the success of *L. fulvus*, *C. argus*, and *L. kasmira*, and the failure of *L. gibbus*, *L. guttatus*, *C. urodelus*, *Epinephelus faciatus*, *E. hexagonatus*, *E. merra*, *E. irroratus*, and *Lethrinus miniatus*. The study employed a computer modelling technique that integrated the introduced species' biological traits and physical oceanographic conditions (i.e., surface-ocean current, temperature, salinity, and depth) in order to replicate the invasion event in the MHI. Previously, the model was used to reconstruct the historic Atlantic lionfish (*Pterois volitans/miles*) invasion (Johnston and Purkis, 2011) and also to forecast the potential spread of panther grouper in South Florida, USA (Johnston and Purkis, 2013). Further, the model has been used to assess the lionfish invasion risk in the tropical eastern Pacific and Mediterranean Sea (Johnston and Purkis, 2014a,b) and also to show how hurricanes may have accelerated the spread of invasive lionfish to the Bahamas (Johnston and Purkis, 2014a,b). Implementing such a model allows a reconstruction of the historic fish introduction in the MHI and also suggests that computer simulation can facilitate an understanding of the factors that conspire to yield a successful marine invasion.

1.1. Chronology of invasion, fisheries, and ecosystem impacts

Five locations in the MHI were selected by the HDFG as introduction sites. The majority of releases were conducted offshore O'ahu, an island centrally located in the MHI (see Table S1 in Gaither et al., 2012). The inductees, however, did not remain confined to the MHI. By the year 1992, *L. kasmira* reached Midway Atoll – a distance of 2000 km from the initial point of introduction (Randall et al., 1993). By the year 2013, *L. kasmira* had permeated the entire Hawaiian archipelago to Kure Atoll, a span of 2600 km (Gaither et al., 2013). *L. fulvus*, by contrast, remained confined to the MHI – a range of only 600 km. *C. argus*, a grouper, was intermediately successful to the two introduced snapper species and can be found as far west as the French Frigate Shoals – a distance of 1200 km from the MHI where it was released (Gaither et al., 2012). Long distance migrations are not known from most adult reef fishes. Rather, the dispersal of reef fishes is primarily conducted on ocean currents as buoyant larvae that are transported long distances over the pelagic larval duration period (i.e., the *PLD* – defined as the period of time larvae remain viable in water column until settlement). This dispersal mechanism suggests that water circulation likely conducted the spread of the introduced Hawaiian species, similar to the invasive lionfish (*Pterois volitans/miles*) in the Atlantic and Caribbean (Friedlander et al., 2002; Johnston and Purkis, 2011).

Despite the great abundance and fisheries potential of *L. kasmira*, Hawaiian fishermen consider this fish a nuisance, rather than a product for market (Friedlander et al., 2002). *L. kasmira* exhibits a generalized predatory diet that includes fish, crustaceans, and cephalopods and therefore is perceived as a threat to native fauna (Oda and Parrish, 1982; Schumacher and Parrish, 2005). Given its broad diet, *L. kasmira* is well adapted to exploit varied food