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Spatial analysis of the invasion of lionfish in the western Atlantic and Caribbean

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ABSTRACT

Pterois volitans and *Pterois miles*, two sub-species of lionfish, have become the first non-native, invasive marine fish established along the United States Atlantic coast and Caribbean. The route and timing of the invasion is poorly understood, however historical sightings and captures have been robustly documented since their introduction. Herein we analyze these records based on spatial location, dates of arrival, and prevailing physical factors at the capture sights. Using a cellular automata model, we examine the relationship between depth, salinity, temperature, and current, finding the latter as the most influential parameter for transport of lionfish to new areas. The model output is a synthetic validated reproduction of the lionfish invasion, upon which predictive simulations in other locations can be based. This predictive model is simple, highly adaptable, relies entirely on publicly available data, and is applicable to other species.

1. Introduction

Biological invasions by introduced species are unfortunately common, though marine invasions are not as apparent as terrestrial. The impacts from predation and habitat displacement are hard to quantify in the marine as patterns of introduction and recruitment are hidden from casual view and hence often not well understood, however the potential deleterious effects of non-native species in all habitats are well documented (O'Neill, 1997; Dittel and Epifanio, 2009).

This paper focuses on *Pterois volitans* and *Pterois miles* (red lionfish and devil firefish) which have become established in the eastern Atlantic and entire Caribbean probably though aquarium releases (Hare and Whitfield, 2003). Both species have been confirmed in Atlantic waters with *P. miles* composing a small percentage of records (Hamner et al., 2007; Morris and Freshwater, 2008; Freshwater et al., 2009). For brevity, this manuscript will refer to both of the species found in the Atlantic as simply 'lionfish'.

The lionfish is a voracious piscivore, preying on small reef fish and crustaceans up to their own body size (Hare and Whitfield, 2003; Morris and Akins, 2009). Few fish prey on lionfish in their introduced range with only the coronet fish documented as a natural predator in their native Pacific (Bernadsky and Goulet, 1991; Hare and Whitfield, 2003). Lionfish are highly fecund, producing floating egg masses, free swimming pelagic larvae, have high initial growth rates, slow maturation, and ability to survive extended periods of time with no or little food intake (Fishelson, 1997; Freshwater et al., 2009). This makes them a highly successful invader.

Non-native lionfish are known to populate most benthic habitats in the western Atlantic and Caribbean basin. This includes both reefs and mangrove systems which are important nursing grounds for juvenile reef fishes. A short-term study on artificial reef tracts containing a single lionfish has shown a significant reduction in recruitment of reef fish species (Albins and Hixon, 2008). Additionally, lionfish in mangrove systems in the Bahamas have been shown to be polyphagus and in direct competition with juvenile grouper species (Barbour et al., 2008).

The locus of introduction to the western Atlantic is unknown. However, six individuals which were released into Biscayne Bay during hurricane Andrew in 1992 are often cited as the initial introduction, though this release is anecdotal and not well documented (Courtenay, 1995). Records also indicate a 1985 capture of a single lionfish in Dania Beach (Florida) (USGS-NAS, 2010). Subsequent to the Biscayne Bay release, lionfish have been recorded from South Florida, northward to North Carolina, which boasts numerous sightings beginning in the year 2000 (USGS-NAS, 2010).

Ocean current has been cited as the likely transport mechanism for juvenile lionfish (Hare and Whitfield, 2003); however the mechanics of connectivity for this invasion have not previously been fully explored. Most marine population models involving connectivity in other species also cite ocean current as a main means of larval dispersal. Hare et al. (2002) demonstrated larval fish transport in the Gulf Stream from the southeastern continental shelf to coastal areas north of Cape Hatteras, North Carolina. Working with Atlantic Cod (*Gadhus morhua*), Huret et al. (2007) found strong connectivity between spawning grounds and downstream

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habitats in the Gulf of Maine. Other models have examined the effects of current on range limitations as compared to more traditional models exploring physical property gradients like temperature on range (Gaylord and Gaines, 2000).

Our main objective in this study was to develop a simple invasion model, based upon data assembled entirely from public sources, which could artificially simulate the spatial pattern of the lionfish invasion in the western Atlantic and Caribbean. Based on this simulation, the model could then be used to predict lionfish introductions in other geographical areas. The model, based upon a cellular automata algorithm, evaluates the effects of four common physical oceanographic characteristics widely evaluated in other studies (salinity, temperature, current, and water depth) on lionfish distribution in the study area. The model is not limited to these four characteristics; it is easily configurable to examine any number of parameters and can also be used to predict introductions of other invasive species. The model is unique in its simplicity, ability to examine compounding effects of parameters, and reliance on pattern-matching of historical records to predict future occurrences.

To accomplish our objectives, we follow Schofield (2009, 2010) and Betancur-R et al. (2011) and examine lionfish capture and sighting records obtained from the USGS Non-indigenous Aquatic Species (NAS) database. This database is a compilation of records received from literature, governmental, and private sources for the United States and Caribbean nations. Records in the USGS-NAS database include capture date and location, providing a means to temporally sequence first occurrences of lionfish in the introduced area. We use computational GIS to combine lionfish records with ocean current, salinity, depth, and temperature data at the observation and capture sights to (1) determine their possible compounding effects and (2) establish a predictive Regional Scale Model (RSM – defined in this study as a model which uses a discrete geographical unit area of approximately 100 km × 100 km) of the establishment based on these parameters which could be an important tool in forecasting invasions of lionfish in other areas. The performance of this RSM, which covers the eastern seaboard of the United States, Bahamas, Gulf of Mexico, and Caribbean basin, will be validated through correlation testing as well as the construction of a high resolution Local Scale Model (LSM – defined in this study as a model which uses a discrete geographical unit area of approximately 10 km × 10 km) in an area where appropriately rich ancillary data can be compiled; the eastern seaboard of the United States and the Bahamas. The resulting models (RSM and LSM) are not species specific and can be applied to other marine invasives. Additionally, we provide a stage-map illustrating a series of current-driven and proximity-based recruitment periods. As a secondary objective of this study, we also present a detailed statistical analysis of physical parameters present at capture locations, analysis of juvenile versus adult lionfish records, as well as a forecast of captures for 10 years into the future.

2. Methods

2.1. Study data

The interrogated USGS database contained 1174 records at the time this study began, with the first recorded observation on October 16th 1985 and the most recent record on January 2nd 2010. The records vary in their degree of accuracy and completeness; many only indicate a year of capture or are otherwise missing capture-date altogether. There are cases too where geographic coordinates are missing. Only those records with complete geographic and date information were used for the study, yielding a database of 987 records. Selective treatment of the USGS database delivers a robust regional-scale assay of the lionfish invasion, which has been the basis for several recent studies (Schofield, 2009, 2010; Betancur-R et al., 2011).

In order to establish the possible relationship that salinity, temperature, depth, and current had on the distribution and temporal sequence of the lionfish invasion, values for these parameters had to be calculated for each point in the USGS database. Mean monthly salinity and temperature data were obtained from the World Ocean Atlas 2005 (WOA05) database and then matched to the month recorded in the capture record. Values for water depth were obtained from the ETOPO1 1 Arc-Minute Global Relief Model which combines bathymetry and topography data based on underway hydrographic soundings and satellite altimetry estimates (Amante and Eakins, 2009). Meanwhile, yearly average current data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Ocean Surface Current Analysis – Real Time (OSCAR) database as well as from the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) (Bonjean and Lagerloef, 2002). All of these parameters were assembled for a

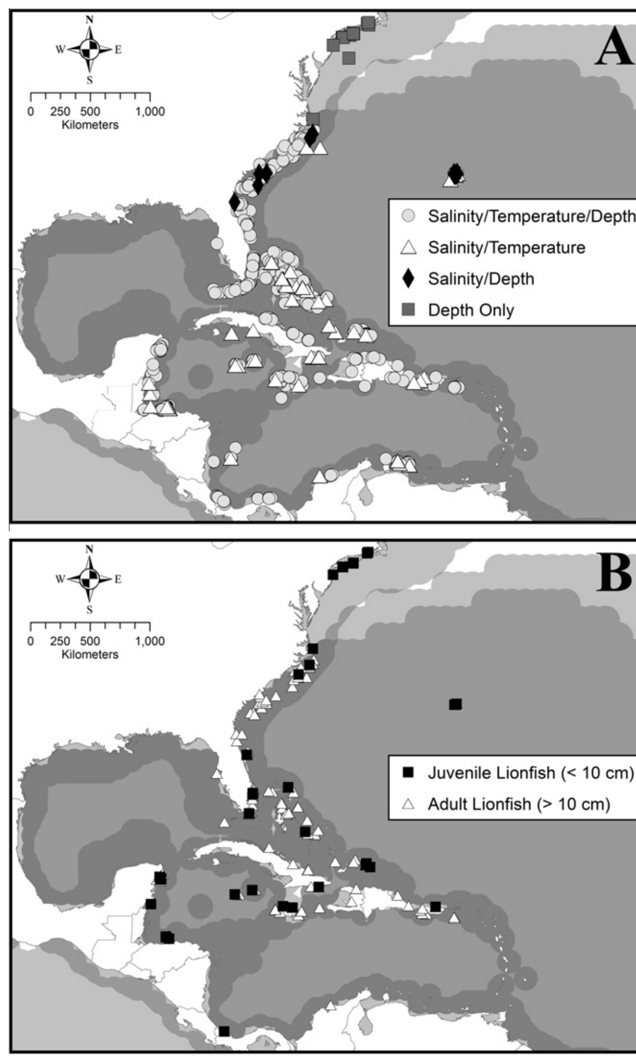

Fig. 1. USGS-NAS Lionfish Capture Location Distribution Maps. Distribution map (A) of 987 lionfish capture record sites from the USGS-NAS database as of 1/2/10. Parameter corridors are represented as darker regions, with the darkest representing areas where temperature, depth, and salinity are all within lionfish tolerances. Records which fall within these different corridors are assigned different shapes. The juvenile verses adult distribution map (B) shows locations of juveniles (squares) and adult (triangles) captures. Only records which included specimen size were included.