Journal of Experimental Marine Biology and Ecology 461 (2014) 233–242

Contents lists available at ScienceDirect

Journal of Experimental Marine Biology and Ecology

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

Estimating the dispersal capacity of the introduced green mussel, *Perna viridis* (Linnaeus, 1758), from field collections and oceanographic modeling

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ARTICLE INFO

Article history:
Received 13 May 2014
Received in revised form 6 August 2014
Accepted 7 August 2014
Available online xxxx

Keywords:
Introduced species
Larval dispersal
Perna viridis
Range expansion

ABSTRACT

Introduced species can often cause negative environmental and economic effects, but also offer opportunities to study the rate of range expansion from localized population centers. The green mussel, *Perna viridis*, was introduced to the waters of the Caribbean and Florida from the Indo-Pacific and remains relatively isolated in portions of northeastern Florida. The present study aimed at identifying the factors that influence the spatial and temporal patterns of green mussel larval settlement throughout the Intracoastal Waterway (ICW) of northeastern Florida, and to estimate dispersal distance using both field observations and a hydrographic model. Green mussel spat were collected from sites within the ICW on a monthly basis for much of 2007, 2008 and 2010 and a particle tracking model was used to predict larval movement during observed settlement periods from 2007. Settlement typically occurred during the summer months and was correlated to water temperature but not salinity or chlorophyll a concentration. Habitat also significantly influenced settlement patterns since most of the settlement occurred within the main channel of the ICW and not in adjacent feeder creeks. Observed settlement patterns suggested that most green mussel larvae likely dispersed 10 km or less but some were collected a minimum of 18 km from a potential source population. Model projections suggested that dispersal distance could often exceed 100 km but most of the particles dispersed along the coast as opposed to remaining within the ICW making comparisons between the model results and the observed settlement patterns difficult.

1. Introduction

Due to the well documented negative effects of many non-native species on the economies and ecology of the areas to which they have been introduced (Pimentel et al., 2000), there is considerable interest in predicting the potential for range expansion and the speed at which expansion is likely to occur. The potential and realized range expansion of introduced species is often determined by first, the ability of the species to move outside its current range, and second, it's ability to survive in the areas to which it disperses (Andow et al., 1990; Grosholz, 1996). The ability of a particular species to do either of these things is going to be determined by a variety of abiotic and biotic factors. For example, in marine invertebrates that have a pelagic larval stage, their ability to expand their range will be determined by their own behavior (or lack thereof) in the larval stage, the prevailing directions of currents (tidal, wind, etc.), the presence or absence of predators, appropriate habitat in which to settle, and the physical environmental conditions of the area in which they settle among other considerations.

Considerable effort has been put into understanding the movement of invertebrates with pelagic larvae using a variety of different tools (reviewed in Levin, 2006). Many studies have utilized spatial population genetic structure to estimate historical dispersal patterns within regions (Hutchinson and Templeton, 1999; Neigel, 2002; Palumbi, 2003; Weersing and Toonen, 2009). Some of the best work has utilized some kind of natural marker, such as polymorphic genetic loci or chemical signatures that can be used to identify the origin of larvae that are settling at a given location (DiBacco and Levin, 2000; Hellberg et al., 2002; Sotka et al., 2004; Gilg et al., 2007). In several cases, these estimates or observations of larval dispersal have been combined with dispersal simulation models in an effort to describe the observed patterns from the prevailing oceanic currents and wind vectors (Gilg and Hilbish, 2003a, 2003b; Galindo et al., 2010; Selkoe et al., 2010).

One of the unique aspects of introduced species is that their relatively localized range during the initial stages of introduction can

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http://dx.doi.org/10.1016/j.jembe.2014.08.004
0022-0981/

also be utilized to estimate larval dispersal. Since the population is typically introduced to a very narrow range, that area can be assumed to be the source for any larvae settling outside that range. For example, McQuaid and Phillips (2000) estimated the effective dispersal range of the introduced blue mussel *Mytilus galloprovincialis* by observing settlement of *M. galloprovincialis* larvae outside of the known adult range. The distance between the source population and the newly settled larvae could be considered the effective dispersal distance in that situation.

The green mussel, *Perna viridis*, is native to the waters of the Indo-Pacific and has been subsequently introduced to a number of locations in the Caribbean and the Southeastern United States (Agard et al., 1992; Rylander et al., 1996; Benson et al., 2001; Ingrao et al., 2001; Buddo et al., 2003; Gilg et al., 2013). It was first discovered in the United States in Tampa Bay on the Gulf coast of Florida in 1999 (Benson et al., 2001). In 2002 and 2003 isolated populations of *P. viridis* had been observed on the Atlantic coast of Florida near St. Augustine and on off-shore reefs near the coast of Georgia (Power et al., 2004; Baker et al., 2007). *P. viridis* populations showed a rapid initial expansion in Tampa Bay and the surrounding area but have since declined substantially in numbers throughout that region, with population declines sometimes associated with low temperatures (Firth et al., 2011; Urian et al., 2011) or susceptibility to red tides (Leverone et al., 2007; May et al., 2010). Along the Atlantic coast, intertidal populations of *P. viridis* have been identified from approximately the Georgia/Florida border south to the Indian River Lagoon (Spinuzzi et al., 2013). Within that area, however, populations tend to be very isolated due to a number of factors, including lack of hard substrates for settlement, reduced reproductive success due to low population density (allee effects), and mortality events associated with cold winter temperatures. Therefore, nearly all of the mussels are found near inlets where jetties and bridges provide more hard substrates.

Within the Intracoastal Waterway (ICW) of northeastern Florida, for instance, several hundred green mussels could be found in the intertidal zone on rock structures in three specific locations at the St. Augustine inlet. Another population of several hundred individuals could be found on floating docks and a rock jetty at the Matanzas inlet. Surveys of the ICW between these sites and further north of St. Augustine by the authors and the staff of the Guana Tolomato Matanzas National Estuarine Research Reserve (GTM NERR) between 2005 and 2009 found very few specimens at locations outside the two specified inlets (unpublished data). So even though the mussels have been present in the area since 2002, little expansion has occurred away from the inlets in that time. While a few mussels can be found at locations away from inlets, they rarely exist in groups that are close enough in space to successfully reproduce, and they are often ephemeral (most likely due to significant winter mortality events every 2–3 years). Outside the ICW, the closest population of mussels is in the waters at the mouth of the St. Johns River approximately 60 km to the North of St. Augustine Inlet with a second population on the Florida/Georgia border on Amelia Island.

Therefore, the purpose of the present study was to determine the factors that influence dispersal and settlement of introduced *P. viridis* populations in the ICW of northeastern Florida, and to utilize their isolated range to estimate the dispersal potential of *P. viridis* larvae. This estimation included both the approximate distance of dispersal as well as the amount of settlement within different habitats, and the influence of various environmental factors on the timing of observed settlement. Furthermore, we attempted to determine whether the observed settlement patterns corresponded to predictions based on a model of the local physical oceanography (CH3D — Sheng, 1986). By understanding the factors that govern spawning and the movement and subsequent settlement of *P. viridis* larvae we can better predict locations that are susceptible to future range expansion.

2. Methods

2.1. Spat collections

Recently settled green mussel larvae, or spat, were collected from several locations in the waters of the Northeast Florida ICW and adjacent feeder creeks in 2007, 2008 and 2010. At each location, a spat collector consisting of a frame made of PVC that held four 12 cm × 12 cm quarry tiles were deployed for one month, after which the quarry tiles would be collected and replaced with clean tiles. These frames were either strapped onto channel markers or other large posts within the ICW, or in cases where such structures could not be found, were suspended underneath buoys that had been anchored to the bottom. In all cases, the tiles were placed such that they were 1–3 m below the low tide mark. After collection, fouled tiles were allowed to dry in the sun for at least two weeks before being analyzed. The surface of tiles was observed under a dissecting microscope at 20× magnification to look for the presence of *P. viridis* spat. Any spat found were measured using an optical micrometer and the total number and sizes found on each tile were recorded.

In the first year of the study, spat collectors were deployed at seven sites within the main channel of the ICW at varying distances from known source populations of *P. viridis* near St. Augustine and Matanzas inlets. These sites included channel markers 25, 51, 1, 46, and 77, as well as the Conch House Marina (CH), and a dock at the Whitney Laboratory (WL) (Fig. 1). An additional collector was placed in each of four feeder creeks of the ICW including Casacola Creek (CC), Oyster Creek (OC), Moses Creek (MC), and Pellicer Creek (PC). The collectors in each of the feeder creeks were essentially paired with a collector in the main channel of the ICW that was at a similar distance from either of the two inlets. This allowed us to compare settlement density in the two different habitats (feeder creek vs. main channel) while controlling for distance from source. Monthly collections were made from July through December in year one.

In years two and three of the study, collectors were only deployed within the main channel of the ICW at the same sites as in year one, except for the addition of channel marker 55 near the mouth of St. Augustine inlet, and a sign post near Fort Matanzas (FM) near the Matanzas inlet. Collections were made from January through November in 2008, but only from April through October in 2010 since no settlement had been observed in previous years outside of that time period (see below).

Sites 25, 1, FM and PC all have permanent data sondes maintained by the GTM NERR and, therefore, allow us to obtain environmental data including temperature and salinity which are collected at 15 minute intervals, and chlorophyll a which is sampled twice on the same day (diel sampling) on one day each month.

Settlement density in each month at each location was recorded as the number of *P. viridis* spat per plate. Since settlement density consistently had unequal variances and did not conform to a normal distribution, all comparisons among means utilized non-parametric tests. A Mann–Whitney U test was used to compare settlement density between feeder creeks and the main channel sites located at similar distances from the inlets to determine if habitat differences were associated with differences in settlement density. The mean number of spat per plate collected over all sampling events in 2007 were included in the analysis. Since settlement was extremely limited within feeder creeks (see below), all other analyses of spatial and temporal settlement patterns were confined to sites within the main channel of the ICW. Kruskal–Wallis tests were used to test for temporal and spatial variation in settlement density within the same habitat. We used Pearson Correlations to determine if settlement density was correlated with distance from the nearest inlet, with mean monthly temperature, salinity or chlorophyll a concentration. All statistical tests were performed using SPSS software and distances between locations were estimated using GoogleEarth.