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Population dynamics of *Corbicula fluminea* (Müller, 1774) in mesohaline and oligohaline habitats: Invasion success in a Southern Europe estuary

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ABSTRACT

Due to its range expansion and potential ecological effects, *Corbicula fluminea* is considered one of the most important non-indigenous species (NIS) in aquatic ecosystems. Its presence since 2003 in the upstream area of Mondego estuary (oligohaline and mesohaline sectors) was studied during thirteen months, from December 2007 to December 2008. Monthly mean abundance and biomass ranged from 542 to 11142 individuals m^{-2} and 13.1–20.4 g Ash Free Dry Weight m^{-2}, respectively. Populations of *C. fluminea* were composed mostly of juveniles, always present in extremely high densities compared to other estuarine ecosystems (e.g. Minho estuary) suggesting a continuous recruitment pattern. The hydraulic regime of the River Mondego favours the downstream colonization of the upper Mondego estuary by recruits produced upstream. However, salinity in these sectors of the estuary apparently neither favours growth nor the establishment of structured populations of this species. Other factors like contaminants and predation, which were not studied, could also contribute to the community structure observed.

1. Introduction

The Asian clam, *Corbicula fluminea*, is an invasive freshwater bivalve mollusc native to Southeast Asia that has had large ecological and economic impacts in many aquatic ecosystems (reviewed in Karatayev et al., 2005a; McMahon, 2000). The *Corbicula* genus was confined to its native distribution in Asia, Africa and Australia in the beginning of the last century but has now spread sufficiently to be considered one of the most important non-indigenous species (NIS). In recent decades, studies of *C. fluminea* have indicated considerable geographic dispersion and invasive behaviour in its indigenous environment which also aid their successful invasion of new territories (Mouthon, 1981; Cataldo and Botolvskoy, 1999; McMahon, 2002).

The first record of inter-continental *Corbicula fluiminea* invasion was in the United States of America in the 1920s (Counts, 1986). It was then recorded in Argentina around 1960–1970, (Ituarte, 1981, 1994). In the early 1980s, the discovery of *C. fluminea* in the estuaries of the rivers Tagus (Portugal) and Dordogne (France) was the first evidence of its invasion into Western Europe. This invasion timeline has led Mouthon (1981) to suggest that continued introductions are likely to lead to a transhemispheric or worldwide distribution of *C. fluminea*.

The rapid spread of *Corbicula fluminea* has involved human vectors, including dispersal due to curiosity and transport by tourists, use as fish bait, transport in dredged river sand or gravel, and use by aquarium hobbyists (Mouthon, 1981; Cataldo and Botolvskoy, 1999; McMahon, 2000). *Corbicula fluminea* also has extensive natural dispersal capacities. Their transport downstream is aided by their ability to attach to floating objects with byssal threads as juveniles, to be transported as pediveligers and juveniles as bedload, to be transported within the water column as individuals suspended on mucous drag lines (Prezant and Chalermwat, 1984), and to be passively transported between water bodies on the feet or feathers of aquatic birds (Darrigran, 2002; McMahon, 2002).

It has been hypothesized that tolerance to a wide range of physical conditions allows invasive species to colonize a variety of habitats. However, there is evidence that the ability of *Corbicula fluminea* to withstand physiological stressors is generally less than that of other freshwater bivalve species (McMahon, 2002). In fact, *C. fluminea* are not tolerant of hypoxia, temperature extremes and emersion (McMahon, 1991). *Corbicula fluminea* is an unusual freshwater bivalve in that it can tolerate salinities of 10–14, a sign of their relatively high capacity for osmotic regulation and their physiological link to an estuarine ancestor (McMahon, 1983, 1991; Morton and Tong, 1985). Nevertheless, the invasive success of the Asian clam relies more on its life history characteristics than on its physiological tolerance. Morton (1997) suggests that *C. fluminea* has

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several characteristics that an invasive species should have to be successful in a new environment: a short life span (e.g. 2–3 years), rapid individual growth, rapid sexual maturity, high fecundity, the ability to colonize a wide range of habitat types, some form of association with human activities (e.g. as food sources; inhabitants of estuaries, harbours, etc. where humans reside), wide genetic variability, and phenotypic plasticity (resulting from habitat influences). Its ability to repopulate previously colonized habitats following massive population crashes caused by extreme physical conditions is surely indicative of a species adapted to unstable habitats (i.e., *r-selected species*). Such species have experienced selective pressure to evolve and adapt traits that are necessary to survive unstable habitats and they can be very successful as invaders regardless their capacity to tolerate environmental stress (McMahon, 2002).

The success of *Corbicula fluminea* in American and European ecosystems and the effects of these *C. fluminea* populations on some invaded ecosystems have been very significant. For example, ecosystem effects have included alterations in organic matter cycling in the sediment (Hakenkamp and Palmer, 1999) and cascading system-level changes due to a decrease of turbidity from *C. fluminea* filtration that resulted in beds of submerged aquatic vegetation (Phelps, 1994). As ecologists have become aware of the potential effect of *C. fluminea* on ecosystems there is significant interest in understanding its spread in Europe and South America. However, predicting the invasion trajectory and success of NIS has had limited success and doing so with *C. fluminea* is no exception despite the extensive literature that has been produced on the species (Counts, 2006). With its continuing worldwide spread, we have an opportunity to learn more about its invasion traits and possible environmental limits on its spread. Three estuaries in Portugal give us a unique opportunity to examine its success in three hydrologically similar systems; it was discovered 20 + years ago (1989) in the Minho River, and 10 years ago (2002) in the Lima River and in the Mondego River (2001). The Minho estuary was greatly altered by *C. fluminea* where it dominates the abundance, biomass and secondary production of the benthic community. Its dominance has altered the trophic structure of the system and the spatial distribution of the native bivalve, *Pisidium amnicum*, (Sousa et al., 2008b, 2008c). The appearance of *C. fluminea* in the Lima Estuary, in 2002, did not result in similar large changes to the ecosystem. Sousa et al. (2006) suggests that *C. fluminea* in the Lima estuary may be in a lag phase, waiting for environmental conditions to become more favourable at which time it will resemble the populations in the Minho estuary. Lag patterns are common with invasive species (Crooks, 2005) and can be due to several environmental and ecological factors such as improving or declining environmental conditions or the lag inherently present in a species that has an exponential growth pattern. Ferreira et al. (2004) first recorded the presence of the Asian clam in the River Mondego in 2001 and Vinagre (pers. comm.) observed it in the estuary in 2003. Therefore the Mondego estuary *C. fluminea* populations have a similar timeline as the populations in the Lima estuary and if relative time since invasion is significant in the lag effect, we might expect the *C. fluminea* population to be similar in these two environmentally-stressed estuaries. We hypothesize that the invasion state of *C. fluminea* in the Mondego estuary will be similar to that in the Lima estuary. If true, the invasion will be in an early stage and will display characteristics of a lagged invasion with the population not achieving its full potential, i.e. as in populations in the Minho estuary. Hence this study is needed in understanding the possible expansion of *C. Fluminea* in the Mondego estuary and similar ecosystems and that it will support management measures for the mitigation of the impacts caused by this invasive species (Sousa et al., 2006).

The goals of this study were a) to investigate the population dynamics (abundance, biomass and population structure) of *Corbicula fluminea* as an intrusive species in the mesohaline and oligohaline sectors of the Mondego estuary; b) to evaluate the effects of several environmental variables on *C. fluminea* populations, and c) compare these data with those reported in the Minho and Lima estuaries.

2. Materials and methods

2.1. Study area

The Mondego estuary (40°08′N, 8°50′W) is located in a warm temperate region on the western coast of Portugal, and extends 21 km inland. At about 7 km from the coast it splits in two arms, North and South (Fig. 1). The two arms are separated by an island (Murraceira Island), and join again near the mouth (Marques et al., 2003). The North arm is deeper (5–10 m during high tide, with a tidal range of 2–3 m) and as the main navigation channel, supporting the harbour and the city of Figueira da Foz, is constantly dredged. In addition to the harbour facility, the estuary supports industrial activities, salt-works and aquaculture farms. Higher current velocity together with greater tidal penetration of sea water leads to larger salinity changes in the lower part of the North arm than in the South Arm. The bottom sediments are predominantly medium to coarse sand in the North Arm. The margins of the North arm are artificially armoured with stones resulting from the re-routing of the Mondego River to facilitate the diversion and transport of water used by agriculture in the valley and to limit damage from flood events. The sampling area, located in the North arm of the Mondego estuary (upper part - last 7 km) has more freshwater influence than the down-bay part of the arm due to the lower intrusion of sea water, even during the high tide, and is composed only of subtidal areas (Marques et al., 1993; Martins et al., 2001; Martinho et al., 2007; Neto et al., 2008).

The soft-bottom subtidal communities of the Mondego estuary have been regularly monitored since the winter of 2003 with a network of 25 sampling stations covering the entire estuary (Fig. 1). Based on these monitoring data, Teixeira et al. (2007) proposed dividing the estuary into five reaches based on salinity and sediment characteristics in order to distinguish different habitats for benthos to settle.

Based on *Corbicula fluminea* abundance from previous studies (Teixeira et al., 2007 and Vinagre, unpublished data), three sampling stations were selected in the upper estuarine sector: ST 19, located in the mesohaline reach (mean bottom salinity 14); and ST 21 and ST 24, located in the oligohaline reach (mean bottom salinity 1.7) of the estuary (Fig. 1).

2.2. Sampling and laboratory procedures

Benthic samples were collected monthly from December 2007 to December 2008, during high tide. Four samples (three for biological analysis and one for sediment analysis) were collected at each station using a hand operated van Veen grab with an area of 0.08 m^2. The benthic samples were sieved through a 0.5 mm mesh-size bag and were preserved in 4% neutralized formalin. In the laboratory, samples were sieved through a 0.5 mm mesh sieve and *Corbicula fluminea* specimens were separated, sorted and preserved in 70% ethanol for further processing. All *C. fluminea* were passed through a column of five sieves with a mesh size increment of 1.0 mm between each sieve (0–5.0 mm), except for the first size class where the increment was 0.5 mm (0.5 to 1 mm), in order to divide individuals' into the first five size classes.

Clams were then counted and the maximum shell lengths (SL) was measured to the nearest 0.1 mm with an eye piece micrometre