THE SPREAD OF AN ALIEN BIVALVE (MUSCULISTA SENHOUSIA) IN THE SACCA DI GORO LAGOON (ADRIATIC SEA, ITALY)

M. MISTRI, R. ROSSI AND E. A. FANO

Department of Biology, University of Ferrara, via L. Borsari 46, I-44100 Ferrara, Italy
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ABSTRACT

The Asian date mussel, Musculista senhousia (Mytilidae), which is endemic in the western Pacific, appeared and became abundant in the Sacca di Goro, a brackish lagoon in the Po River Delta (northern Adriatic Sea, Italy) in the early 1990s. The course of the invasion was documented through a macrobenthic monitoring programme at three sites in the Sacca. From 1994, when the new mussel was first collected, M. senhousia spread throughout the lagoon and, within a few years, reached densities exceeding 10,000 individuals m\(^{-2}\). Mussel effects on biodiversity were assessed by comparing macrobenthic community structure and composition; over a 5-year period some changes in the macrobenthic community seem to be apparent, suggesting a positive effect of the mussel on the number of species and benthic richness. Considering trophic guilds, significant positive correlations were found between M. senhousia and detritivores and herbivores, while suspension feeders probably suffered competition from the mussel. Musculista senhousia was initially successful because it exploited a naturally disturbed, sparsely occupied environment. The well-dated documentation of the first collections, increasing abundance and spread of M. senhousia at our study sites provided an opportunity to observe a biological invasion of a habitat in progress.

INTRODUCTION

The invasion of non-indigenous species is altering the composition of biotic communities worldwide. (Vitousek, 1990). One species capable of both interspecific effects and habitat-alteration is the Asian date mussel, Musculista senhousia (Benson in Cantor, 1842). The date mussel is an outstanding example of a species that has dispersed outwards from its native area through human-mediated transport, establishing sustaining populations in distant parts of the world. Endemic to the Asian continent, the date mussel was introduced to northwestern America in the 1920s (Dexter, 1983), and to Australia and New Zealand in the 1980s (Willan, 1987). Around the Mediterranean Sea, a few beached shells were found in Tel Aviv in 1964, and in Bardawil Lagoon in 1969; these Israeli and Egyptian records, if not accidentally transported, are thought to be lessesian migrants of the Red Sea species locally called Modiola (Arenulina) arenulina (Hanley, 1844) (Barash & Danin, 1972). In the western Mediterranean, M. senhousia was first discovered in the late 1980s in several lagoons of the Marseille area (Etang de Tau, Balaruc les Bains, Languedoc-Roussillon, Etang d’Or) (Hoenselaar & Hoenselaar, 1989), at the beginning of the 1990s on the northern Adriatic coasts (Lazzari & Rinaldi, 1994), in the late 1990s in the Gulf of Olbia (Sardinia, northwestern Tyrrhenian Sea) (Savarino & Turolla, 2000), and in 2001 in Mar Piccolo of Taranto (Apulian Peninsula, Ionian Sea) (Mastrototaro, Matarrese & D’Onghia, 2003).

Estuaries and brackish water environments are common sites of biotic invasions (Ruiz et al., 1997). We report here the establishment of M. senhousia in a northern Adriatic lagoon (Sacca di Goro), and its increase in numbers and spread between 1994 and 1998. The Sacca is a microtidal, coastal lagoon located in the southernmost Po Delta area. It has a surface area of ~26 km\(^2\), an average depth of ~1.5 m, and receives nutrient-rich fresh water primarily from two deltaic branches of the Po River. In the last years, many non-indigenous organisms have been detected in the Sacca (Turolla, 1999). Most of these species have the potential to proliferate and spread, and some of them have grown to large populations (Mistri, Rossi & Ceccherelli, 1988). Analyses of species invasions (Carlton et al., 1990) suggest that, while the success of any given species introduction is not very predictable, the important factors to be considered are the availability of a suitable habitat, the characteristics of that species, and the nature of the community present in the invaded area. Our early detection of the invasion of the Sacca di Goro by M. senhousia allows us to discuss these factors.

MATERIAL AND METHODS

Three sampling sites (A, B and C) were chosen along a NW–SE transect, reflecting a gradient of confinement. Site A (44°50.112’N, 12°17.422’E) was located in the northernmost, quite confined area of the Sacca; site B (44°49.617’N, 12°18.478’E) was located in the central area of the lagoon, and site C (44°49.094’N, 12°19.960’E) was positioned in the easternmost part of the lagoon. At the three sites seasonal proliferation of fast-growing macroalgal beds occur. A monitoring programme on these sites was interrupted (other studies on the date mussel have recently been carried out, but in different areas of the Sacca, e.g. Mistri, 2002).

Macroalgal beds (mostly Gracilaria verrucosa and Ulva rigida, together with Cladophora liniformis), whenever present, were sampled between December 1992 and December 1998, and considered both macroalgal beds and the macrofauna associated with sediments. From the latter date, the monitoring programme on these sites was interrupted (other studies on the date mussel have recently been carried out, but in different areas of the Sacca, e.g. Mistri, 2002).

Correspondence: M. Mistri; e-mail: m.mistri@unife.it

0.5-mm sieve. The material retained on the sieve was fixed in 8% buffered formalin, and stained with rose bengal to facilitate sorting and identification. The abundance of individuals of each taxon, identified to species level when possible, was measured for each sample. Macrobenthos was also classified into different feeding groups, identifying guilds such as detritivores (surface-deposit feeders, subsurface-deposit feeders and suspension feeders), herbivores and carnivores.

Benthic macroinvertebrate community structure was described at each site at each sampling date on the basis of the following parameters: abundance (N), number of taxa (S), richness (as Margalef’s d), diversity (as Shannon-Wiener’s H), and evenness (as Pielou’s J). Differences in univariate indices were tested using two-way ANOVA with sites and years as fixed factors and, whenever Levene’s tests indicated significant heterogeneity of variances, the data were log-transformed. Factors detected to be significant by ANOVA were further analysed using the a posteriori Tukey HSD test. The effect of *M. senhousia* on benthic community structure was tested by means of Spearman rank-correlation analysis, after recalculation of the univariate indices excluding the Asian date mussel whenever present. Rank-correlation analysis was also used to examine relationships among feeding guilds and mussel occurrence (obviously after exclusion of *M. senhousia* from the guild of suspension feeders), and significance assessed by *t*-tests.

**RESULTS**

The initial distribution and increasing abundances of *Musculista senhousia* over the total associated fauna to macroalgal beds from 1992 to 1998 are shown in Figure 1. The first specimens of Asian date mussel in the Sacca di Goro were collected in April 1994 at site A (2.5 ind. m–2 ± 4.3 SD), in January 1995 at site B (0.8 ind. m–2 ± 1.3 SD), and in July 1995 at site C (0.4 ind m–2 ± 1.0 SD). Earlier collections (from December 1992 onwards) contained no *M. senhousia*, thus it would appear unlikely that the mussel was abundant in the lagoon prior to 1994. From 1997 onwards, date mussels constituted the most abundant animal taxon associated with macroalgal mats, with densities sometimes exceeding 6,000 ind. m–2, e.g. March 1997 at site B (6940 ind. m–2 ± 3,857.9 SD), and December 1998, at site A (7646.5 ind. m–2 ± 10,516 SD).

From the benthic samples, the first *M. senhousia* specimens were collected in December 1994 at site B (3 ind. m–2 ± 2.5 SD), in January 1995 at site A (5.6 ind. m–2 ± 7.1 SD), and in May 1995 at site C (25.3 ind. m–2 ± 20.8 SD). By autumn 1995 the species was well established in the Sacca. The time course of *M. senhousia* (Fig. 2) shows a rapid abundance increase at site C in 1995–96, followed by the other two sites in 1996–97. As might be expected following such large settlements (e.g. February 1998 at site C: 12,452.6 ind. m–2 ± 10,053.8 SD), densities fell off dramatically with population ageing during the remainder of each year. Mismatching abundance patterns at the three sites further suggest a complex picture of patchy recruitment in space and time. Since 1996–97 *M. senhousia* has been the most abundant benthic macrofaunal organism in the Sacca, generally occurring in greater numbers than those of any other species (Fig. 2).

Table 1 reports ANOVA significance for log-transformed community attributes through the period 1995–1998. Sites dif-

**Figure 1.** Mean abundance (individuals m–2) of total macrofauna (black diamonds) and *Musculista senhousia* (white squares) associated with macroalgal mats at the three study sites, from December 1992 to December 1998.

**Figure 2.** Mean abundance (individuals m–2) of total macrofauna and *Musculista senhousia* (symbols as in Fig. 1) from bottom samples at the three study sites, from January 1994 to December 1998.
ferred in species number (Tukey HSD test: A vs B and A vs C, both \( P < 0.05 \)), abundance (C vs A and C vs B, both \( P < 0.01 \)), richness and evenness (A vs B, \( P < 0.01 \)), and diversity (A vs B and A vs C, \( P < 0.001 \) and \( P < 0.05 \), respectively) while, among years, differences were evident in number of species (95–96 vs 97–98, \( P < 0.05 \)) and richness (95–96 vs 97–98, \( P < 0.05 \)). The abundance of \( M. \) senhousia correlated positively with macrofaunal abundance at Site C (\( r = 0.62, P < 0.001 \)), but negatively with number of species (\( r = -0.38, P < 0.01 \)), richness (\( r = -0.39, P < 0.01 \)), and diversity (\( r = -0.29, P < 0.05 \)) at Site B.

Table 2 reports Spearman’s rank correlations and their significance through tests between abundances of \( M. \) senhousia and trophic guilds (SSDF: subsurface-deposit feeders; SDF: surface-deposit feeders; SF: suspension feeders; HER: herbivores; PR: predators). Significant positive correlations were found between date mussels and SDF at Site A and C, and with HER at Site C. Conversely, negative correlations were found with SF at Site B, and PR at both Sites B and C.

**DISCUSSION**

The absence of \( M. \) senhousia from intermediate localities between Mediterranean areas where the species was first detected and the northern Adriatic Sea, preclude its natural transport to the Po River deltalc lagoons. While in Australia and New Zealand the dramatic increase of Asian date mussel populations are presumed to be due to transfer in the ballast water of ships (Willan, 1987). The initial invasion of the West coast of America is attributed to a transport with oysters imported from Japan (Kincaid, 1947). In the Mediterranean too, the invasion of the Asian date mussel appears to have been strictly linked to shellfish farming and trading. Mussel populations inhabiting French lagoons have probably been introduced with oysters from Japan (Hoenesaar & Hoenesaar, 1989), and mollusc farms have served as gateways into Mediterranean coastal waters. So, we hypothesize that, through a leapfrog effect of further human transfer, \( M. \) senhousia in the Sacca di Goro has possibly been introduced with oysters or clams from French cultivation. Finally, Sardinian and Apulian mussel populations have possibly been introduced with cultured mussels (*Mytilus galloprovincialis* Lamarck, 1819), which are imported from the northern Adriatic. The sudden arrival of the Asian date mussel in the Sacca di Goro (but also its spread in other distant areas which all support mollusc cultures) appears to be related to such an extensive shellfish trading activity. Many other cases of unintentional introductions of pathogens, parasites and pest species, resulting from unrestricted transport of commercially important alien bivalves, are known for the Mediterranean Sea (Galil, 2000).

In the Sacca di Goro, we collected the first specimens of *M. senhousia* in 1994, but the date of introduction may be difficult to establish with certainty. It is possible that the mussel was introduced at a considerably earlier date, and underwent an initially slow population expansion as it established reproducing populations, since many alien species appear to have long lag times between initial introduction and subsequent population explosions (Crooks & Soulé, 1999). Biological surveys of the region have been carried out over many years, with intensive benthic sampling surveys in the Valli di Comacchio in 1974 (Colombo, Cecherelli & Gaiani, 1977), in the Sacca di Goro in 1982–84 (Franzoi et al., 1986) and 1989–90 (Cecherelli et al., 1994), in the Sacca di Scardovari in 1976 (Cecherelli et al., 1985) and 1989 (Mistri, Cecherelli & Rossi, 2000a), and in the Sacca del Canarin in 1984–85 (R. Rossi, unpublished data); individuals of uncommon species were sometimes collected during these surveys, but never Asian date mussels. There is anecdotal evidence that shellfish farmers occasionally began to find uncommon, small greenish mussels since 1993, which we presume to have been *M. senhousia*. In the Sacca di Goro, the colonization process and population spread of the date mussel seemed to have different dynamics from that exhibited in another well-studied area (Mission Bay, San Diego, CA, USA) where the mussel appeared in the mid-1960s, but it was not until the early 1980s that *M. senhousia* could be found commonly in high-density patches (Crooks & Soulé, 1999). In the Sacca, the population spread of the date mussel was explosive and only a few years after its first discovery, it carpeted thousands of square meters of the lagoon’s subtidal. An important role in determining the patchy
distribution of *Musculista senhousia* was probably also played by macroalgal mats. In the Sacca, the Asian date mussel spawns from the end of summer to late autumn (Sgro et al., 2002); later juveniles will settle onto the bottom during winter. Yet, when pleustophytic macroalgae start their growing season (Viaroli, Pugnetti & Ferrari, 1992), spat and dispersing post-larvae may actively recruit where macroalgal mats are developing because of the altered physical environment. At relatively low biomass, it is known that stands of macroalgae may facilitate the recruitment of fauna through the entrainment of larvae (Raffaelli, Raven & Poole, 1998). Then, the settled mussels may undergo a secondary redistribution throughout the Sacca by ‘rafting’ on the drifting macroalgae, in response to hydrodynamic conditions.

The successful colonization of the lagoon by *Musculista senhousia* suggests that a number of trophic-level effects (direct or indirect interactions with other guilds), and benthiec dynamic effects (differential inhibition/enhancement of infauna/epifauna due to substrate alteration) should take place. By removing a huge volume of suspended organic material from the water column, *Musculista senhousia* deposits that filtered material on the bottom as faeces and pseudofaeces and thus alters the nature of the sediment (Creese et al., 1997). Mussels may modify the nutritional quality of sediments (Mistri, Modugno & Rossi, 2003), have the potential to affect the resident fauna (Crooks, 2001), and render the environment within or under mats unsuitable to adults of other species and/or larval recruitment, through diminishing the depth of the redox potential discontinuity layer, suppressing growth and affecting survival (Morton, 1974; Creese et al., 1997; Crooks, 1998). In the Sacca di Goro, from the community point of view, and over a short-term period (1995–98), some differences seemed evident between community descriptors through time (number of taxa and richness), suggesting a positive effect of mussels on at least a part of the benthic community. We speculate that this may be due to the fact that *Musculista senhousia* creates novel three-dimensional epi-surface structures that can provide increased habitat heterogeneity on an otherwise soft bottom, including hard-surface areas and crevices, holes or cracks for the colonization of sessile and vagile species. These species are likely responding to a variety of proximate factors that result from the modification of the habitat, including a refuge from predation, an amelioration of environmental factors (desiccation and temperature), and an increase in food supplies for detritivores. De Montaudouin, Audemard & Labourg (1999) came to a similar conclusion when studying the effects of the common slipper limpets [*Crepidula fornicata* (Linnaeus, 1758)] on macrobenthic assemblages. In the Sacca, differences in macrobenthic community structure were also detected among sites, but these probably reflected the gradient from the back to the front of the lagoon due to different hydrodynamic conditions at the three sites. From a trophic-dynamic point of view, on the other hand, a negative relationship was detected between mussel and the abundance of other suspension-feeders, suggesting strong competitive relationships within the guild. Because *Musculista senhousia* is a densely living suspension feeder, its filtration of near-bottom water may locally deplete food supplies (Reusch & Williams, 1990) and, as recently observed in Mission Bay by Crooks (2001), strongly affects other suspension-feeding bivalves. Furthermore, suspension-feeder mussels could destroy the larvae of potential recolonizing organisms.

The characteristics of benthic communities in the Sacca di Goro prior to the arrival of *Musculista senhousia* were summarized by Franzoi et al. (1986). In the 1980s, annual patterns in benthic community structure in the Sacca were mostly coupled with limited water circulation and the pattern of development of macroalgal mats (mostly *Ulva rigida*). Macrobenthic communities were commonly subjected to harsh summer dystrophic and anoxic crises (e.g. dissolved oxygen concentration: July 1989, 0.0 mg l⁻¹; July 1990, 0.4 mg l⁻¹; Colombo et al., 1994). At the beginning of the 1990s, to increase seawater inflow the southern sandbank, which spatially enclosed the Sacca, was artificially cut. So when *Musculista senhousia* was introduced, the Sacca di Goro was mostly inhabited by a depauperate benthic community. Depauperate biota and extreme natural disturbance events are factors known to facilitate non-indigenous species establishment in new habitats (Cohen & Carlton, 1998). We suggest that the Asian date mussel was initially successful because it exploited a naturally disturbed, sparsely occupied environment.

The dominance of *Musculista senhousia* in the macrobenthic community was not limited to these study sites. In fact, the Asian date mussel has recently spread to most other areas of the Po River delta, such as Valle Fattibello (Mistri et al., 2000b) and Valle Lido di Magnavacca (Munari et al., 2003), two enclosed lagoons; Sacca di Scardovari (E. Turolla, personal communication), an open lagoon: Logonovo Channel (G. Caramori, personal communication), a tidal creek; and Lido degli Scachi (M. Mistri, personal observation), a truly marine site. Ongoing field sampling in some of these areas will allow us to evaluate better how successful the mussel is at colonizing other habitats, and its role in pre-established benthic communities.

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