Rapid Communication

The arrival of the invasive tubeworm *Ficopomatus enigmaticus* (Fauvel, 1923) (Annelida: Serpulidae) to the Azores, possibly via migratory birds

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Abstract

The non-indigenous polychaete *Ficopomatus enigmaticus*, also known as the Australian tube worm, was recorded from Paul da Praia da Vitória (Praia da Vitória Marsh), Terceira island (Azores) in July 2016. This is the first record of this species on the Atlantic islands of the Macaronesia biogeographical region. At present, *F. enigmaticus* is exclusively in the lagoon of Paul da Praia where it is established and exhibits invasive behaviour. To explain the arrival of *F. enigmaticus* in this wetland system, which is not directly connected to the sea, we hypothesize natural mediated dispersal through migratory bird phoresy. This vector is crucial to consider in terms of risk assessments as this species spreads to other ecologically fragile areas. Potential impacts of *F. enigmaticus* on these sensitive and rare systems in the region are discussed.

Key words: biogenic reefs, bird phoresy, invasive polychaete, salt marsh

Introduction

Ficopomatus enigmaticus (Fauvel, 1923), also known as the Australian tubeworm, is a gregarious, reef-building serpulid polychaete worm that builds and inhabits whitish calcareous tubes. The cylindrical tubes, up to about 10 cm long and 2 mm in diameter, exhibit characteristic, irregularly spaced rings (peristomes) that are persisting remnants of the flared aperture after each growth episode. *Ficopomatus enigmaticus* is a member of a distinct clade of serpulids (*Ficopomatus*) that has adapted to brackish water (see Ten Hove and Weerdenburg 1978). Under favourable conditions of protected areas with weak currents and high turbidity, *F. enigmaticus* is capable of massive growth (Goulletquer 2016). Reef-like structures down to 3 m deep, formed mainly in meso- (8–18) to hyperhaline (> 40) conditions (Dittmann et al. 2009), can cover tens of m^2, with a layer more than 1 m thick (Bianchi and Morri 1996; Fornós et al. 1997). Reproduction occurs at temperatures higher than 18 °C (Dittmann et al. 2009). In the Mediterranean Sea, it may attain an annual production in dry weight of almost 21 $kg.m^{-2}.yr^{-1}$

(Fornós et al. 1997) and a density of 150,000 ind.m^{-2} (Bianchi and Morri 2001). *Ficopomatus enigmaticus* feeds on zooplankton, phytoplankton, and detritus particles that it filters from the water, transporting them to their mouths by the cilia on their radioles.

Ficopomatus enigmaticus may be a habitat engineer that can modify habitats, water conditions and physical environments resulting in changes to native communities (Katsanevakis et al. 2014). This worm affects overall estuarine primary production and relative availability of planktonic and benthic carbon sources to higher trophic levels (Bruschetti et al. 2008). By considerably altering the physical structure of benthic habitats (Fornós et al. 1997), *F. enigmaticus* directly or indirectly affects benthic communities by providing a suitable new habitat for other species that seek shelter within the worm reefs (Goulletquer 2016).

Being a suspension feeder, *F. enigmaticus* can substantially contribute to water purification by increased biofiltration, through removal of suspended particulate matter and subsequent deposit onto the sediment as faeces and as particles captured but not consumed (e.g. Davies et al. 1989). Such increased sedimentation, although reducing environmental turbidity and thus improving oxygen and nutrient status, can also represent a significant loss of energy and nutrients from the water column and decrease pelagic production (Vanni 2002). The enormous agglomerates of individuals have caused problems by clogging the intake pipes of industrial and power plants, fouling equipment in aquaculture facilities, and also fouling surfaces in ports and docks, floating structures, hulls and propellers, requiring frequent maintenance and cleaning (Goulletquer 2016).

The native range of *F. enigmaticus* is not clear, but it probably originated in the Southern Hemisphere, from the Indian Ocean and the coastal waters of Australia (e.g. Dittmann et al. 2009; Goulletquer 2016; Styan et al. 2017). Recent molecular studies demonstrated that *F. enigmaticus* is a species complex and doubts remain on whether the *F. enigmaticus sensu lato* group has an Australian origin and how Australian populations are related to invasive populations of this species elsewhere (Styan et al. 2017). This species complex displays a disjunctive distribution in both hemispheres, including sites in North and South America, Japan, southern Australia and South Africa (Dittmann et al. 2009). In European waters *F. enigmaticus* is known from the Netherlands (e.g. Wolff 2005) southwards to Portugal, where it was reported in the lagoons of Santo André (Fonseca 1989) and Albufeira (Freitas et al. 1994). It also occurs in the Mediterranean (Bianchi and Morri 1996), the Sea of Marmara, the Black Sea and the Caspian Sea (Read and Gordon 1991; Çinar 2013; Çinar et al. 2014).

Here we formally record for the first time the presence of the invasive serpulid worm *F. enigmaticus* in Macaronesia, discuss its probable introduction vectors to Paul da Praia da Vitória, and discuss the possible impacts on the local biodiversity resulting from its eventual dispersion.

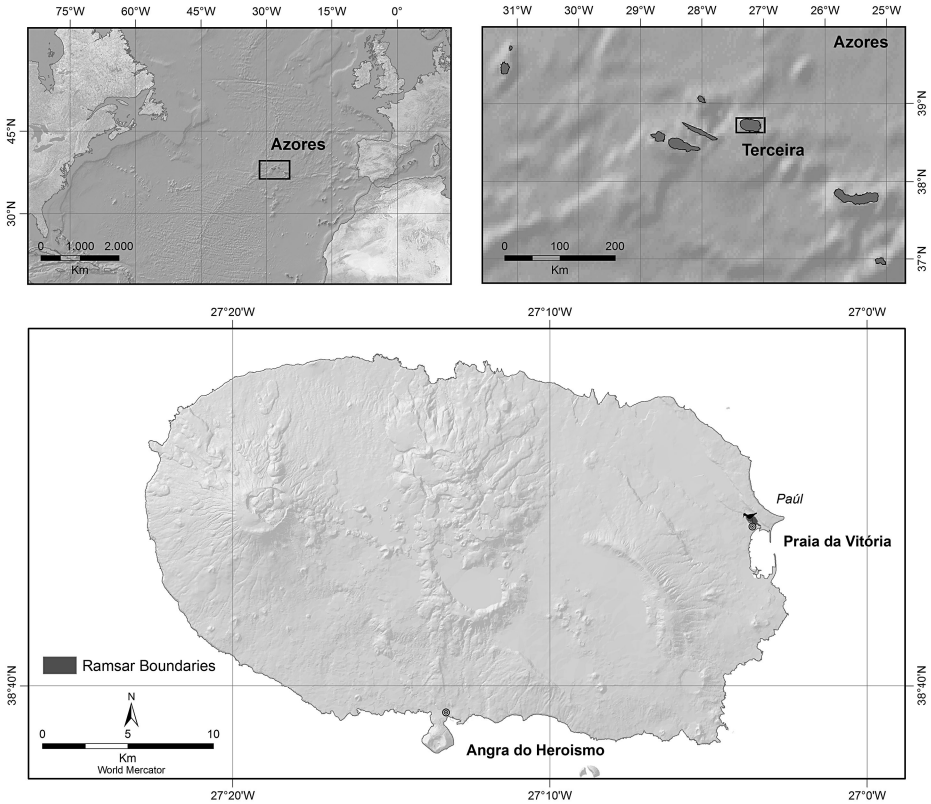

Figure 1. Atlantic location of Paul da Praia da Vitória in Terceira island (Azores).

Materials and methods

Ficopomatus enigmaticus was collected in July 2016 during a biodiversity survey of Paul da Praia da Vitória (38°44N; 027°04W) at Terceira island, Azores (Figure 1, Supplementary material Table S1), a Ramsar classified marsh of about 16 ha located at the edge of the urban centre of Praia da Vitória.

Site description

The Paul da Praia da Vitória (Figure 2) is the remnant of a once vast marsh that occupied the back land of the dunes behind the Praia da Vitória beach. It is located next to a *graben*, an elongated depression between geologic faults, and its normal contact with the sea is by percolation through the sand dunes. According to local information, prior to the development of the sea front, about the middle of the last century and before the construction of the harbor in the early 1980s, waves from very severe storms could reach the lagoon which occupied several acres and was a well-known stopover for many birds, especially Nearctic migratory waders (Bannerman and Bannerman 1966). The expansion of the town of Praia da Vitória led to the demise and destruction of this important wetland. Morton et al. (1997, 1998) conducted a thorough study of the then degraded remnants of the marsh, looking in detail into its biology and ecological dynamics and found no evidence of *Ficopomatus* presence. Due

Figure 2. Praia da Vitória wetland with the location of *Ficopomatus enigmaticus* reefs (stars). (A) Praia da Vitória wetland general view (source: SIARAM). (B) Aerial photograph showing sampling locations (yellow stars) in the Praia da Vitória wetland (1) in relation with Praia da Vitória marina (2) (source: Photo caption from a Google Earth still).

to its historical importance, Morton et al. (1997) proposed the restoration of the wetland as the *ex libris* of the town. Presently, Paul da Praia da Vitória is a restored wetland and has been a Ramsar site since 2012. The coastal lagoon was extensively dug, greatly enlarged, and substantially altered due to the planting of *Juncus maritimus* Lam. along small islets to provide attractive habitat for nesting birds and rehabilitating margins to former marshy habitat. Although still far from its former importance as a migratory bird stopover, it has become attractive as a leisure place and bird-watching location for a considerable number of migratory birds from both European and American continents. The wide diversity of bird species, especially considering its geographical origin and the importance of the site as a refuge for the mid-Atlantic migratory routes, provides the site with a special conservation value. The marsh plays an important role in the local hydrological cycle, regulating floods of the surrounding hydrologic

basin. Eutrophication, largely due to agricultural run-off, is seen as the principal threat (RAMSAR 2013).

Salinity in Paul da Praia da Vitória varies with tide and freshwater input. In 2016, salinity and temperature measurements taken between July and November revealed a salinity minimum of 15.3 in September and a maximum of 32.3 in August when the maximum water temperature was observed (27.6 °C). Minimal water temperature observed was 15.7 °C in October.

Sampling

At the Paul, worm colonies were identified and relevant photos taken. An intensive search in the adjoining marina at the Praia da Vitória Harbor (Figure 2) failed to detect *F. enigmaticus*. Samples were collected and preserved in 95% ethanol and taken to the laboratory for detailed observation and measurements, namely the length and diameter of calcareous tubes. Temperature and salinity were measured from July to November in the northernmost sampling point using a multiparameter probe.

Voucher specimens are deposited in the collection of the Museu Nacional de História Natural e da Ciência (MUNHC), Universidade de Lisboa, Portugal.

Results

Extensive aggregations of *Ficopomatus enigmaticus* calcareous tubeworms on piles, channels and small rocks, which were previously undetected by Morton et al. (1997) in spite of an extensive study (AMFM participated to the survey), were found at some locations in Paul da Praia da Vitória. In this lagoon, *F. enigmaticus* developed micro-atolls or small colonial hummocks (from some centimetres to about 1m^2) of tube aggregations upon hard substrate and was also able to do so on otherwise soft bottoms.

In the sampled northernmost *Ficopomatus enigmaticus* reef, the lowest measured salinity was 24.1 in July whereas the highest was 32.3 in August. In the same spot, temperatures ranged from 15.7 °C in November to 27.6 in August.

Sampled organisms were identified based on descriptions by Ten Hove and Weerdenburg (1978) and Bianchi (1981). Tubes presented two layers, an outer calcareous and an inner tube organic lining. Tubes were brittle, whitish, cylindrical with transverse growth rings and large funnel-like peristomes. The tubes observed were up to 8 cm in length and from 0.2 mm to 1.7 mm in internal diameter (Figure 3). Aggregations of *F. enigmaticus* were present at numerous sites in the lagoon, forming patches of several shapes and sizes, from small circular islets in the middle of channels to larger 1–1.5 m elongated fringing reefs found at the margins of the lagoon (Figure 2). These reefs were formed by thousands of specimens of *F. enigmaticus*.

Figure 3. *Ficopomatus enigmaticus* from the Praia da Vitória wetland. (A) Submerged worm reef. (B) A worm aggregation. (C) Detail of tube worms. (D) A worm extracted from its tube. Photographs by authors.

Discussion

The tube and body morphologies of the *Ficopomatus enigmaticus* specimens from Terceira Island agree with the descriptions given by Ten Hove and Weerdenburg (1978) and (Bianchi 1981). The specimens fall within the reported size ranges for this species, even though the observed maximum sizes were smaller than maximum values reported elsewhere (Aliani et al. 1995).

Ficopomatus enigmaticus appears to be a recent arrival in the Azores as previous studies in the Paul da Praia did not find it at this site (see Morton et al. 1997, 1998). The arrival of *F. enigmaticus* to the Azores is unsurprising given its prior establishment at similar latitudes at diverse localities around the world, including the Mediterranean and mainland Portugal and even distant oceanic islands (e.g. Hawaii, Bastida-Zavala 2008), but the actual time and pathway of introduction of *F. enigmaticus* into the Azorean region remains unknown. Being reported as extremely common in harbours and on ship hulls, transport on or in commercial vessels could be an obvious vector for the introduction of *F. enigmaticus* (e.g. Pernet et al. 2016) to Paul da Praia, considering its vicinity to Praia da Vitória Harbor and marina. However, not only is the lagoon of Paul da Praia inaccessible to boats, but also, an exhaustive survey in the neighbouring marina did not yield a single specimen of this species. Therefore, hull fouling seems to be an unlikely introduction vector for *F. enigmaticus* at this location. Considering that Paul da Praia is a well-known spot for migratory birds, dispersal by birds is a possible introduction pathway in this case, reinforced by the fact that aquatic birds use the reefs as resting sites (Eno et al. 1997). Migratory water birds can be long-distance transport vectors for

aquatic invertebrates and can play a significant role in the expansion of non-indigenous species (Green and Figuerola 2005). Long-distance transport of aquatic invertebrates by birds has been reported within their digestive tracts and on their legs (i.e., bivalves), plumage (i.e., bryozans) (Green and Figuerola 2005) and identification bands (i.e., barnacles) (Tøttrup et al. 2010). Barnacles have a sedentary way of life similar to that of serpulid tube worms, as they filter feed and attach their dwelling to hard surfaces including plastics. Presence of such sedentary organisms on leg bands might support migratory bird phoresy as a vector for marine organism colonization of the Azorean islands, which has been previously hypothesized by Gittenberger et al. (2006) for land snails, and in particular for the dispersal of marine invertebrates among the few Azorean wetland systems (e.g. Morton and Britton 2000). Also, Michin (2014) raised the possibility of wading birds spreading the Asian clam *Corbicula fluminea* (O.F. Müller, 1774) and also included birds as a vector on his risk analysis for Ireland, noting that natural spread by birds may be a more important mechanism for non-indigenous species dispersal than has previously been recognized. It is highly likely that birds have also been a vector for *F. enigmaticus* introduction in the Azores.

Salinity likely plays a role limiting *F. enigmaticus* presence in the Praia da Vitória Marsh. Even though *F. enigmaticus* can survive in oceanic salinities, as an euryhaline species tolerating a wide range of salinities (2–34) (Bianchi 1983), it is possible that it will not grow rapidly, compete effectively with other organisms, or reproduce in high salinities (Pernet et al. 2016). Other important variables that might control the spread of this non-indigenous species may be nutrients and environmental energy, e.g. current speed and depth (Schwindt et al. 2004). In temperate seas, a limiting minimum of 18 °C has been suggested for the successful summer spawning of *F. enigmaticus* (Thames Estuary: Dixon 1981), a temperature largely surpassed in the Paul lagoon in summer conditions.

The ecological impact of *F. enigmaticus* has not been evaluated yet, but it is likely that this species could be beneficial in the lagoon at Paul by reducing particulate matter and improving oxygen and nutrient levels, making waters less eutrophic. It can also cause an increase in the abundance of benthic species, as reported by Bianchi and Morri (1996) for the Pó River Delta in the Adriatic. However, in a scenario of uncontrolled growth, it may have more direct economic impacts in terms of the cost to clean fouled surfaces (Read and Gordon 1991), especially if it spreads to the neighbouring port facilities. Environmental variables, including salinity, nutrient availability, depth and wave action may be the most important factors affecting the growth and spread of the reefs (Bianchi and Morri 1996). Nevertheless, if this is an early stage invasion, and considering the reef forming and rapid growth abilities of *F. enigmaticus* (e.g. Fornós et al. 1997; Bianchi and Morri 2001; Schwindt et al. 2004), the presence of this

species in the Paul will probably alter the geomorphology of the system through effects on hydrodynamics and sediment dynamics to an extent dependent upon the number and size of the reefs that develop.

Dispersal within the Azores and to other Atlantic archipelagos is a possibility and should be monitored. Transitional systems such as wetlands and coastal lagoons are the areas of most concern, since the oligotrophic character of the other natural adjacent coastal areas of oceanic islands are not favourable for *F. enigmaticus* survival. At present, this reef building species has not been observed in other transitional water masses in the Azores (Morton et al. 1998); however, it is crucial to monitor its presence in other local and more pristine estuarine lagoons and marsh wetlands (eg. São Jorge costal lagoon). Further monitoring studies on the population structure and the potential dispersal of this species is essential to assess and mitigate impacts of this invasive species on sensitive ecosystems of the Azores.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Details of *Ficopomatus enigmaticus* surveys conducted in June 2016 Praia da Vitória (Terceira island, Azores): location name, coordinates and habitat features

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2019/Supplements/BIR_2019_Costa_etal_Table_S1.xlsx