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ORIGINAL ARTICLE

New alien barnacles in the Azores and some remarks on the invasive potential of Balanidae

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Abstract Global homogenization of biota is underway through worldwide introduction and establishment of non-indigenous (exotic) species. Organisms fouling ship hulls are continually in transit and can affect communities through biodiversity loss and serious damage to economy and public health. In the Azores, for the first time, underwater alien species prospection was conducted in marinas and recreational harbours, at São Miguel Island. Populations of three locally previously unknown barnacle species were found: *Amphibalanus amphitrite*, *Amphibalanus eburneus* and *Perforatus perforatus*. These species account for the more than 50% of alien barnacles worldwide that belong to Balanidae family. Hence, some considerations about morphology and life cycle of this family are advanced, discussed and related to their invasive potential.

Keywords Barnacles · Marine alien species · Invasive potential · Balanidae · Azores

Introduction

Over recent centuries, many marine species have been transported around the globe by human activities. Nowadays, the introduction of non-indigenous species is an issue of global concern due to its potential impacts on biodiversity economy and public health. Hull fouling, ballast water, fisheries, aquaculture and recreational boating contribute to the spreading of marine species to areas far outside of their natural dispersal potential (Bax et al. 2003).

Ocean-going vessels act as "mobile stepping stones" for fouling species from harbours and estuaries, providing a substratum from which attached adults can release larvae in suitable situations (Apte et al. 2000). Fouled ships have plied the oceans since the beginning of oceanic navigation, but changing trading routes, increased traffic volume and speed and relatively long port residence times have effectively facilitated the crossing of substantial distances and biogeographical barriers by marine organisms (Carlton 1985).

Biofouling can cause roughness of submerged surfaces of marine structures (Chakrabarti 1991), increase hydrodynamic loadings (Wolfram and Theophanatos 1985), accelerate corrosion processes (Patil et al. 1988) and impede underwater inspection and maintenance (Houghton 1978). The inadequacy of data will likely cost money in overdesign, failure of structures or damage to the environment. Thus, the extent and type of biological fouling and the development of fouling communities should be ascertained before engaging in economic activities in offshore waters.

The dispersal of marine organisms by shipping has long been used in interpreting the biogeography of marine invertebrates (Foster and Willan 1979; Carlton and Geller 1993; Zardus and Hadfield 2005). One of the first well-documented introductions of a barnacle by shipping was that of *Austrominius modestus* (= *Elminius modestus*) (Darwin, 1854) from New Zealand to England, most likely via convoys during World War II (Southward et al. 1998).

Barnacles, a highly successful group in terms of global dispersion (Newman and Ross 1976), are usually found in aggregations of conspecifics and other fouling organisms

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(Arnsberg 2001). At present, many barnacle species are extending their geographical range, spreading to regions where they did not occur before (Zullo 1992).

Cirripedia can be transported as fouling on the hull of ships or as larvae in ballast water. In fact, ballast water often contains larvae of littoral or harbour cirriped species (e.g. Carlton 1985; Carlton and Geller 1993; Lavoie et al. 1999). Being able to survive for a long time in ballast tanks, larvae when released from these tanks may successfully settle in a new environment. Larvae may also originate from gravid individuals present on ship hulls. Larvae settle on hulls of ships staying in harbours and then can grow very quickly while carried away to others areas. Many barnacles have taken advantage of this opportunity to reach new regions where they often successfully colonized harbour installations, pontoons, floating objects such as buoys, and other hard substrata (Bishop 1951; Southward 1975).

The volcanic islands of the Azores were shaped relatively recently and are one of the youngest groups of oceanic island in the Central Atlantic. Given the islands' location and age, their colonization by marine organisms is believed to occur mainly through oceanic currents. Little is known on anthropogenic introductions of marine species in the Azores as only a single study was published on Azorean marine aliens (Cardigos et al. 2006). Nevertheless, the islands are exposed to a high risk of species introductions, considering the increase in transatlantic leisure boat traffic and commercial maritime traffic stopping at the islands over the last decade, not to mention potential naturalizations since the fifteenth century when the discovery of the archipelago resulted in an obligatory stop over for most ships crossing the north Atlantic or on their way to Africa and India.

Given the unique position of the islands far from continental Europe in the heart of the Atlantic, the invasive susceptibility of the archipelago as well as barnacles' life cycle and invasive potential, this study intended to identify alien barnacle species established in the marina harbours of Ponta Delgada, on the Island of São Miguel, Azores. Furthermore, the invasive potential of the Balanidae is discussed, with special reference to the Azores.

Materials and methods

Study area

The archipelago of the Azores (36–39′N, 25–31°W) consists of nine volcanic islands forming three groups (western, central and eastern) along a tectonic zone running about 600 km (Fig. 1a). The islands emerged at a triple junction along the mid-Atlantic Ridge, separated from the continent by at least 1,300 km (Morton et al. 1998). The coastline is largely rocky, with boulder shores and frequently with cliffs up to 500 m.

The oceanographic conditions in the Azores are strongly influenced by the Gulf Stream, which, in the central North Atlantic, has a southern multibranched current system with many unstable meanders and eddies at the Azores front (Gould 1985; Pollard and Pu 1985). Average winter and summer sea surface temperatures are 15–16 and 22–24°C, respectively (Santos et al. 1995). Oceanic waters present low productivity with primary production below 150 mg C m^{-2} $year^{-1}$ (Raymont 1980). All Azorean islands were uninhabited by humans until the late fifteenth century, when they were colonized by Portuguese.

In spite of a long history of exploitation of littoral marine resources, the pressure on the littoral zone has been increasing in recent years with dumping of solid wastes, fisheries, recreation, infrastructure activities (harbours, roads) and tourist developments (Depledge et al. 1992; Santos et al. 1995). Ponta Delgada's marina harbour has recently quadruplicated its number of berths to about 670. The new marina is part of the Sea Gateways project, which also includes a cruise ships' quay. Both marinas, the new extension and the old one, are surrounded by rocks, have a maximum depth of about 7 m and are located within the larger commercial harbour area (Fig. 1c).

Field and laboratory procedures

Underwater surveys were conducted in the subtidal areas (maximum of 10 m depth) at the pontoons and peers of the marinas and the harbour of Ponta Delgada, São Miguel Island, Azores, to sample and identify alien barnacle species. All species were recorded and collected for later identification.

A species was considered alien to the Azores when the following criteria were met: (1) it is new to the Azores; (2) its occurrence in the Azores constitutes a geographic discontinuity to the species' known range; (3) the extension of its range can be linked, directly or indirectly, to human activities; (4) its new occurrence is at first very localized; and (5) a persisting population has been established.

Identification of barnacles (mainly based on size, shape and number of calcareous, parietal plates) was performed according to Dionísio et al. (2011). Also, the shape and relative size of the movable, opercular plates (tergum and scutum) were considered. Colour and ornamentation of the plates are useful for some species. For identification in the laboratory, 10 complete, fresh (not preserved) specimens of each species, representing the full adult range size, were selected and photographed. The barnacles were dissected, and the pattern and colour of the wall plates and the tergoscutal flaps were recorded (see Southward and

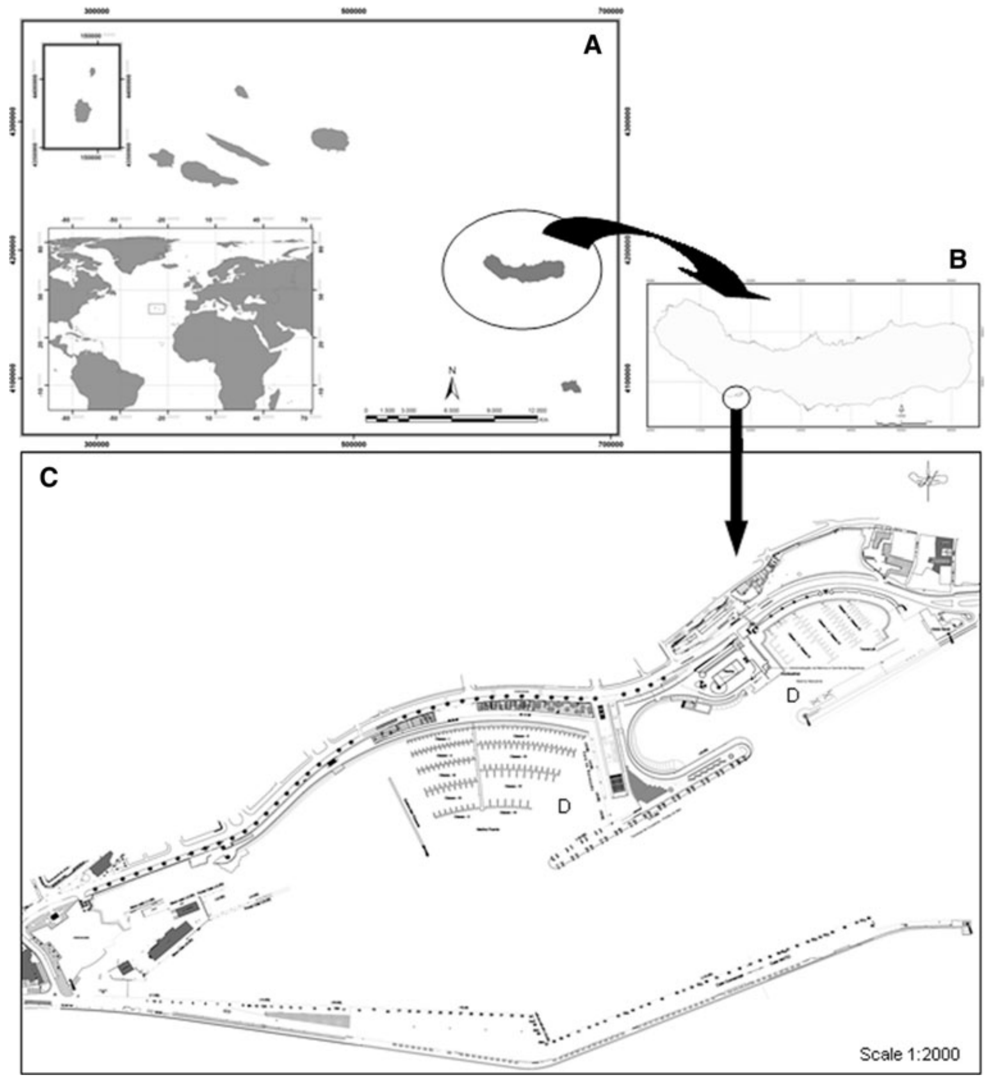

Fig. 1 Study area. *A* Azores; *B* São Miguel Island; *C* Ponta Delgada harbour; *D* Marina harbours

Crisp 1963). The opercular plates and soft parts of the body were removed from the wall plates. Operculum maximum diameter, basal maximum diameter, carinal height, rostral height, width and length of right and left tergum and scutum were measured to the nearest 0.05 mm using digital callipers. The scuta and terga were then immersed in concentrated sodium hypochlorite solution for 2 days and rinsed thoroughly in water, and the inner sides were examined and photographed under a compound microscope with an attached Cannon Power Shot G6 camera.

Results

Three exotic cirriped species new to the Azores were recorded at the marina harbour of Ponta Delgada, occurring at the sampled pontoons, attached to the metal pillars down to 5 m depth or to the pontoons themselves (PVC substrate) at water level: two species of the genus *Amphibalanus* (generic name changed according to Pitombo 2004), *Amphibalanus amphitrite* (Darwin, 1854) and *Amphibalanus eburneus* (Gould, 1841), and further *Perforatus perforatus* (Bruguière, 1789). The latter species dominated the barnacle fauna along with *Balanus trigonus* Darwin, 1854, an exotic species which has already established itself in the Azores.

All three species were found in clusters in distinct sites and were represented by individuals of different size including mature specimens. This indicates their potential to maintain self-sustaining populations in the area.

Amphibalanus amphitrite (Darwin, 1854)

Amphibalanus amphitrite (Fig. 2) is a cosmopolitan tropical and subtropical species (Newman and Ross 1976) that

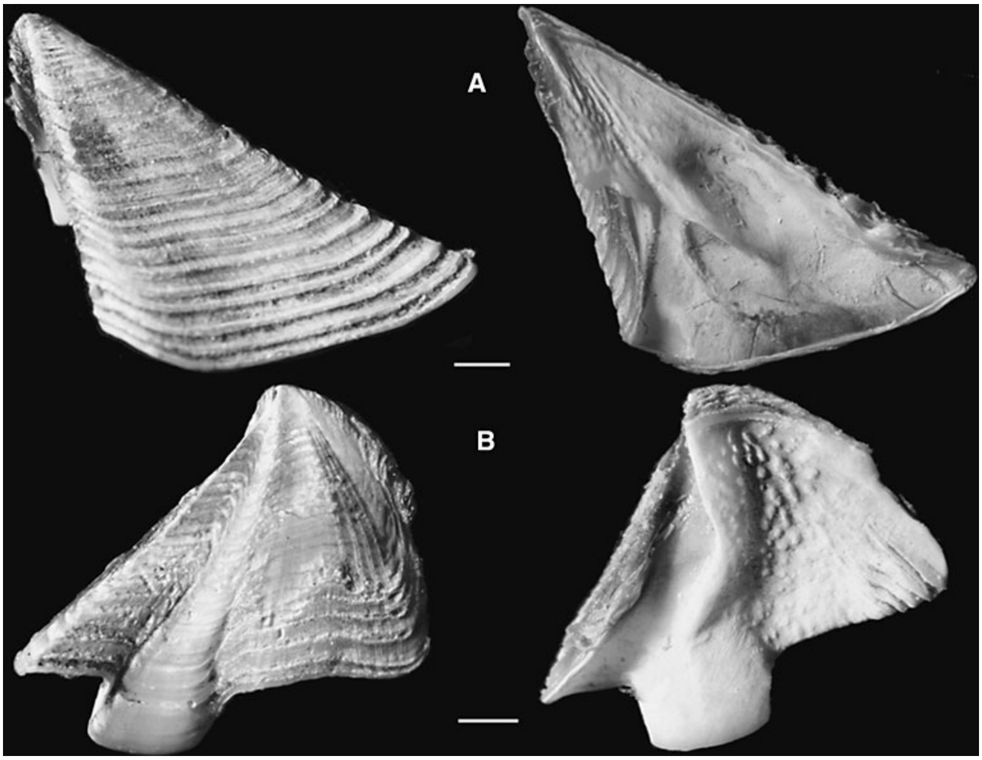

Fig. 2 *Amphibalanus amphitrite* collected at Ponta Delgada, Azores. *A* scuta (*left* external, *right* internal), *B* terga (*left* external, *right* internal). *Scale bar* 1 mm

normally occurs intertidally, often in brackish waters (Henry and McLaughlin 1975). Looking at Darwin's type material, Harding (1962) established that its origin was Natal, South Africa. But several current authors (see Carlton et al. 2011) have considered the species to originate from the Indo-Pacific Ocean. Furthermore, several other authors (e.g. Farrapeira 2009) classified it as cryptogenic. It is a typical fouling and harbour species, able to withstand low salinity levels (Southward 1975; Utinomi 1960) and often abundant in habitats exposed to physical stress and pollution (Lipkin and Safriel 1971; Shkedy et al. 1995). In tropical and subtropical areas, *A. amphitrite* occurs abundantly in the intertidal zone of sheltered coasts, usually below the mean seawater level. In more northern temperate areas such as the Japanese and Californian coasts, the species is generally restricted to enclosed bays or harbours (Utinomi 1960). Along the western European coasts, this species was considered to live mainly in harbours and, in the eastern Channel and the southern North Sea, at sites where temperature was artificially raised (Bishop 1950; Southward and Crisp 1963; Hayward and Ryland 1999).

In the Azores, this species was reported for Faial (Gruvel 1920), but its presence was not confirmed ever since. In fact, Young (1998) doubted the unconfirmed record.

Amphibalanus eburneus (Gould, 1841)

This large barnacle is native to the east coast of the USA, from Nova Scotia to Florida, including the Caribbean and Gulf of Mexico (Kaplan 1988). Nowadays, the ivory barnacle is found worldwide probably due to introductions via ballast water and hull fouling of ships (e.g. Hawaii, see Matsui et al. 1964). It is a typical fouling species introduced in Europe about 100 years ago and is well established in waters of reduced salinity in the Mediterranean and in the southern Bay of Biscay (Southward 1962). *A. eburneus* (Fig. 3) can be found on a variety of hard surfaces from the low tide line to a depth of about 37 m (Voss 1980), including rocks; oysters; mussels and other mollusc shells; pilings; buoys; seawalls; and even prop roots of mangroves (Kaplan 1988).

For the Azores, Southward (1998) confirmed the species' presence, in small numbers, at the waterline of stagnant pools in the nearly dried-out estuary at the north end of Horta Bay at Faial Island. This species was present in fewer numbers on pontoons below the water line.

Perforatus perforatus (Bruguière, 1789)

Perforatus perforatus is an eastern Atlantic warm-water species, occurring commonly in the Mediterranean

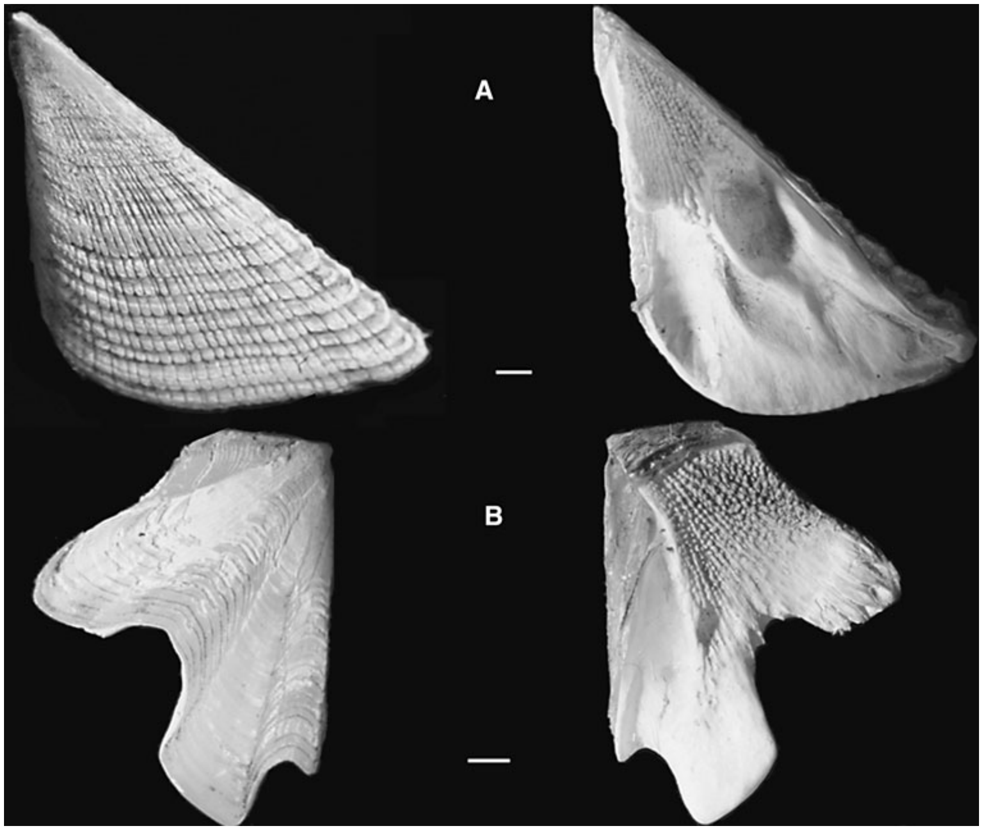

Fig. 3 *Amphibalanus eburneus* collected at Ponta Delgada, Azores. *A* scuta (*left* external, *right* internal), *B* terga (*left* external, *right* internal). *Scale bar* 1 mm

(Koukoura and Matsa 1998). Its range extends southward to the north-western coast of Africa. Along the English Channel, it occurs up to the Isle of Wight (Stubbings 1967). *P. perforatus* (Fig. 4) is a shallow-water species, common on wave-exposed shores. It is usually found near the low water mark and does not extend far into the subtidal zone. Near the northern limit of its distribution, it tends to be confined to the sublittoral zone and to embayed locations (Bassindale 1964). In the southern North Sea, the species is regularly found on drifting objects washed ashore (Pelseneer 1881a, b). In 1978, it was recorded from buoys off the Dutch coast (Buizer 1978, 1980). It is the largest common shore barnacle of north-west Europe, but on drifting objects, usually only small individuals occur.

For the Azores, this is the first record of *P. perforatus.*

Discussion

Balanidae: an invasive family?

It is not fully clear what makes a successful invader. Factors that have been considered in the literature include the ability to survive the process of introduction (conditions and duration), the ability to form resting stages, special life-history traits (e.g. pelagic larval dispersal, direct development, high reproduction rate), the capacity to overcome abiotic stress and to adapt to a new trophic niche, and special features of the recipient environment that prevent or facilitate survival and establishment of new species. However, a clear picture has not yet emerged (Streftaris et al. 2005).

Cirripedia is one of the most common groups of organisms in the fouling communities on ship hulls (Gollasch et al. 2002; Godwin 2003). This may have contributed considerably to the cosmopolitan or circum-tropical distribution of several species, especially of those adapted to physiologically rigorous environments such as in estuaries and harbours (Van Syoc 2009).

The Cirripedia have evolved several morphological, physiological and larval features that allow for spreading with subsequent colonization of and adaptation to new areas. The primitive balanomorphs were characterized by loss of the peduncle and by a skeleton composed of eight parietal and smaller accessory plates (Palmer 1982). In the course of their radiation, most balanomorphs reduced the number of plates while increasing their mechanical

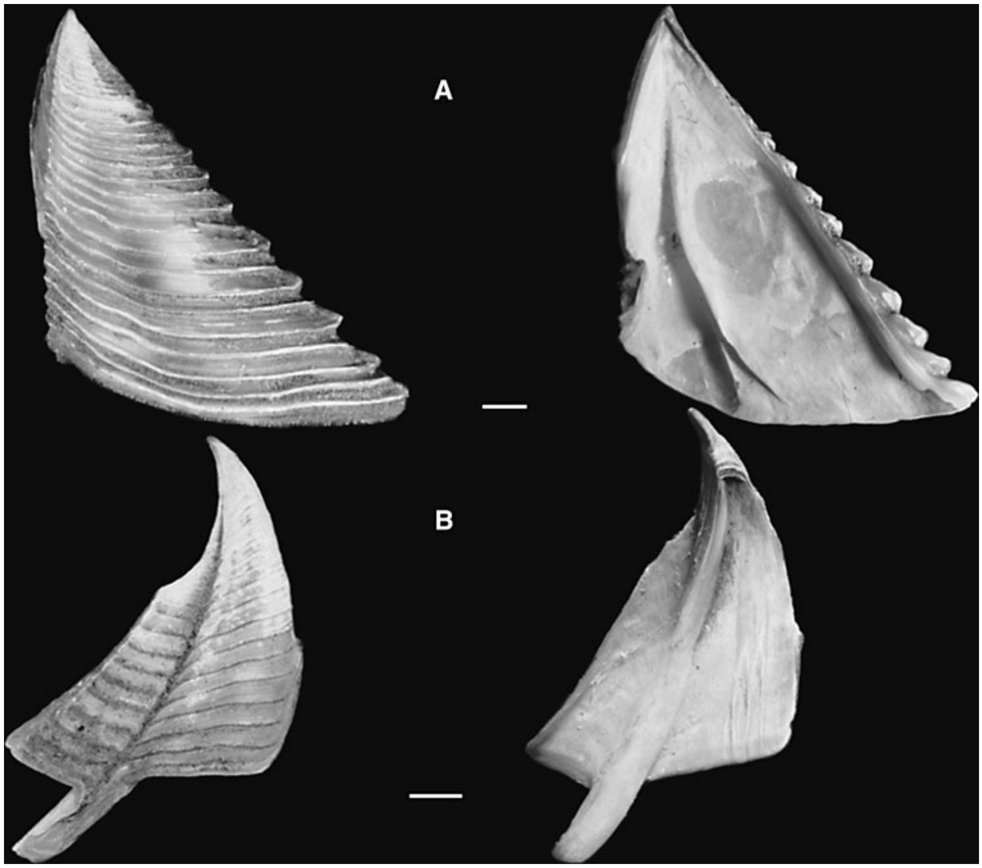

Fig. 4 *Perforatus perforatus* collected at Ponta Delgada, Azores. *A* scuta (*left* external, *right* internal), *B* terga (*left* external, *right* internal). *Scale bar* 1 mm

strength (Newman et al. 1969). This evolutionary process may be regarded as a successful adaptation to intertidal life, in particular with respect to wave action and predator resistance (Palmer 1982). According to Van Syoc (2009), the shell combined with planktonic larval dispersal enables some Cirripedia species to invade and persist in diverse and physiologically challenging environments.

Balanomorph barnacles settle and grow on a wide range of substrata in the sea and thus have become a serious problem as fouling organisms on ships and industrial installations (Crisp 1976). Advantages of such site selection may be found in avoidance of smothering on the sea floor by detritus or competitive colonial animals and seaweeds, avoidance of predators, conveyance to alternative water masses, improved feeding and increased aggregation to enhance cross-fertilization. Gregarious behaviour may also be an important adaptive feature, since barnacles save energy for growth and reproduction, which would otherwise be used for locomotion and defence (Wu et al. 1977). Barnacles follow the r-strategy, which is characterized by high fecundity and larvae with short development time. This strategy occurs mainly with species specialized in rapidly colonizing new habitats or with species with strongly fluctuating population sizes (Foster 1987), two features generally reported for exotic species.

The duration of the larval development, a key feature for dispersal, depends on temperature and varies in laboratory cultures (Table 1). Larvae of *A. amphitrite* and *A. eburneus* can reach an age of about 17 and 13 days, respectively. In fact, cyprid larvae of *A. eburneus* can successfully settle one to three days following the final naupliar moult

Table 1 Duration of larval development

Species	Duration of larval development (days)	Temperature (°C)	Reference
Amphibalanus amphitrite	7–17	20–26	Costlow and Bookhout (1958)
Amphibalanus eburneus	7–13	26	Costlow and Bookhout (1958)
Perforatus perforatus	7–15	16–25	Yule (personal communication)

(Costlow and Bookhout 1957). In the laboratory, *P. perforatus* requires 16–17°C to produce larvae, but multiple broods can be produced when conditions remain favourable (Patel and Crisp 1960). The larvae are small, and at 25°C, they are ready to settle within 1 week after hatching. Taking into account the duration of the brooding period and the average temperatures reported for the Azores, the three reported species may produce 2–3 generations of larvae over the summer–autumn season.

Given the predominance of alien species among the Balanidae of the Azores, a literature survey (Table 2) was conducted to evaluate the invasion potential of this barnacle family in different areas around the world (Fig. 5). The high percentages of Balanidae species considered exotic for any location studied give proof of an extraordinarily high invasive potential of this taxon. Out of a total of 185 barnacle species worldwide, 128 (69%) Balanidae species have been reported as alien for some locations. Thus, any effort should be made to identify and monitor these marine aliens before they may propagate, establish themselves and impact native populations.

Balanidae in the Azores

The Azorean shallow-water barnacles show a rather low diversity. This may reflect the insular position, the young age and small size of the islands as well as the absence of more complex systems such as estuaries, which are known to harbour a large number of barnacle species. In fact, the majority of species reported for the Azores are deep-water species (Southward 1998). Only nine shallow-water cirripedes occupy the intertidal, two of which are probably misclassified (*Elminus cristallinus* Gruvel, 1907 and *Semibalanus balanoides* (Linnaeus, 1767)). Of the remaining seven, four belong to the family Balanidae: *Megabalanus azoricus* (autochthonous), *Balanus trigonus*, *A. amphitrite* (now confirmed in the Azores) and *A. eburneus* (now confirmed in São Miguel Island). Except for *M. azoricus*, all these species are considered alien (Southward 1998). *P. perforatus* is a new record to add to the alien Balanidae established at the Azores. Although the species can occur sublittorally to 40 m depth and settle on floating objects, it was thought to be unable to cross sea barriers given its absence in both Madeira and the Azores Islands (Herbert et al. 2003). According to the same authors, successful larval development and settlement may depend on a degree of thermal stratification within the water column that is more likely to occur within sheltered bays than near rocky headlands. This may account for the species' occurrence on piers, built on sandy beaches within the relatively embayed coasts of the Ponta Delgada marina harbours. The presence of artificial substrates, including piers, and the increasing number of breakwaters, marinas and sea defences (the newly constructed marina) may have facilitated recent colonization along this coast.

Table 2 Studies on exotic barnacles performed at different locations

Location	Reference
Aegean, Marmara, Black, Azov and Caspian Seas	Panov (2004)
Australia	Jones (1992)
Azores	Southward (1998)
Baltic Sea	Leppäkoski and Gollasch (2006)
Belgium	Kerckhof and Cattrijsse (2001)
	Kerckhof et al. (2007)
Brazil	Farrapeira (2008)
	Farrapeira (2009)
	Farrapeira et al. (2010)
Canaries	Moro et al. (2003)
England	Arenas et al. (2006)
Europe	Gollasch et al. (2002)
Hellenic sea	Pancucci-Papadopoulou et al. (2005)
India	Anil et al. (2002)
Madeira	Wirtz et al. (2006)
Mediterranean Sea	Zenetos et al. (2005)
New Zealand	Cranfield et al. (1998)
South Africa	Robinson et al. (2005)
United States	Fuller (2009)

Because of the fouling propensity of the reported species, given their natural distribution and locally limited establishment in the Azores, their introduction has surely been mediated by the increasing recreational boat traffic in the last years. They are well known for their invasive potential and thus need some preliminary effort in the management of their populations. Furthermore, given the importance of the marine recreational traffic in the Azores, there is an increased probability in the spread of non-native species, especially on a local scale (Bax et al. 2002).

Although local species number and thus probably competition for space are increasing, apparently no species has become outcompeted yet. The recorded alien species occur predominantly on man-made substrates and in heavily disturbed habitats, which are particularly susceptible to invasive species. Due to competition, some species, like *A. amphitrite* or *P. perforatus*, may be pressed to more unfavourable habitats such as harbours, where they are becoming abundant. Due to the young age of the Azorean islands, there has not been enough time for the evolution of endemic species. Moreover, species are still colonizing and spreading, filling unoccupied niches, a process fastened by man. As a result, more exotic species may take advantage of the favourable habitat characteristics and the recent climate change.

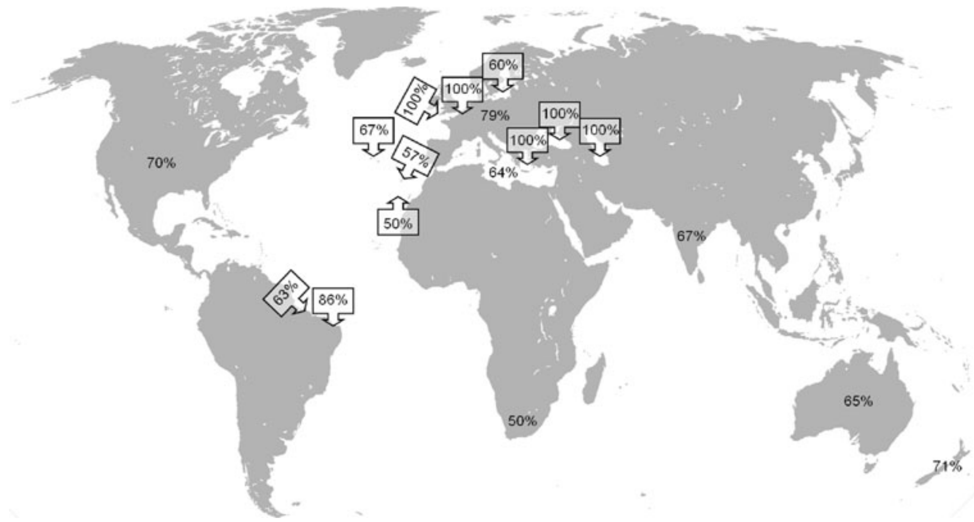

Fig. 5 Percentage of exotic species among shallow-water Balanidae in several places of the world. *Unframed values* relate to large areas such as continents (Europe), countries (United States, South Africa, Australia, New Zealand, India) and the Mediterranean Sea. Dubious reports were not considered. Data were taken from the literature given in Table 2

Future studies should address population dynamics of these alien barnacles, to understand their annual successions and impact on native species and address control and management protocols to allow a successful monitoring of these potentially invasive species.

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