Aquatic Invasions (2012) Volume 7, Issue 4: 475–482
doi: http://dx.doi.org/10.3391/ai.2012.7.4.004

Research Article

Colonization plasticity of the boring bivalve *Lithophaga aristata* (Dillwyn, 1817) on the Southeastern Brazilian coast: considerations on its invasiveness potential

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Received: 16 February 2012 / Accepted: 28 May 2012 / Published online: 22 June 2012

Handling editor: Demetrio Boltovskoy, University of Buenos Aires, Argentina

Abstract

Lithophaga aristata is a boring bivalve native to the Caribbean Sea, first recorded in 2005 as an introduced species on the Southeastern Brazilian coast. The geographic distribution and density of *L. aristata* and of its native congeneric *L. bisulcata* were assessed in four areas of Brazil (24 sites), additionally considering their relationship with types of substrate, depth and wave exposure. This study records the first occurrence of *L. aristata* in the Sepetiba Bay and also reports the species at five new localities in the Arraial do Cabo Bay. *Lithophaga aristata* is established in the four surveyed regions. At intertidal habitats, the exotic species only colonizes the infralittoral fringe but its density was not related to wave action. At subtidal habitats, the species colonizes natural and artificial substrates, from shallow (0.5m) to deep (5.0-7.0m) zones but no relationship between density and these evaluated factors was detected. Broad geographical and ecological distributions and higher densities of this introduced species in relation to its native congeneric are suggested as contrary to Darwin's naturalization hypothesis and instead indicate a high invasiveness potential.

Key words: rocky shore; artificial substrate; depth, wave exposure; scissor-mussel

Introduction

Resources acquirement capability is the major factor affecting establishment, range expansion and invasiveness potential of introduced species, if they show no physiological restrictions to survive in the new environment (Shea and Chesson 2002). For epibenthic communities the most limiting resource is space (Sutherland and Karlson 1977) and the artificial structures resulting from the increased urbanization of coastal areas (moorings, piers, breakwaters and seawalls) represent important sources of substrate (Bulleri and Chapman 2010; Farrapeira 2011; Gittenberger and Stelt 2011). Since artificial structures are usually related to commercial and recreational shipping activities, which are recognized vectors of biological introductions (Carlton 1996), these substrates can be a great opportunity for the establishment and spread of introduced species (Glasby et al. 2007; Tyrrell and Byers 2007; Ignacio et al. 2010).

Mariculture is also related to non-intended biological introductions, especially for epibiotic and boring organisms as previously reported for *Amphibalanus improvisus* (Darwin, 1854) and *Lithophaga aristata* (Dillwyn, 1817) (Ruiz et al. 2000; Simone and Gonçalves 2006, respectively). The latter is an introduced bivalve in Brazil, congeneric with the native *Lithophaga bisulcata* (d'Orbigny, 1853). Both species bore hard-shelled organisms, corals and soft rocks and *Lithophaga aristata* is primarily identified by the pointed, crossed tips at the posterior part of valves (Simone and Gonçalves 2006). This species, also cited as *Myoforceps aristatus* and *Leiosolenus aristatus*, is native to the Caribbean and its first record in Brazil dates from 2005 in both the states of São Paulo and Rio de Janeiro (Simone and Gonçalves 2006).

In spite of the association between boring bivalves and cultured hard-shelled organisms (Simone and Gonçalves 2006), there is no clear evidence for considering mariculture as the primary vector of introduction for this species on the Brazilian coast, and other potential vectors (ballast water and hull fouling) cannot be dismissed. Indeed, hull fouling was documented as a vector of introduction for this boring species. In fact, in 2006, *Lithophaga aristata* was recorded as a biofoulant on a oil rig under tow which left Brazil (Macaé - state of Rio de Janeiro) to go to the Port of Singapore and became stranded en route on the remote island Tristan da Cunha. Fortunately, monitoring surveys suggested no evidence of a rig-mediated secondary introduction for *L. aristata* on this island (Wanless et al. 2010).

Despite the recognized need for ecological studies focusing on recently recorded introductions mainly for management strategies, there is no published ecological data for *L. aristata* on the Brazilian coast. The aims of this study were to assess the density patterns and geographical distribution of this introduced bivalve and the native *L. bisulcata* in relation to types of substrate, depth and wave exposure. For the purpose of the research, four areas (24 sites) located on the Southeastern Brazilian coast were sampled in 2004-2005.

Methods

Information on the geographical and ecological distributions as well as on the density estimation of *Lithophaga aristata* and *L. bisulcata* were obtained during three surveys focusing on species inventory and assessment of the main factors structuring benthic communities (substrate type, depth, wave exposure). Surveys were performed in 2004-2005 in the Ilha Grande Bay (IGB, 22°55′ to 23°15′S, 44°00′ to 44°43′ W), the Sepetiba Bay (SB, 22º53′ to 23º05′S, 43º35′ to 44º03′W) and the Arraial do Cabo Bay (ACB, 22°57′ to 23°00′S, 41°59′ to 42°01′W), all of them in the state of Rio de Janeiro, Southeastern Brazil. IGB is an oligotrophic system that, despite zoobenthic introductions (Ignacio et al. 2010), is not considered a heavily-impacted ecosystem for most of the human-mediated disturbances and it supports a number of critical fisheries and marine resources (*e.g.* Cardoso et al. 2001; Ignacio et al. 2010). SB is a semi-confined water body under strong human influences such as heavy metal contamination and organic pollution as well as intense port activity (*e.g.* Leal Neto et al. 2006; Gomes et al. 2009). ACB is an area subject to spring-summer stochastic upwelling events. Human-mediated disturbances are usually localized and most of this bay is part of a marine protected area (Maritime Extractive Reserve) focusing on the sustainable use of natural resources by protecting the common property resources upon which small-scale fishermen depend (Silva 2004; Coelho-Souza et al. 2012). Additionally, the TEBIG oil terminal (23°03′ to 23°04′S, 44°15′ to 44°14′W) was surveyed, which lies between the IGB and the SB with associated intense shipping traffic and frequent discharge of ballast water.

In the subtidal zone, the association of the introduced and the native bivalves with natural (rocky shores) and artificial (harbor pillars) substrates was analyzed separately at 0.5 m depth by sampling five sites in IGB, three sites in SB and two sites in TEBIG. Vertical changes of the bivalves' density were assessed at sites where hard substrate extended to more than 4.0 m deep. As IGB is shallower than SB and TEBIG, the survey on both natural and artificial substrates was conducted at depths of 0.5, 2.0 and 5.0 m from the mean low water (MLW) level in IGB and 0.5, 3.0 and 7.0 m in SB and TEBIG. Three and four 0.10 m^2 quadrats were placed randomly on the substrate at each substrate/site/depth in SB/TEBIG and IGB, respectively, and all organisms were carefully scraped off into a 0.5 mm nylon mesh bag. In the intertidal zone on the Southeastern Brazilian rocky shores, sessile filter feeding invertebrates (mainly represented by different barnacle species and the bivalves *Perna perna*, *Brachidontes solisianus* and *Isognomon bicolor*) are more abundant at exposed than at more sheltered areas (Christofoletti et al. 2011). Since these hard-shelled species are suitable habitat for boring bivalves, wave exposure was considered as a factor to be evaluated in this study. In this zone, two shore levels were considered (low midlittoral and infralittoral fringe) and seven 0.01 m^2 randomly-placed quadrats were scraped

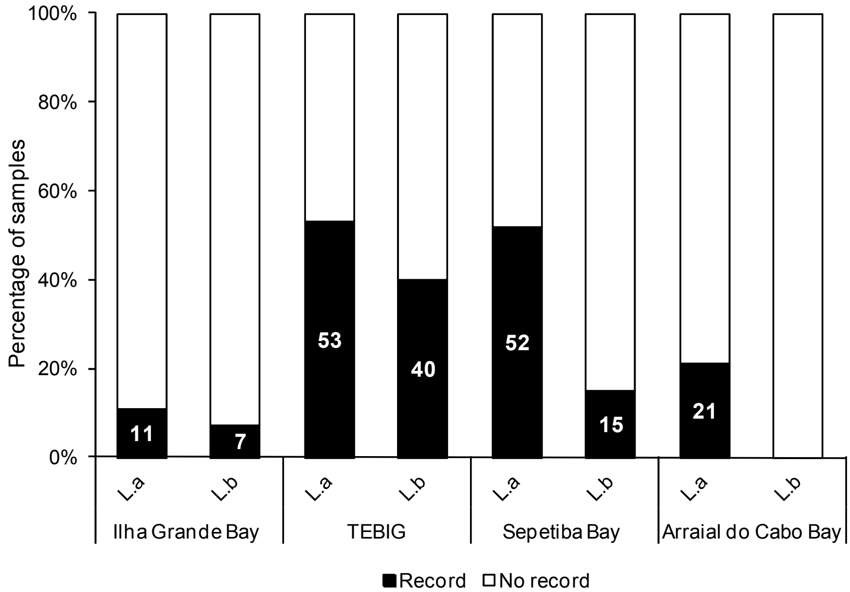

Figure 1. Percentage of total of samples in which the introduced (*Lithophaga aristata* – L.a) and the native (*Lithophaga bisulcata* – L.b) boring bivalves were recorded at Ilha Grande Bay (n= 68), Sepetiba Bay (n= 48), TEBIG oil terminal (n= 15) and Arraial do Cabo Bay (n= 84).

on three wave-protected and three moderately wave-exposed rocky shores in ACB. In the laboratory, all samples were carefully scrutinized to quantify *L. aristata* and *L. bisulcata* individuals.

Densities of the introduced bivalve (transformed to log (x+1)) were compared using nested ANOVAs: a) in the subtidal zone, separately for each bay (IGB and SB), considering type of substrate (fixed, two levels) and site nested in substrate (random, five levels for IGB and three levels for SB) as factors, b) in the intertidal zone, separately for each shore level (low midlittoral and infralittoral fringe) with wave exposure (fixed, two levels) and site nested in wave exposure (random, three levels) as factors. For TEBIG, since *L. aristata* was only recorded on one type of substrate (see Results below), the statistical analysis (factor: type of substrate; Student *t* Test) was not performed. One-way ANOVAs were conducted for *L. aristata* density comparisons among depths (fixed, three levels) in the subtidal zone for each site. The SNK post hoc test was used to examine the nature of differences detected with ANOVAs (0.05 significance level). Based on the low occurrence of the native bivalve, data did not meet minimal assumptions for statistical tests so ANOVAs were not performed. Statistical analyses were done using GMAV5 for Windows.

Results

Lithophaga aristata was more frequent than *L. bisulcata* in the samples of all areas, but mainly in ACB and in SB. In the former the native species was not recorded, and in latter the introduced was more than three times more frequent than the native species (Figure 1).

The mean density values (± standard errors) of *L. aristata* and *L. bisulcata* found in the four surveyed areas are summarized in Tables 1 and 2. Densities of the introduced *L. aristata* were frequently higher than those found for the native bivalve in IGB, SB and TEBIG. At the depth of 0.5 m, the genus *Lithophaga* was recorded at three of the ten sampled sites in IGB, at five of the six sites in SB and at one of the two sites in TEBIG. More specifically, the introduced species *L. aristata* was found at two of the ten sites in IGB, four of the six sites in SB and one of the two sites in the TEBIG area (Table 1). Considering the intertidal zone in ACB, the introduced species was not recorded at the low midlittoral, although it was recorded at five of the six sampled sites on the infralittoral fringe (Table 2).

In the subtidal zone (0.5 m depth), there was no difference of *L. aristata* density between natural and artificial substrates in IGB ($F_{1,30}$= 2.65; p= 0.142) and SB ($F_{1,12}$= 0.07; p= 0.80).

Table 1. Mean number of individuals.m^{-2} ± SE of the introduced *Lithophaga aristata* and the native *Lithophaga bisulcata* at the subtidal zone of natural and artificial substrates on Southeastern Brazilian coast. Three depths were sampled at each site in Ilha Grande Bay (n = 4 per site/depth), Sepetiba Bay (n = 3 per site/depth) and TEBIG (n = 3 per site/depth). Shallow = 0.5m depth. Mid = 2.0m in Ilha Grande Bay and 3.0m in Sepetiba Bay and TEBIG. Deep = 5.0m in Ilha Grande Bay and 7.0m in Sepetiba Bay and TEBIG. '-' No available data.

Sampled sites	Geographic coordinates	Sampling date	Boring bivalve species/subtidal depth					
			Lithophaga aristata			*Lithophaga bisulcata*		
			Shallow	Mid	Deep	Shallow	Mid	Deep
Ilha Grande Bay		September 2004						
Natural Substrate								
Gipoia Island	23º02′08″S; 44º22′25″W		15.0±11.9	0	-	0	0	-
Itanhangá Island 1	22º59′34″S; 44º24′35″W		0	0	5.0±5.0	0	5.0±5.0	2.5±2.5
Itanhangá Island 2	22º59′33″S; 44º24′37″W		12.5±6.3	0	0	2.5±2.5	0	7.5±7.5
Itanhangá Island 3	22º59′25″S; 44º24′41″W		0	-	-	0	-	-
Anil Beach	23º00′32″S; 44º18′07″W		0	-	-	0	-	-
Artificial Substrate								
Gipoia Island	23º02′10″S; 44º22′19″W		0	-	-	2.5±2.5	-	-
Mombaça	23º01′01″S; 44º16′40″W		0	-	-	0	-	-
Bracuhy	22º57′08″S; 44º23′29″W		0	-	-	0	-	-
Itanhangá Island 3	22º59′21″S; 44º24′46″W		0	-	-	0	-	-
Anil Beach	23º00′53″S; 44º18′52″W		0	2.5±2.5	0	0	0	0
Sepetiba Bay		December 2005						
Natural Substrate								
Cabra Island	22º56′45″S; 43º51′01″W		16.7±8.8	0	6.6±6.6	0	10.0±10.0	0
Martins Island	22º57′00″S; 43º51′49″W		0	-	-	7.5±6.7	-	-
Guaíba Island	23º00′00″S; 44º01′59″W		100.0±15.3	36.7±8.8	20.0±11.6	0	0	0
Artificial Substrate								
CPBS Terminal	22º55′55″S; 43º50′10″W		0	0	0	0	0	3.3±3.3
TCS Terminal	22º56′07″S; 43º49′48″W		6.7±6.7	3.3±3.3	2.0±1.5	6.7±6.7	3.3±3.3	6.6±3.3
Guaíba Terminal	23º00′44″S; 44º01′53″W		73.3±15.6	113.3±20.3	143.3±26.1	0	0	0
TEBIG		December 2005						
Natural substrate	23º03′17″S; 44º13′58″W		0	0	-	0	0	-
Artificial substrate	23º03′14″S; 44º14′09″W		60.0±45.9	50.0±10.0	70.0±5.8	16.6±8.8	30.0±25.2	10.0±5.8

Table 2. Mean number of individuals.m^{-2} ± SE of the introduced *Lithophaga aristata* and the native *Lithophaga bisulcata* at the intertidal, low midlittoral (LM) and infralittoral finge (IF), of sites with different wave exposure (n = 7 per site/shore level) in the Arraial do Cabo Bay, Southeastern Brazilian coast.

Sampled sites	Geographic coordinates	Sampling date	Boring bivalve species/intertidal level			
			Lithophaga aristata		*Lithophaga bisulcata*	
			LM	IF	LM	IF
Wave-exposed sites		February and September 2005				
Anjos Beach	22º58′40″S; 42º00′47″W		0	57.1±43.5	0	0
Pedra Vermelha	22º59′08″S; 41º59′32″W		0	157.1±68.4	0	0
Fortaleza	22º58′12″S; 42º00′43″W		0	128.5±96.7	0	0
Wave-protected sites		February and September 2005				
Porcos Island	22º58′00″S; 41º59′37″W		0	0	0	0
Forno Beach 1	22º57′56″S; 42º00′28″W		0	385.7±140.2	0	0
Forno Beach 2	22º58′05″S; 42º00′20″W		0	100.0±43.5	0	0

However differences were found for sites nested within types of substrate in both bays (IGB: $F_{1,8}$= 2.51; p= 0.032 and SB: $F_{1,4}$= 21.2; p< 0.001). In IGB, this bivalve was only recorded on natural substrates showing similar density values on Gipoia Island and Itanhangá Island-2. In SB, density of *L. aristata* on the natural substrates was higher on Guaíba Island than on Cabras Island and there was no record of this species at Martins Island. On artificial substrates, the highest density of this species was found at Guaíba Terminal (Table 1). Considering the TEBIG area, *L. aristata* was only recorded on the artificial substrate (Table 1). Variation of the density related to depth was statistically significant only on the natural substrate on Guaíba Island ($F_{2,6}$= 5.66; p= 0.04) with higher mean density in the 0.5 m (100 ± 15.3 individuals. m^{-2}) than in the 7.0 m samples (20 ± 11.6 individuals.m^{-2}).

On the infralittoral fringe of the intertidal zone in ACB, there was no pattern of *L. aristata* density related to wave exposure ($F_{1,36}$= 0.18, p= 0.67) but differences were found for sites nested within each wave exposure condition ($F_{4,36}$= 3.19; p= 0.024). At the wave-protected sites, high densities were recorded at the two sites in Forno Beach. There were no significant differences among moderately wave-exposed sites (Table 2).

Discussion

This study records the first occurrence of *L.aristata* in Sepetiba Bay and it also reports the species at five new localities in the Arraial do Cabo Bay. Since previous records of this species date to 2005 at Ubatuba (state of São Paulo), Búzios and Arraial do Cabo (state of Rio de Janeiro) (Simone and Gonçalves 2006), the present report of *L. aristata* in Ilha Grande Bay (individuals collected in 2004) updates the first record for this species in Brazil. *Lithophaga aristata* may be considered as established (*sensu* Ruiz et al. 2000) in these areas. In 2007, the species was recorded boring *Nodipecten nodosus* (Linnaeus, 1758) in mariculture farms in the Santa Catarina state on the Southern Brazilian coast (Nelson Silveira, personal communication).

Moreover, this is the first study assessing ecological aspects of the introduced *L. aristata* in Southwestern Atlantic. *Lithophaga aristata* has colonized intertidal and subtidal habitats, at different depths on natural and artificial substrates and sites under different conditions of wave exposure and anthropogenic pressures (e.g. areas with inputs of raw sewage discharge and inside or nearby port areas). However, statistical analysis did not indicate any clear patterns of association between the introduced bivalve density and the evaluated factors (types of substrate, depth and wave exposure) probably because local conditions are playing more important roles in the establishment process of this species. These results suggest that the introduced *L. aristata* is a generalist species with broad environmental tolerances and high colonization potential, which are important features conferring invasiveness potential to an exotic species (Smith 2009).

In the subtidal zone, the greatest densities of the introduced bivalve were found in the two anthropogenically-modified areas (Sepetiba Bay and TEBIG). However, the results could also be due to a range of favorable conditions - other than those considered in this study like local hydrodynamics enhancing larval supply and/or larval retention, settlement facilitation by the recipient community and also enhanced survival due to low rates of predation and competition - or different population ages. The artificial substrates – efficiently colonized by *L. aristata* and commonly found in these bays – should also be considered as a positive factor in population growth (*e.g.* Bulleri and Chapman 2010). Based on the available information, it is not possible to establish a cause-effect relationship and further studies are needed.

The natural rocky shore where the introduced *L. aristata* showed largest densities in Arraial do Cabo Bay is adjacent to a mariculture area (oyster, mussels and scallops). Boring bivalves of the genus *Lithophaga* are usually found in association with other bivalves (Simone and Gonçalves 2006), barnacles (Reimer 1976) and live and dead coral skeletons (Kleemann 1980) and its association with scallop mariculture is responsible for economic losses in many countries (Bondad-Reantaso 2007), including Brazil (Simone and Gonçalves 2006). However, at present there is no information about the level of cultured organisms that are infested by boring bivalves in Arraial do Cabo Bay. Shells of cultured organisms, which are available as substrate for boring bivalve colonization, and the restricted seawater circulation in this area, could both be factors enhancing this *L. aristata* population on both the natural rocky shores and at the mariculture farm. Further studies focusing on the proper inference of cause-effect relationship between mariculture and density of this species in Arraial do Cabo are of great environmental and economical concern for both ecologists and managers.

The mid-intertidal zone of Arraial do Cabo Bay, which is dominated by the barnacle *Tetraclita stalactifera* (Lamarck, 1818), was not colonized by *L. aristata*. In the midlittoral zone of Panamá, *T. stalactifera* carapaces were successfully colonized by *L. aristata* and these eroded barnacles were more susceptible than non-eroded ones to removal by wave action (Reimer 1976). In Arraial do Cabo, *L. aristata* was often found on the infralittoral fringe associated with the barnacle *Megabalanus* spp., mainly with the ones forming hummock structures, which were less commonly formed by *T. stalactifera* in the surveyed sites. It is possible that the constitutive complexity of these structures facilitates the colonization by the boring bivalve on the infralittoral fringe. Correspondingly, in the mid-intertidal zone of Ilha Grande Bay, the introduced bivalve was found boring complex structured beds developed by the vermetid gastropod *Petaloconchus varians* (d'Orbigny, 1841) (Breve-Ramos et al. 2010). Thus, the complexity of habitats created by some hard-shelled organisms of the recipient community seems to be essential to the successful colonization of new environments by *L. aristata* and may be the main factor responsible for the high spatial variability of *L. aristata* densities shown in this study.

Although there is no information about predation on the *Lithophaga* species on Brazilian coast, the effect of predators as drivers of the spatial variability of the bivalves' density cannot be rule out. In this context, it is known that the starfish (*Comasterias lurida*) preys upon *L. patagonica* on the Argentinian coast (Pastor-de-Ward et al. 2007) and the pointed and crossed tips exclusively shown by *L. aristata* were proposed to inhibit predation (Morton 1993). Thus, different predation rates may be a reasonable explanation for the high densities of *L. aristata* in comparison with *L. bisulcata* found in the four surveyed areas on Southeastern Brazilian coast.

This study assessed rocky shores and artificial substrates where hard corals are rare. However, since the native *L. bisulcata* is frequently found as bioeroders of corals such as *Mussismilia hispida* (Verrill, 1901) (an endemic species on the Brazilian coast) and *Siderastrea stellata* (Verrill, 1868) (Oigman-Pszczol and Creed 2006), the introduction of *L. aristata* may represent an additional ecological threat for hermatypic coral-structured communities.

Darwin's naturalization conundrum (Diez et al. 2008) (the phylogenetic relatedness of invaders to natives and its relation to community invasibility) has been investigated by several authors and many contrasting results and several proposed criteria for analysis are found in the literature (see for example Rejmánek 1996; Proches et al. 2008; Thuiller et al. 2010). Based on the present findings, which showed higher values of frequency of occurrence and density of the introduced boring bivalve *L. aristata* in comparison to its native congener *L. bisulcata*, there is no support for Darwin's naturalization hypothesis (that introduced species should be less successful in places with native congeners due to competitive interaction and shared enemies). As reviewed by Truiller and collaborators (2010) for several biological groups, it is possible that some niche differentiation between native and introduced congener species or some species-specific traits (maybe more plastic traits), like reproductive effort, individual growth rate, environmental tolerance and/or dispersal abilities, confer the introduced bivalve differential capabilities to cope with the recipient environment.

This study extended the geographic distribution of the boring bivalve *L. aristata* within Brazil and presented findings on the distribution and density of this introduced species and its native congener in relation to types of substrate, depth and wave exposure in areas under different anthropogenic pressures. The recent history of introduction at the time this study was carried out, combined with the broad ecological attributes, strongly suggests an invasiveness potential of *L. aristata*. This study on the Brazilian coast contributes to filling some gaps in limited regional knowledge on marine invasions by providing basic information and also some ecological aspects about a poorly studied introduced species with considerations for future experimental studies.

Acknowledgements

Authors would like to thank Luiz Ricardo Simone, Flávio Fernandes and Ricardo Absalão for generously sharing their taxonomic expertise, all field workers and researchers that helped us with sample sorting. We also thank managers of Angra dos Reis Port, Marina Bracuhy, Guaíba terminal, TEBIG oil terminal, Sepetiba Port and IEAPM for the facilities; and Nelson Silveira for data about *L. aristata* in mariculture. Furthermore, we would like to thank the editor and referees, Pedro Morais, Mariana Guimarães e Sergio Coelho Souza for theirs insightful comments and generous revision. This is a contribution of NP-BioMar, USP (M.S. López).

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