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Clam population dynamics as an indicator of beach urbanization impacts

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ABSTRACT

Modification of natural environments due to human activities has become an issue of great concern in the last years. In this study, beach urbanization impact was assessed through population dynamics of two dominant infaunal clam species: *Amarilladesma mactroides* and *Donax hanleyanus*. The beaches used as sampling sites were characterized by an urbanization index, which exhibited three levels of urbanization. Recruits and juveniles of both studied species were collected monthly during a two years sampling. Results showed that beach urbanization reduces *A. mactroides* recruits and juveniles' abundances, whereas the abundance of *D. hanleyanus* juveniles increased with higher urbanization degree. Also, the observed effects were limited to summer and autumn, coinciding with the time of higher impact due to recreation activities. The interspecific differences found and the importance of the sampling period when studying anthropic impacts over beaches, are discussed.

1. Introduction

Sandy beaches occupy most of the world's coastline. They shelter high biodiversity and provide key ecosystem services such as fishing and shellfish harvesting, recreation and tourism, storm buffering and nutrient cycling (Schlacher et al., 2008a). However, human pressures are increasingly evident in this environment, acting at different time and space scales (Defeo et al., 2009), being urbanization a critical modifying factor for coastal ecosystems (Baird, 2009). The installation of breakwaters and ports, the construction of buildings over the back shore and the beaches, and pollution, are some of the impacts on sandy beaches due to coastal urbanization (Meyer-Arendt, 2001; Nasr-Eddine, 2016). Moreover, tourism is an important factor associated with urbanization, which entails many pressures for sandy beaches such as beach cleaning and nourishment, trampling, off-road vehicles over sand, among others (Defeo et al., 2009). Particularly in temperate areas, where tourism is usually concentrated at a specific period of the year (summer), permanent pressures (as the presence of building on primary dunes or breakwaters) can be distinguished from impact pulses (as grooming or trampling). Although organisms inhabiting beaches are adapted to a very dynamic environment, these human interventions modify physical factors (e.g., beach slope, sediment particle size) which are essential to the proper development of beach resident communities (Muñoz-Lechuga et al., 2018). Thus, adverse effects like abundance decrease or changes in community structure and composition on coastal organisms have been reported as consequences of many urbanization-related activities (Fanini et al., 2009; Reyes-Martínez et al., 2015; Schlacher et al., 2008b).

The assessment of urbanization impact on beach ecosystems is commonly accomplished by the use of bioindicators (e.g., Huijbers et al., 2013). The main strength of this method is that the effect of any impact is being measured rather than just the impact itself, providing information on the quality of the studied environment (Markert, 2007). Due to the several constraints found in long-term samplings, many studies using species populations as bioindicators evaluate individuals' density in limited periods of time; although they provide relevant knowledge, the natural temporal variation of the different population components (recruits, juveniles, adults) is not being considered. On the other hand, studying beach urbanization effects on the population dynamics of species would provide information integrated in time that would conduce to a more accurate appreciation of the real impact on the beach ecosystem.

In this context, clams' population dynamics would be a potential good bioindicator of beach urbanization since these organisms are key ecosystem components of sandy beaches (Turra et al., 2016). Along the South West Atlantic coasts, the yellow clam *Amarilladesma mactroides* and the wedge clam *Donax hanleyanus* are the dominant infaunal bivalves of sandy beaches. Yellow clams were one of the most important

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mollusk resources of Argentina (Coscaron, 1959). However, massive mortalities of the species led to a considerable population decline, which even prompted some authors to suggest to place it as a critically endangered species (Fiori and Cazzaniga, 1999). Nonetheless, the impact of beach urbanization on this species has been poorly studied. The clams *D. hanleyanus* has been mainly touristic and artisanal exploited, although new commercial fishing is being observed (Dadon, 2002). Vieira et al. (2012) studied the effects of beach urbanization on the macrobenthic community off the Brazilian coast and found a reduction in the abundance of *D. hanleyanus*.

The population dynamics of these species are intimately related because they share and compete by space and resources (Defeo and Mclachlan, 2005). Thus, a density-dependence of *D. hanleyanus* recruitment on juveniles and adults' densities of *A. mactroides* has been reported (Defeo, 1996). On the other hand, *A. mactroides* present an intraspecific over-compensatory relationship between spawning stock and recruitment density (Defeo et al., 1992). Furthermore, the yellow clam is a seasonal migratory species: at the end of the austral spring, clam individuals colonize the intertidal zone of the sandy beaches where lives until the end of the autumn. Then, clams return to the shallow subtidal, staying there during the austral winter and spring (McLachlan et al., 1996).

Recruitment of these clam species takes place mainly during February to April-May (Defeo and de Alava, 1995; Defeo et al., 1992). Since they live in temperate regions, these recruitment events coincide with the period of highest touristic pressure, when the beach conditioning for recreational purposes and the arrival of tourists occur. The present study aimed to assess the impact of beach urbanization on the population dynamics of these two dominant intertidal clams. Consequently, the following hypotheses were tested: i) the population dynamics of *Amarilladesma mactroides* and *Donax hanleyanus* will vary among beaches with different urbanization degree; ii) the abundance of the studied species will be lower at urbanized beaches.

2. Materials and methods

2.1. Study area

The study was carried out at three beaches located in the northern region of Argentina coast, between (37°42′39.92″S; 57°24′20″W) and (38° 03′ 56.38″S; 57°32′ 50″W) (Fig. 1). This coastal area has a temperate climate with a water temperature range of 8–21 °C and semidiurnal tides, which vary between 0.6 and 0.9 m (Guerrero and Piola, 1997; Isla, 1991). The three selected beaches are dissipative, namely, beaches characterized by fine grain size, gentle slope and low energy. Two of them have different degrees of anthropic impact whereas the third is located within a protected area. Varese (VA) and Punta Mogotes (PM) beaches are located in Mar del Plata city, the most important beach resort of Argentina, with touristic activity present almost all year round but being higher during summer when population increases more than 300% (Bouvet et al., 2005). Thus, VA and PM beaches are subjected to beach conditioning, grooming, breakwaters, harvesting, urban contamination, trampling and the backshore is modified and urbanized. However, VA presents a higher degree of all those anthropic impacts. On the other hand, Mar Chiquita beach (MC) is located within the grounds of the Air Force where the backshore is naturally occupied by dunes and the public access is restricted.

2.2. Urbanization index

In order to estimate the level of urbanization of the studied beaches, an urbanization index was calculated following that developed by González et al. (2014) with some modifications. Thus, the index was composed of six variables: (1) proximity to urban centers, (2) infrastructure on the sand, (3) beach cleaning, (4) solid waste on the sand, (5) vehicles traffic on the sand and (6) frequency of visitors. Variables 1, 2, 4 and 5 were estimated by direct observation in the field. Information about beach cleaning was obtained from the official website of Mar del Plata municipality (https://www.mardelplata.gob.ar) and direct observation. The frequency of visitors was estimated from a report about tourism demand in Mar del Plata provided by the Research and Development Department of the Municipal Tourism Entity, Mar del Plata.

2.3. Sampling

A preliminary survey was done during 2008 in order to ensure the presence of populations of both clam species in the selected beaches and effectively, they were found present on site. During this sampling, it was observed that about 80% of adults *A. mactroides* clams broke due to the core pressure. Therefore, only juveniles (1–2.5 cm of *A. mactroides* and 5.5–15 mm of *D. hanleyanus*) and recruits (< 1 cm of *A. mactroides* and 1–5 mm of *D. hanleyanus*) (Defeo et al., 1992; Defeo and De Alava, 1995) were considered to assess the population dynamics. However, adults were sampled by fishing effort during one hour to evaluate the influence of their abundance on juveniles and recruits due to density-dependence.

The sampling of recruits and juveniles was carried out monthly between January 2009 and December 2010. At each beach, three equidistant (3 m) and across-shore transects were plotted from the maximum range mean of three waves during low tide conditions. Each transect comprised three equidistant points stratifying the study sites in high, medium and low sections. At each sampling point, organisms were collected through a 30-cm diameter plastic core to a depth of 50 cm. The extracted material was sieved using a 5 mm mesh. Retained clams anterior-posterior axis was measured *in situ*, and then the organisms were counted and released.

2.4. Data analysis

Data were pooled by season. Population dynamics and its relation with the level of urbanization were studied through multivariate generalized linear models (many GLMs) for both species employing the 'mvabund' library and the function "manyglm" (Wang et al., 2012). manyglm fits a separate GLM to each species, using a common set of explanatory variables taking into account the correlation between species, which is not possible using standard glm tools (Wang et al. 2012). These models, as any GLM, can handle count data without the need for data transformation by using Poisson or negative binomial distributions. Thus, first, we tested the fitting of distributions through the Akaike information criterion [AIC (Akaike, 1973)] and selected the distribution that best fitted our data. The model assumptions of mean-variance and log-linearity were examined with residual vs. fitted values plots and a normal quantile plot.

Then, we compared models by season with urbanization index, adults' abundances and year as explanatory variables. The adults' abundances were included due to the potential intra and interspecific density-dependence among the different population phases of clams. In order to determine which explanatory variables were significant at each season, the relative importance (RI) of the predictive variables (urbanization, adults' abundances and year) was calculated using model averaging based on modified Akaike information criterion (see Nakamura et al., 2015, for more details on model averaging procedures). For this, we used the models that constitute a cumulative AIC weight of 0.95 (Burnham and Anderson, 2002). We considered a strong explanatory variable if the RI was close to 0.9, moderate for an RI of 0.9–0.7, and weak if the RI was less than 0.7 (Burnham and Anderson, 2002). A *posteriori* pairwise comparisons were subsequently conducted using R's summary.manyglm() function with p.uni = "adjusted" command. This is applied to a manyglm model to perform resampling-based hypothesis testing to identify which variable or groups of variables are statistically significantly associated with differences in recruits and juvenile bivalve assemblages. All analyses were conducted in R 3.3.1.

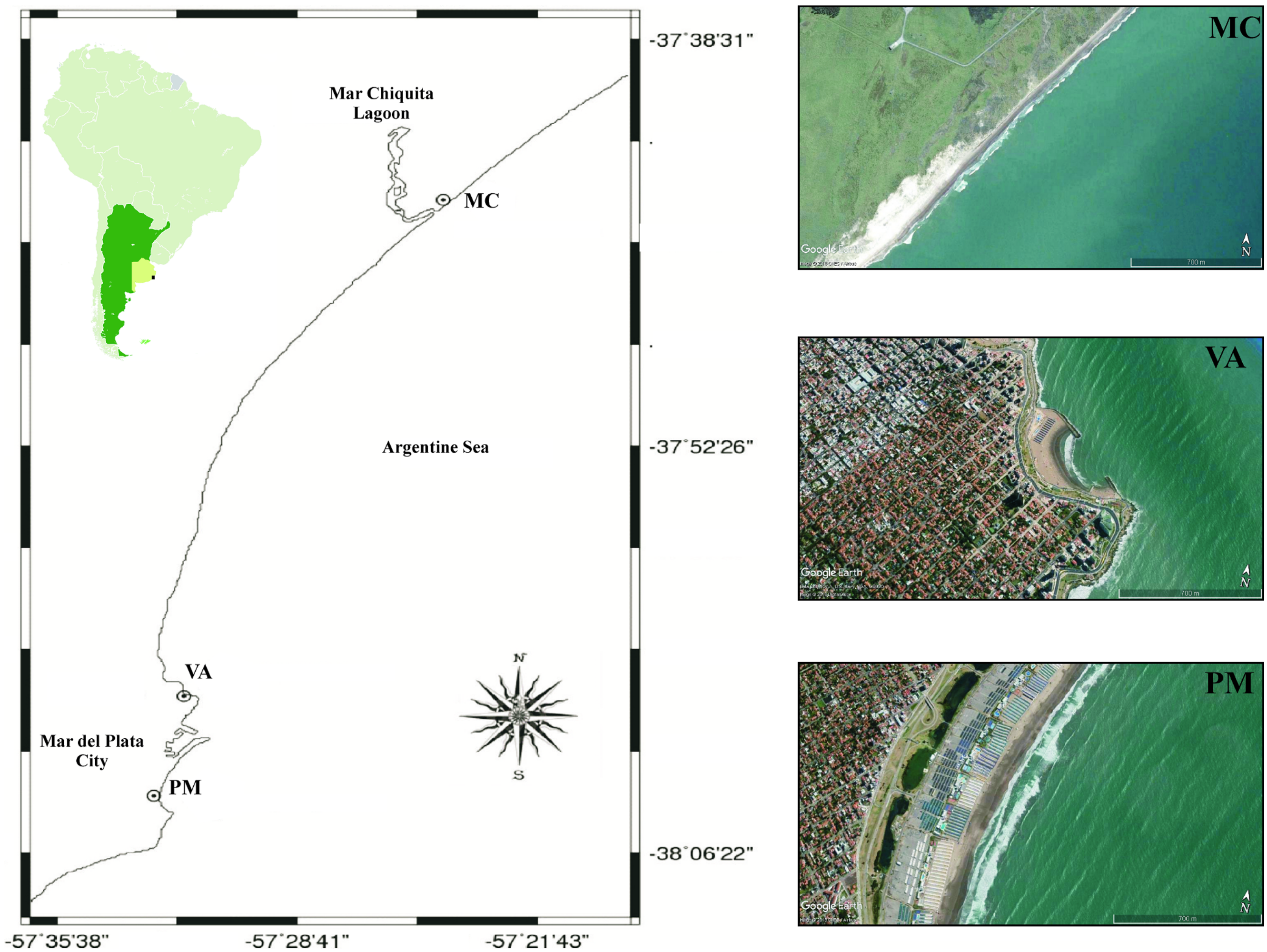

Fig. 1. Map showing the location and satellite images of the studied sites. MC: Mar Chiquita beach (not urbanized); VA: Varese beach (urbanized); PM: Punta Mogotes beach (urbanized).

3. Results

The values assigned to each urbanization indicator per beach and the consequent urbanization indexes are presented in Table 1. As expected, VA beach has the highest index and MC the lowest. Although PM present an intermediate urbanization index, as expected, it is quite higher than 0.5, which indicates that PM present a sizeable degree of urbanization, but lower than that of VA.

Modeling results through Multivariate GLM indicated that variations in recruits and juvenile bivalve assemblages were explained by different variables depending on the season analyzed (See Table 2). At summer, the relative importance (RI) of adults' abundance and year on recruits and juvenile bivalve assemblages was weak (RI < 0.7, Table 2), indicating that these variables did not affect recruits and juvenile dynamics. However, the urbanization index showed a moderate value of RI indicating that this factor modified the infaunal clams' abundances. Subsequent pairwise testing showed that *A. mactroides* were affected at both recruit and juvenile stages, showing higher abundances at the beach with the lowest urbanization index (MC), whereas *D. hanleyanus* juveniles presented higher abundance in the most urbanized beach (VA) (P-value < 0.01, see Fig. 2).

At autumn, the relative importance (RI) of adults' abundance explaining recruits and juveniles variation was weak (RI < 0.7, Table 2), indicating that this variable had no effect on recruits and juvenile dynamics. On the other hand, urbanization index and year showed a high value of RI which indicates that these factors modified the infaunal clams' abundances. Subsequent pairwise testing showed that *A. mactroides* were affected at both recruit and juvenile stages in 2009 and only recruits in 2010, both cases showing higher abundances at the beach with the lowest urbanization index (P-value < 0.01, see Fig. 3).

At winter, the relative importance (RI) of urbanization index and year on recruits and juvenile bivalve assemblages was weak (RI < 0.7, Table 2), indicating that these variables did not affect the recruit and juvenile dynamics. On the other hand, the abundance of *D. hanleyanus* adults showed a high value of RI which indicate that this co-variable modified the recruits and juveniles' abundances. Subsequent pairwise testing showed that both stages of both bivalve species were related with Donax adults abundances through a positive slope value (see Fig. 4).

Table 1
Urbanization index of the studied beaches. MC: Mar Chiquita beach; VA: Varese beach; PM: Punta Mogotes beach.

	VA	PM	MC
Proximity to downtown	4	2	1
Buildings on the sand	5	5	0
Beach cleaning	5	4	0
Solid waste on the sand	5	4	1
Vehicle traffic on the sand	3	2	0
Amount of visitors	5	4	0
Urbanization index	0.9	0.7	0.07

Table 2
The results of the models used to test the effect of urbanization index, year and density of adults on the recruits and juvenile bivalve assemblages. The best four models are reported. N° par represents the number of parameters of the models. +/− indicates the presence/absence of the effect of the variables. The Akaike's Information Criterion (AIC_i), the Akaike's weight (w_i) and the Δ_i values are reported to show the selection information criteria while RI represents the Relative Importance of the explicative variables. Strong or moderate influences of explanatory variables are highlighted in bold. Density A. represents the density population of adult of *Amarilladesma mactroides* and Density D. represents the density population of adult of *Donax hanleyanus*.

Season	Model	N° par	Urban index	Year	Density A.	Density D.	AIC_i	Δ	w_i
Summer	m1	4	+	+	+	+	13.64	0.0	0.12
	m2	3	+	+	−	+	13.71	0.07	0.11
	m3	2	+	+	−	−	13.94	0.30	0.10
	m4	3	+	+	−	+	13.97	0.33	0.10
RI			**0.77**	0.57	0.55	0.53			
Autumn	m1	4	+	+	+	+	49.16	0.0	0.33
	m2	3	+	+	−	+	49.20	0.04	0.32
	m3	3	+	+	+	−	50.56	1.40	0.17
	m4	2	+	+	−	−	50.60	1.44	0.15
RI			**0.99**	**0.99**	0.67	0.50			
Winter	m1	4	+	+	+	+	10.33	0.0	0.16
	m2	3	+	+	+	−	10.34	0.01	0.16
	m3	3	+	−	+	+	10.82	0.13	0.13
	m4	2	+	−	+	−	10.82	0.13	0.13
RI			0.56	0.68	0.52	**0.88**			
Spring	m1	4	+	+	+	+	4.14	0.0	0.08
	m2	3	+	+	−	+	4.26	0.11	0.08
	m3	3	+	+	+	−	4.38	0.24	0.07
	m4	2	+	+	−	−	4.39	0.25	0.07
RI			0.59	0.56	0.52	0.55			

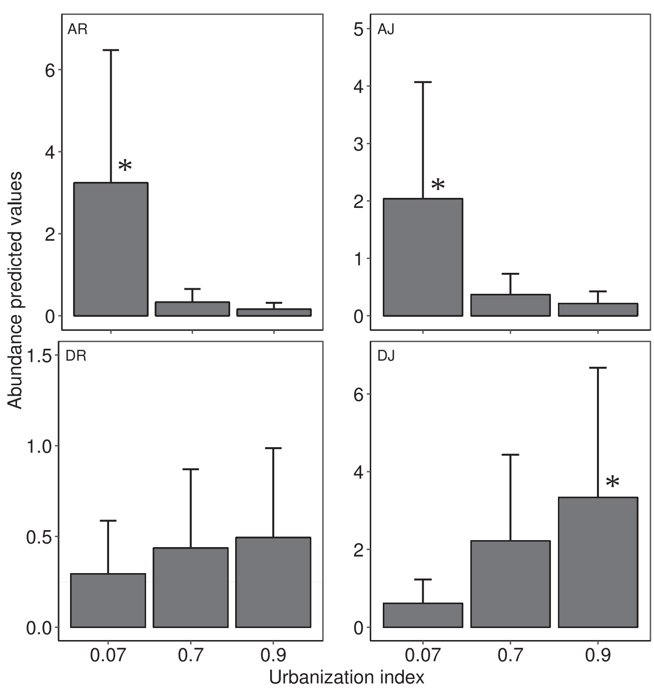

Fig. 2. Bar plot of the predicted abundance in relation to the urbanization index for each clam species/stage, in summer. Bars indicate the mean and vertical lines the standard error estimated by manyGLM models. Asterisk corresponds to significant differences respect to the other urbanization index according to the *a posteriori* univariate test. AR: recruits of *Amarilladesma mactriodes*, AJ: juveniles of *A. mactriodes,* DR: recruits of *Donax hanleyanus,* DJ: juveniles of *D. hanleyanus.*

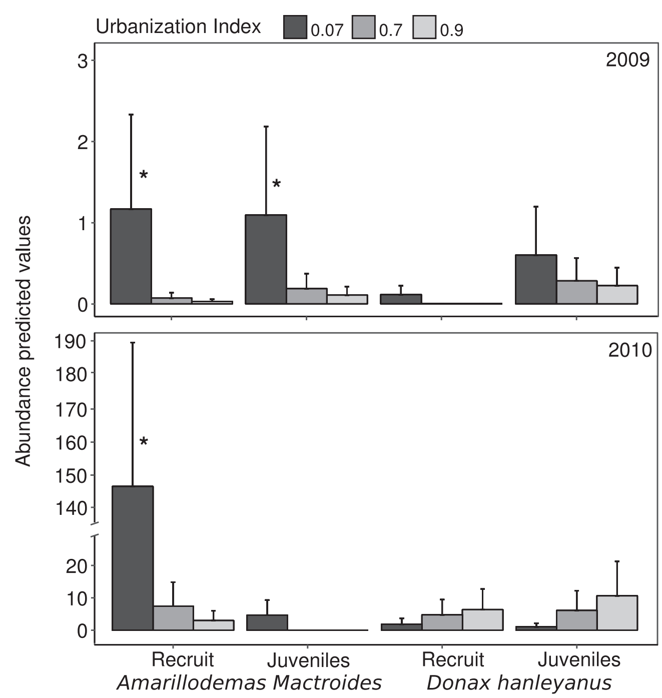

Fig. 3. Bar plot of the predicted abundance in relation to the urbanization index for each clam species/stage, in autumn of both sampling years. Bars indicate the mean and vertical lines the standard error estimated by manyGLM models. Asterisk corresponds to significant differences respect to the other urbanization index according to the *a posteriori* univariate test. AR: recruits of *Amarilladesma mactriodes*, AJ: juveniles of *A. mactriodes,* DR: recruits of *Donax hanleyanus,* DJ: juveniles of *D. hanleyanus.*

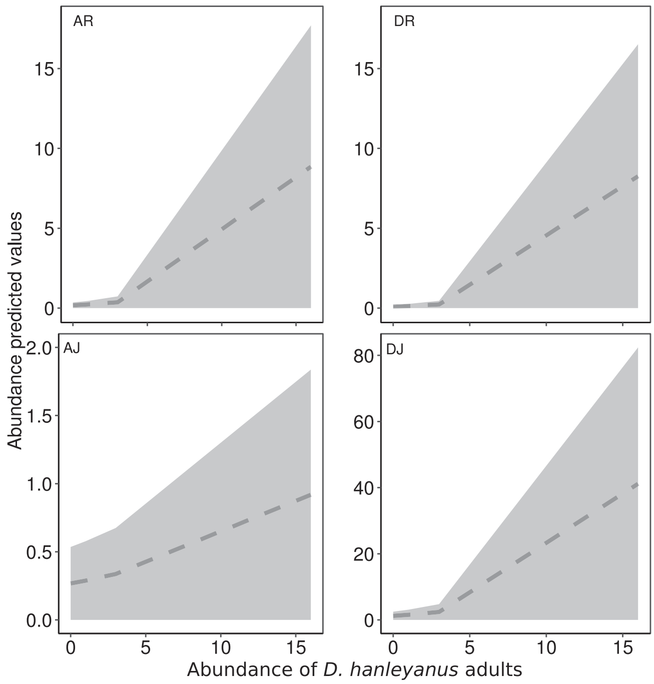

Fig. 4. Regression plot of the predicted abundance in relation to the abundance of *Donax hanleyadun* adults for each clam species/stage, in winter. Estimated abundance mean (black line) with 95% confidence interval (shaded area). AR: recruits of *Amarilladesma mactriodes*, AJ: juveniles of *A. mactriodes,* DR: recruits of *D. hanleyanus,* DJ: juveniles of *D. hanleyanus.*

At spring, the relative importance (RI) of all the assessed variables on recruits and juveniles variation was weak (RI < 0.7, Table 2), indicating that these variables had no effect on the abundances of the infaunal clams analyzed.

4. Discussion

The impact of urbanization over natural ecosystems is an issue of great concern, and sandy beaches constitute a relevant case on this subject. Several studies have demonstrated how different urbanization-related activities affect natural beach communities. Fanini et al. (2009) found alterations in sandy beach macrofauna at both community and population levels due to beach nourishment and the installation of breakwaters. Nourishment cause changes in sedimentology, which affects intertidal beach invertebrate densities and abundances due to habitat degradation (Peterson et al., 2006). Schlacher et al. (2008b) reported lethal damages on the surf clam *Donax deltoides* as consequence of off-road vehicles on beaches. Further, the intensity of human trampling has been associated with a decrease of sandhopper population (Ugolini et al., 2008) and beach macrofauna community densities (Reyes-Martínez et al., 2015). Adverse effects of beach urbanization (which includes all the factors mentioned above) have also been determined on wild populations (González et al., 2014). In the present study, we evaluated the effects of beach urbanization on the population dynamics of two dominant infaunal clam species. Indeed, results demonstrate modulation of clam population components abundance over time relative to beach urbanization.

Beach urbanization affected the abundance of recruits and juveniles of *A. mactroides* (yellow clam), and juveniles of *D. hanleyanus* (wedge clam). Regarding the former, they were found in higher number in MCH as expected. On the other hand, juveniles of *D. hanleyanus* presented higher abundances at VA, an impacted beach, which could be showing an opportunistic behavior of the wedge clams. These species compete for space, and juveniles of *D. hanleyanus* may be directly related to the density of juveniles of the yellow clam (Defeo, 1996). In fact, the increase of wedge clam population densities due to higher fishing effort performed over *A. mactroides* (Defeo and de Alava, 1995) and as a consequence of its massive mortalities (Dadon, 2005) has been reported. Thus, in the face of *A. mactroides* population decline due to beach urbanization at VA, it is very probable that *D. hanleyanus* increase its recruitment due to space release. This pattern does not occur at the other urbanized beach, PM, probably because it is fairly impacted and therefore *A. mactroides* population was less affected and reduced. However, this would be a hypothesis to corroborate in further studies.

An interesting issue to analyze from the results is the different sensitivity of the two studied species (higher in yellow clams). Different shell hardness (Moffett et al., 1998) or different burrowing speed (Schlacher and Thompson, 2012) can lead to differential vulnerability to human trampling, a key factor of recreational beach use. Indeed, this is the case of the species studied here, since *A. mactroides* has a thinner and frailer shell compared to that of *D. hanleyanus*. Also, the differential susceptibility between yellow and wedge clams can be found in literature dealing with other issues than the presented here. Between 1993 and 1995 mass mortalities events of *A. mactroides* has been registered along Brasil, Uruguay and Argentina (Fiori and Cazzaniga, 1999; Mendez, 1995; Odebrecht et al., 1995). The causes of these events are still unknown, although epidemics, red tides, climatic factors, and viruses have been suggested as such (Thompson and Sánchez de Bock, 2007). Interestingly, during these massive mortalities of the yellow clams, *D. hanleyanus* population remained stable (Dadon, 2005); indeed, due to the lack of competition, in some cases, its population increased (Dadon, 2002). Moreover, different tolerance to natural physical factors can be deduced since *D. hanleyanus* is found in reflective, intermediate and dissipative beaches (*sensu* Short and Wright, 1983), whereas *A. mactroides* is restricted to dissipative ones (Herrmann, 2008). The physical characteristics that define those different types of beaches, like granulometry, slope, and energy, are frequently disturbed by beach urbanization (Muñoz-Lechuga et al., 2018). Therefore, it is probable that other intrinsic features of the clam species studied here are triggering the different resilience to beach urbanization.

The effects of beach urbanization on yellow clams were not homogeneous along the two studied years: effects were observed in summer and autumn of both years. During summer, impacts directly related to recreation, like grooming and trampling, would add up to the permanent beach urbanization pressures. In the urbanized beaches studied here, before the arrival of tourists, the sand is smoothed by bulldozers while during their stay, as in most touristic beaches, they are grooming with heavy machines to remove wrack and litter. In general, studies assessing adverse effects of this action over beach macrofauna are focused on wrack-associated invertebrates because they are directly affected due to wrack remove (e.g., Dugan et al., 2003; Gilburn, 2012). However, this action causes an intense habitat disturbance by removing, taking out and compacting sand; therefore, adverse effects on no wrack-associated populations should also be expected (Fanini and Lowry, 2016). In addition, it is well reported that trampling decreases beach macrofauna densities (Machado et al., 2017; Schlacher et al., 2016). Injuries would be done by direct crushing or by sediment compaction (Reyes-Martínez et al., 2015). Therefore, it is likely that these activities are the causes of a higher decrease of the studied bivalve populations during summer. Furthermore, the higher occurrence of the most sensitive components (recruits) of clam populations over this period (Defeo and de Alava, 1995; Defeo et al., 1992) could be leading to higher effects. The effect of beach urbanization observed during autumn would be related to the time needed by the population to recover from the impact. Anywise, these results highlight the importance of sampling also during low-impact periods to avoid an overestimation of the effects of beach urbanization. On the other hand, a difference between years was found in beach urbanization effect during autumn in *A. mactroides* juveniles. In 2010, no effects were found because their abundances decreased at all beaches respect to 2009, which cannot be explained from the variables measured in this study and would be related with natural variation patterns.

Given the previously reported density-dependence of the studied clams (Defeo, 1996; Defeo et al., 1992), and the temporal migration of adults of *A. mactroides* (McLachlan et al., 1996) (see the Introduction section), the potential effect of adult abundances on those of recruits and juveniles was evaluated; however, results showed no influence of this variable on the other population components for both species. The dynamics of natural populations is not determined just by density-dependence factors, but also by density-independent ones, namely, environmental factors (Lima et al., 1999). In fact, this phenomenon has been demonstrated for *A. mactroides* in a study of nine years, where the interaction of such factors explained the temporal variability of an Uruguayan population (Lima et al., 2000). In the case of this study, given the lack of density-dependence with adults, external disturbances would be modulating population dynamics of the studied clams. From results, we can deduce that at least one of such external disturbances is related with beach urbanization. Regarding the observed effect of *D. hanleyanus* adults' abundance on recruit and juveniles of both species during winter, it is probable that the decrease of environmental influences intensifies the inter and intraspecific modulation, although this needs further confirmation.

Besides the effects of beach urbanization reported in the present study, broader ecological consequences can be expected since bivalves play key roles in the beaches ecosystem functioning. In particular, in those environments where these organisms are dominant, as is the case in this study, the benthic community structure could be severely modified (Dadon, 2005). Moreover, clams are important prey items of fishes and shorebirds. The effects of invertebrates' populations decline due to human impacts over their predators have been widely demonstrated (Pereira et al., 2015; Schlacher et al., 2016). Therefore, as stated by other authors, management strategies and conservation policies aimed at reducing the impact of urbanization over beach bivalves are especially needed. In the case of the environments studied here, great efforts would be necessary because the natural state of the beaches is too degraded and the touristic industry is highly developed and established; also, the recovery of a commercial bivalve population could be constrained by these human impacts.

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