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Suspended sediment contribution resulting from bioturbation in intertidal sites of a SW Atlantic mesotidal estuary: data analysis and numerical modelling

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Summary: The suspended sediment contribution arising from the bioturbation activity of *Neohelice granulata* at intertidal sites of the Bahía Blanca estuary was analysed using several approaches, ranging from field experiments to numerical modelling. Crabs from the mudflat remove, trap and erode more sediment from their burrows per unit area than those from saltmarshes, as a consequence of the high population density and the mobility of cohesive sediments. The results obtained through the MOHID simulations showed that the sediments that were bioavailable in the intertidal of Puerto Cuatreros were maintained in the water column much longer than sediments in Villa del Mar. This longer residence time in the area could be because of the geomorphological and hydrodynamic characteristics of the internal area of the estuary, where numerous tidal channels coexist and phenomena of "retention" occur before entry into the main channel. By contrast, in Villa del Mar, located in the middle of the estuary, the sediments are affected by a greater water depth and higher tidal current speeds. In addition, the waves caused by the winds can be a determining factor in the spatio-temporal evolution of the bioavailable sediment in the water column of the study areas.

Keywords: sediments; bioturbation; burrowing organisms; brackish water environment; ecological zonation; burrows.

Contribución de sedimento de suspensión proveniente de la bioturbación en sitios intermareales de un estuario mesomareal del SO atlántico: análisis de datos y modelación numérica

Resumen: La contribución del sedimento en suspensión debido a la actividad de bioturbación de *Neohelice granulata* en diferentes sitios intermareales del estuario de Bahía Blanca, se analizó utilizando diferentes enfoques. Estos enfoques van desde experimentos de campo hasta modelos numéricos. Los cangrejos de la planicie de marea remueven, atrapan y erosionan más sedimentos de sus galerías por unidad de área que los de las marismas, como consecuencia de la alta densidad de población y la movilidad de los sedimentos cohesivos. Los resultados obtenidos a través de las simulaciones MOHID mostraron que aquellos sedimentos biodisponibles en la zona intermareal de Puerto Cuatreros se mantuvieron en la columna de agua mucho más tiempo que los sedimentos de Villa del Mar. Este tiempo de residencia más prolongado en la zona podría deberse a la geomorfología y características hidrodinámicas del área interna del estuario, donde numerosos canales de mareas coexisten y se producen fenómenos de "retención" antes de ingresar al Canal Principal. Por el contrario, en Villa del Mar, ubicado en el medio del estuario, los sedimentos se ven afectados por una mayor profundidad de agua y mayores velocidades de corriente de marea. Además, las olas causadas por los vientos pueden ser un factor determinante en la evolución espacio-temporal del sedimento biodisponible en la columna de agua de las áreas de estudio.

Palabras clave: sedimentos; bioturbación; organismos excavadores; ambiente estuarial; zonificación ecológica; galerías.

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INTRODUCTION

Sediment dynamics is an important aspect to be considered in studies of water quality and problems related to the engineering of coastal areas, estuaries and lagoons. Many contaminants can be absorbed in the sediments, and their presence in the water column influences turbidity and reduces light penetration, affecting photosynthesis and food availability. In particular, the dynamics of cohesive sediments influences sedimentation in closed areas such as commercial ports and marinas, as well as accumulation in sectors that must subsequently be dredged, such as navigation channels. These sediments are composed of fine inorganic particles (clays, silts and very fine sands) and also by organic particles, such as detritus (Franz et al. 2014).

Benthic organisms in marine ecosystems modify the environment at different spatial and temporal scales. Many of these modifications are initially at a microscale, but they are likely to have large-scale effects on benthic seascapes (Meadows et al. 2012). Several studies dealing with bioturbation agree that this is an important factor in the evolution of the Earth's surface (Meysman et al. 2006, Escapa 2007, Wilson et al. 2012, Molina 2013). The burrowing crab *Neohelice granulata* (Dana 1851) is a semi-terrestrial species of tropical and subtropical estuaries of South America, ranging from the San José Gulf (42°25'S, 64°36'W) in northern Patagonia, Argentina, through Uruguay to Lagoa Araruama, Rio de Janeiro, Brazil (22°57'S, 42°50'W). This bioturbator crab builds elaborate and stable burrows in the intertidal during low tides, giving a special physiognomy to the regions where they are found (Spivak 2010). *Neohelice granulata* plays a key ecological role in estuaries as an ecosystem engineer, by making changes in the physical environment that strongly affect other organisms, since their absence or presence has a disproportionate impact on the ecosystem (Kristensen 2008).

During the construction of its burrows, *Neohelice granulata* transports sediments from the depth of the burrow to the surface, placing it in the form of mounds near the entrance (Botto and Iribarne 2000). This removed material (biogenic mounds) is exposed to tidal currents and wave action, favouring bioavailability in the water column (Murray et al. 2002). Moreover, the burrows favour the entrapment of sediment and organic matter that arrives with the tide; the disturbance (turbulence) generates velocities in the vertical direction, thus increasing the rate at which the particles fall into the burrows and slip down their walls (Hetsroni 1989, Iribarne et al. 2000). Active burrowing species such as *Neohelice granulata* may increase bioavailability (bioresuspension) and indirectly increase erosion rates, particularly when crab densities are high (Minkoff 2005). Therefore, sites with burrows and biogenic mounds may have effects on water flow over the intertidal and on the dispersion of bioavailable sediment in the water column.

Hydrodynamic numerical models are an important tool for supporting management in aquatic-coastal ecosystems, integrating theory with empirical data in a computer system that simulates the dynamics of a water body in nature. These models provide information on the general functioning of the ecosystem, and the dynamics and variability of its components (tidal currents, winds, waves, suspended solids, etc.). Moreover, once implemented, calibrated and validated, they can be used to predict or simulate the ecosystem response to different environmental management options or disturbances of the environment (natural or anthropic) (Meadows et al. 2012). The MOHID water modelling system was developed by the Centre for Marine Research and Environmental Technology (MARETEC) belonging to the Technical University of Lisbon, Portugal. It is a system of coupled modules that can be used to estimate hydrodynamic and sediment transport, incorporating waves, winds, and more. MOHID adopts an integrated philosophy for the modular simulation of physical, chemical and ecological processes at different scales (Santos et al. 2002).

Several studies have linked biological data on bioturbation to the abstract parameters in bioturbation models. Gilbert et al. (2003) analysed the influence of burrow spacing and diffusive scaling on sedimentary nitrification and denitrification with an experimental simulation and model approach. Solan et al. (2004) quantified particles bioturbated by subtidal macrofauna and monitored their displacement using time-lapse fluorescent sediment profile imaging, luminophore tracers and model simulation. Jarvis et al. (2010) modelled the effects of bioturbation on the redistribution of ^{137}Cs in an undisturbed grassland soil, and even an open source simulation model for soil and sediment bioturbation was presented by Schiffers et al. (2011).

Numerical models have been implemented in the Bahía Blanca estuary, including studies of hydrodynamic characteristics (Pierini 2007, Pierini et al. 2013, Campuzano et al. 2014), analyses of potential effects of the wastewater discharge system (Pierini et al. 2008, Pierini et al. 2012), a study of the suspension sediment flow (Campuzano et al. 2008), a study of larval dispersion and retention of crustacean species (Cuesta 2010, Miguel 2010) and a study of marsh erosion due to the dynamic interaction between *Neohelice granulata* and *Sarcocornia perennis* (Minkoff et al. 2006). However, no numerical modelling has been performed to estimate the sediment contribution from the bioturbation activity of *Neohelice granulata* in the Bahía Blanca estuary.

The main goal of the present study was to evaluate the suspension sediment contribution resulting from the bioturbation activity of *Neohelice granulata* in different intertidal sites of a mesotidal estuary using several approaches, ranging from field experiments to numerical modelling. We hypothesized that the eco-sedimentary and hydrodynamic differences in two coastal areas will translate into different sedimentary contributions from the intertidal to the water column.

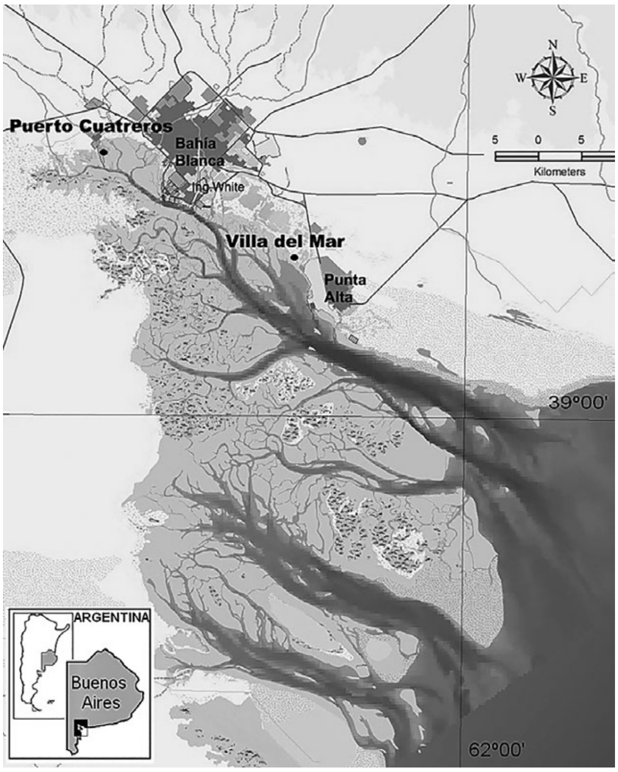

Fig. 1. – The Bahía Blanca estuary, highlighting the sampling sites: Villa del Mar and Puerto Cuatreros.

MATERIALS AND METHODS

Study area

The Bahía Blanca estuary is located in the southwest of the Buenos Aires province and has an approximate area of 3000 km^2 (Fig. 1). It is a mesotidal estuary with a semidiurnal tidal regime. It is characterized by the presence of many islands which are interconnected by an extensive system of tidal channels affected by tides of up to 4 m. The main channel has a long shape with a total length of 68 km and a width varying from 200 m at the header to 4 km at the mouth. The freshwater input to the estuary is weak and comes mainly from two tributaries on the northern shore of the inside of the system: the mean annual runoffs of the Sauce Chico River and Napostá Grande Creek are 1.5-1.9 and 0.5-0.9 m^3 sec^{-1}, respectively (Melo et al. 2004). The seawater salinity in the middle portion of the estuary is about 33.98 (annual mean), while the inner zone becomes hypersaline during dry summers because of the high rate of evaporation (Pierini 2007).

Within the estuary two intertidal sampling areas were chosen to represent the inner and median zone. The first area is located in Puerto Cuatreros (38°44'50"S, 62°23'5"W); it is the most representative site of the inner zone of the estuary in terms of hydrodynamic conditions and shows the most marked differences in both temperature and salinity from the internal sector of the main channel. The inner zone acts as a true estuary where the effect of anthropic actions is significant. The second area is located in Villa del Mar (38°51'25"S, 62°06'59"O) in the middle sector of the same channel and is subject to similar physical conditions to those of the open sea. A distinctive characteristic of this site is the total absence of tidal channels, so there is a total exchange between seawater and sediment on the entire surface of the marsh (Negrín 2011).

Field measurements

We conducted the field experiments in November and December 2015 because these are the months in which the species is most active (Angeletti and Cervellini 2015). Visually identifiable microhabitats characterized by different vegetal compositions and sedimentary and hydrodynamic conditions were preselected. Two sites in the intertidal of Villa del Mar were selected: the high marsh dominated by the species *Spartina densiflora* and *Sarcocornia perennis* (VdM1) and the low marsh dominated by the species *Spartina alterniflora* (VdM2). Two sites in Puerto Cuatreros were also selected: the pure marsh of *Sarcocornia perennis* (PC1) and a plain of non-vegetated tide (PC2). The experiments were carried out following the methodology of Escapa (2007). In the four microhabitats the amount of sediment from biogenic mounds was estimated. Sam-

Fig. 2. – Tubular burrows of *Neohelice granulata.* A, burrow in saltmarsh; B, mock burrow with PVC pipe (the elevation of the mock burrow was only for the purpose of display, after the photograph the pipe was inserted at intertidal level); C, diagram of burrow arrangement.

plings were carried out at low tide, when the area was exposed. From randomly allocated quadrats (0.5×0.5 m side) in each site, all biogenic mounds deposited at the entrance of the active burrows were collected with the help of a small shovel and stored in labelled bags.

In addition, ten active burrows were randomly selected in each microhabitat and their biogenic mounds were collected. These burrows were marked with a labelled stick. After two cycles of tide (24 hours), it was observed whether the burrows had been excavated again. If so, the new mounds placed at the entrance to each burrow were collected with the help of a small shovel and stored in labelled bags to calculate the daily sediment removal rate due to the bioturbation of *Neohelice granulata*.

From the dataset of burrow architecture (Angeletti 2017), mock tubular burrows were made with PVC pipes closed at the posterior end with a plastic cover. PVC pipes simulated the burrows' mouth and vertical development (3 cm diameter and 30 cm length). Five tubes were inserted during low tide in the substrate of each microhabitat to evaluate the effect of burrows on sediment entrapment (Fig. 2). After two tidal cycles (24 hours), the pipes were raked up and the plastic posterior cover was removed to collect the accumulated sediment, which was stored in labelled bags.

To determine the amount of sediment eroded from biogenic mounds by tidal currents, active burrows were selected and their occupants were removed. The mounds were measured and photographed, and then boxes of crab exclusion (0.25 m^2 of plastic frame) were installed in each microhabitat. The boxes were placed around the burrows and their mounds to prevent the crabs from entering the burrows and removing more sediment. After two tidal cycles (24 hours), the excluded mounds were measured and photographed again. All the material was collected with the help of a small shovel and stored in labelled bags for analysis in the laboratory. Replicates of this experience were performed.

Laboratory procedure and data analysis

All sediments collected were oven dried at 60°C for seven days until constant weight was reached. The methodology of the following equations was based on Escapa (2007). The amount of sediment represented by each individual mound was expressed as g burrows^{-1}. The amount of sediment represented by all mounds present in 1 m^2 was expressed as g m^2. The amount of sediment removed per crab per day was calculated as the rate of sediment removal per burrow and was expressed as g burrow^{-1} day^{-1}. To estimate the sediment removal rate per m^2, expressed as g m^{-2} day^{-1}, the following equation was used: TRSi=Sri DCA, where TRS is the sediment removal rate in 1 m^2, SR is the dry sediment removed for a single burrow in a day and DCA is the average density of active burrows in 1 m^2 of each microhabitat (Angeletti 2017).

The sediment entrapped in the mock burrows (PVC pipes) was expressed as g mock burrow^{-1} day^{-1}, and the following equation was used to estimate the entrapped sediment per m^2 (g m^{-2} day^{-1}): STEni=SEni DC, where STEn is the sediment trapped per m^2, SEn is the sediment entrapped in an individual burrow in one day and DC is the average burrow density in 1 m^2 of each microhabitat (Angeletti 2017). In this case, the density of total burrows was used, since all the sediment was entrapped, whether or not the burrows were active.

In order to determine the amount of sediment eroded from the biogenic mounds, the initial and final volumes were calculated through morphometry and height data at different points of the mound (laser distance meter LDM-30 CEM±1.5 mm). Also, in conjunction with the photographs (previous and later views), the volumes of the biogenic mounds were estimated. Subsequently, using humidity percentage data (Angeletti 2017), the initial and final dry weights of the mounds were estimated. The difference between dry weights of biogenic mounds (exposed to the tidal currents during two complete tidal cycles) was calculated and expressed as g burrow^{-1} day^{-1}. To estimate the eroded sediment per m^2 (g m^{-2} day^{-1}), the following equation was used: STEri=SEi DCA, where STEr is the total sediment eroded in 1 m^2, SE is the dry sediment lost by biogenic mound erosion from an individual burrow in a day and DCA is the average density of active burrows in 1 m^2 of each microhabitat (Angeletti 2017).

The null hypothesis of absence of differences among microhabitats was evaluated by one-way analysis of variance (ANOVA) (Zar 1996). In the case of significant differences with ANOVA, posteriori multiple-comparison tests (Tukey test, Zar 1999) were used to identify significant differences. Data were previously transformed to comply with the normality and homoscedasticity assumptions.

Numerical modelling

The MOHID was used to simulate the hydrodynamics (2D integrated into column) of the Bahía Blanca estuary. The model was calibrated and validated by Campuzano et al. (2014). To adequately represent the study areas, we used a modified version of the high-density bathymetry (50×50 m grid) developed by Pierini (2007) with bathymetric data and images provided by remote sensors (Fig. 3).

Monthly average values of discharge from the main tributaries of the estuary (Sauce Chico River and Napostá Grande Creek) were based on monitored data (Pierini 2007, Campuzano et al. 2014). The tide data were provided by the Bahía Blanca Port Management Consortium (CGPBB). Wind intensity (vector module) and wind direction were provided by the CGPBB and by the private company OilTanking-Ebytem (38°49'59"S, 62°0.5'0.1"O), located close to Villa del Mar (6 km). The waves were considered using the fetch, because it is suitable for areas where the ocean does not directly affect the waves and where local waves are generated by wind.

When the MOHID was stabilized (spin up), it was prepared to be able to incorporate the contribution from the bottom resulting from the bioturbation of *Neohelice granulata* in Villa del Mar and Puerto Cuatreros. The

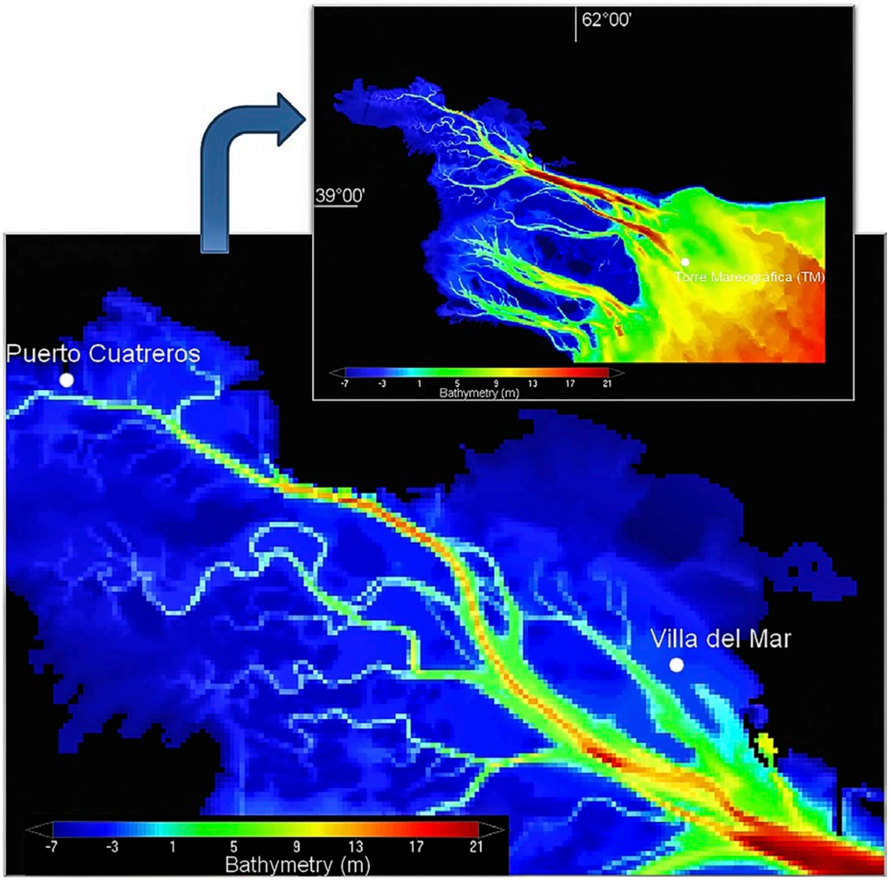

Fig. 3. – Bathymetry of the Bahía Blanca estuary, highlighting the sampling sites (modified from Pierini 2007).

emission rate of bioavailable material obtained in the field experiments was incorporated into the dynamic system as a contribution from the seabed to the water column, considering the dispersion, erosion, flocculation and deposition processes over time (Campuzano et al. 2014; Table 1). The MOHID assumes that the transport of cohesive sediment occurs only in suspension, so the transport depends only on the advection and diffusion equations, with a falling speed included in the vertical advection (Franz et al. 2014). The equations used are described in Nicholson and O'Connor (1986) and Franz et al. (2014).

In order to calibrate some model parameters, they were compared with values obtained by Pratolongo et al. (2010) in Villa del Mar. The model was run during the same dates (23-27 February 2007) to compare shear stress (Tw), wave periods (Tz) and significant wave height (Hs) between measured values and those modelled by the MOHID. The model was calibrated with the information obtained at one of the sampling sites (Villa del Mar). These comparisons could not be done for Puerto Cuatreros due to the lack of backgrounds in this zone, but measurements can be used in this area.

Table 1. – Parameters used in the modelling of Villa del Mar and Puerto Cuatreros.

Parameter	Value	Unit
Erosion shear stress	0.25	N m^{-2}
Erosion rate	1.0 10^{-5}	Kg m^{-2} s^{-1}
Deposit shear stress	0.1	N m^{-2}
Background Roughness Length	2.5 10^{-3}	m
Horizontal diffusion coefficient	0.5	m^2 s^{-1}
Dt	30	s
Dx	50	m
Spin Up	2	days
Runtime	4	days
Courant number	5.6	-

After calibration, the runs in Villa del Mar and Puerto Cuatreros were carried out during the corresponding sampling periods (November and December 2015). In both sectors, the model took into account the tide regime, wave action, winds, tidal currents, suspended sediment in the water column (90 mg l^{-1}; Pierini 2007) and fresh water flow due to continental input, in order to be able to predict the dispersion of the contributed sediment resulting from the bioturbation of *Neohelice granulate* (bioavailable sediment).

RESULTS

Field experiments

The results of the biogenic mounds survey showed that there are significant differences in the amounts of sediment in each mound from each burrow in the microhabitats (F=5.08, $p<0.05$). The smallest ones were found in PC2 (Fig. 4A). Considering the sediment from biogenic mounds in 1 m^2, no significant differences were found among the microhabitats analysed (F=1.10,

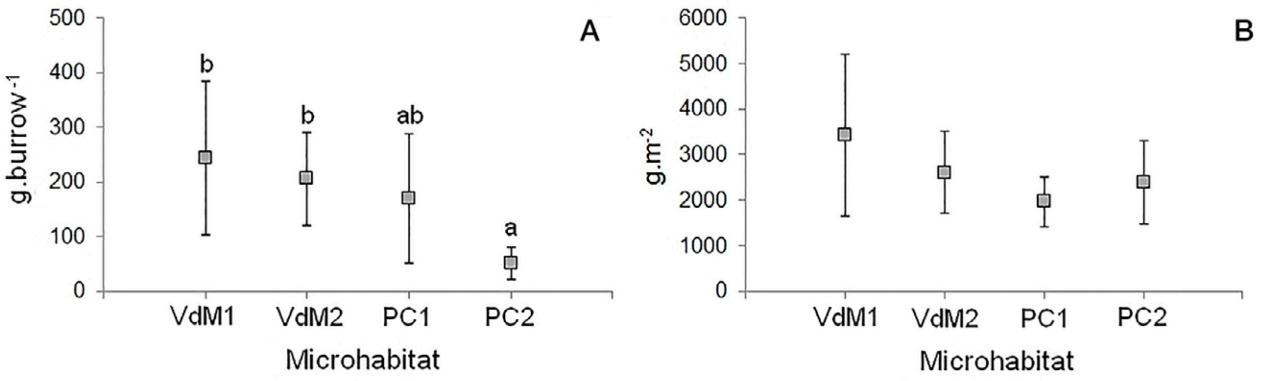

Fig. 4. – Dry sediment from biogenic mounds. A, of an individual burrow. B, in 1 m^2, in the different microhabitats. Mean and standard deviation are shown. Tukey test (same letters indicate that there are no significant differences, α=0.05).

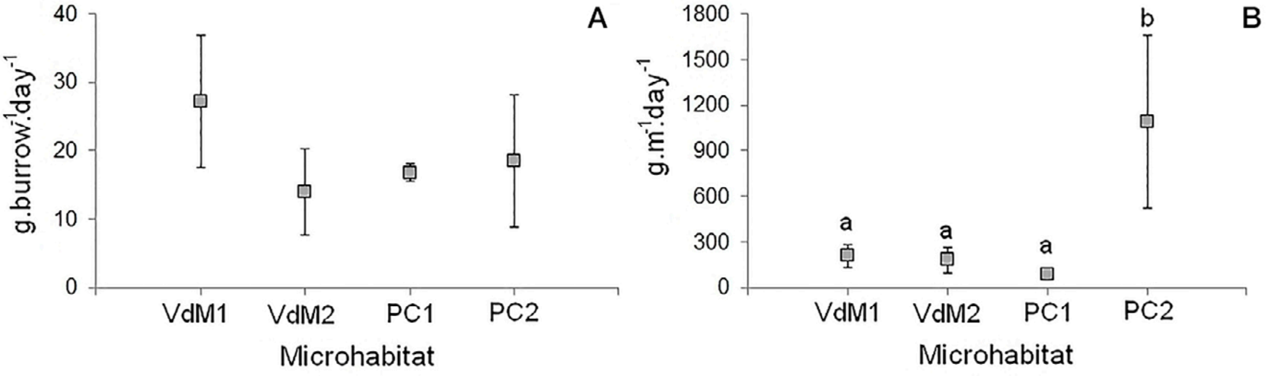

Fig. 5. – Daily dry sediment removal rate. A, of an individual burrow. B, in 1 m^2, in the different microhabitats. Mean and standard deviation are shown. Tukey test (same letters indicate that there are no significant differences, α=0.05).

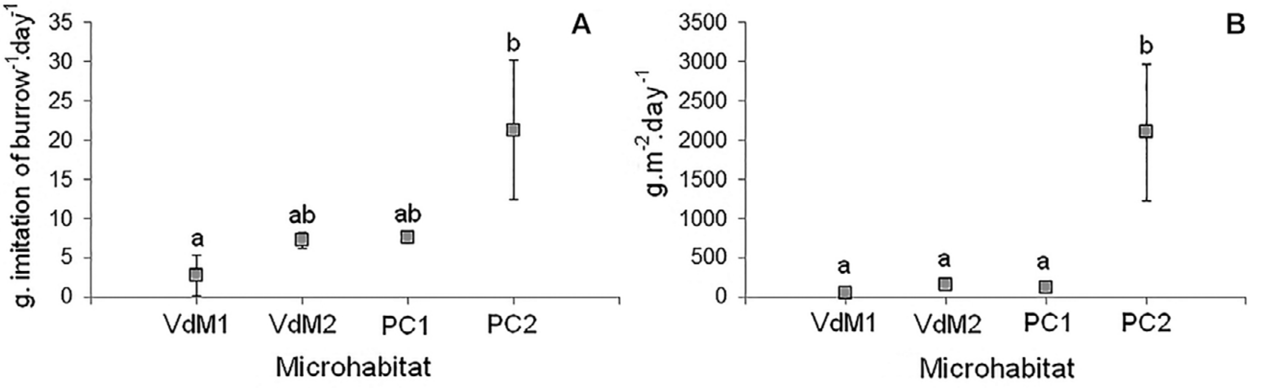

Fig. 6. – Daily dry sediment entrapment. A, of an individual burrow. B, in 1 m^2, in the different microhabitats. Mean and standard deviation are shown. Tukey test (same letters indicate that there are no significant differences, α=0.05).

$p>0.05$). However, it was found that biogenic mounds from Villa del Mar were larger than biogenic mounds from Puerto Cuatreros (Fig. 4B).

The rate of sediment removal in individual burrows was not statistically different among microhabitats ($F=0.32$, $p>0.05$) (Fig. 5A), whereas the sediment removal rate in 1 m^2 showed significant differences among microhabitats ($F=5.30$, $p<0.05$). Burrows at PC2 had a higher removal rate per m^2 than burrows at vegetated sites (Fig. 5B).

Sediment entrapped in mock burrows was statistically different among microhabitats ($F=6.67$, $p<0.05$). Burrows from lower intertidal sites (VdM2 and PC2) entrapped more sediments than burrows from higher intertidal sites (VdM1 and PC1). Burrows from PC2 entrapped the highest quantity of sediment (Fig. 6A). The sediment entrapped in mock burrows in 1 m^2 was also statistically different among microhabitats ($F=15.95$, $p<0.01$). Burrows from PC2 entrapped more sediment per m^2 than burrows at vegetated sites (Fig. 6B).

Eroded sediment from biogenic mounds of individual burrows was not statistically different among microhabitats ($F=1.39$, $p>0.05$). However, it was found that biogenic mounds from Villa del Mar were more eroded than biogenic mounds from Puerto Cuatreros (Fig. 7A). Furthermore, the biogenic mound erosion in 1 m^2 showed significant differences among microhabi-

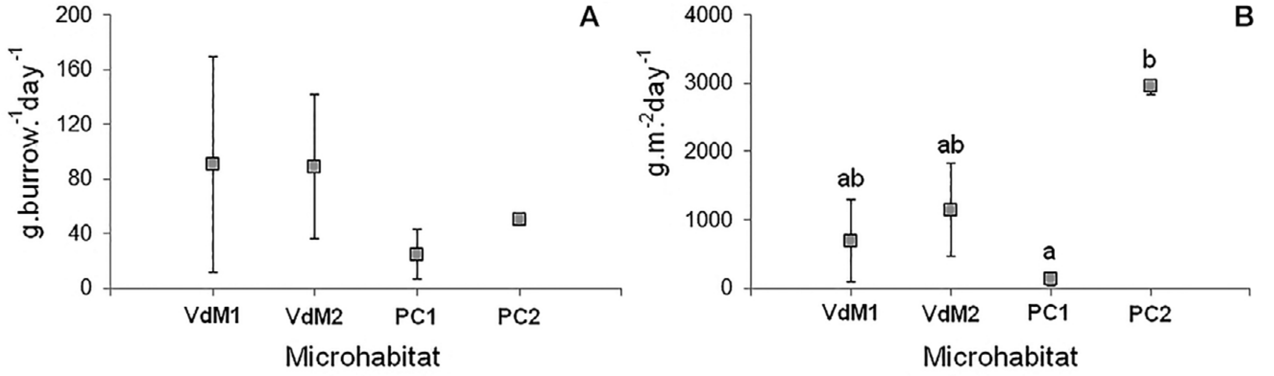

Fig. 7. – Daily dry sediment erosion from biogenic mounds. A, of an individual burrow. B, in 1 m^2, in the different microhabitats. Mean and standard deviation are shown. Tukey test (same letters indicate that there are no significant differences, α=0.05).

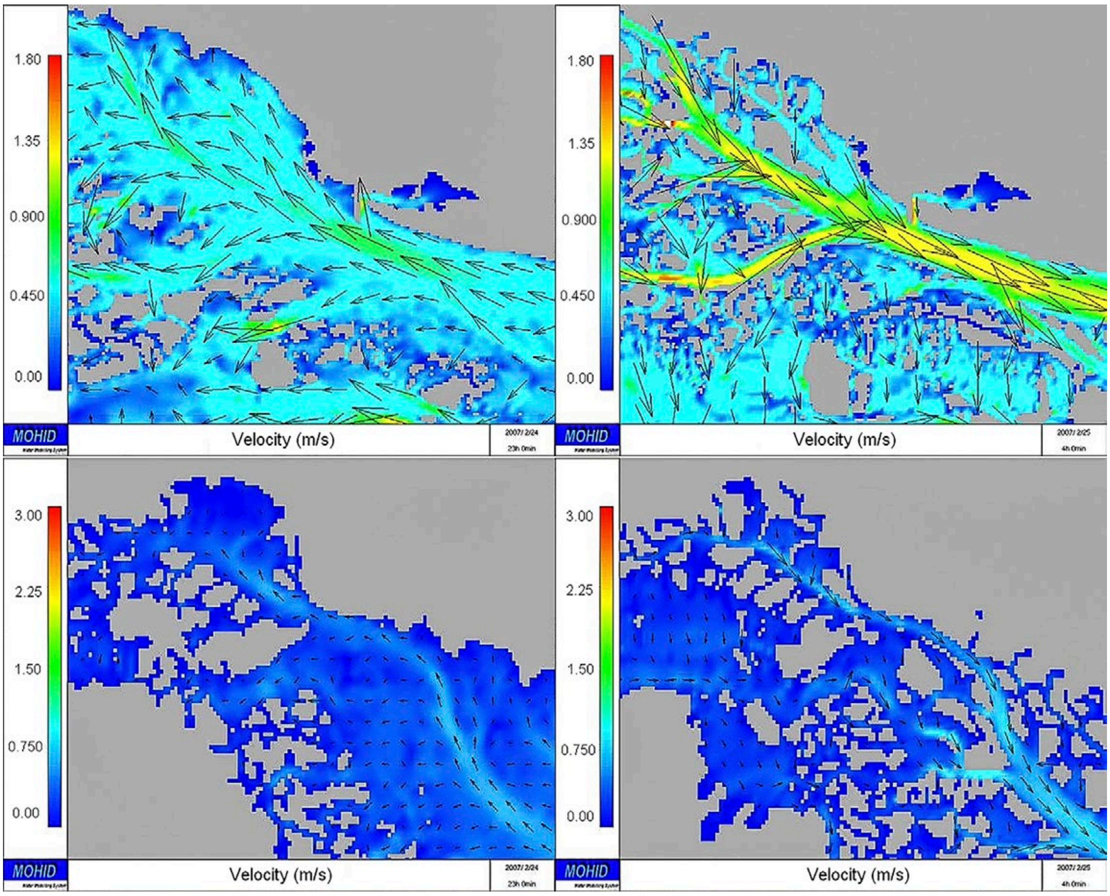

Fig. 8. – Tidal current representation of the middle zone (top) and the inner zone (bottom) of the main channel. To the right the current is observed at rising tide (23 hs on 24-2-2007) and to the left at falling tide (4 hs on 25-2-2007).

tats (F=7.17, p<0.05). The biogenic mounds at PC2 showed greater erosion per m^2 than those at PC1 (Fig. 7B).

Numerical modelling

During the calibration period, the model was running for the same dates as those of Pratolongo et al. (2010), and the wave module was incorporated. The tide comes into the Bahía Blanca estuary from its southern margin, and spreads through the bays and canals. As the tide advances, the water begins to cover the large intertidal areas, amplifying the submerged area. The currents velocities are reduced towards the inner channels of the estuary due to the direct relationship between velocity, depth and surface. During high tides, the connections between channels increase, favouring the exchange of water between adjacent bays. During ebb tide, water drains from the inner channels to the main channel and flows out with higher current intensities (vector module) through central and deeper areas of the channels (Fig. 8).

Simultaneous comparisons were performed between the model results and the values obtained from the reconstruction of current intensities at Villa del Mar (Pratolongo et al. 2010). The tide level reached in the modelling was similar to those obtained by the cited authors. The shear stress, wave height and wave period values (Tw, Tz and Hs, respectively) were also used to compare model results, and correlation coefficients were obtained between these parameters. The Pearson correlation coefficients (r) were greater than 0.70 (r Tw=0.99, r Tz=0.79 and r Hs=0.85). All results indicate a high degree of model performance: high correlation coefficient values and low RMS error values (Fig. 9). Tw had a higher correlation coefficient than the rest of the parameters measured and a lower standard deviation than that found by Pratolongo et al. (2010) (A) (Fig. 9A). Tz values had a lower correlation coefficient than the rest of the measured parameters, a higher RMS error and a smaller standard deviation than A values (Fig. 9B). Hs had a lower standard deviation than the rest of the parameters, resulting in low RMS error values (Fig. 9C).

When the model had been calibrated, the runs were carried out on the sampling dates. The results of the modelling showed that the biosediments are resuspended during high tide and distributed in the water column until homogenized. At Villa del Mar, they remain inside the area until they enter the main channel. The sediment mixture in the water column, visualized through the modelling, was shorter than 24 hours (Fig. 10). On the other hand, the bioavailable sediment at Puerto Cuatreros was mobilized through the inner channels during several tidal cycles, contributing in part to the sedimentary load of these areas. As can be seen in Figure 10D, part of this sediment reached the main channel and another amount returned to the innermost sector. The mixture of this sediment was maintained for more than 24 hours in the water column (Fig. 11).

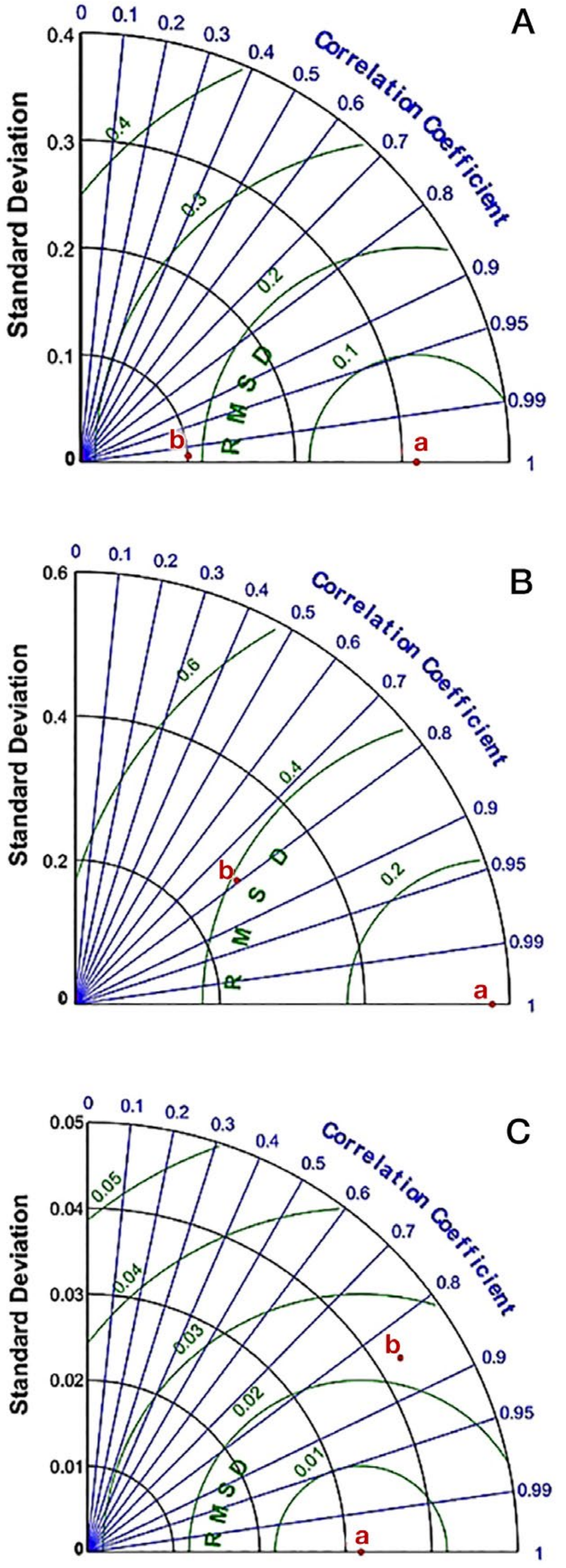

Fig. 9. – Taylor (2001) diagram of model performance for three cases: A, Tw; B, Tz; and C, Hs. In all cases a, Pratolongo et al. (2010) results and b, model results.

DISCUSSION

Neohelice granulata has usually been classified as an ecosystem engineer due to its great burrowing activity and its potential effect on intertidal sediment characteristics. The experiments reported here show that the presence and activity of this crab have more intense effects than those produced by the mere presence of its burrows.

The mean dry weight of each individual biogenic mound differed among microhabitats. Mounds from marshes burrows were larger than mounds from mudflat burrows. If the mounds represent the sediment excavated inside the burrow, it is reasonable to assume that smaller burrows will produce smaller mounds (Escapa 2007), such as burrows from PC2 (Angeletti 2017). Furthermore, the mean dry weight of biogenic mounds in 1 m^2 showed no significant differences among microhabitats. We believe that the high density of active burrows present at PC2 compensates for the small mounds from this microhabitat. It is important to consider that the roughness of the bottom is a consequence of the swell, which puts the sediment in suspension and then the current transports it. Nevertheless, the biogenic mounds contribute significantly to bed roughness and potentially enhance particle trapping

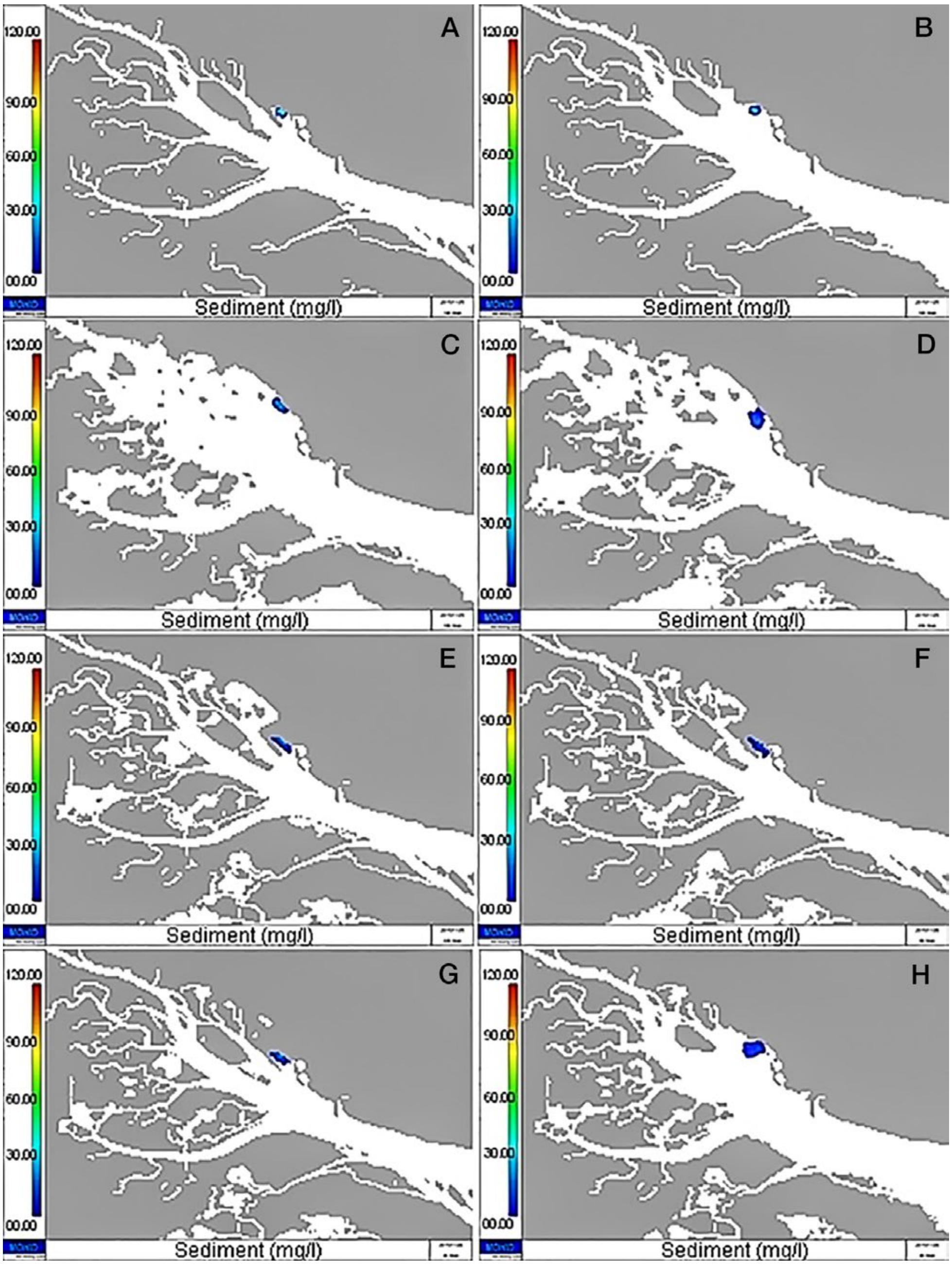

Fig. 10. – Biosediment suspended in the water column at Villa del Mar. A, 14 hs; B, 16 hs; C, 18 hs; D, 20 hs; E, 22 hs on 25-11-2015; and F, 00 hs; G, 02 hs; H, 04 hs on 26-11-2015.

within burrows (Yager et al. 1993, Botto et al. 2006).

The daily sediment removal rate for each individual burrow did not differ among microhabitats, in agreement with Escapa (2007). The differences in daily sediment removal rate per m^2 found among microhabitats were due to the higher density of active burrows inhabiting PC2. In Mar Chiquita Lagoon, Iribarne et al. (1997) found that this species removes 2.5 kg m^{-2} day^{-1} on saltmarshes and 6 kg m^{-2} day^{-1} on mudflats. In Almirante Brown, Escapa et al. (2008) found values of 1.4 kg m^{-2} day^{-1} on saltmarshes and 2.5 kg m^{-2} day^{-1} on mudflats. The process of continuous sediment removal generates a very high bioturbation coefficient, estimated experimentally at 250 cm^2 year^{-1} on tidal flats in Mar Chiquita (Fanjul et al. 2007).

Mock burrows proved to be a useful tool to quantifying entrapped sediment. Burrows on mudflats entrapped more sediment, individually and per area unit, than burrows on saltmarshes. The entrapment of the burrows was continuous throughout the year, as the burrows persist in great numbers even during the winter. In low-flow-energy habitats, such as the inner zone of the estuary, it is expected that bioturbators organisms will generate more sediment entrapment because burrowing activity has different consequences depending on the hydrodynamic conditions of the study site (Murray et al. 2002, Escapa 2007). The burrows act as passive traps of sediment, but depending on the combination between crab density, burrow architecture and tidal flat elevation, different trapping rates are

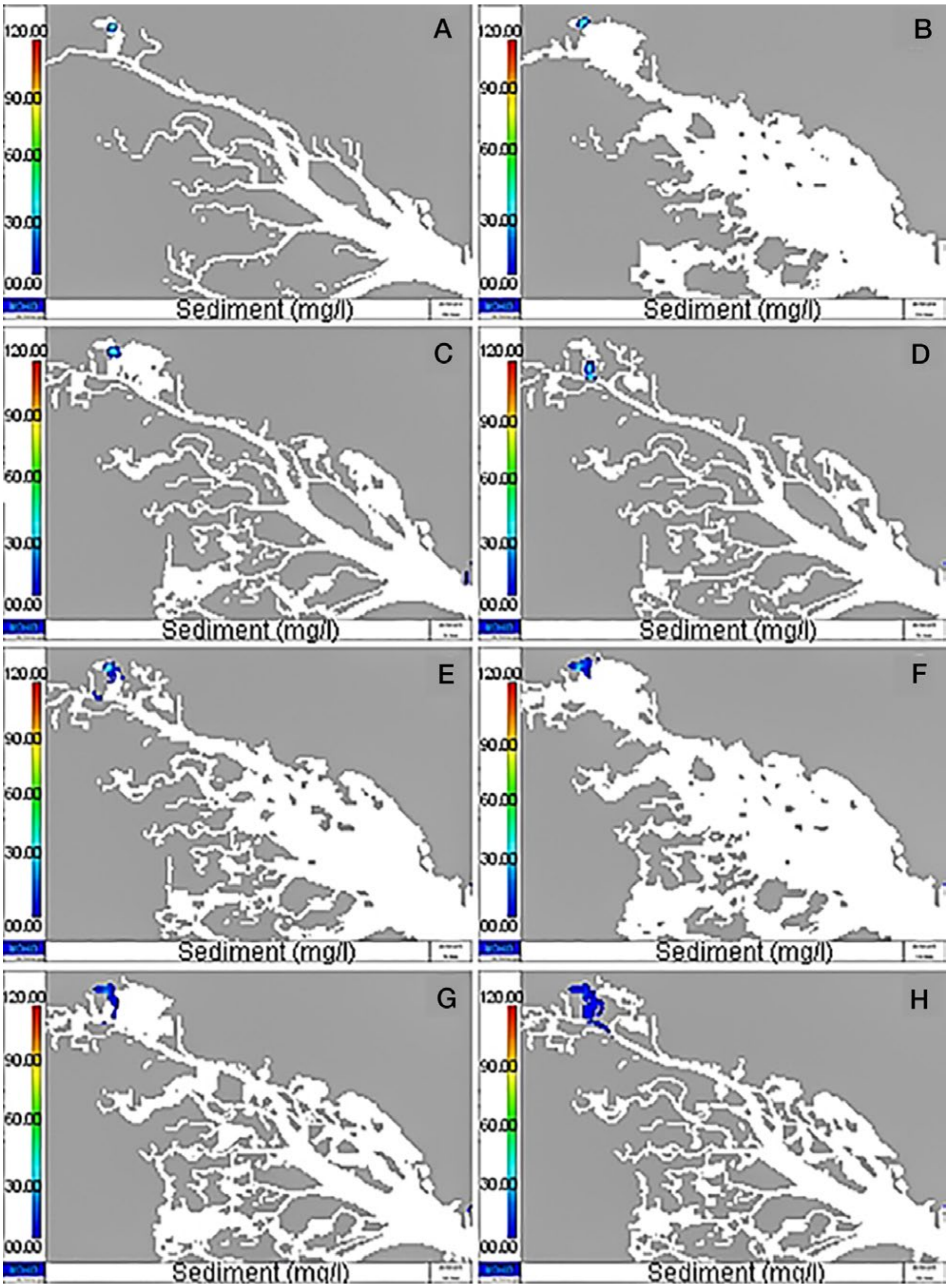

Fig. 11. – Biosediment suspended in the water column at Puerto Cuatreros. A, 15 hs; B, 21 hs on 14-12-2015; and C, 03 hs; D, 05 hs; E, 07 hs; F, 11 hs; G, 14 hs; H, 18 hs on 15-12-2015.

generated in intertidal microhabitats. Previous studies performed in Mar Chiquita reported an average of 93 g burrow^{-1} day^{-1} (Botto and Iribarne 2000), a higher value than those obtained in our field experiments.

The burrowing activity exposes sediment to tidal currents, mainly due to biogenic mound formation. Although mounds were present in all studied microhabitats, they were eroded differentially because sediment transport depends on the grain size and on chemical, biological and hydrodynamic influences (Botto and Iribarne 2000). The biogenic mounds were more eroded in Villa del Mar (VdM1 and VdM2) than in Puerto Cuatreros (PC1 and PC2), although this difference was not statistically significant. Biogenic mounds are more easily eroded in areas with greater current velocity, leading to a greater net loss of sediment (Escapa et al. 2008). Considering active burrow density of each microhabitat (which potentially generated biogenic mounds available to be eroded by current tides), greater erosion per m^2 was found at PC2. The high values of imported sediments inside the burrows and the sediments exported into the water column found in PC2 highlight the dynamism of mudflats compared with saltmarsh areas.

From the results of the four field experiments, we can conclude that removal activity of *Neohelice granulata* is similar in all four microhabitats, considering the daily rate calculated for individual burrows. However, mudflat burrows entrap more sediment than saltmarsh burrows, and in our study we were able to relate this finding to the fine and uncompact nature of sediment at PC2 (Angeletti 2017). Moreover, with no halophyte plants which promote stabilization and sediment deposition, sediment can be mobilized easily on mudflats. Finally, if we consider erosion of biogenic mounds per area unit, the bioavailability of sediment on mudflats is greater.

One of the great advantages of using a mathematical model for integrated coastal zone management is that data sets collected in different periods and sampling intervals can be integrated into a single tool to reproduce and analyse the processes taking place in the water body. The hydrodynamic module of the MOHID has been calibrated for the entire estuary, but there is more information about the principal channel than the rest of the estuary (Campuzano et al. 2014). The results concerning the calibration of the model in Villa del Mar showed good agreement between the measured parameters and the modelled parameters. The results obtained through the simulations coincided with the conceptual model.

The Bahía Blanca estuary is a shallow environment (less than 20 m) with vertical mixing caused by tide and wind effects, establishing a homogeneous column (Pierini 2007, Campuzano et al. 2014). In view of the low sediment input in the system resulting from the reduced flow from rivers and streams and the small contribution of sediments from the open sea, the margins of the channels and the extensive intertidal areas should be considered the main sediment contributor to the water column (Campuzano et al. 2008, Pierini et al. 2008). According to Campuzano et al. (2008), the study area is undergoing an erosion process, in which the sediments are eroded from the channel's margins and eventually exported to the continental shelf. Subtidal areas are a residual source of compacted sediments that would require higher shear stress to erode than the intertidal areas (Pierini et al. 2008).

The results of the modelling showed that sediments were present in the water column for a longer time at Puerto Cuatreros than at Villa del Mar. This longer residence time in this area must be due to the geomorphological and hydrodynamic characteristics of the inner zone of the estuary, where numerous tidal channels coexist. In this area, the bioavailable sediment reaches inland channels of the Bahía Blanca estuary, leading to greater deposition (a "retention" phenomenon) at these sites if propitious conditions (lower velocity) occur before the sediment reaches the main channel. On the other hand, in the middle zone of the estuary, sediments are affected by tidal currents that lead them towards the main channel, so the bioavailable sediment in the water column can be exported to the ocean through the residual streams found in this area (Pierini 2007, Campuzano et al. 2014).

It should be noted that these results are an initial approximation of the bioavailable sediment contribution caused by *Neohelice granulata* bioturbation. The bioavailable sediment is distributed according to tidal currents, predominant winds and wave effects, and can be deposited on the main channel bottom or intertidal areas, or exported to the open sea. The sediment emission rate caused by the bioturbation is a good approximation to a bioturbation coefficient, considering the high crab density of Bahía Blanca estuary (Escapa 2007, Fanjul et al. 2007, Angeletti 2017). It is assumed that entrapment is continuous through the year but numbers of burrows could change between seasons because of the activity of *Neohelice granulata* (Angeletti and Cervellini 2015), so sediment availability (from this source and other sources) could also change. The size of the bathymetry grid (50×50 m) was large enough to respond to the process to be evaluated. It is important to note that the crab areas are much larger than the resolution of the model.

The small-scale analyses presented in this paper showed that *Neohelice granulata* bioturbation interacts with local physical processes such as hydrodynamic conditions. In particular, this factor can affect a wide variety of sedimentological parameters of the study sites. Given the high proportion of intertidal areas that can be potentially eroded by hydrodynamic and biological processes, such as bioturbation, it is important to obtain knowledge of these dynamic processes. As the Bahía Blanca estuary is the most important deep water port system in Argentina and must maintain its navigability permanently, this type of study is fundamental for dealing with a real problem and developing strategies for decision making.

CONCLUSION

Finally, we can conclude that sediment bioturbated by crabs was more bioavailable and stayed longer in the water column in Puerto Cuatreros intertidal than at Villa del Mar. This longer residence time in the area must be due to the geomorphological and hydrodynamic characteristics of the estuary's inner area, where numerous tidal channels coexist and "retention" takes place before the sediment enters the main channel.

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