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EROSIVE PROCESSES DUE TO PHYSICAL - BIOLOGICAL INTERACTIONS BASED IN A CELLULAR AUTOMATA MODEL

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Abstract: The Bahía Blanca Estuary (38° 50' S, 62° 30' W) presents salt marshes where interactions between the local main plant and the dominant crab generate some very characteristics salt pans. These pans alter the normal water circulation and condition its trajectory generating an erosive process. The removed sediment is then exported to the main estuary through the creeks that evolve from those biological-physical interactions. To study it, a conceptual model is proposed, based on the laws deduced from observation of these phenomena in the field, and then verified with measurable data within macroscale time units.

The objective of this article is to model how the interaction between the crab *C. granulatus* and the plant *S. perennis* modifies the landscape of the salt marsh and influences the loss of sediment with a Cellular Automata model. Originally developed to study the effect of the interaction plant – crab in the formation of tidal creeks, the model copies the basic laws that dominate the problem based on purely biological factors. Finally, the volume of sediment that is removed and how it varies in time are evaluated. The model results a very good tool to integrate a large quantity of data collected recently and to be able to extract conclusions on processes that have a very slow dynamics. Additionally, it could reproduce faithfully the salt marsh landscape product of the plants – crab interaction.

Resumen: En el estuario de Bahía Blanca (38° 50' S, 62° 30' O) existen marismas donde la interacción entre la planta principal y el cangrejo predominante generan cuencos salados muy característicos. Estos cuencos alteran la circulación normal del agua y condicionan su trayectoria generando procesos erosivos. El sedimento removido es transportado al estuario a través de los canales de marea que evolucionan a partir de estas interacciones físico-biológicas. Para estudiar estas interacciones se propone un modelo conceptual basado en leyes deducidas de mediciones en el campo de esos procesos y luego verificadas con unidades de macroescala.

El objetivo de este artículo es modelar como la interacción entre al cangrejo *C. granulathus* y la planta *S. Perennis* modifica el paisaje de la marisma e influencia una pérdida de sedimento con un modelo de Autómatas Celulares. Este modelo fue concebido originalmente para estudiar como la interacción planta – cangrejo modifica el desarrollo de los canales de marea. El modelo copia las leyes básicas que dominan el problema, basado exclusivamente en factores biológicos. Finalmente se evalúa cuanto volumen de sedimento es erosionado y su dinámica temporal. El modelo resultó una muy buena herramienta para integrar gran cantidad de datos y posibilitó extraer conclusiones en procesos que tienen una dinámica muy lenta. Además, se pudo reproducir satisfactoriamente el paisaje que la interacción planta – cangrejo generan en la marisma.

Keywords: Salt marshes. Plant – crab interactions. Salt pans. Cellular Automata. Bahía Blanca Estuary (Argentina).

Palabras clave: Marismas. Interacciones planta – cangrejo. Cuencos salados. Autómatas celulares. Estuario de Bahía Blanca (Argentina).

INTRODUCTION

Salt pans and tidal creeks are the main physiographic features in salt marshes (Chapman, 1960). There are opposite evidences where the formation of tidal creeks is attributed to the salt pans (Yapp, 1917; Chapman, 1960; Pethick, 1974; Frey and Basan, 1985; Perillo *et al.*, 1996; Perillo and Iribarne, 2003a,b) and reciprocally (Yapp, 1917; Chapman, 1960; Pethick 1974; Frey and Basan, 1985). Furthermore, salt pan formation involves an important erosive mechanism of which, few quantitative studies are known.

Primary salt pans are formed in zones where vegetation is not uniform, whereas ponds develop in zones where the rate of compactación is greater than the rate of sedimentation (Frey and Basan, 1985). Channel pans are generated by damming of creeks by bank fall out (Yapp, 1917; Chapman, 1960; Pethick, 1974). The latter mechanism is completely opposite to the one described by Perillo *et al.* (1996) and Perillo and Iribarne (2003a) where small pans increase their size obtaining a similar shape to the channel pans by the effect of infragravity waves, and become integrated into a channel by microcliff erosion.

The effects of infaunal and invertebrate activities in marshes have been extensively documented in the literature. They act reducing the resistant capacity of soil, removing the material (Hughes, 1999; Botto and Iribarne, 2000) and preventing the pioneer plants to settle and develop. These organisms that promote changes in the habitat and affect the availability of resources for other organisms have been denominated

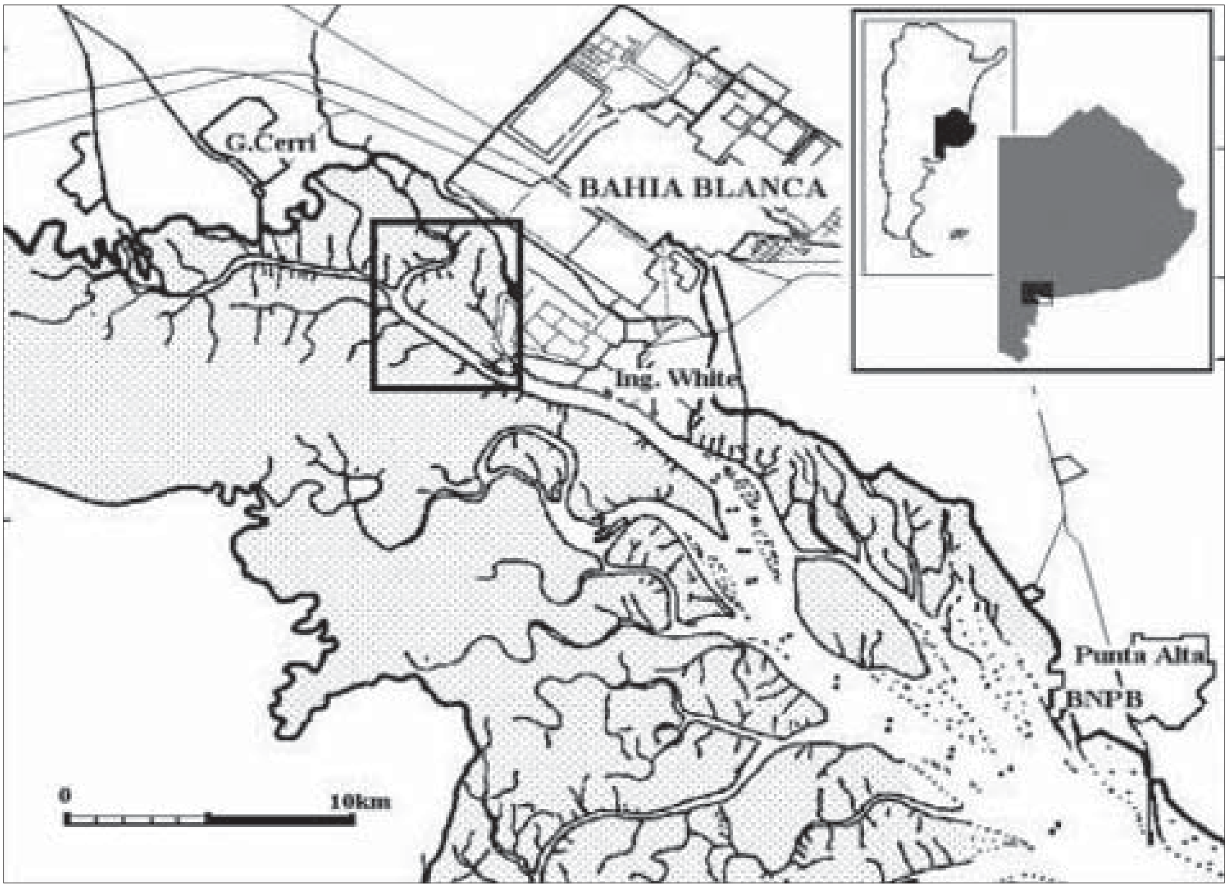

Figure 1. Study area in the Bahía Blanca Estuary (38° 50'S, 62° 30'W) with a surface of 4.5 km^2 including the vegetated marsh (270 Ha) and intertidal zone. This marsh has a mean vegetated coverture of 35%.

Figura 1. Area de estudio en el Estuario de Bahía Blanca (38° 50'S, 62° 30'W) con una superficie de 4.5 km^2 que incluye la zona cubierta por vegetación (270 Ha.) y la zona intermareal. Esta marisma tiene una cobertura vegetal media del 35%.

«ecosystem engineers» (Jones *et al.*, 1994, 1997).

The Bahía Blanca Estuary (38° 50' S, 62° 30' W, Fig.1) presents salt marshes where interactions between the local flora and fauna generate some very characteristics salt pans. These pans alter the normal water circulation and condition its trajectory (Perillo and Iribarne, 2003a,b). The removed sediment is then exported to the main estuary through the creeks that evolve from those biological-physical interactions.

This estuary has a total surface of 2300 km^2, of which about 410 km^2 correspond to islands and 1150 km^2 to the intertidal sector (Piccolo and Perillo, 1999). It is a mesotidal system with very little fluvial input covered by extensive tidal flats and predominance of low salt marshes, although few mean and high marshes are observed. The particular area where this study was developed corresponds to one of the high marshes with an area of about 4.5 km^2 (Fig. 1) which is covered by the tides on average 40 times per year and the tidal amplitude reaches 0.6 m above the salt marsh (Minkoff *et al.*, 2005a).

In the SW Atlantic Ocean bays and estuaries from southern Brazil to San Antonio Bay (Argentina), the tidal flats and salt marshes are dominated by the burrowing crab *Chasmagnathus granulatus* (Iribarne *et al.*, 1997; Bortolus and Iribarne, 1999; Botto and Iribarne, 2000). This species lives in tidal flats and marshes vegetated by the halophitic plants of the genus *Spartina* and *Sarcocornia* (Spivak *et al.*, 1994; Iribarne *et al.*, 1997; Bortolus and Iribarne, 1999). The studied salt marsh is dominated by *Sarcocornia perennis* with sporadic individuals of *Spartina alterniflora* and *Spartina densiflora*.

S. perennis grows forming ellipses whose axes reach up to 30 to 50 cm being up to 30 cm tall in summer. This condition is propitious for the crab *C. granulatus* to dig its burrows among the bushes. Once the crab has colonized the bushes, the bushes grow outward in such a way that the central part is depopulated of vegetation. As a consequence a depressed ring is formed (called ring salt pan, Minkoff *et al.*, 2005a) (Fig. 2), and it continues growing outwards enclosing a population of crabs which in turn continues displacing the inner ring (Perillo and Iribarne, 2003a, b).

In a more advanced state of growth, the rings will reach a diameter of 10 m being up to 1.5 m wide. Eventually in the proximity of another ring, they may join forming «8-like» figures or still more complex (called patch salt pan, Minkoff *et al.*, 2005a) (Fig. 2). The inside of these patches become slightly depressed due to the crab activity where the sediment is soft and with high water content (Perillo and Iribarne, 2003a). Surface lowering is most likely due to sediment extraction by the crabs and subsurface erosion by groundwater.

Whether an isolated patch (ring salt pan structure) or several integrated patches (patch salt pan structure) occur near the arm of a creek, the creek then behaves like a water concentrator when the tide ebbs or after rainfall, through which all the water is discharged to a main channel (Minkoff *et al.*, 2005a) (Fig. 2). Because those pans are composed by a softer material with a high density of burrows (until 50/m^2) (Iribarne *et al.*, 2003) it is easily eroded and becomes a new tributary of the creek where it drains. In all the salt marsh, this pattern of ring salt pans and patch salt pans are associated with the tributaries in formation.

The crab-vegetation dynamics in the salt marsh presents variations that cannot be quantified in a reasonable period of time. To study it, a conceptual model is proposed based on the laws deduced from observation of these phenomena in the field, and then verified with measurable data within macroscale time units (Perillo, 2003). The result of this phase is applied to the modelling of the topography, which inherits the typical characteristics of the crab-vegetation interaction and is the final result of the model

The interaction between *S. perennis* plant and *C. granulatus* crab is based on simple laws, but whose result is a complex biological mechanism that causes an erosive process on the salt marsh and favours the formation of tidal creeks (Escapa, 2003). These types of problems, based on simple laws, have been modelled with good precision by Cellular Automata models (Dunkerley, 1997; Matsinos and Troumbis, 2002; Aassine and El Jai, 2002; Bandini and Pavesi, 2002).

Therefore, the objective of this article is to model how the interaction between *C. granulatus* and *S. perennis* modifies the landscape of the salt marsh and influences the loss of sediment with a Cellular Automata model. Originally developed to study the effect of the interaction plant - crab in the development of tidal creeks (Minkoff *et al.*, 2005b), the model copies the basic laws that dominate the problem based on purely biological factors. These laws were deduced from field measurements and verified with a second field data set (Minkoff *et al.*, 2005b). Finally, the volume of sediment that is removed and how it varies in time are evaluated.

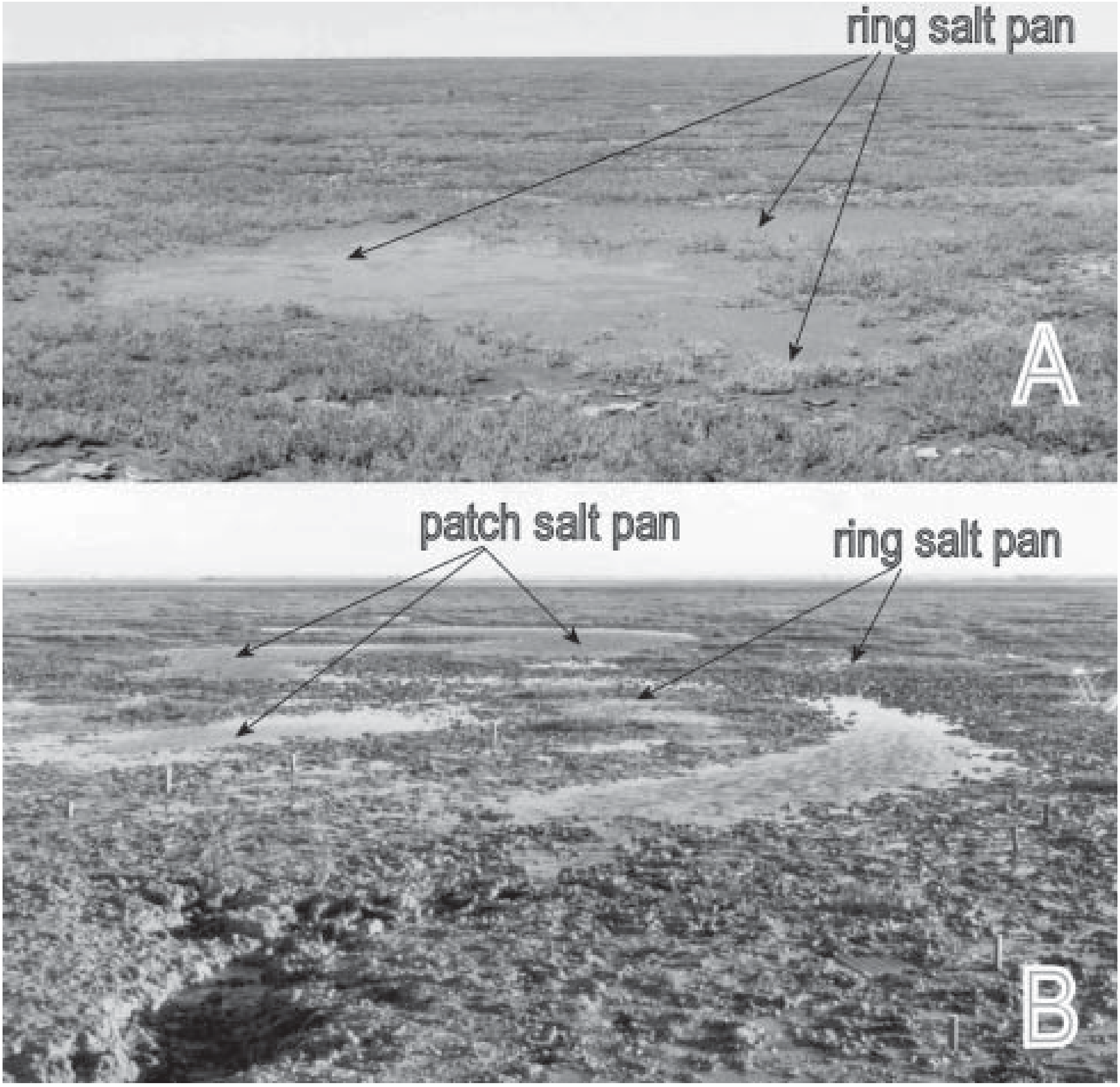

Figure 2. Scheme of ring salt pans and patch salt pans. a) Patch salt pan formed from several ring salt pans. b) The wet zone shows a subbasins formed by the merging of various patch salt pans that drain towards the creek.

Figura 2. Esquema de los cuencos de anillos de plantas y los cuencos de parches de plantas. a) Cuencos de parches de plantas formados por varios cuencos de anillos de plantas. b) La zona húmeda muestra una subcuenca formado por la unión de varias cuencos de parches de plantas que drenan hacia un mismo canal.

CELLULAR AUTOMATA MODEL DESCRIPTION

Basically Cellular Automata (CA) models are idealizations of real systems, applied in a dimension lattice, where the space and time are discrete variables. The laws that they represent are simple, can be deterministic or stochastic, and are applied simultaneously in all points of the grid. Definitions of CA are given by Wolfram (1994) and Sipper (1997) whereas a complete description can be found in Worsch (1999). Formally, they can be summarized by considering CA as a set of rules (A)

$$A = (L, S, N, f), \qquad (1)$$

where L is a grid of d dimensions with cells c depending on the shape of the grid, S is the finite set of values that a cell can take, *N (c)* is the neighborhood of cells that interact with *c*, and *f* is the transition function that defines the dynamics of the CA. Thus the state

$$s_{t+1} = f(s_t(N(c))) \qquad (2)$$

That is, in any point of the grid, the state of the following step depends on the application of the transition function in the neighborhood that interacts with it in the present step. In addition, an initial and boundary conditions must be established for each problem.

The bidimensional CA model proposed is based on the bidimensional neighborhood scheme of Moore (El Yacoubi, 2003) with a 5 cm resolution. The transfer functions are deduced by the rate of growth of the external and internal diameter of the rings, the internal vs. external diameter relation and the accretion of the salt pan versus the external diameter (Minkoff *et al.*, 2005b, Fig. 3). The sampling period was 30 days «10 days, which is the time step of the model. To simplify the problem, it is supposed that the diameters correspond to circles with area equal to that of the patches. The initial condition is a random and uniform distribution of plant seeds. The distribution of external and internal diameters, the relation between the internal vs. external diameters and a power law between the area and perimeter of plant patches obtained from an aerial photo are controlling parameters for the model.

As a first step in the model application, the external ring growth is studied applying a transfer function where each cell that represents a portion of the plant (Fig. 4a) is transformed into a cell array (Fig. 4b) with

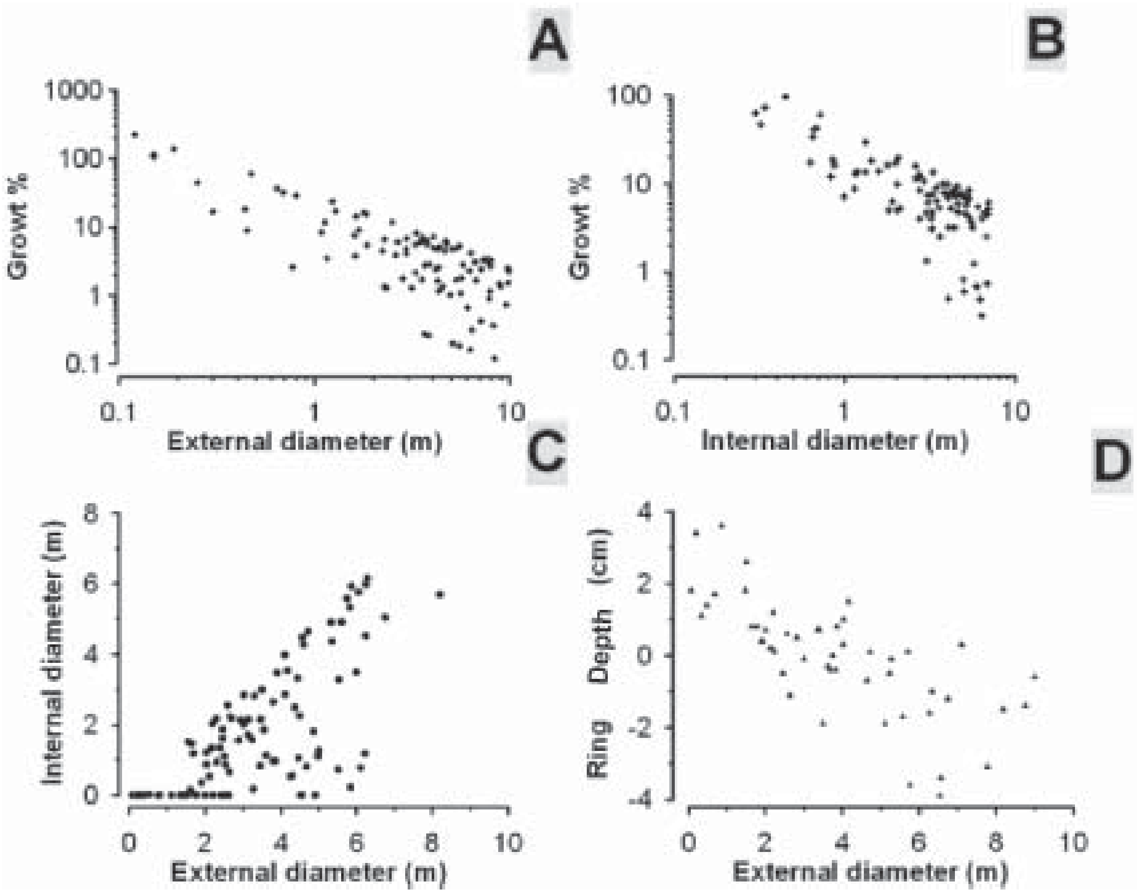

Figure 3. Measured variables in the salt marsh employed to estimate the transition functions for the Cellular Automata model considering a total sampling period of 3 years. a) percentage growth of the external ring vs the external diameter of the *S. perennis* ring, b) percentage growth of the internal ring vs the internal diameter of the *S. perennis* ring, c) relation between the internal diameter vs the external diameter of *S. perennis* rings, d) accretion of the patch of plant vs the external diameter of *S. perennis* rings.

Figura 3. Variables medidas en la marisma empleadas para estimar la función de transición para el modelo da Autómatas Celulares considerando un período de muestra de tres años, a) Crecimiento porcentual del anillo externo vs. diámetro externo del anillo de *S. perennis,* b) Crecimiento porcentual del anillo interno vs el diámetro del anillo interno de *S. perennis*, c) Relación entre el diámetro interno vs el diámetro externo de *S. perennis*, d) Acumulación en el parche de plantas vs el diámetro externo de *S. perennis*.

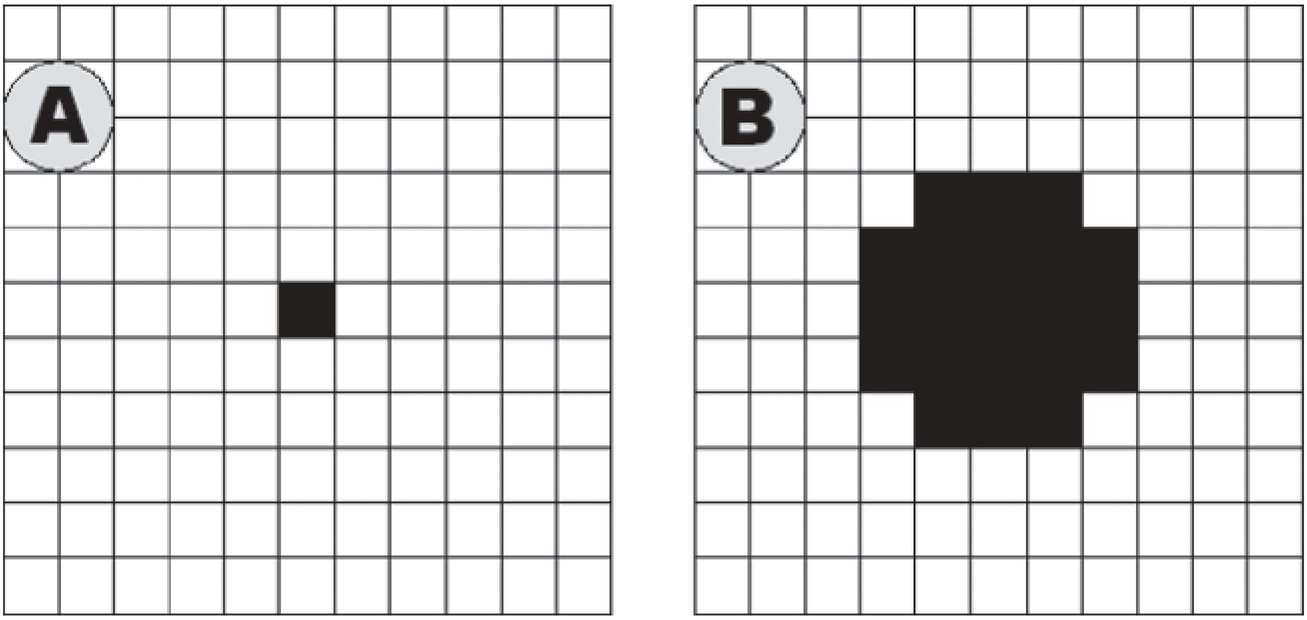

Figure 4. Array through which a cell (A) can be dilated by an array of cells (B)
Figura 4. Arreglo por el cual una célula (A) puede ser dilatada por un arreglo de células (B).

a given probability distribution as the model iterates. This operation is known as dilation (Gonzales and Woods, 1992; Haralick and Shapiro, 1992) but conditioned to the probability distribution. The shape of the resulting array represents a circle formed by a small number of cells. The probability distribution may or may not be constant and must satisfy the law of real-plant growth according to the external diameter. It was found that this relation of probabilities versus diameters was well represented by an asymptotic exponential curve (Minkoff *et al.*, 2005b):

$$\mathrm{Pr}\_D_{te} = 0.005427 + 0.6623.e^{\frac{-D_{te}}{1.5841}} \tag{3}$$

being Pr_D_{te} the probability whereupon the process of expansion in a cell occupied by plants can take place, so that in an iteration the model simulates the growth in a sampling period and D_{te} *is* the external diameter measured at time *t.*

The same procedure was applied for the inner part of the ring colonized by crabs. In this case the function found was (Minkoff *et al.*, 2005b):

$$\mathrm{Pr}\_D_{ti} = 0.3 + 0.3 \times \eta \tag{4}$$

where *ç* is an uniform random number in the range [0,1], and Pr_D_{ti} the probability whereupon the process of expansion in a cell occupied by crabs can take place, so that in an iteration the model simulates the growth in a sampling period and D_{ti} *is* the internal diameter measured at time *t.*

Finally, the depth of the patches (*h* (cm)) versus the external diameter was adjusted with the curve (Minkoff *et al.*, 2005b):

$$h = 1.859 - 0.498 \times D_{te} \tag{5}$$

This depression is the level value measured in the center of the ring. The ring salt pan formed within the ring is assumed to have a form of revolution paraboloid, whose maximum depression agrees with *h* in the midpoint of the ring.

RESULTS AND DISCUSSION

The simulated land surface area was 2.25 Ha, whereas the salt marsh has a surface covered of vegetation of 270 Ha. This simulated zone is small compared to the whole surface of the salt marsh but responds to the large power of calculation and amount of memory that is needed for this type of models (Worsch, 1999). The model was verified satisfactorily with the additional set of laws by means of statistical tests (Minkoff *et al.*, 2005b). From the point of view of biological processes, the model is a simplification because rates of natality or mortality are not considered. The competition by resources and the limitation of space were not considered either. Additionally, it could reproduce faithfully the salt marsh landscape product of the plants – crab interaction (Fig. 5). To reach the maturity state (that is, the actual state) in the salt marsh

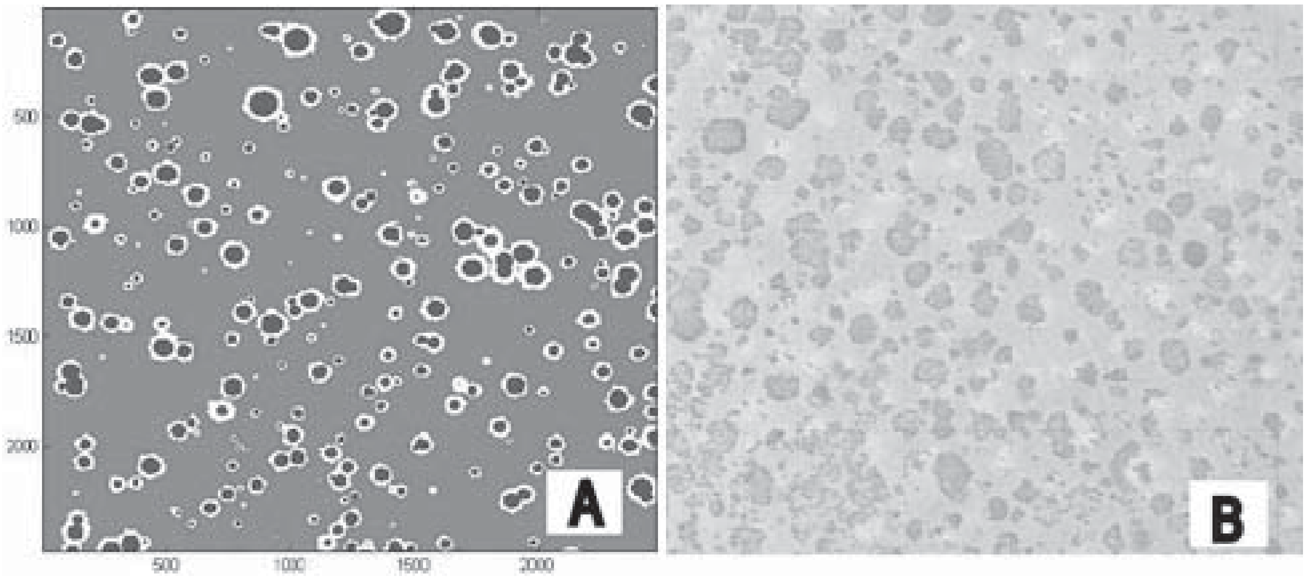

Figure 5. Results of the Cellular Automata model, a) distribution of patches of *S. perennis* in the area where the gray color indicates the bare soil, the dark color the inner part of the patches colonized by crabs and the light color the rings of plants, b) aerial photo showing the plant patern over the marsh.

Figura 5. Resultados del modelo de Autómatas Celulares, a) distribución de parches de *S. perennis* en la zona, donde el color gris indica suelo desnudo, al color oscuro indica la parte interna de los anillos colonizada por cangrejos y el color blanco el anillo de plantas, b) Fotografía aérea mostrando el patrón de plantas en la marisma.

took a total of 182 iterations. The modeled processes occur in the warm period for the Southern Hemisphere, mainly from December to March, which means a time interval of 45 years.

In the analyzed period, 5.11 $m^3 Ha^{-1}$ of sediment were brought into circulation in the estuary for the plant – crab effect (Fig. 6a) according with the results of the simulation. A small initial accumulation is observed because the small patches are not colonized by crabs, and in this state they trap sediments. Based on (5), the erosion starts when a critical diameter is reached of $D_{te} > 3.7$ m. Whereas the rate of erosion increases, there is also a stage where sediment accretion occurs (Fig. 6b). These stages of accumulation must give birth to new plants that trap sediments, in opposition with the developed patches where erosion is dominant. For the last year (last 4 iterations), 0.38 $m^3 Ha^{-1}$ of sediment coming from the patch plants entered in circulation in the estuary.

Extrapolating the results to the 270 Ha of analyzed salt marsh, 1380 m^3 of sediment where transferred from the marsh to the estuary during the whole process. Only in the last year more than 13 % (183 m^3) of the total sediment exported were distributed in the estuary indicating that the process keeps exporting more sediment every year in a pronounced exponential curve.

Quantitative reference data of erosive processes by salt pans are unknown. If we suppose that all the removed material is uniformly distributed in the salt marsh surface by means of a transformation, it would be possible to compare it with rates of erosion – accretion over the marsh. For the whole period of simulation, the rate of transformed sedimentation was 0.026 mm $year^{-1}$, whereas for the last year only was 0.068 mm $year^{-1}$. In this marsh, erosion – accretion over the surface was surveyed in the last 4 years (Minkoff *et al.*, 2005a) resulting in a mean value of -1.75 mm $year^{-1}$, with a maximum value of 14.76 mm $year^{-1}$ and a minimum value of -9.5 mm $year^{-1}$. Several authors agree that the erosion-accretion rates are in the order of mm $year^{-1}$ (Chapman, 1960; Frey and Basan, 1985: Luternauer *et al.*, 1995), but their reference values correspond to accretion rates. Therefore comparing the transformed erosion product of the salt pans vs the erosion in the surface, we observe that it is a relatively low value (two orders of magnitude smaller).

CONCLUSIONS

The model presented is a very good tool to integrate a large quantity of data collected recently (Minkoff *et al.*, 2005b). Also it was able to extract conclusions on

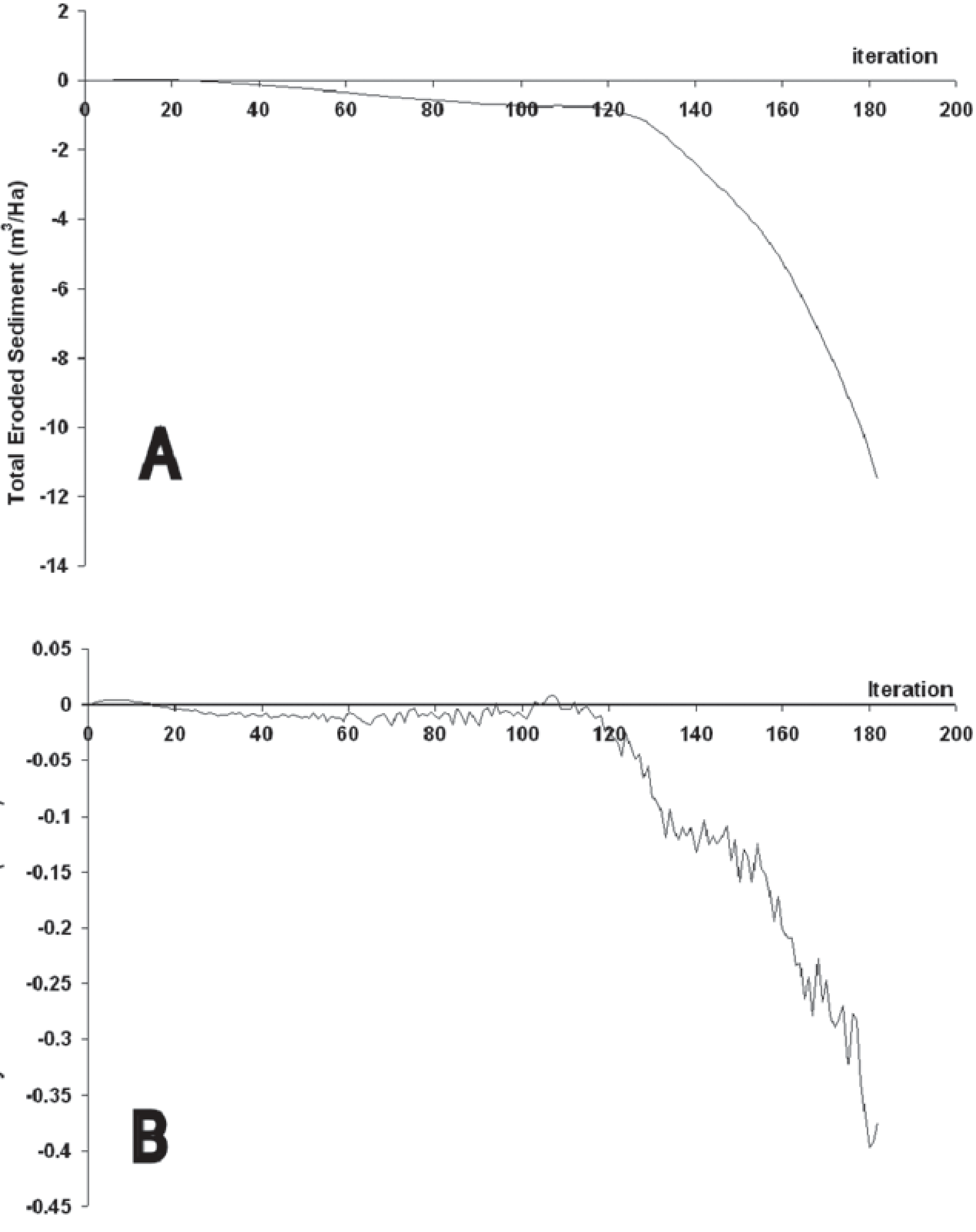

Figure 6. Eroded sediments in the whole simulation in m^3 Ha^{-1}, a) sediment accumulated/eroded vs. iteration number, b) eroded sediments between 2 iterations vs. iteration number.

Figura 6. Sedimento erosionado durante toda la simulación en m^3 Ha^{-1}, a) Sedimento erosionado/acumulado versus al número de iteración., b) Sedimento erosionado en dos iteraciones sucesivas versus el número de iteración.

processes that have a very slow dynamics. From the point of view of the biological processes, the model is a simplification because it does not consider rates of natality and mortality of plants and crabs. The competition by resources and the limitation of space were not considered either. Additionally, it could reproduce faithfully the salt marsh landscape product of the plants – crab interaction. To reach the state of maturity in the salt marsh took 182 iterations, that is, a lapse of 45 years from a state without vegetation to reach the present state. Nevertheless, when reaching the final situation it represents the present conditions in the salt marsh and shows the landscape adequately. Therefore, the results of the last iterations are more representative, whereas the initial results are only illustrative, since a ratification of the information is not possible for the period modelled.

In the analyzed period, 5.11 m^3 Ha^{-1} of sediment were brought in circulation into the estuary, whereas for the last year, 0.38 m^3 Ha^{-1} of sediment was removed. Extrapolating the results to the 270 Ha of analyzed salt marsh, 1380 m^3 of sediment entered in circulation in the system during the whole process and 183 m^3 of sediment in the last year. For the whole period of simulation, the rate of transformed sedimentation was 0.026 mm $year^{-1}$, whereas for the last year was 0.068 mm $year^{-1}$. Comparing the transformed erosion product of the salt pans vs the actual measured erosion in the surface, we observe that it is a relatively low value (2 orders of magnitude smaller).

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