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Causes and consequences of salt-marsh erosion in an Atlantic estuary in SW Spain

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Abstract. This study reports on the quantification of horizontal erosion by undermining of slopes in the atlantic mesotidal salt marshes of Odiel, SW Spain, and analyses its causes and consequences. Horizontal erosion has produced considerable losses of salt marsh area, including zones of mature salt marsh. Human pressure, such as from water-borne traffic or the exploitation of the slopes for the capture of bait, increases the natural erosion processes. The role of vegetation in protecting the slopes against erosion is studied. Channel banks covered with plants, many of which belong to species with long-living, above-ground creeping stems, were less eroded than those without vegetation cover. The enormous volume of sediments moved (ca. 7000 m^3 in one year) could contribute to the silting-up of the navigable channels of the estuary, so that continual dredging is necessary to allow access to shipping. These sediments are highly contaminated, and dredging exposes them more directly to the trophic network of the estuary. There is a considerable loss of natural resources. Finally, the integrated management of this coastal ecosystem is discussed.

Keywords: Bank; Erosion control; Heavy metal; Human pressure; Odiel; Undermining.

Nomenclature: Tutin et al. (1968-1993).

Introduction

Coastal salt marshes are ecosystems of great ecological and economic importance. Their functions include providing habitats and breeding areas for many animal species. They have a very important role in the food chain, in the quality control of the environment, and in sedimentation in estuarine systems (DeLaune & Gambrell 1996; Greeson et al. 1979; Tiner 1984).

In the last two decades, many studies have revealed large losses of coastal marshes in estuaries of the United States (DeLaune et al. 1983; Gagliano et al. 1981; Gosselink & Bauman 1980; Kearney & Stevenson 1991; Phillips 1986), Asia (Chung 1982) and Europe (Ranwell 1967; Barros 1996; Brivio 1996). The causes and mechanisms of such losses must be identified if effective control measures are to be established and optimum results achieved in restoration and conservation projects for these areas.

Continental subsidence, insufficient vertical accretion, rise in sea level and human activities have been identified as causes of marsh loss (DeLaune et al. 1983; Stevenson et al. 1985; Palanques & Guillén 1998). In most cases, the main mechanism has been attributed to erosion (Kearney & Stevenson 1991; Nyman et al. 1994; Phillips 1986), although plant degeneration has been indicated as a first step (Pezeshki et al. 1991; Turner 1990). Of the erosive processes, undermining or undercutting of the drainage channel banks has caused considerable loss of salt marshes through erosion under the living root zones caused by flowing drainage water, which leads to the overhang of marsh vegetation growing over the banks (Nyman et al. 1994; Stevenson et al. 1985). The result is the formation of slopes which are steep at the marsh-channel interface (Broome et al. 1992).

This study was carried out in the Odiel salt marshes (marismas del Odiel) (SW Spain). They form one of the most extensive mesotidal salt marshes in the Iberian Peninsula. Because of their high ecological value, with a great variety of animal and plant species, they are protected as a Natural Park (Paraje Natural) and as a Biosphere Reserve by UNESCO.

Recently, shipping, establishment of industrial centres (from the 1960s), construction of two dykes (1970s - 1980s) and bait capture (from the 1980s), have increased in the Odiel salt marshes. This has been accompanied by loss of salt marsh due to the erosion of banks at both sides of many channels, which is endangering areas of great ecological value. Silting-up of navigable channels, probably partly as a result of deposition of the eroded sediments, is causing serious economic problems to the local industry, which has to provide continual dredging to allow the entrance of shipping. The eroded sediments are highly contaminated with heavy metals (Luque et al. 1997), so their movement by dredging and erosion would introduce them into the estuarine trophic network (Luque et al. 1999). The aims of this study are: (1) to characterize and quantify erosive processes throughout the estuary, (2) to identify their causes and possible consequences with a view to creating an integrated management plan for this coastal ecosystem and (3) analyse the role of the vegetation in erosion control.

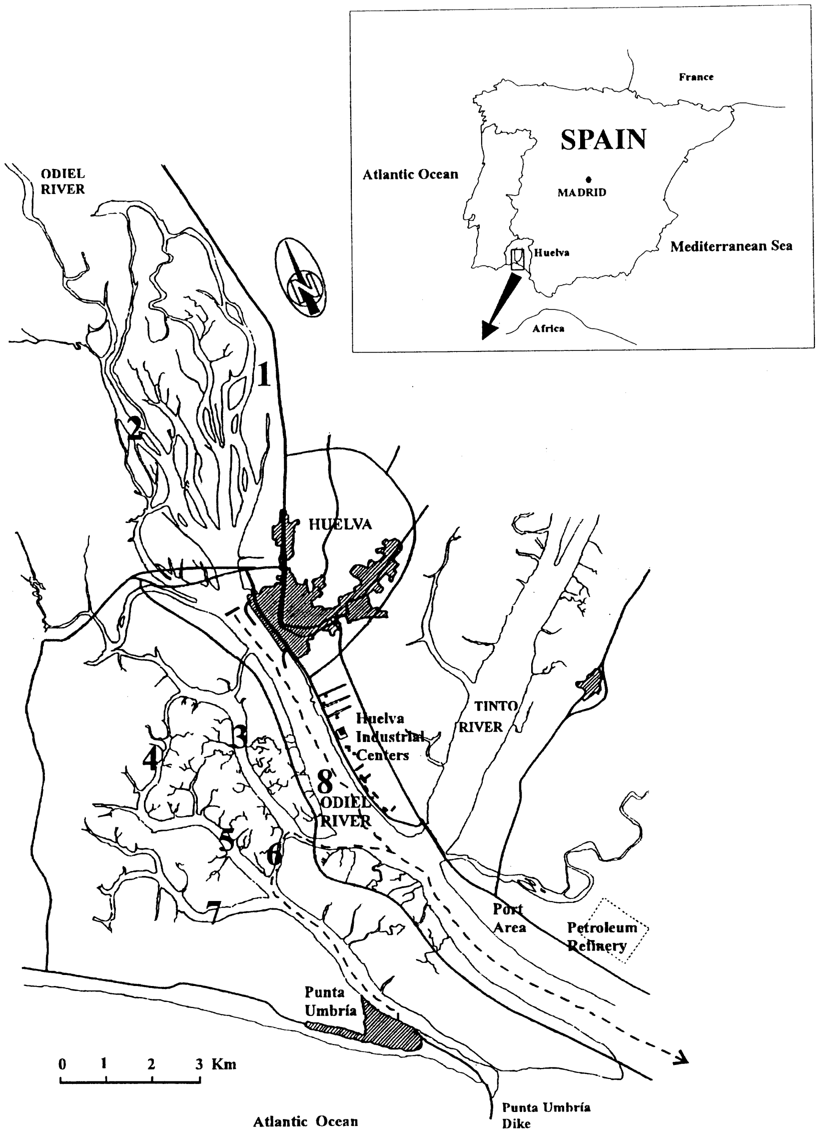

Fig. 1. The Iberian Peninsula and map of the Odiel estuary. Channels studied are numbered from 1 to 8. – – – Main shipping route. ⟶ Exit to open sea. — Roads. ▨ = Population centres.

Study area

The Odiel salt marshes are situated at the joint estuary of the Odiel and Tinto Rivers (37º15' - 37º37' N, 6º57' - 6º58' W). This estuary has a mesotidal semidiurnal character (mean tidal range is 2.10 m and mean spring tidal range is 2.97 m, 0.40 - 3.37 m above Spanish hydrographic zero) (Castellanos et al. 1994). In 1983 the marshes, with an area of 7158 ha, were declared a Biosphere Reserve by UNESCO; they include a Special Area for the Protection of Birds, as designated by the European Union. Its strategic position, at the Euro-African and Atlantic-Mediterranean crossroads, accentuates its great ecological interest. The zone is of great importance as a passage of bird migration. A busy fishing and shell-fishing activity exists in these salt marshes.

The joint estuary is a Holocene estuary installed on a 25 km long stretch of river incision and underlain by Neogene sandy-silty sediments. The oldest estuarine sediments have been dated at 6715 ± 115 yr BP. The first five m of sedimentological profiles from two high marsh areas, with clay and plant remains, correspond to the change from an intertidal plain (low marsh) to a supratidal marsh (high marsh), which occurred ca. 960 ± 100 yr BP. Sediment accretion (ca. 5 mm/yr) indicates a fast filling of the estuary during the two last millennia (Lario 1996).

The Atlantic estuary is located in an area with a Mediterranean climate, with a dry season during the summer. Mean annual precipitation is 506 mm with a variation coefficient of 31% (Rubio 1985).

The Odiel salt marshes area polluted with heavy metals from two sources. First, the Rivers Tinto and

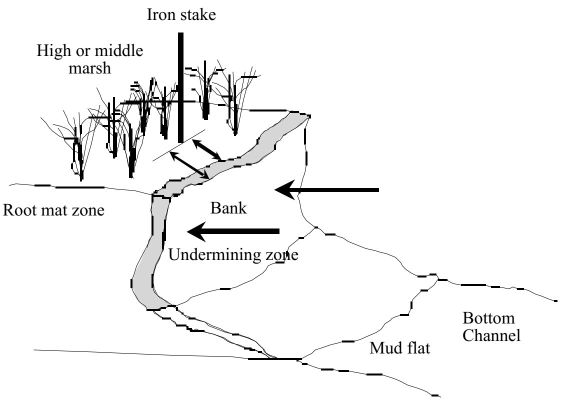

Fig. 2. Diagram showing the placement of markers on the channel bank.

Odiel rise in and drain the Riotinto mining basin (to the north of the estuary), which is rich in metal cations (Fe, Cu, Pb, Zn, Au, Ag, etc.), and has been mined for more than 5000 yr (Ruiz et al. 1998). This inorganic load is transported with hardly any dilution by both rivers to the Odiel salt marshes, thereby constituting a serious pollution problem (Anon. 1994a). So, old sediments have high heavy metal loads (Ruiz et al 1998). The second pollutant factor is the Huelva Industrial Centre of Development, established in the 1960s. Its concentration of mining and chemical companies is one of the highest for this sector in Spain. Residues with high contents of heavy metals have been dumped directly from the Centre into the waters of the estuary up to the middle of the 1990s (Anon. 1994 b).

Methods

An exhaustive mapping (at a scale of 1:10000) of the channel banks was carried out using photo-interpretation and field trips in small boats. After this, eight of the wider channels were selected throughout the estuary, enclosing almost all protected areas (Fig. 1). The perimeter of the slopes and the width of each channel were measured on the maps, using an image analyser (Quantimet-500, Leica). The main navigation routes and points of erosion resulting from the capture of fishing bait (a traditional local activity) were localized on the maps.

On the eight channels selected, a network of 73 markers was set up to quantify horizontal erosion. The markers consisted of iron bars approximately 1.5 m tall and 1 cm in diameter. They were inserted to a depth of around 1 m at the upper edge of the slopes. The distance of the markers from the lower edge was measured bimonthly from July 1996 to July 1997 (Fig. 2). The rate of horizontal erosion at a point was the difference between two consecutive measurements.

At each sampling point, the vertical height of the slope was measured, and the plant species present and their levels of covering (C) were noted. The latter was expressed using a semi-quantitative scale:

1 = < 5%; 2 = < 25%; 3 < 50%; 4 = < 75%; 5 = > 75%.

Determination and denomination of species was according to Tutin et al. (1968-1993).

In the absence of previous studies, the variation over time resulting from horizontal erosion of the selected slopes was estimated from aerial photos taken in 1956 (1 : 33000), 1980 (1 : 25000) and 1990 (1 : 15000), using a micrometer to make measurements. The difference in width of a channel between two photos was expressed as salt marsh area losses (m^2), and length of marsh losses (m).

The denomination of the different marsh zones (depending on their topographical level – mature or high, middle and low – was in accordance with Long & Mason (1983).

The rates of annual erosion of the different channels were compared using one-way analysis of variance. Least significant differences (LSDs) between means were calculated only if the *F*-test was significant at the 0.05 level of probability (Steel & Torrie 1960). The data were tested for similarity of variance using the Levene test, with a significance level of 95%.

Results

The mechanism producing marsh loss was erosion below the zone of live roots. This led to the formation of vertical slopes (usually concave in their lower part), the appearance of mass-movement phenomena, and the detachment of blocks of substrate. Horizontal erosion of these slopes typically begins with the undermining of the lower part, just below the zone of live roots. This is followed by the detachment of substrate blocks from the upper part of the slope, carrying away the plants growing there (Fig. 3).

The intensity of the erosion mechanism described was not constant throughout the estuary, and varied significantly between channels (ANOVA; $F = 7.3689$; $p < 0.0001$) (Fig. 4). Thus, the rates of erosion in channels 1 and 2 were the lowest of the estuary. In contrast, the erosion rates in channels 6 and 8 were greater than on the others. In channel 6, the slope retreat recorded was sometimes greater than 110 cm annually. Channel 7 also showed high rates of erosion (Table 1).

With the aim of estimating the total loss of marsh on the channels studied, an overall mean rate of erosion was calculated. This was expressed as the mean of the erosion rates of each channel, weighted by their length. The mean retreat of the slopes so calculated was 22 cm/yr. At this

Fig. 3. Effect of erosion by undermining in channel 6. A block of substrate of ca. 0.5 m^3 detached from the slope and exposed roots of *Spartina densiflora* can be observed.

rate of erosion, the marsh surface lost annually from the total length of channels under study (63523 m) would be around 13 951 m^2. This horizontal erosion, on slopes having a mean height of 0.5 m, would move around 6987 m^3 of sediments. Some 20 % of this sediment volume would come from the navigable channel 6, which contributes barely 3% of the total length of the slopes studied.

From the aerial photos, clear differences were seen in the rates of erosion between the different channels. From 1980 to 1990, channels 1 and 2 showed no real differences in width, whereas the rate of erosion in channel 3 was 0.7 m/yr (58618 m^2/yr) and in channel 6 was 2.2 m/yr (43582 m^2/yr) (Table 2).

Study of the aerial photos also revealed the existence of erosive periods of different intensity in almost all the channels (Table 2). From 1980 to 1990, the erosion was much greater than between 1956 and 1980. Thus, the estimated erosion rate in channel 6 for the period 1980-90 was ca. 2.2 m/yr, which represents an increase of 22 m from bank to bank. However, in the period 1956-1980, erosion was imperceptible. From 1956 to 1990, 511 000 m^2 of salt marshes, mainly middle and high, have been eroded by undermining in the Odiel salt marshes. This loss corresponds to 0.71% of the total area of these marshes and 68% of them occurred during the last 10 years.

The slopes with vegetation (channels 1 and 2) were the least eroded. The most frequent plant species were *Arthrocnemum perenne* and *Halimione portulacoides*.

Table 1. Mean annual horizontal erosion (in cm/year S.E.), length of slope edges (m), mean vertical height of slope (cm ± S.E.), area of marsh eroded (in m^2/yr), mean width of the channels (m), level of capturing bait and amount of boat traffic (H hight, L low, - Nil) and plant species present (with their relative abundance) on the slopes of the main channels of the estuary (Hp = *Halimione portulacoides*; Sd = *Spartina densiflora*; Sp = *Arthrocnemum perenne*; Sr = *Salicornia ramosissima*). For cover class, see Text.

Channel	Nº of markers	Mean erosion (cm/yr)	Length of slopes (m)	Height (cm)	Area eroded (m^2/yr)	Mean width (m)	Boat traffic	Bait capture	Plant species (cover class)
1	4	7.3 ± 3.7	11167	37.5 ± 6.3	815.2	112.7 ± 16.4	-	-	Sd (1), Hp (3), Sr (1), Sp (5)
2	5	12.4 ± 6.1	16393	40.3 ± 6.0	2032.7	101.0 ± 16.7	-	-	Sp (3), Sd (4), Sr (1)
3	7	25.3 ± 5.5	8374	51.3 ± 3.5	2118.6	222.2 ± 36.9	-	L	0
4	10	23.9 ± 5.6	5643	58.3 ± 4.3	1348.7	134.0 ± 14.6	-	H	0
5	11	25.2 ± 4.4	6351	64.3 ± 2.8	1600.4	260.0 ± 7.3	-	L	0
6	15	71.6 ± 7.7	1981	93.0 ± 2.9	1418.4	165.0 ± 15.0	H	-	0
7	13	36.8 ± 9.4	9140	59.0 ± 1.9	3363.5	163.1 ± 13.2	-	H	0
8	8	36.5 ± 6.3	600	51.8 ± 1.9	219.0	710.2 ± 30.8	H	-	0
Total	73	22.0	63523	50.3	13950.9				

Table 2. Horizontal erosion in the channels in the periods 1956-1980 and 1980-1990, expressed as marsh loss (m^2), and length of marsh eroded (m) in brackets.

	Channels							
Year	1	2	3	4	5	6	7	8[a]
1956-80	55835 (5)	*	33496 (4)	22572 (4)	50808 (8)	*	*	-
1980-90	*	*	58618 (7)	33858 (9)	120669 (7)	43582 (22)	91400 (10)	-

[*] Imperceptible.

[a] Variations in the width of channel 8 cannot be calculated due to the great changes of infrastructure recorded on the banks.

Both have creeping stems, which in the case of *A. perenne* are rooting. Their levels of cover always exceeded 50%, and they covered almost the whole area of the colonized zones. On the other hand, *Spartina densiflora*, with upright stems, appeared only on the upper edge of the slope, and was carried away with falling blocks of detached sediments. When it appeared rooted directly on the slope, its cover never exceeded 75%. *Salicornia ramosissima*, a small annual species, was found on the slopes only from spring to autumn.

In the year of the study, precipitation reached 799 mm, and was markedly seasonal. Thus, 67% of the annual rainfall occurred in 21 days of December and January. The periods of torrential rain coincided with increases in the flow of the River Odiel. This marked climatic seasonality did not lead to any erosion patterns during the year of the study, and wide variations were found in the erosion rate between the different markers of the same channel. Thus, erosion was continuous in almost all the channels, except those covered with plants, where periods without erosion were recorded (Fig. 5).

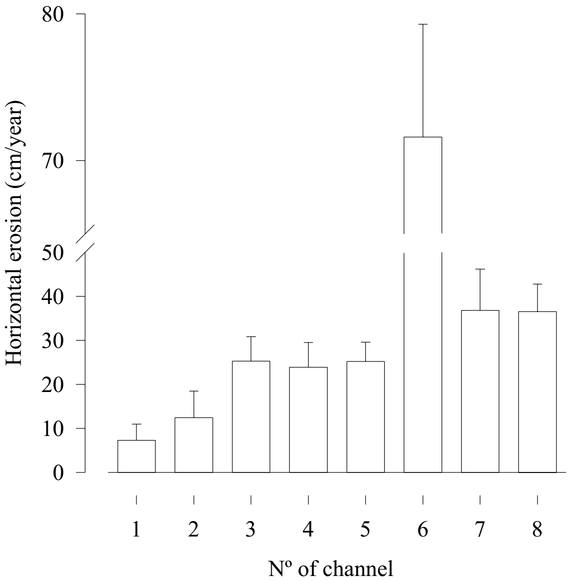

Fig. 4. Annual horizontal erosion, in cm/yr, recorded for the different channels. Mean and mean standard error are given.

Discussion and Conclusions

The present study is the first quantification of bank erosion in Atlantic mesotidal salt marshes under Mediterranean climate. The erosion mechanism described is

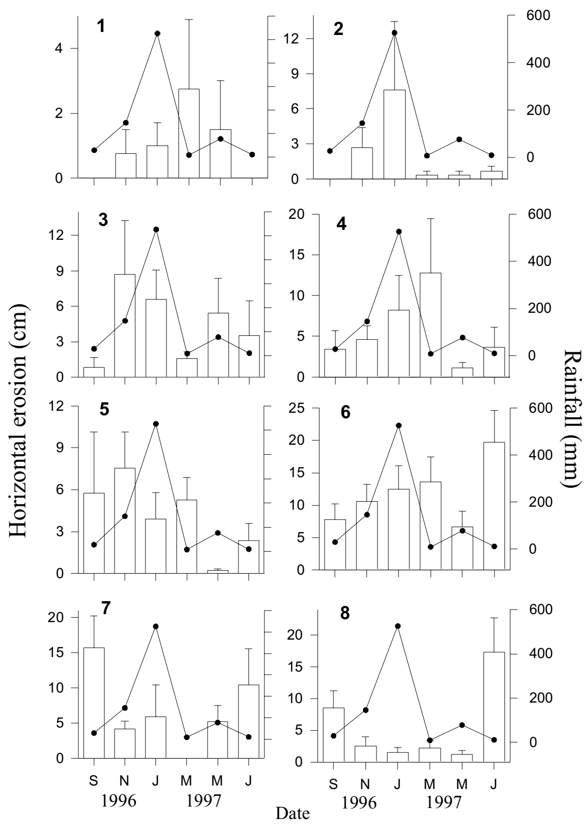

Fig. 5. Horizontal erosion, in cm, in the different channels (1-8) throughout the study period. Mean and mean standard error are given. —●— Monthly precipitation (mm).

similar to that observed by other authors on estuaries of the United States (Nyman et al. 1994; Stevenson et al. 1985).

Herke & Rogers (1993) classified the losses of estuarine habitat as natural or man-induced and they stated that often the effects of the latter component are either at least additive to, or more rapid than, natural effects. The causes of undermining can be natural, such as drainage flowing water (Nyman et al. 1994). In our study, the highest erosion rates were registered in channels 6 and 8. These high rates could be due to natural causes, as special hydrodynamic conditions (Ojeda et al. 1995). But, we have pointed out that these two channels coincide with an area bearing a heavy traffic of shipping (Fig. 1, Table 1), which increases erosion. Pezeshki & DeLaune (1996) identified shipping as a relevant factor in erosion, as proved in our study. High erosion rates were registered too in channel 7. In this case, human pressure was the capture of fishing bait directly on the banks (Table 1).

On aerial photos (1956-1990) it was seen that the greater part of the marsh loss took place in the last 10 years. The high erosion rates detected between 1980 and 1990 coincided with the increase in human activity in much of the estuary. It is of particular interest that from the early 1980s, the construction of a dam at Punta Umbría sealed off the exit nearest to the mouth, so that shipping has had to use other exit routes via channels 6 and 8. Further research is needed to quantify, evaluate and discriminate between natural and anthropogenic causes in bank erosion increase.

Various consequences of horizontal erosion are shown in this study: the loss and alteration of considerable areas of mature and middle salt marsh, increased rates of silting in the estuary channels, the moving of contaminated sediments by erosion and dredging, and changed plant composition of the communities on the low and middle salt marsh, where slopes develop, with greater abundance of species having decumbent growth.

As a result of this horizontal erosion, already-stabilized zones of middle and high marsh have been directly exposed to regression of the slopes. This erosion of the channel banks has caused the loss of consolidated marsh that had taken a long time to form, and having more evolved soils than the intertidal flats (Rubio 1985) replacing them. The loss of middle-high marsh reduces the habitat of certain plant communities, contributing to a decrease in their diversity, and even to the disappearance of some of them, which are being replaced by intertidal flat without vegetation. Our results agree with Grootjans et al. (1997), when they point out that changes in landscape and vegetation succession, due to changes in land use, reduce biodiversity and conservation values in many coastal ecosystems. Horizontal erosion of the slopes is therefore a disorganizing factor that leads to a direct loss of natural resources and a sharp retreat in the evolution of the ecosystem.

Barros (1996) defined erosion, on an Atlantic estuary of the Iberian Peninsula, as the main factor controlling sedimentological dynamics, deposition being highly dependent on the prevailing erosion regime. According to this model, the high rates of erosion quantified in this study (ca. 7000 m^3/yr) would move sediments that would be dispersed by currents and tides and they could contribute to the silting of the navigable channels of the estuary. Considerable economic expense is incurred in the dredging of channel 8 (the main navigable channel) to enable the entrance of large ships into the port of Huelva, and to a lesser extent, of channel 6. At the same time, erosion and dredging moves sediments contaminated with heavy metals (Luque 1996; Luque et al. 1997). If dredging was not carried out, these heavy metals would remain deposited on the river bed, relatively isolated and interacting less with other elements of the estuarine ecosystem (DeLaune & Gambrell 1996). However, deposited on the surface, they can be more easily introduced into the estuarine food chain.

The study of the plants on the slopes showed a predominance of species with long-living above-ground creeping stems (see the classification of van Groenendael et al. 1996). These are able to survive more easily in a habitat of such extreme hydrological conditions (high degree of exposure to waves, currents, and tides) and steep slopes because their stems, being attached to the soil, do not break under wave impact. In the case of *Arthrocnemum perenne*, the nodal rooting confers a chain of anchor points with the substrate, helping to prevent the plant from being carried away. Thus, *Arthrocnemum perenne* would be a species of great use in projects to curb erosion and restore degraded banks. Its rapid decumbent growth, together with plant multiplication and the high levels of coverage reached, would mean a rapid and efficient occupation of zones in which it was implanted artificially.

As in our study, the protective capacity of vegetation against erosion has been described by numerous authors (Broome et al. 1992; Moeller et al. 1996; van Dijk et al. 1996). Once vegetation has been removed from a slope, erosion increases. This leads to a steepening of the slope, which in turn causes further erosion and prevents recolonization. The loss of vegetation on the slopes can be a consequence of natural events, such as upsurges of the river. According to Herke & Rogers (1993), these natural losses are usually not too serious, at least in the long term. However, human pressures with great erosive power, such as exploitation of the slopes for bait capture, or heavy shipping traffic, can contribute decidedly to the destruction of vegetation.

Some authors have described processes of sedimentation and erosion in coastal zones and fluvial courses related with climatology (Cahoon 1994; Cahoon et al. 1996; Jansson 1996; Nordstrom & Jackson 1995; Sajeev et al. 1996; Zedler 1983). However, despite the marked seasonality of the Mediterranean climate, which affects the Odiel marshes (Castellanos et al. 1994), no temporal patterns of erosion have been detected. This lack of seasonality in our results may be due to the erosion mechanism (undermining). There are, probably, seasonal patterns in the undermining, below the mass of live roots, giving rise to higher rates of erosion in periods of greater water flow. However, the undermining is not followed immediately by detachment of the overhanging block. As the delay is not constant, the undermining results in processes of continuous erosion at the high bank zone, where we recorded the erosion, rather than the seasonal patterns expected from the climatic regime of the area.

In view of the considerable deterioration suffered by the Marismas del Odiel, which has been measured, protection measures must be taken urgently to control erosion. Direct management over the erosive banks and adjacent intertidal plains, aimed at reducing erosion and re-establishing natural gradients with low-cost methods causing low environmental impact, must be accompanied by administrative measures. On the intertidal plains, offshore wooden breakwaters parallel to the tidal line (Broome et al. 1992), as well as the introduction of salt marsh plant species adapted to high flooding periods, as *Spartina maritima* (Sánchez et al. 1996), would reduce the impact of waves and the speed of the drainage water, lowering the undermining and favouring accretion and marsh regeneration in these unvegetated plains generated after the disappearance of low, medium and sometimes high marshes. This would re-establish the gradient from high marsh to low marsh, since unvegetated plains would change to vegetated low marshes, which gradually rise up to medium and high marsh levels, removing the banks. This method could be classified as constructive geo-ecological management (according to de Vries et al. 1996), because it aims at environmental protection, restoration and development of natural values. On the banks, introduction of species with long-living above-ground creeping stems would reduce their erosion, as shown in this study. In addition to these direct erosion controls, administrative measures must be taken, such as limitation of the speed of vessels and confinement of bait capture to intertidal flats and never directly on the banks. These measures would result in an improvement of the integrated management of the resources of this coastal ecosystem.

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