Facies identification within the playa-lakes of the Monegros desert, Spain, from field and satellite data

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ABSTRACT

The Monegros desert and its saline wetlands, called saladas (literally translated as “the salties”), are a unique European landscape of great scientific and ecological value. The saladas (i. e. playa-lakes and other small saline depressions) are dynamic environments; changing their surface morphology on a seasonal-diurnal basis in response to both climate and groundwater fluxes. To depict changes in these natural systems, we have identified five surface facies classes which are detectable both in the field and from remote sensing data. These facies are crucial for describing and promoting the protection of these habitats. Remote sensing has provided worthwhile historical data and additional information that compensate for scarce field records. Combined field and satellite criteria are used to catalog these facies with a new conceptual integration that manages the asynchronism between the field and satellite data. The catalog of facies is intended to be helpful for monitoring these wetlands, and for understanding the current hydrological patterns and trends in the playa lakes. This work will serve as a baseline for studying the future evolution of the saladas which may soon fall under manmade environmental forces such as increased water input from

adjacent newly irrigated lands. It is hoped that identification of these facies will be useful, with minor adaptations, in using more advanced sensors or in studying similar habitats.

Keywords: facies, playa-lake, saline depression, remote sensing, wetland.

INTRODUCTION

In ecological, social and economic terms, wetlands are among the most valuable and productive ecosystems on earth, necessitating research to ensure wise development and protection (Ramsar Convention Secretariat, 2004). The wetlands of the Spanish Monegros desert comprise both playa lakes and occasionally flooded salty depressions (Figure 1). The conservation of these wetlands, locally called saladas, needs to be reconciled with the proposed irrigation of Monegros.

Conservationists worldwide are beginning to recognize the importance of these ecosystems. Although playas are found in the western US (Rosen, 1991; 1994), they are not included in the original Classification of Wetlands of the United States, largely used in the National Wetlands Inventory (Cowardin et al., 1979). The Endorheic System has been added to the South African National Wetland Inventory in recognition of the significant ecological role played by pan ecosystems in southern Africa (Dini et al. 1998). This same System shares hydrological, geomorphological and ecological features with the wetlands of Monegros. More recently, the playa lakes have been considered as nontidal marshes wetland by the US Environmental Protection Agency (http//www.epa.gov/owow/wetlands/facts/types.pdf).

[Figure 1]

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The saladas are a unique European landscapes and have great scientific and ecological importance. Given the water scarcity in Monegros, temporary water has an ecological significance much greater than in wet regions. A part of the Monegros area enclosing some saladas was recently put under legal protection. In spite of that, some saladas are being destroyed for irrigation and many others risk disappearing due to flooding since irrigation is being established nearby (Figure 2). The irrigation works are conducted by the Government of Aragon after 10 years of European Union funds blocking due to the pressure of ecology activists. From among all the causes of alteration in Spanish wetlands established by the Dirección General de Obras Hidráulicas (1991), there are legitimate fears that these saladas will soon be significantly altered by water flows from the contiguous irrigated lands, from dumping, or from other human actions. These fragile, as yet undisturbed habitats need to be described and their natural seasonal changes recorded using earth-bound traditional observations corroborated with remote sensing so as to make the best use of the less-costly stand-alone remote sensing for their continued study and surveillance.

[Figure 2]

A review of the literature shows that remote sensing was applied early to wetlands monitoring, but its use is less frequent for playa lakes. Closed lakes of arid and semiarid regions are of interest because of their sensitivity to regional climate. In Ethiopia, Harris (1994) estimated changes in the extent of a closed salt lake as related to the climate. Bryant (1999) estimated changes in the water extent of Tunisian playas in order to assess changes in regional aridity. In Nigeria, Schneider et al. (1985) observed variations of Lake Chad and related them with the climate record, and Birkett (2000) examined the inundation variability of this same basin using remote area/level measurements and regional precipitation. The flooding on Tunisian and Algerian playas has been investigated by Bryant and Rainey (2002) and the inundation process within the saline pan was monitored by measuring changes in the surface reflectance of the playa-lake bed. The playas studied by these authors have extents of thousands of hectares.

Mapping depositional environments and other surface soil features on playas by remote sensing techniques is much less frequent and it is usually tested with *in situ* observations. In this manner, Bryant (1996) detected evaporate minerals on an ephemeral salt playa in Tunisia, using as a basis previous sedimentary and geological data. Epema (1990; 1992) defined several surface types within Tunisian playas by comparing Landsat TM images and simultaneous field reflectance measurements; these surface types represented various combinations of soil moisture, roughness and chemistry.

The remote sensing investigation of the playas and salt lakes in the Monegros desert demands an approach adapted to their singular characteristics. The first peculiarity is their small size, ranging from 1.8 ha to 200 ha; the second is their irregular and rapid change of appearance, and third, their alteration due to the agriculture intensification. This variability is influenced by the season, the weather and the groundwater dynamics. Thirdly, there is simply a lack of *in situ* data, which is common for playas.

Moreover, to our knowledge, no standard definitions of the playa-lake land-covers aplicable to this study are available. Terms such as saline pan, saline mudflat, dry mudflat describe depositional environments useful to interpret geological record (Smoot and Lowenstein, 1991; Rosen, 1991; Pérez et al., 2002) but unsuited for linking field and remote observations.

As the saladas land-covers are interrelated and change quickly either in time or space, we prefer the term "facies" (from Latin face, form, aspect, condition) as it has a similar meaning to the French term "état de surface", or "surface condition", defined by Escadafal (1992) in order to characterize the surface of the arid soils using field observations and remote sensing. Both terms take into account all the outstanding features of the interface atmosphere-soil. With a similar approach, Taft et al. (2003) use radar remote sensing to define four habitat classes based on the cover of vegetation and the presence of ephemeral discrete small shallow ponds in agricultural lands.

The aim of this article is first to define the observed facies, to describe and catalog them, and second to discover the remote sensing attributes that uniquely correspond to the above descriptions and categories. It is essential their dual identification in field and by remote sensing.

The five facies defined in this work represent the varied settings observed in the field in the Monegros saladas. The on-site monitoring of these facies is difficult because of the general untrafficability of the muddy bottoms, along with a lack of personnel.

THE PLAYA-LAKES OF BUJARALOZ-SÁSTAGO

The saladas studied here are located in the Monegros desert (Figure 1), one of the most arid regions of Europe (Herrero and Snyder, 1997). The dry season comprises the hottest period, from June to September and the wet season from October to May. Rainfall displays high inter-annual and seasonal variability, with the mean annual total recorded at the Bujaraloz weather station (see Figure 1) being 388 mm (mainly falling in the winter months). The annual reference evapotranspiration is 1255 mm.

Balsa et al. (1991) produced an inventory of one hundred closed depressions within the Monegros; some of them hosting playa lakes. These depressions are developed in horizontal Miocene lacustrine strata and are largely formed by karstic processes acting on the underlying limestone and gyprock. Pueyo (1978) described these saladas and their brines observing several sub-environments that he described as dry mudflats, saline mudflats, small coastal areas, and sand flats.

The saladas usually stand out in the landscape by one or more of the following characteristics: a flat bed topography with water and/or salt efflorescence, dark soil, and specific (halophilous) vegetation. Pueyo (1978) observed the disappearance of some depressions due to farming practices; more recently, some of the salada borders have been used for dumping stones cleared from neighboring cultivated lands, as noted by Herrero (1982) and by Balsa et al. (1991). Dumping of waste has increased in recent years; as has industrial machinery and construction traffic.

Most of the larger saladas are bordered by a sharp escarpment from one to twenty meters high which delimits the northern and southern extent of these depressions. The common orientation of these escarpments is NW-SE, where the tectonic patterns converge with the prevailing wind direction. The smaller depressions, usually not flooded, have gentle margins and a wet bottom with halophytes, although they may be invaded by volunteer barley. If cultivated, these depressions become difficult to identify due to the agricultural use and more recently to land consolidation, standing out only when flooded.

As a saline system, the saladas can be considered *discharge playas* and *closed saline lakes*, depending on the closeness of the groundwater level to the ground surface (Yechieli and Wood, 2002). This fact, combined with the climate, determines the alternation of wet and dry periods in the saladas. In this work, we study thirty-nine depressions (Figures 1 and 2), detected with Landsat imagery in 1997, the most humid year in the period studied (Castañeda et al., 2001). All but one of these depressions appears in the inventory of Balsa (1991).

CRITERIA USED IN THE CATALOG

The playa facies were distinguished by applying specific criteria to both field and satellite image data. The field criteria were developed from own observation backed up by information derived from relevant literature (Gutiérrez-Elorza et al., 2002; Pedrocchi, 1998; Pueyo, 1978; Pueyo and Inglès, 1987). For every facies, these criteria were: location in the depression, arrangement, appearance, evolution, and relation with the other facies. The field description was targeted at useful data extraction from remote sensing, and thus considered issues such as the spatial and spectral resolution of available remote sensing imagery. Consequently, our definitions were not based solely on lithological, chemical or mineralogical criteria (e.g. used by Smoot and Lowenstein, 1991); but also include factors such as the spatial and spectral heterogeneity /homogeneity and separability of specific surfaces.

Our study data includes ground observations from two sources (Castañeda, 2002) covering 1987 to 1990 and 1993 to 1997, together with our own observations acquired during 2001 and 2002.

The remote sensing criteria were applied to 26 Landsat images from different seasons, acquired from 1985 to 2000 and atmospherically/geometrically corrected. These criteria comprise the spectral features of every facies and their visual discrimination on all the images, where previously digital values had been changed to reflectance values. The spectral features refer to the reflectance in the visible, medium and near-infrared spectra both in dry and wet season. Visual analyses were based on the variation and spatial distribution of tone and color features. The different facies were best identified using a colour composite of Landsat channels 4, 5 and 7, since these bands are the most useful as proved by Frazier and Page (2000) and described in Castañeda (2002).

The extent of the facies for every date, obtained from the unsupervised classification of the images using the ISODATA clustering method (Swain, 1973; Swain and Davis, 1978), is another attribute incorporated into the catalog, providing a key contribution to understanding their evolution during the period studied. The surface extent of the facies described in the catalog was obtained for each date in relation to the total surface, and the maximum extension for the period was also related to the weather and environmental conditions. Finally, the facies surface trend was found for the period studied, and conclusions were drawn as to what the trends mean from the hydrological point of view.

Apart from these criteria, three additional descriptors have been designed which contribute to the accurate definition of the five facies: their (i) entity, (ii) significance and (iii) separability. The entity refers to the pervasiveness of the facies both temporally, i.e. persistence in the images, and spatially i.e. occurrence in most saladas. This quality is easily traced, which is important in long term monitoring. The significance refers to their ecological meaningfulness or value, i.e. it is important that each of the facies represent different habitats, unique and singular in a regional context. Separability refers to the ease of field and remote recognition. The last quality is crucial for us since we lack the budget for long term *in situ* monitoring. The existence of features such as facies that have entity and significance allow the remote monitoring of the environmental status of the corresponding habitats whether in their natural state or suffering changes induced by humans.

CATALOG OF FACIES

For every facies, the catalog has the following sections: (i) description, (ii) location (iii) arrangement and quantification, (iv) visual discrimination assessment, and (v) spectral signature. The catalog also contains graphic information, such as field photos, satellite images and thematic maps, to portray the facies as seen in different seasons (Figure 3).

The catalog contains the five facies detected in the saladas by Castañeda (2002), associated with the flooding and drying events. The facies, in order of decreasing humidity, are: Water, Watery Ground, Wet Ground, Vegetated Ground, and Dry Bare Ground. Their distribution is often in concentric fringes with diffuse borders.

These five facies are clearly distinguished by remote sensing as five distinct spectral classes (Figure 4b to f), but the bright salty efflorescence can hide any of the facies in remote detection. The ephemeral efflorescence, only occurring in the image of March 2000, was not considered a facies but a noise for the detection of the ecologically significant facies at our scale, and then is not represented in Figure 4.

The thematic significance of each facies is based on knowledge of the terrain. A genetic or functional interpretation of the surface conditions represented in the maps we obtained would require additional data, i.e. geology, soil and vegetation maps, etc.

[Figure 3]

Water

Description. This is a water body having a depth that is measurable with a ruler driven into the bed (Plate 1). Water is the only facies having some field records; these records extend from 1993 to 1997 and show a maximum water depth of 51 cm. This water can cover the saline pan and the mudflat.

Location. Water often occurs towards the southwest extreme of a depression, according with the prevalent wind direction. Wind may keep the water body displaced from the deepest area. This can lead to a zero depth reading on the ruler despite an observable water body in the field or on the satellite image (Plate 1: a, b).

Arrangement and quantification. Water was identified in fifteen of the twenty-six studied images. This cover can occur all year round, its extent varying considerably even during the same season (Figure 4a). Its maximum detected extent was 261 ha in April 1997, which encompasses 26 % of the total surface area of the depressions. Water occurs in almost all the major depressions when the previous year has been rainy enough. Also water is observed in dry periods, resulting from other factors such as groundwater discharge as discussed by Rosen (1994).

Visual discrimination. Water is discriminated by the darkest tone in band 4, near infrared. In the RGB 457 composition it appears as black, and in the RGB HSI composition, as cyan.

Spectral signature. This cover shows the typical spectral behaviour of water (Chuvieco, 2002). Figure 4b shows the mean reflectance values in the six bands for the twenty-six studied images from 1985 to 2000. Reflectance values have been obtained separately for wet and dry periods. January through May are grouped as the wet period, whereas June, July and August are grouped as the dry period. Values are very low overall, and are slightly lower in the wet than in the dry season, with a maximum reflectance of 13 % in band 4. Also the variability is higher in the dry period, as the standard deviation shows.

Differences between the signature of this facies and the classical water signature have been observed both in the medium-infrared and in the visible. The bands 5 and 7 can show values > 0, but always < 9 %, attributable to the underlying soil reflectance caused by the shallow depth of the water. Also, a decrease is observed in band 1, perhaps due to algal pigments (Han, 1997).

[Plate 1]

Watery Ground

Description. This is an extremely thin sheet of shallow water, imprecise and difficult to measure, sometimes forming scattered ponds. As the water is a very concentrated brine, salts precipitate and crystals (Plate 2: f, g) can emerge and glisten, giving the look of crushed ice. Frequently in spring, this facies has algal mats that stain the water bright red (Hernández, 1998; Pueyo 1978). Both precipitates and algal structures give a rough look to this surface. A similar facies, but with fresh water, has been studied by Taft et al. (2003). This facies represents a flooded salt pan or its margin almost dried up.

Location. In the field, this facies is observed contiguous with the Water facies described above and it is difficult to distinguish a defined frontier between them. In dry periods, this facies remains until the desiccation of the salada. The wind and the bottom topography determine their spreading (Plate 2).

Arrangement and quantification. Watery-Ground is present in all the studied images with a maximum extent ranging from 195 ha in January 1987 to 4 ha in August 1985 (Figure 4a). For most years the extent is less than 50 ha, less than the 5 % of the total surface of the saladas.

Visual discrimination. Watery-Ground is detected in band 4, by a slightly brighter tone than the water. In the RGB 457 composition, this cover is brown. In the RGB HIS composition it is not possible to differentiate this facies from the Wet Ground.

Spectral signature. Figure 4c shows the mean reflectance values for the period studied, higher than those for the Water facies for both the wet and dry seasons, perhaps due to the contribution of the facies bed (Durand et al, 2000; Lyon and Hutchinson, 1995). The maximum reflectance is about 24 % in band 4. Variability is higher in the dry season and, similarly to the water facies, is also higher in the visible spectra. Watery Ground reflectance in the visible is always greater than the water facies, perhaps due to the high salt content and the presence of algal structures. All these elements add turbidity and roughness to this thin water film, contributing to the diffuse reflection (Chuvieco, 2002) and the scattering effect (Kloiber et al., 2002) that increase the reflectance. Similarly to the Water facies, band 1 always has a lower reflectance in the visible perhaps due to the algal pigments (Hernández, 1998). Watery Ground has a very strong peak in the near infrared allowing a neat separation from Water. The peak could correspond to the algal activity (Han, 1997).

[Plate 2]

[Plate 2 (cont)]

Wet Ground

Description. This facies stands out as a flat surface of homogeneous appearance in the playa-lakes, occupying most of the what was previously a bottom surface when water was present. The monotonous appearance continues up to the edge, which is frequently colonized by halophytes and by accumulations of vegetable remains, swept there by the swell (Plate 3). In the small closed depressions, occasionally cultivated, the Wet Ground is less homogeneous, with halophytes and/or an agricultural mixture.

Wet Ground is over-saturated in water even in summer, and oozes when stepped on. This fact makes it very difficult to hike along the bottom depressions. When this facies dries, it becomes rough because of the desiccation cracks and polygons and the outcrops of algal mat remains.

Wet Ground is usually brown, and darkens as the water content increases. This dark hue accentuates the difference between this facies and the Dry Ground facies.

Occasionally this facies is covered by white efflorescence, giving it a surprising and blinding brightness in the field and a high albedo or bright reflectance in the VNIR. The efflorescence is at times deposited on fringes revealing the slow and continuous retraction of the water sheet towards the center of the depression. These efflorescences can have different looks and consistencies, appearing at times like a powder similar to newly fallen snow or in other cases like a solid crust that crunches under each footfall. Their extent is very variable sometimes winding along in intermittent strips several meters long and at times occupying the full extent of the salada bottom. In this last case, this facies represents the saline mudflat and the salt-pan environments. The permanence of the feature depends on rain and evaporation. However, the accumulation of the efflorescence is hindered because the frequent wind often sweeps the powdery deposits away (Samper-Calvete and García-Vera, 1998; Sanchez et al., 1998; Valero-Garcés et al., 2001).

In the small saladas, there are often failed attempts at farming on Wet Ground facies. Vestiges of these failed attempts are frequently observed. In these cases an irreversible change is detected: the bottom of the depression is partially incorporated by farmlands, the halophytic vegetation is lost and the edge of the depression is less distinct. Frequently, the settled area floods again and the intended agricultural use is compromised.

Location. Wet Ground usually borders Watery Ground extending up to the outer limit of the depression or to the halophytic fringe. Sometimes Wet Ground is interrupted by patches of Watery Ground. Even in the dry season, this facies is easily identified in the saladas both in the field and on the satellite images.

Arrangement and quantification. Wet Ground is present in all the studied images and its extent decreases as Water or Vegetated Ground expands over the bottom. The maximum extent was registered in August 1985, with 561 ha. The minimum was registered during March 2000, with 175 ha. Usually, Wet Ground comprises 300 to 500 ha, 30 % to 50 % of the total surface of the saladas (Figure 4a).

Visual discrimination. The wet surface is always detected in bands 4 and 5 with a dark hue contrasting with the lighter dry ground around it. In the RGB 457 composition it appears as maroon. The HSI composition confuses this facies with Watery Ground.

Spectral signature. Figure 4d shows the mean reflectance values for the six bands during the period studied. Its variability is lower than the previous facies. The reflectance values in the dry season are slightly higher than in the wet season. Reflectance increases from band 1 to band 5, with a maximum of 21 %. In the wet season a reflectance increase in band 4 has been observed, attributable to the seasonal occurrence of sparse halophytes. In band 7, both the soil humidity and its dark color produce a decreased reflectance.

According to the literature (Crowley, 1993; Epema, 1990; 1992; Escadafal, 1992; 1994), the efflorescence should be recognized by high values of reflectance in the bands 5 and 7, but only under dry conditions. Although field observations in 2000 to 2002 have noted efflorescence in the saladas, the corresponding spectral signature seems masked by moisture. Only in the March 2000 satellite image do some saladas show an area of high reflectance in all the bands, ranging from 30 % to 70 %. This high reflectance could be reasonably related with the presence of efflorescence though no field data are available to corroborate. This image has not been used in the average estimations, in the supposition that a new facies might be described for efflorescence when more images supported by field observations demonstrate the existence of such a facies.

[Plate 3]

Vegetated Ground

Description. The facies Vegetated Ground inside the saladas refers mainly to the halophytes where natural conditions are preserved, but also includes barley or volunteer plants in the small depressions where dry farming is occasionally attempted. In this case, the bottom is plowed but frequently abandoned because of the soil salinity (Plate 4). This facies would correspond with the saline mudflat margins in large playa-lakes or with the salt pan in small salty depressions.

Location. When the saladas have water several months every year, the halophytes grow in the external area of the topographic depression, bordering the Wet Ground or the Watery Ground. During periods when the saladas do not usually have water, Vegetated Ground covers their bottom, either partially or completely. Halophytes extend towards the center of the saladas as the water regime allows it, resulting in Vegetated Ground fringes according to the tolerance of each plant species to flooding and salinity.

Arrangement and quantification. Vegetated Ground has been detected in all the images and its extension varies according to the season and to the farming use. In spring, natural vegetation and crops are well developed, whereas in winter the natural vegetation has less density and less photosynthetic activity. Possible disturbances of the ecological conditions reflected in the modification of these fringes could be detected by long term studies. For the moment, only invasion by farming, agricultural infrastructures and dumping have been detected, but the main threat is the fresh water flooding by effluents from projected irrigated lands, endangering valuable endemisms (Cervantes and Sanz, 2002).

This facies is highly variable in the field and in the satellite image, both in its appearance and extent. This agrees with the intrinsic variability of halophytic vegetation in terms of perennial species substitution and canopy alterations following the flooding/drying episodes, phenological states, and annual halophyte blossoms. Moreover, this facies includes field conditions like plowed land, growing crops, stubble, etc. in areas with a coextensive intermittent barley crop.

The minimum Vegetated Ground extension was 97 ha, detected in January 1987, and the maximum was 488 ha, detected in July 1997, the most humid year of the period studied. Of the total surface occupied by the saladas, the Vegetated Ground extent ranges from 18 % to 42 % (Figure 4a).

Visual discrimination. In the Landsat bands 4 and 5, the hue varies with the phenology, making the systematic detection of this cover impossible. Vegetated Ground facies appear red in the RGB 457 composition, with differences in intensity according to the season. This facies is green in the RBG HSI composition.

Spectral signature. Figure 4e shows the mean reflectance values in wet and dry seasons during the period studied. In the wet season the spectral curve has the appearance of mixed soil and vegetation, with a peak in band 4 of about 24 %, and a similar value of 22 % in band 5. In the dry season, the peak occurs in band 5 with 27 %. The size of the Landsat pixel versus the extent and shape of the vegetation patches make it inpractical to look for spectral signatures in order to split this facies by plant density or by species or seasonal changes of either the plants or the soil background.

[Plate 4]

Dry Bare Ground

Description. Dry Bare Ground is the topsoil in a dry state usually recognized by a light hue in the field, having negligible or no vegetation, and including a variety of conditions. The border between this facies and Wet Ground is frequently a very neat line often representing the limit of the groundwater discharge into the saladas.

In the most external fringe of the playa-lakes, Dry Bare Ground is a smooth surface, more extensive in dry periods, which would correspond with a dry mudflat. In some small depressions Dry Bare Ground occurs over the entire bottom, and can contain stones also with light hues such as tabular limestone and gyprock fragments from a few centimeters to one meter in size (Plate 5). This stoniness, increased by plowing, gives a rough appearance to this facies. When the stones are removed by farmers, this appearance changes greatly and generally turns smoother and darker. On the other hand, the removed stones together with debris and rubbish are being dumped in the saladas, covering the Vegetated Ground or other facies which are then classified by remote sensing as Dry Bare Ground.

Location. Dry Bare Ground occurs in the most external area of the saladas and over their borders. In very dry conditions, this facies can extend over the entire bottom of some depressions, especially in summer. The Dry Bare Ground extent is inversely related to the Vegetated Ground and Wet Ground extent.

Arrangement and quantification. The dry ground has been detected in all the images. Their maximum extension is 260 ha in June 1994, and the minimum is 62 ha in August 1985. Its extent ranges between 10 % and 25 % of the total surface of the saladas (Figure 4a).

Visual discrimination. The Dry Bare Ground is clearly discernible in Landsat bands 4 and 5 because it has the lightest tone, brighter in summer than in spring, and an even lighter tone than the Wet Ground. In the RGB 457 composition this facies varies from light blue to white; in the RGB HSI composition, it is orange.

Spectral signature. Figure 4f shows the mean reflectance values during the wet and dry seasons of the period studied. The Dry Bare Ground has the highest reflectance values in all the bands, increasing gradually from the visible to the infrared. The peak is very clear in band 5 in all the images, for either the dry or wet seasons. In the dry season, the average reflectance value in band 5 is 35 %, clearly different from the wet surface, which has an average of 21 % for the same season. In the wet season, a small increase in reflectance in band 4 is noticeable due to the influence of some scarce vegetation.

[Plate 5]

[Figure 4]

Monitoring the surface extent of facies

Monitoring the facies extent is crucial for detecting environmental alterations or other changes in the saladas. Although discrimination of the five facies is possible in the field, their accurate location and spatial determination is only feasible by remote sensing, as we have done for the period 1985-2000.

The total saladas area established by remote sensing is 1000 ha. From this total area, the mean extent of Water plus Watery Ground is only 9 %, with a maximum of 40 % in January 1987 whereas a minimum extent of 0.9 % occurred in August 1987 for these facies taken together. It should be stressed that in April 1997, the most humid year of the last thirty years, both these facies taken together only occupied 35 % of the total salada extent. Some bias can be supposed because no satellite images are available during cloudy periods. Notwithstanding, the above comparisons illustrate the complex relationships between flood extent and weather that have been explored in detail

(Castañeda, 2002; Castañeda and Herrero, in revision) and modelized by Castañeda and García (2004).

The mean extent of Dry Bare Ground is 18 %. The maximum of 34 % occurred before the start of a series of land systematization projects, in June 1986, when the satellite image shows that farming was rare in the saladas. Wet Ground is the facies with the highest average extent, with a mean of 38 %, reaching a maximum of 56 % in August 1985. Vegetated Ground has a mean extent of 40 %, with a minimum of 10 % for the winter of 1987.

Figure 5 shows the distribution of the surface extent of each facies for the studied images. For each facies, the boxplots show the range box, with whiskers extending from the lowest value within the lower limit, Q1 - 1.5 (Q3-Q1), to the highest value within the upper limit, Q3 + 1.5 (Q3-Q1), according to Chambers et al. (1983); and the outliers, i. e., values outside these limits.

Vegetated Ground, Wet Ground and Dry Bare Ground show the broadest range of extent in Figure 5, but the variation of Water and Watery Ground are the most striking, with a minimum observed extent of 0 ha and 4.2 ha, respectively. Water and Watery Ground also stand out by their skewed distribution, emphasized by the outliers. They have the shortest ranges, but their coefficients of variation, 172 % and 124 % respectively, are much higher than wet ground (23 %), Vegetated Ground (32 %), and Dry Bare Ground (38 %). For Watery Ground and Water, a possible bias must be taken into account in the dates of the records with cloudy periods being under-represented, as already referred. The extent distribution of each facies recorded in this study will serve as a base for future monitoring and environmental warnings. So, we have undertaken another study with radar imagery in order to overcome this bias.

[Figure 5]

Temporal changes in the surface area occupied by each facies are noticeable but their long-term (15 years) variation is small, as shown by the trend lines in Figure 6. Water and Watery Ground vary in the same way and their trend lines remain almost constant. Vegetated Ground shows the clearest ascending trend line. Wet ground and Dry Bare Ground trends slightly decrease, and it is noticeable that they behave in opposition, an increase in one corresponds to a decrease in the other (Figure 7). In this Figure, Vegetated Ground seems independent from the Wet Ground and Dry Bare Ground variation extent. One reason for the increase of Vegetated Ground is that this facies includes some cropped fields in areas where farmers hope it will not flood. Moreover, this inclusion precludes the interpretation of Figure 7 as solely a representation of waxing and waning episodes of the halophytes. Since image dates have not continuity enough for providing a clear evolution of this facies in relation with dry and wet ground; and its relationship with groundwater and soil salinity would need more detailed field work.

[Figure 6]

[Figure 7]

Most of the changes in Water and Watery Ground extent are episodic judging by our experience, but the duration of these episodes can only be established by organized monitoring with more frequent observations, either in the field or by remote sensing. Results from this monitoring will need to establish thresholds for the allowable duration of flow episodes in order to preserve the hydric regime of the saladas ecosystems.

From the hydrological point of view, saladas are discharge areas of groundwater, mainly by evaporation. The five facies are related to the presence of water in the saladas, and excepting Dry Bare Ground are evaporative surfaces, as shown by the hydrological model of Castañeda and García (2004). For the evaporative facies we have computed an evaporation rate in two ways. First, we have considered Ev1, i.e., the sum of Water, Watery Ground and Wet Ground extent for each date (Figure 8), the available surface source of water discharge by direct evaporation. Secondly, the evaporation contribution of Vegetated Ground is also computed (Ev2 = Ev1 + Vegetated Ground), as the plants contribute to the water discharge by transpiration (Figure 8). Ev_1 is more variable, ranging from 24 % to 76 %, and with a mean of 50 % of the total saladas surface. Ev2 remains more constant ranging from 63 % to 93 %, with a mean of 80 %. Both Ev1 and Ev2 are very variable in the short-term, though the trend lines remain almost constant, with a slight decrease for Ev1. Including the Vegetated Ground facies as part of the evaporative surface, the result being Ev2, the short-term variability decreases considerably.

[Figure 8]

CONCLUSIONS

A catalog of different land covers, here defined as facies, has been created to describe and monitor the valuable habitats hosted by the playa-lakes in the Monegros region of Spain. The catalog includes five facies: Water, Watery Ground, Wet Ground, Vegetated Ground, and Dry Bare Ground. The adopted criteria make for an easy distinction of these facies either in the field or using the Landsat images.

In practice, the extent of each facies can only be estimated from remote sensing. These extents will be the key to appraising the conservation status of these singular habitats and to study their evolution. From the total extent of the saladas area, the mean extent of Water plus Watery Ground is only 9 %; the mean extent of Dry Bare Ground is 18 %. Vegetated Ground has a mean extent of 34 % and Wet Ground is the facies with the highest average extent, with a mean of 38 %. Temporal variations are noticeable but they were small for the 15 year span of this study. Only Vegetated Ground shows a slightly ascending trend. Wet Ground increases when Dry Bare Ground decreases, perhaps because of variations in agricultural use or in weather conditions. The episodic condition of water occurrence, recognized in the field observations, is confirmed by the high coefficients of variation of Water (172 %) and Watery Ground (124 %). The total evaporative surface, represented by the extent of the facies contributing to the water discharge in the saladas, does not show a significant change during the period studied. It will be necessary to monitor the Water and Watery Ground facies in order to establish threshold limits for the allowable duration of flow episodes in order to preserve the hydric regime of the saladas ecosystems.

The Landsat TM and ETM+ images have provided worthwhile historical data and additional information that completes the scarce field records. The definition of the facies with appropriate criteria has overcome the asynchronism between the field and satellite data. Satellite imagery has allowed us to quantify the extent of facies and to study their evolution from 1985 to the present. This analysis will serve as a baseline for studying the evolution of this ecosystem, especially with the integration of new environmental factors such as increased water input from newly irrigated conjoining lands.

Landsat images used in combination with field observations have provided thematic detail and a new conceptual integration for cataloging the facies of these habitats. This catalog, the most extensive register in time and space of these valuable habitats that exists, will be a crucial tool for understanding any future natural or man-induced changes.

The facies definitions are expected to be useful in similar environments with flooding and drying episodes. A more detailed subdivision of these land covers or surface types will be possible with improved sensors having better spatial resolution and with the support of simultaneous field data.

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Facies identification within the playa-lakes of the Monegros desert, Spain, from field and satellite data

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ABSTRACT

The Monegros desert and its saline wetlands, called saladas (literally translated as "the salties"), are a unique European landscape of great scientific and ecological value. The saladas (i. e. playa-lakes and other small saline depressions) are dynamic environments; changing their surface morphology on a seasonal-diurnal basis in response to both climate and groundwater fluxes. To depict changes in these natural systems, we have identified five surface facies classes which are detectable both in the field and from remote sensing data. These facies are crucial for describing and promoting the protection of these habitats. Remote sensing has provided worthwhile historical data and additional information that compensate for scarce field records. Combined field and satellite criteria are used to catalog these facies with a new conceptual integration that manages the asynchronism between the field and satellite data. The catalog of facies is intended to be helpful for monitoring these wetlands, and for understanding the current hydrological patterns and trends in the playa lakes. This work will serve as a baseline for studying the future evolution of the saladas which may soon fall under manmade environmental forces such as increased water input from

adjacent newly irrigated lands. It is hoped that identification of these facies will be useful, with minor adaptations, in using more advanced sensors or in studying similar habitats.

Keywords: facies, playa-lake, saline depression, remote sensing, wetland.

INTRODUCTION

In ecological, social and economic terms, wetlands are among the most valuable and productive ecosystems on earth, necessitating research to ensure wise development and protection (Ramsar Convention Secretariat, 2004). The wetlands of the Spanish Monegros desert comprise both playa lakes and occasionally flooded salty depressions (Figure 1). The conservation of these wetlands, locally called saladas, needs to be reconciled with the proposed irrigation of Monegros.

Conservationists worldwide are beginning to recognize the importance of these ecosystems. Although playas are found in the western US (Rosen, 1991; 1994), they are not included in the original Classification of Wetlands of the United States, largely used in the National Wetlands Inventory (Cowardin et al., 1979). The Endorheic System has been added to the South African National Wetland Inventory in recognition of the significant ecological role played by pan ecosystems in southern Africa (Dini et al. 1998). This same System shares hydrological, geomorphological and ecological features with the wetlands of Monegros. More recently, the playa lakes have been considered as nontidal marshes wetland by the US Environmental Protection Agency (http//www.epa.gov/owow/wetlands/facts/types.pdf).

[Figure 1]

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The saladas are a unique European landscapes and have great scientific and ecological importance. Given the water scarcity in Monegros, temporary water has an ecological significance much greater than in wet regions. A part of the Monegros area enclosing some saladas was recently put under legal protection. In spite of that, some saladas are being destroyed for irrigation and many others risk disappearing due to flooding since irrigation is being established nearby (Figure 2). The irrigation works are conducted by the Government of Aragon after 10 years of European Union funds blocking due to the pressure of ecology activists. From among all the causes of alteration in Spanish wetlands established by the Dirección General de Obras Hidráulicas (1991), there are legitimate fears that these saladas will soon be significantly altered by water flows from the contiguous irrigated lands, from dumping, or from other human actions. These fragile, as yet undisturbed habitats need to be described and their natural seasonal changes recorded using earth-bound traditional observations corroborated with remote sensing so as to make the best use of the less-costly stand-alone remote sensing for their continued study and surveillance.

[Figure 2]

A review of the literature shows that remote sensing was applied early to wetlands monitoring, but its use is less frequent for playa lakes. Closed lakes of arid and semiarid regions are of interest because of their sensitivity to regional climate. In Ethiopia, Harris (1994) estimated changes in the extent of a closed salt lake as related to the climate. Bryant (1999) estimated changes in the water extent of Tunisian playas in order to assess changes in regional aridity. In Nigeria, Schneider et al. (1985) observed variations of Lake Chad and related them with the climate record, and Birkett (2000) examined the inundation variability of this same basin using remote area/level measurements and regional precipitation. The flooding on Tunisian and Algerian playas has been investigated by Bryant and Rainey (2002) and the inundation process within the saline pan was monitored by measuring changes in the surface reflectance of the playa-lake bed. The playas studied by these authors have extents of thousands of hectares.

Mapping depositional environments and other surface soil features on playas by remote sensing techniques is much less frequent and it is usually tested with *in situ* observations. In this manner, Bryant (1996) detected evaporate minerals on an ephemeral salt playa in Tunisia, using as a basis previous sedimentary and geological data. Epema (1990; 1992) defined several surface types within Tunisian playas by comparing Landsat TM images and simultaneous field reflectance measurements; these surface types represented various combinations of soil moisture, roughness and chemistry.

The remote sensing investigation of the playas and salt lakes in the Monegros desert demands an approach adapted to their singular characteristics. The first peculiarity is their small size, ranging from 1.8 ha to 200 ha; the second is their irregular and rapid change of appearance, and third, their alteration due to the agriculture intensification. This variability is influenced by the season, the weather and the groundwater dynamics. Thirdly, there is simply a lack of *in situ* data, which is common for playas.

Moreover, to our knowledge, no standard definitions of the playa-lake land-covers aplicable to this study are available. Terms such as saline pan, saline mudflat, dry mudflat describe depositional environments useful to interpret geological record (Smoot and Lowenstein, 1991; Rosen, 1991; Pérez et al., 2002) but unsuited for linking field and remote observations.

As the saladas land-covers are interrelated and change quickly either in time or space, we prefer the term “facies” (from Latin face, form, aspect, condition) as it has a similar meaning to the French term “état de surface”, or “surface condition”, defined by Escadafal (1992) in order to characterize the surface of the arid soils using field observations and remote sensing. Both terms take into account all the outstanding features of the interface atmosphere-soil. With a similar approach, Taft et al. (2003) use radar remote sensing to define four habitat classes based on the cover of vegetation and the presence of ephemeral discrete small shallow ponds in agricultural lands.

The aim of this article is first to define the observed facies, to describe and catalog them, and second to discover the remote sensing attributes that uniquely correspond to the above descriptions and categories. It is essential their dual identification in field and by remote sensing.

The five facies defined in this work represent the varied settings observed in the field in the Monegros saladas. The on-site monitoring of these facies is difficult because of the general untrafficability of the muddy bottoms, along with a lack of personnel.

THE PLAYA-LAKES OF BUJARALOZ-SÁSTAGO

The saladas studied here are located in the Monegros desert (Figure 1), one of the most arid regions of Europe (Herrero and Snyder, 1997). The dry season comprises the hottest period, from June to September and the wet season from October to May. Rainfall displays high inter-annual and seasonal variability, with the mean annual total recorded at the Bujaraloz weather station (see Figure 1) being 388 mm (mainly falling in the winter months). The annual reference evapotranspiration is 1255 mm.

Balsa et al. (1991) produced an inventory of one hundred closed depressions within the Monegros; some of them hosting playa lakes. These depressions are developed in horizontal Miocene lacustrine strata and are largely formed by karstic processes acting on the underlying limestone and gyprock. Pueyo (1978) described these saladas and their brines observing several sub-environments that he described as dry mudflats, saline mudflats, small coastal areas, and sand flats.

The saladas usually stand out in the landscape by one or more of the following characteristics: a flat bed topography with water and/or salt efflorescence, dark soil, and specific (halophilous) vegetation. Pueyo (1978) observed the disappearance of some depressions due to farming practices; more recently, some of the salada borders have been used for dumping stones cleared from neighboring cultivated lands, as noted by Herrero (1982) and by Balsa et al. (1991). Dumping of waste has increased in recent years; as has industrial machinery and construction traffic.

Most of the larger saladas are bordered by a sharp escarpment from one to twenty meters high which delimits the northern and southern extent of these depressions. The common orientation of these escarpments is NW-SE, where the tectonic patterns converge with the prevailing wind direction. The smaller depressions, usually not flooded, have gentle margins and a wet bottom with halophytes, although they may be invaded by volunteer barley. If cultivated, these depressions become difficult to identify due to the agricultural use and more recently to land consolidation, standing out only when flooded.

As a saline system, the saladas can be considered *discharge playas* and *closed saline lakes*, depending on the closeness of the groundwater level to the ground surface (Yechieli and Wood, 2002). This fact, combined with the climate, determines the alternation of wet and dry periods in the saladas. In this work, we study thirty-nine depressions (Figures 1 and 2), detected with Landsat imagery in 1997, the most humid year in the period studied (Castañeda et al., 2001). All but one of these depressions appears in the inventory of Balsa (1991).

CRITERIA USED IN THE CATALOG

The playa facies were distinguished by applying specific criteria to both field and satellite image data. The field criteria were developed from own observation backed up by information derived from relevant literature (Gutiérrez-Elorza et al., 2002; Pedrocchi, 1998; Pueyo, 1978; Pueyo and Inglès, 1987). For every facies, these criteria were: location in the depression, arrangement, appearance, evolution, and relation with the other facies. The field description was targeted at useful data extraction from remote sensing, and thus considered issues such as the spatial and spectral resolution of available remote sensing imagery. Consequently, our definitions were not based solely on lithological, chemical or mineralogical criteria (e.g. used by Smoot and Lowenstein, 1991); but also include factors such as the spatial and spectral heterogeneity /homogeneity and separability of specific surfaces.

Our study data includes ground observations from two sources (Castañeda, 2002) covering 1987 to 1990 and 1993 to 1997, together with our own observations acquired during 2001 and 2002.

The remote sensing criteria were applied to 26 Landsat images from different seasons, acquired from 1985 to 2000 and atmospherically/geometrically corrected. These criteria comprise the spectral features of every facies and their visual discrimination on all the images, where previously digital values had been changed to reflectance values. The spectral features refer to the reflectance in the visible, medium and near-infrared spectra both in dry and wet season. Visual analyses were based on the variation and spatial distribution of tone and color features. The different facies were best identified using a colour composite of Landsat channels 4, 5 and 7, since these bands are the most useful as proved by Frazier and Page (2000) and described in Castañeda (2002).

The extent of the facies for every date, obtained from the unsupervised classification of the images using the ISODATA clustering method (Swain, 1973; Swain and Davis, 1978), is another attribute incorporated into the catalog, providing a key contribution to understanding their evolution during the period studied. The surface extent of the facies described in the catalog was obtained for each date in relation to the total surface, and the maximum extension for the period was also related to the weather and environmental conditions. Finally, the facies surface trend was found for the period studied, and conclusions were drawn as to what the trends mean from the hydrological point of view.

Apart from these criteria, three additional descriptors have been designed which contribute to the accurate definition of the five facies: their (i) entity, (ii) significance and (iii) separability. The entity refers to the pervasiveness of the facies both temporally, i.e. persistence in the images, and spatially i.e. occurrence in most saladas. This quality is easily traced, which is important in long term monitoring. The significance refers to their ecological meaningfulness or value, i.e. it is important that each of the facies represent different habitats, unique and singular in a regional context. Separability refers to the ease of field and remote recognition. The last quality is crucial for us since we lack the budget for long term *in situ* monitoring. The existence of features such as facies that have entity and significance allow the remote monitoring of the environmental status of the corresponding habitats whether in their natural state or suffering changes induced by humans.

CATALOG OF FACIES

For every facies, the catalog has the following sections: (i) description, (ii) location (iii) arrangement and quantification, (iv) visual discrimination assessment, and (v) spectral signature. The catalog also contains graphic information, such as field photos, satellite images and thematic maps, to portray the facies as seen in different seasons (Figure 3).

The catalog contains the five facies detected in the saladas by Castañeda (2002), associated with the flooding and drying events. The facies, in order of decreasing humidity, are: Water, Watery Ground, Wet Ground, Vegetated Ground, and Dry Bare Ground. Their distribution is often in concentric fringes with diffuse borders.

These five facies are clearly distinguished by remote sensing as five distinct spectral classes (Figure 4b to f), but the bright salty efflorescence can hide any of the facies in remote detection. The ephemeral efflorescence, only occurring in the image of March 2000, was not considered a facies but a noise for the detection of the ecologically significant facies at our scale, and then is not represented in Figure 4.

The thematic significance of each facies is based on knowledge of the terrain. A genetic or functional interpretation of the surface conditions represented in the maps we obtained would require additional data, i.e. geology, soil and vegetation maps, etc.

[Figure 3]

Water

Description. This is a water body having a depth that is measurable with a ruler driven into the bed (Plate 1). Water is the only facies having some field records; these records extend from 1993 to 1997 and show a maximum water depth of 51 cm. This water can cover the saline pan and the mudflat.

Location. Water often occurs towards the southwest extreme of a depression, according with the prevalent wind direction. Wind may keep the water body displaced from the deepest area. This can lead to a zero depth reading on the ruler despite an observable water body in the field or on the satellite image (Plate 1: a, b).

Arrangement and quantification. Water was identified in fifteen of the twenty-six studied images. This cover can occur all year round, its extent varying considerably even during the same season (Figure 4a). Its maximum detected extent was 261 ha in April 1997, which encompasses 26 % of the total surface area of the depressions. Water occurs in almost all the major depressions when the previous year has been rainy enough. Also water is observed in dry periods, resulting from other factors such as groundwater discharge as discussed by Rosen (1994).

Visual discrimination. Water is discriminated by the darkest tone in band 4, near infrared. In the RGB 457 composition it appears as black, and in the RGB HSI composition, as cyan.

Spectral signature. This cover shows the typical spectral behaviour of water (Chuvieco, 2002). Figure 4b shows the mean reflectance values in the six bands for the twenty-six studied images from 1985 to 2000. Reflectance values have been obtained separately for wet and dry periods. January through May are grouped as the wet period, whereas June, July and August are grouped as the dry period. Values are very low overall, and are slightly lower in the wet than in the dry season, with a maximum reflectance of 13 % in band 4. Also the variability is higher in the dry period, as the standard deviation shows.

Differences between the signature of this facies and the classical water signature have been observed both in the medium-infrared and in the visible. The bands 5 and 7 can show values > 0, but always < 9 %, attributable to the underlying soil reflectance caused by the shallow depth of the water. Also, a decrease is observed in band 1, perhaps due to algal pigments (Han, 1997).

[Plate 1]

Watery Ground

Description. This is an extremely thin sheet of shallow water, imprecise and difficult to measure, sometimes forming scattered ponds. As the water is a very concentrated brine, salts precipitate and crystals (Plate 2: f, g) can emerge and glisten, giving the look of crushed ice. Frequently in spring, this facies has algal mats that stain the water bright red (Hernández, 1998; Pueyo 1978). Both precipitates and algal structures give a rough look to this surface. A similar facies, but with fresh water, has been studied by Taft et al. (2003). This facies represents a flooded salt pan or its margin almost dried up.

Location. In the field, this facies is observed contiguous with the Water facies described above and it is difficult to distinguish a defined frontier between them. In dry periods, this facies remains until the desiccation of the salada. The wind and the bottom topography determine their spreading (Plate 2).

Arrangement and quantification. Watery-Ground is present in all the studied images with a maximum extent ranging from 195 ha in January 1987 to 4 ha in August 1985 (Figure 4a). For most years the extent is less than 50 ha, less than the 5 % of the total surface of the saladas.

Visual discrimination. Watery-Ground is detected in band 4, by a slightly brighter tone than the water. In the RGB 457 composition, this cover is brown. In the RGB HIS composition it is not possible to differentiate this facies from the Wet Ground.

Spectral signature. Figure 4c shows the mean reflectance values for the period studied, higher than those for the Water facies for both the wet and dry seasons, perhaps due to the contribution of the facies bed (Durand et al, 2000; Lyon and Hutchinson, 1995). The maximum reflectance is about 24 % in band 4. Variability is higher in the dry season and, similarly to the water facies, is also higher in the visible spectra. Watery Ground reflectance in the visible is always greater than the water facies, perhaps due to the high salt content and the presence of algal structures. All these elements add turbidity and roughness to this thin water film, contributing to the diffuse reflection (Chuvieco, 2002) and the scattering effect (Kloiber et al., 2002) that increase the reflectance. Similarly to the Water facies, band 1 always has a lower reflectance in the visible perhaps due to the algal pigments (Hernández, 1998). Watery Ground has a very strong peak in the near infrared allowing a neat separation from Water. The peak could correspond to the algal activity (Han, 1997).

[Plate 2]

[Plate 2 (cont)]

Wet Ground

Description. This facies stands out as a flat surface of homogeneous appearance in the playa-lakes, occupying most of the what was previously a bottom surface when water was present. The monotonous appearance continues up to the edge, which is frequently colonized by halophytes and by accumulations of vegetable remains, swept there by the swell (Plate 3). In the small closed depressions, occasionally cultivated, the Wet Ground is less homogeneous, with halophytes and/or an agricultural mixture.

Wet Ground is over-saturated in water even in summer, and oozes when stepped on. This fact makes it very difficult to hike along the bottom depressions. When this facies dries, it becomes rough because of the desiccation cracks and polygons and the outcrops of algal mat remains.

Wet Ground is usually brown, and darkens as the water content increases. This dark hue accentuates the difference between this facies and the Dry Ground facies.

Occasionally this facies is covered by white efflorescence, giving it a surprising and blinding brightness in the field and a high albedo or bright reflectance in the VNIR. The efflorescence is at times deposited on fringes revealing the slow and continuous retraction of the water sheet towards the center of the depression. These efflorescences can have different looks and consistencies, appearing at times like a powder similar to newly fallen snow or in other cases like a solid crust that crunches under each footfall. Their extent is very variable sometimes winding along in intermittent strips several meters long and at times occupying the full extent of the salada bottom. In this last case, this facies represents the saline mudflat and the salt-pan environments. The permanence of the feature depends on rain and evaporation. However, the accumulation of the efflorescence is hindered because the frequent wind often sweeps the powdery deposits away (Samper-Calvete and García-Vera, 1998; Sanchez et al., 1998; Valero-Garcés et al., 2001).

In the small saladas, there are often failed attempts at farming on Wet Ground facies. Vestiges of these failed attempts are frequently observed. In these cases an irreversible change is detected: the bottom of the depression is partially incorporated by farmlands, the halophytic vegetation is lost and the edge of the depression is less distinct. Frequently, the settled area floods again and the intended agricultural use is compromised.

Location. Wet Ground usually borders Watery Ground extending up to the outer limit of the depression or to the halophytic fringe. Sometimes Wet Ground is interrupted by patches of Watery Ground. Even in the dry season, this facies is easily identified in the saladas both in the field and on the satellite images.

Arrangement and quantification. Wet Ground is present in all the studied images and its extent decreases as Water or Vegetated Ground expands over the bottom. The maximum extent was registered in August 1985, with 561 ha. The minimum was registered during March 2000, with 175 ha. Usually, Wet Ground comprises 300 to 500 ha, 30 % to 50 % of the total surface of the saladas (Figure 4a).

Visual discrimination. The wet surface is always detected in bands 4 and 5 with a dark hue contrasting with the lighter dry ground around it. In the RGB 457 composition it appears as maroon. The HSI composition confuses this facies with Watery Ground.

Spectral signature. Figure 4d shows the mean reflectance values for the six bands during the period studied. Its variability is lower than the previous facies. The reflectance values in the dry season are slightly higher than in the wet season. Reflectance increases from band 1 to band 5, with a maximum of 21 %. In the wet season a reflectance increase in band 4 has been observed, attributable to the seasonal occurrence of sparse halophytes. In band 7, both the soil humidity and its dark color produce a decreased reflectance.

According to the literature (Crowley, 1993; Epema, 1990; 1992; Escadafal, 1992; 1994), the efflorescence should be recognized by high values of reflectance in the bands 5 and 7, but only under dry conditions. Although field observations in 2000 to 2002 have noted efflorescence in the saladas, the corresponding spectral signature seems masked by moisture. Only in the March 2000 satellite image do some saladas show an area of high reflectance in all the bands, ranging from 30 % to 70 %. This high reflectance could be reasonably related with the presence of efflorescence though no field data are available to corroborate. This image has not been used in the average estimations, in the supposition that a new facies might be described for efflorescence when more images supported by field observations demonstrate the existence of such a facies.

[Plate 3]

Vegetated Ground

Description. The facies Vegetated Ground inside the saladas refers mainly to the halophytes where natural conditions are preserved, but also includes barley or volunteer plants in the small depressions where dry farming is occasionally attempted. In this case, the bottom is plowed but frequently abandoned because of the soil salinity (Plate 4). This facies would correspond with the saline mudflat margins in large playa-lakes or with the salt pan in small salty depressions.

Location. When the saladas have water several months every year, the halophytes grow in the external area of the topographic depression, bordering the Wet Ground or the Watery Ground. During periods when the saladas do not usually have water, Vegetated Ground covers their bottom, either partially or completely. Halophytes extend towards the center of the saladas as the water regime allows it, resulting in Vegetated Ground fringes according to the tolerance of each plant species to flooding and salinity.

Arrangement and quantification. Vegetated Ground has been detected in all the images and its extension varies according to the season and to the farming use. In spring, natural vegetation and crops are well developed, whereas in winter the natural vegetation has less density and less photosynthetic activity. Possible disturbances of the ecological conditions reflected in the modification of these fringes could be detected by long term studies. For the moment, only invasion by farming, agricultural infrastructures and dumping have been detected, but the main threat is the fresh water flooding by effluents from projected irrigated lands, endangering valuable endemisms (Cervantes and Sanz, 2002).

This facies is highly variable in the field and in the satellite image, both in its appearance and extent. This agrees with the intrinsic variability of halophytic vegetation in terms of perennial species substitution and canopy alterations following the flooding/drying episodes, phenological states, and annual halophyte blossoms. Moreover, this facies includes field conditions like plowed land, growing crops, stubble, etc. in areas with a coextensive intermittent barley crop.

The minimum Vegetated Ground extension was 97 ha, detected in January 1987, and the maximum was 488 ha, detected in July 1997, the most humid year of the period studied. Of the total surface occupied by the saladas, the Vegetated Ground extent ranges from 18 % to 42 % (Figure 4a).

Visual discrimination. In the Landsat bands 4 and 5, the hue varies with the phenology, making the systematic detection of this cover impossible. Vegetated Ground facies appear red in the RGB 457 composition, with differences in intensity according to the season. This facies is green in the RBG HSI composition.

Spectral signature. Figure 4e shows the mean reflectance values in wet and dry seasons during the period studied. In the wet season the spectral curve has the appearance of mixed soil and vegetation, with a peak in band 4 of about 24 %, and a similar value of 22 % in band 5. In the dry season, the peak occurs in band 5 with 27 %. The size of the Landsat pixel versus the extent and shape of the vegetation patches make it inpractical to look for spectral signatures in order to split this facies by plant density or by species or seasonal changes of either the plants or the soil background.

[Plate 4]

Dry Bare Ground

Description. Dry Bare Ground is the topsoil in a dry state usually recognized by a light hue in the field, having negligible or no vegetation, and including a variety of conditions. The border between this facies and Wet Ground is frequently a very neat line often representing the limit of the groundwater discharge into the saladas.

In the most external fringe of the playa-lakes, Dry Bare Ground is a smooth surface, more extensive in dry periods, which would correspond with a dry mudflat. In some small depressions Dry Bare Ground occurs over the entire bottom, and can contain stones also with light hues such as tabular limestone and gyprock fragments from a few centimeters to one meter in size (Plate 5). This stoniness, increased by plowing, gives a rough appearance to this facies. When the stones are removed by farmers, this appearance changes greatly and generally turns smoother and darker. On the other hand, the removed stones together with debris and rubbish are being dumped in the saladas, covering the Vegetated Ground or other facies which are then classified by remote sensing as Dry Bare Ground.

Location. Dry Bare Ground occurs in the most external area of the saladas and over their borders. In very dry conditions, this facies can extend over the entire bottom of some depressions, especially in summer. The Dry Bare Ground extent is inversely related to the Vegetated Ground and Wet Ground extent.

Arrangement and quantification. The dry ground has been detected in all the images. Their maximum extension is 260 ha in June 1994, and the minimum is 62 ha in August 1985. Its extent ranges between 10 % and 25 % of the total surface of the saladas (Figure 4a).

Visual discrimination. The Dry Bare Ground is clearly discernible in Landsat bands 4 and 5 because it has the lightest tone, brighter in summer than in spring, and an even lighter tone than the Wet Ground. In the RGB 457 composition this facies varies from light blue to white; in the RGB HSI composition, it is orange.

Spectral signature. Figure 4f shows the mean reflectance values during the wet and dry seasons of the period studied. The Dry Bare Ground has the highest reflectance values in all the bands, increasing gradually from the visible to the infrared. The peak is very clear in band 5 in all the images, for either the dry or wet seasons. In the dry season, the average reflectance value in band 5 is 35 %, clearly different from the wet surface, which has an average of 21 % for the same season. In the wet season, a small increase in reflectance in band 4 is noticeable due to the influence of some scarce vegetation.

[Plate 5]

[Figure 4]

Monitoring the surface extent of facies

Monitoring the facies extent is crucial for detecting environmental alterations or other changes in the saladas. Although discrimination of the five facies is possible in the field, their accurate location and spatial determination is only feasible by remote sensing, as we have done for the period 1985-2000.

The total saladas area established by remote sensing is 1000 ha. From this total area, the mean extent of Water plus Watery Ground is only 9 %, with a maximum of 40 % in January 1987 whereas a minimum extent of 0.9 % occurred in August 1987 for these facies taken together. It should be stressed that in April 1997, the most humid year of the last thirty years, both these facies taken together only occupied 35 % of the total salada extent. Some bias can be supposed because no satellite images are available during cloudy periods. Notwithstanding, the above comparisons illustrate the complex relationships between flood extent and weather that have been explored in detail

(Castañeda, 2002; Castañeda and Herrero, in revision) and modelized by Castañeda and García (2004).

The mean extent of Dry Bare Ground is 18 %. The maximum of 34 % occurred before the start of a series of land systematization projects, in June 1986, when the satellite image shows that farming was rare in the saladas. Wet Ground is the facies with the highest average extent, with a mean of 38 %, reaching a maximum of 56 % in August 1985. Vegetated Ground has a mean extent of 40 %, with a minimum of 10 % for the winter of 1987.

Figure 5 shows the distribution of the surface extent of each facies for the studied images. For each facies, the boxplots show the range box, with whiskers extending from the lowest value within the lower limit, Q1 - 1.5 (Q3-Q1), to the highest value within the upper limit, Q3 + 1.5 (Q3-Q1), according to Chambers et al. (1983); and the outliers, i. e., values outside these limits.

Vegetated Ground, Wet Ground and Dry Bare Ground show the broadest range of extent in Figure 5, but the variation of Water and Watery Ground are the most striking, with a minimum observed extent of 0 ha and 4.2 ha, respectively. Water and Watery Ground also stand out by their skewed distribution, emphasized by the outliers. They have the shortest ranges, but their coefficients of variation, 172 % and 124 % respectively, are much higher than wet ground (23 %), Vegetated Ground (32 %), and Dry Bare Ground (38 %). For Watery Ground and Water, a possible bias must be taken into account in the dates of the records with cloudy periods being under-represented, as already referred. The extent distribution of each facies recorded in this study will serve as a base for future monitoring and environmental warnings. So, we have undertaken another study with radar imagery in order to overcome this bias.

[Figure 5]

Temporal changes in the surface area occupied by each facies are noticeable but their long-term (15 years) variation is small, as shown by the trend lines in Figure 6. Water and Watery Ground vary in the same way and their trend lines remain almost constant. Vegetated Ground shows the clearest ascending trend line. Wet ground and Dry Bare Ground trends slightly decrease, and it is noticeable that they behave in opposition, an increase in one corresponds to a decrease in the other (Figure 7). In this Figure, Vegetated Ground seems independent from the Wet Ground and Dry Bare Ground variation extent. One reason for the increase of Vegetated Ground is that this facies includes some cropped fields in areas where farmers hope it will not flood. Moreover, this inclusion precludes the interpretation of Figure 7 as solely a representation of waxing and waning episodes of the halophytes. Since image dates have not continuity enough for providing a clear evolution of this facies in relation with dry and wet ground; and its relationship with groundwater and soil salinity would need more detailed field work.

[Figure 6]

[Figure 7]

Most of the changes in Water and Watery Ground extent are episodic judging by our experience, but the duration of these episodes can only be established by organized monitoring with more frequent observations, either in the field or by remote sensing. Results from this monitoring will need to establish thresholds for the allowable duration of flow episodes in order to preserve the hydric regime of the saladas ecosystems.

From the hydrological point of view, saladas are discharge areas of groundwater, mainly by evaporation. The five facies are related to the presence of water in the saladas, and excepting Dry Bare Ground are evaporative surfaces, as shown by the hydrological model of Castañeda and García (2004). For the evaporative facies we have computed an evaporation rate in two ways. First, we have considered Ev1, i.e., the sum of Water, Watery Ground and Wet Ground extent for each date (Figure 8), the available surface source of water discharge by direct evaporation. Secondly, the evaporation contribution of Vegetated Ground is also computed (Ev2 = Ev1 + Vegetated Ground), as the plants contribute to the water discharge by transpiration (Figure 8). Ev_1 is more variable, ranging from 24 % to 76 %, and with a mean of 50 % of the total saladas surface. Ev2 remains more constant ranging from 63 % to 93 %, with a mean of 80 %. Both Ev1 and Ev2 are very variable in the short-term, though the trend lines remain almost constant, with a slight decrease for Ev1. Including the Vegetated Ground facies as part of the evaporative surface, the result being Ev2, the short-term variability decreases considerably.

[Figure 8]

CONCLUSIONS

A catalog of different land covers, here defined as facies, has been created to describe and monitor the valuable habitats hosted by the playa-lakes in the Monegros region of Spain. The catalog includes five facies: Water, Watery Ground, Wet Ground, Vegetated Ground, and Dry Bare Ground. The adopted criteria make for an easy distinction of these facies either in the field or using the Landsat images.

In practice, the extent of each facies can only be estimated from remote sensing. These extents will be the key to appraising the conservation status of these singular habitats and to study their evolution. From the total extent of the saladas area, the mean extent of Water plus Watery Ground is only 9 %; the mean extent of Dry Bare Ground is 18 %. Vegetated Ground has a mean extent of 34 % and Wet Ground is the facies with the highest average extent, with a mean of 38 %. Temporal variations are noticeable but they were small for the 15 year span of this study. Only Vegetated Ground shows a slightly ascending trend. Wet Ground increases when Dry Bare Ground decreases, perhaps because of variations in agricultural use or in weather conditions. The episodic condition of water occurrence, recognized in the field observations, is confirmed by the high coefficients of variation of Water (172 %) and Watery Ground (124 %). The total evaporative surface, represented by the extent of the facies contributing to the water discharge in the saladas, does not show a significant change during the period studied. It will be necessary to monitor the Water and Watery Ground facies in order to establish threshold limits for the allowable duration of flow episodes in order to preserve the hydric regime of the saladas ecosystems.

The Landsat TM and ETM+ images have provided worthwhile historical data and additional information that completes the scarce field records. The definition of the facies with appropriate criteria has overcome the asynchronism between the field and satellite data. Satellite imagery has allowed us to quantify the extent of facies and to study their evolution from 1985 to the present. This analysis will serve as a baseline for studying the evolution of this ecosystem, especially with the integration of new environmental factors such as increased water input from newly irrigated conjoining lands.

Landsat images used in combination with field observations have provided thematic detail and a new conceptual integration for cataloging the facies of these habitats. This catalog, the most extensive register in time and space of these valuable habitats that exists, will be a crucial tool for understanding any future natural or man-induced changes.

The facies definitions are expected to be useful in similar environments with flooding and drying episodes. A more detailed subdivision of these land covers or surface types will be possible with improved sensors having better spatial resolution and with the support of simultaneous field data.

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FIGURES:

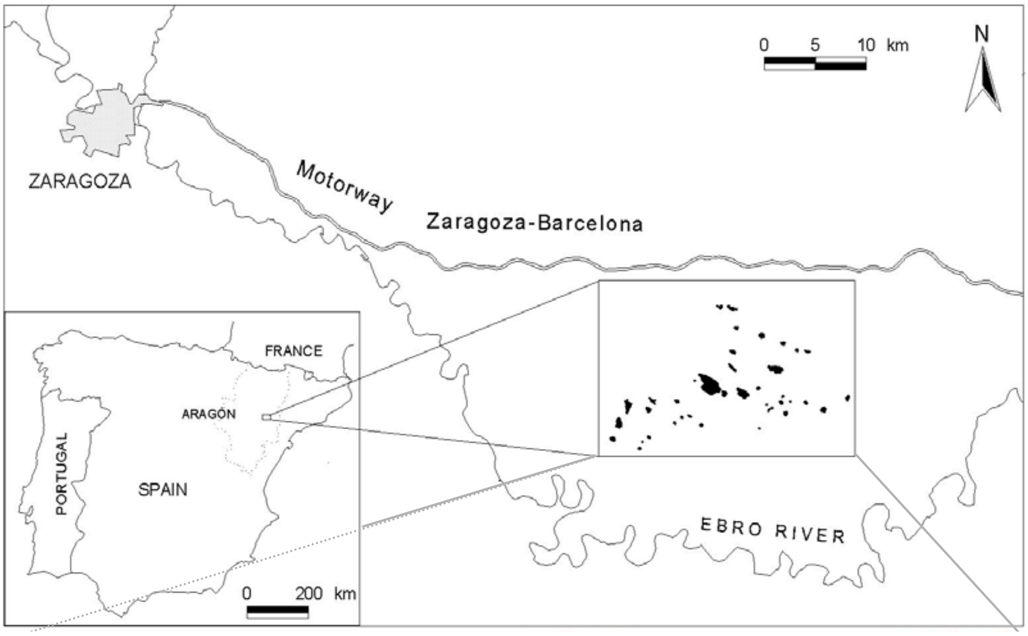

Figure 1: Location of the Monegros playa-lakes.

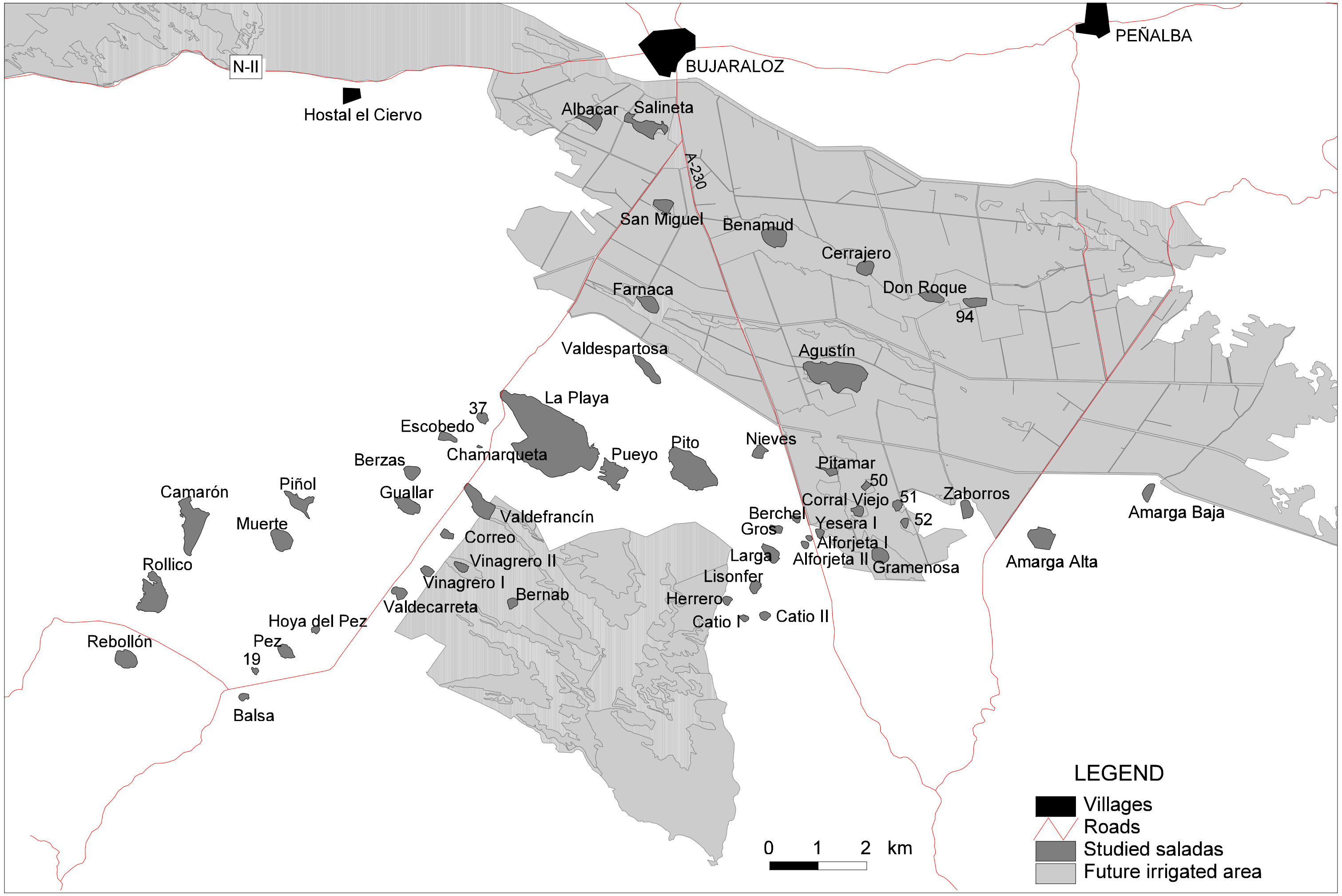

Figure 2: The remotely detected saladas of Monegros that are under study, and the future irrigated area bordering them.

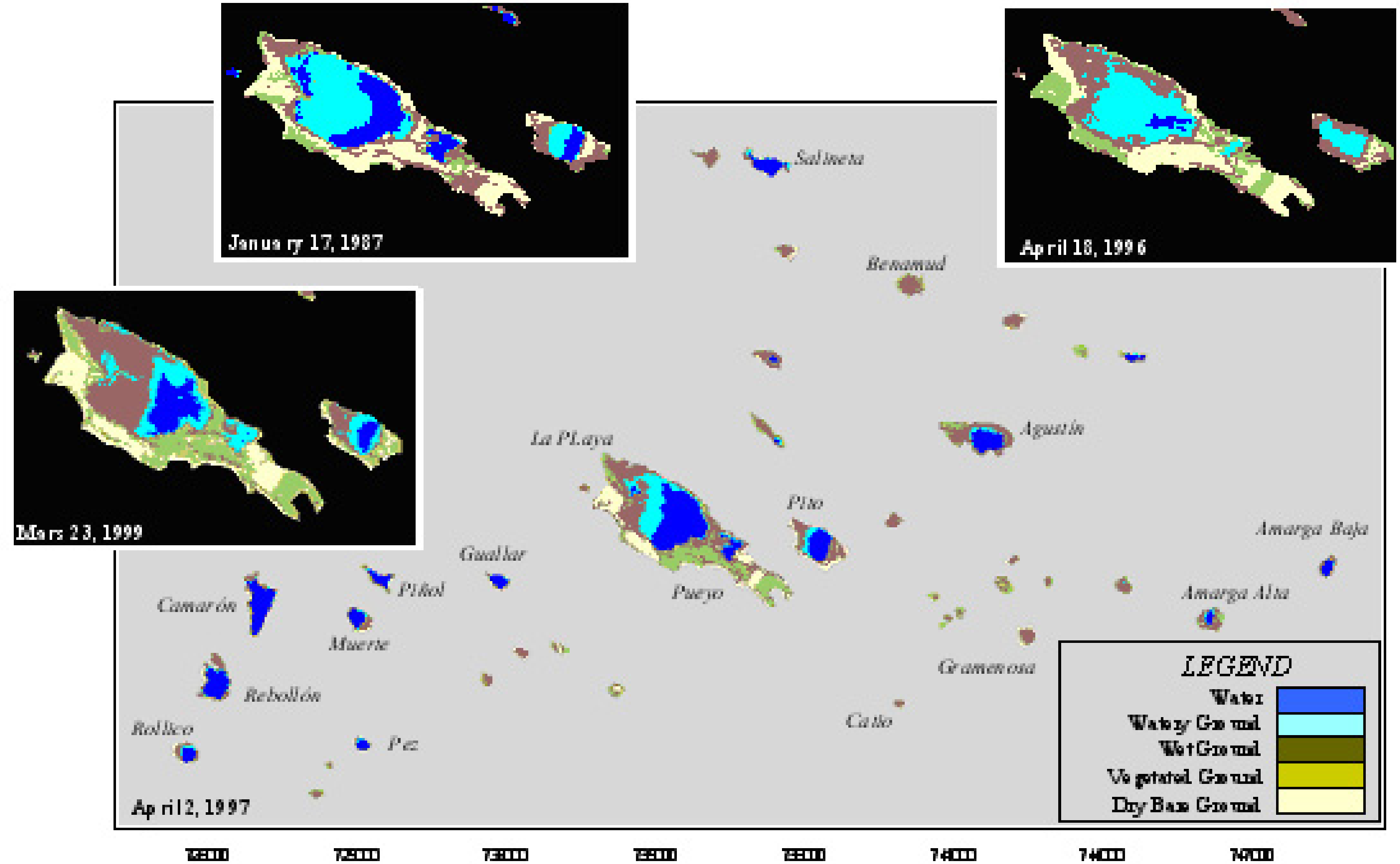

Figure 3. An example of a thematic map showing the facies distribution during in the wet period.

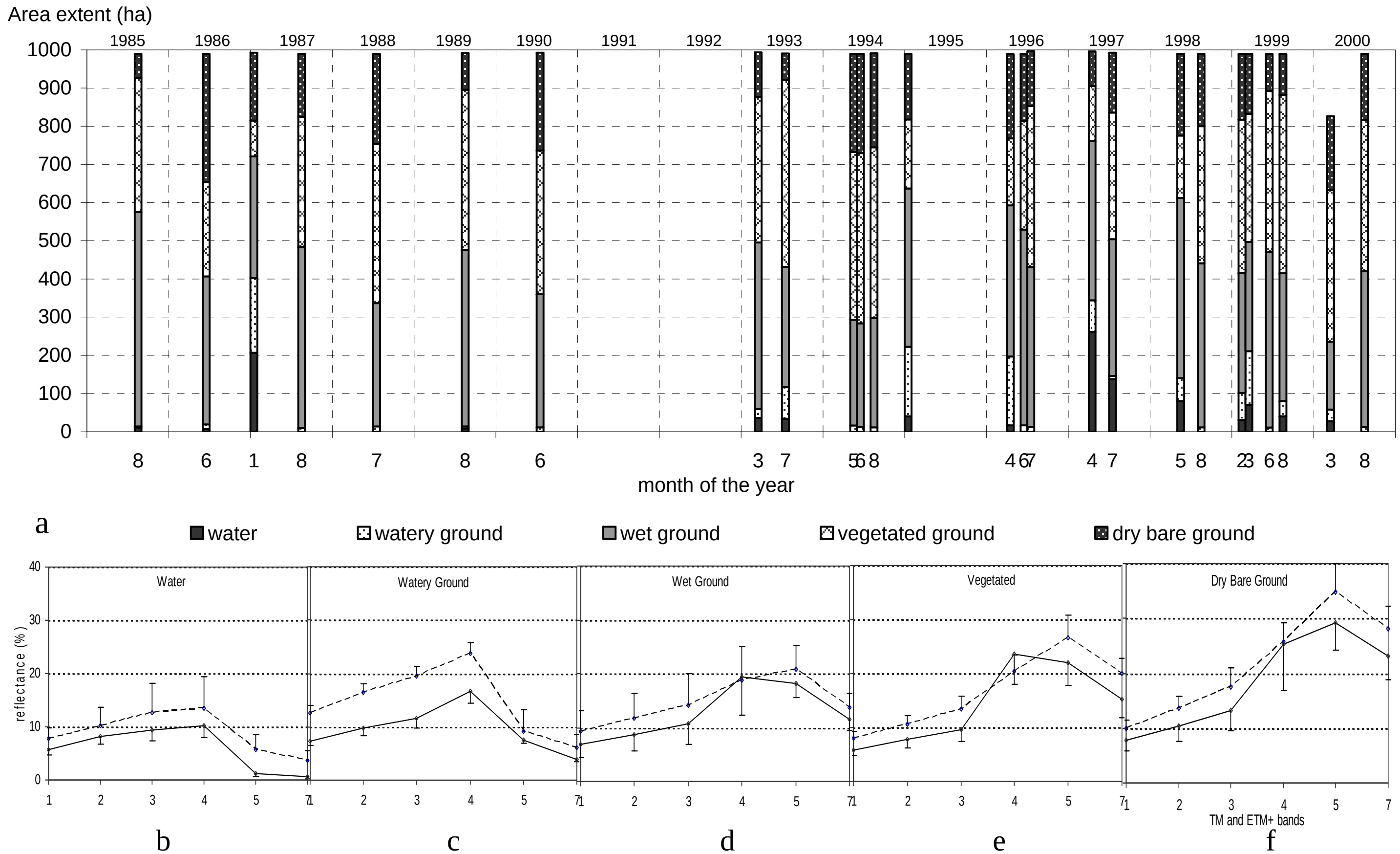

Figure 4. (a): The extent of the facies from 1985 to 2000, obtained by unsupervised classification of Landsat images, all the images are labelled by their month number on the x-axis. The lacking segment in the bar of March 2000 corresponds to the surface covered by salt efflorescence. (b to f): The facies spectral signatures in the wet season (solid line) and dry season (dashed line) represented by the medium reflectance of all the images in the period studied.

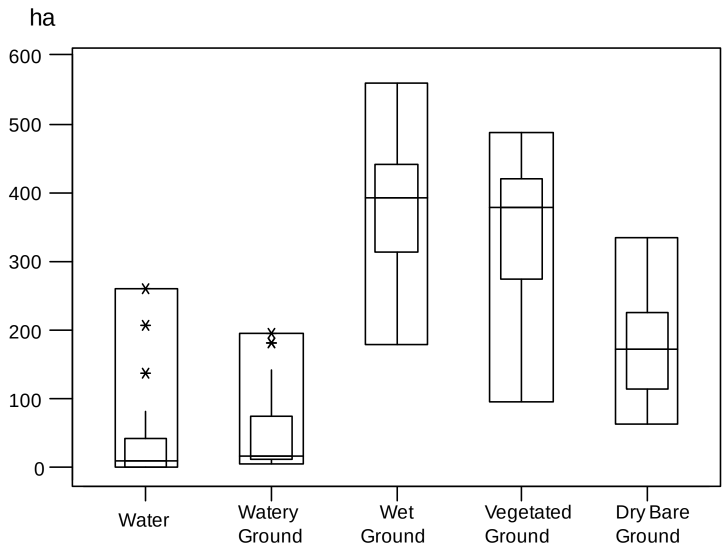

Figure 5. Boxplots of the surface extent (ha) of each facies from 1985 to 2000 for the 26 Landsat images studied.

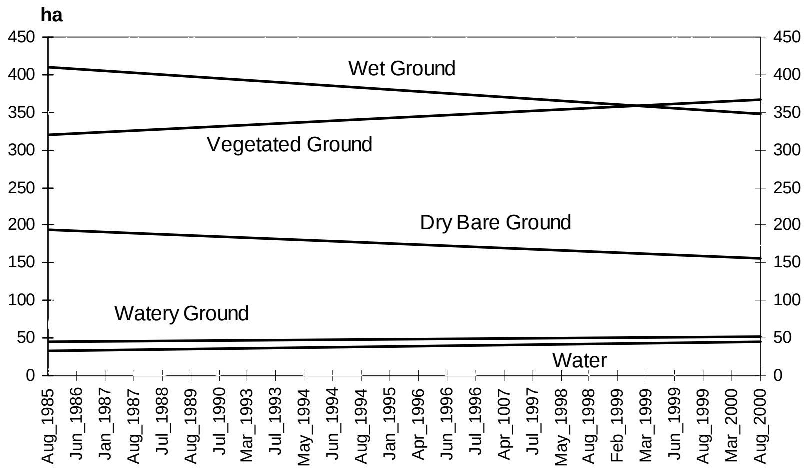

Figure 6. Trend lines for each facies computed from the studied Landsat images between 1985 and 2000.

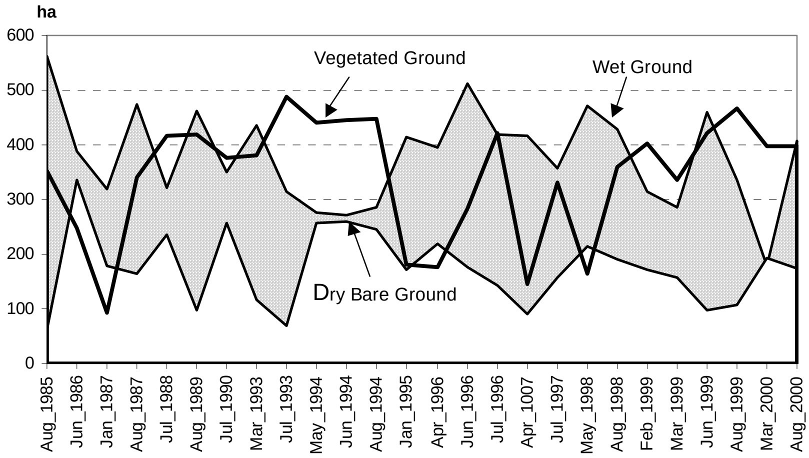

Figure 7. Opposed extent of Wet Ground and Dry Bare Ground, represented by the areas so indicated. The record of the Vegatated Ground extent is superposed.

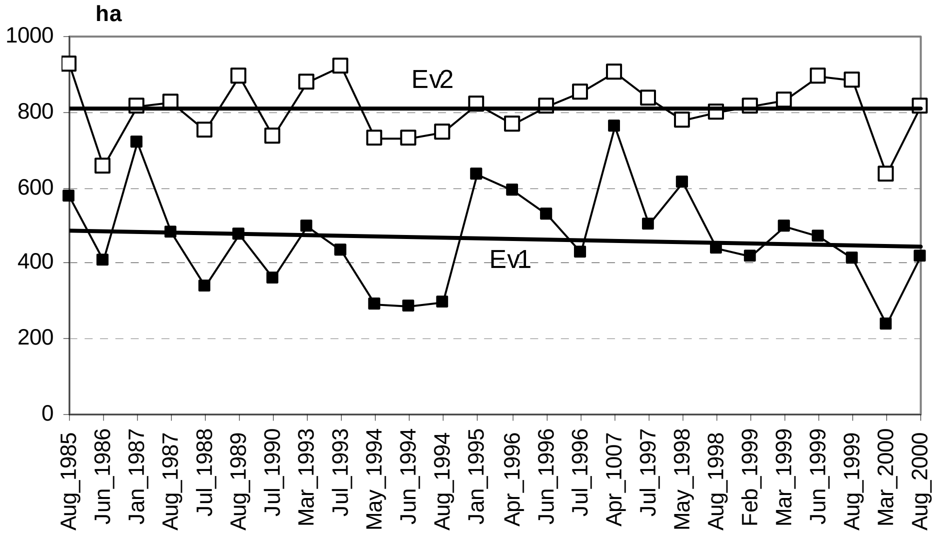

Figure 8. Variation of the evaporative surface within the saladas. Ev1 = Water + Watery Ground + Wet Ground; Ev2 = Ev1 + Vegatated Ground.

Plate 1. Water facies in different saladas during January and February of 2000: (a) La Playa, (b) Guallar, (c) Escobedo and (d) Rollico. The ruler (in a, b and d) is used to measure the water depth. It is usually read using binoculars from the edge of the salada, or as near as firm footing permits. In (a) and (b) the water body is shifted far from the ruler by the wind. Some saladas such as Escobedo (c) are depressions with gentle or no borders. They are usually cultivated and flooded (even in the same year), and they are only noticeable because of the presence of water in the wet season. As soon as the water disappears, they are worked again.

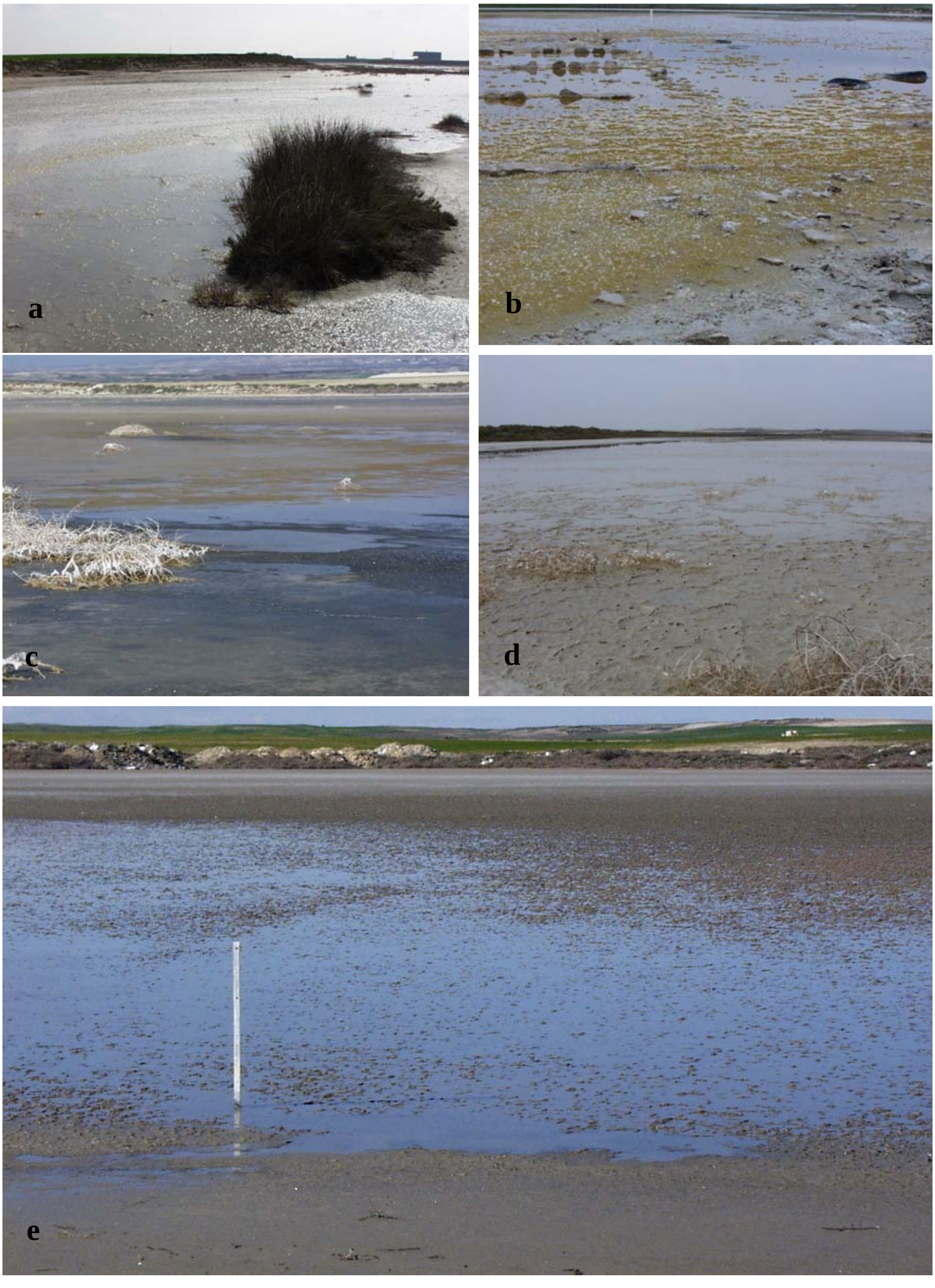

Plate 2. Watery Ground identified in different saladas. This facies usually looks like crushed iced in region of Salineta (photos a and b). The algal mats and other remains frequently produce a putrescent mud (photo c) with dome structures (photo d). This facies can-not be measured by ruler, as shown in photo e.

Plate 2 (cont). Details of the Watery Ground in Salineta in March 2000. This facies is a mixture of a highly concentrated brine with crystal salts and algae, which usually act as the precipitation nucleus.

Plate 3. Different views of the saladas bed when the water sheet disappears. Usually, their flat and uniform bottom appears as a smooth wet surface (a), darker when the accumulation of organic remains in the soil surface is greater. Salty algal mats (b) and efflorescence (c) cover the salada bottom partially or completely, making the saladas appear as bright white patches on the plain. These efflorescences are usually ephemeral

because they are soon whisked away by wind or reworked by new water input or agricultural activity.

Plate 4. The Vegatated Ground facies is organized in fringes along the border of the saladas bottom depending on plant salinity tolerance. The most tolerant halophytes reach from the edge toward the center of the salada, with the center reach depending on the presence of the ephemeral brines. When there is less water, there is more Vegatated Ground. Some depressions have the bottom completely covered by halophyte with the varied density of covering shown in (c) and (e).

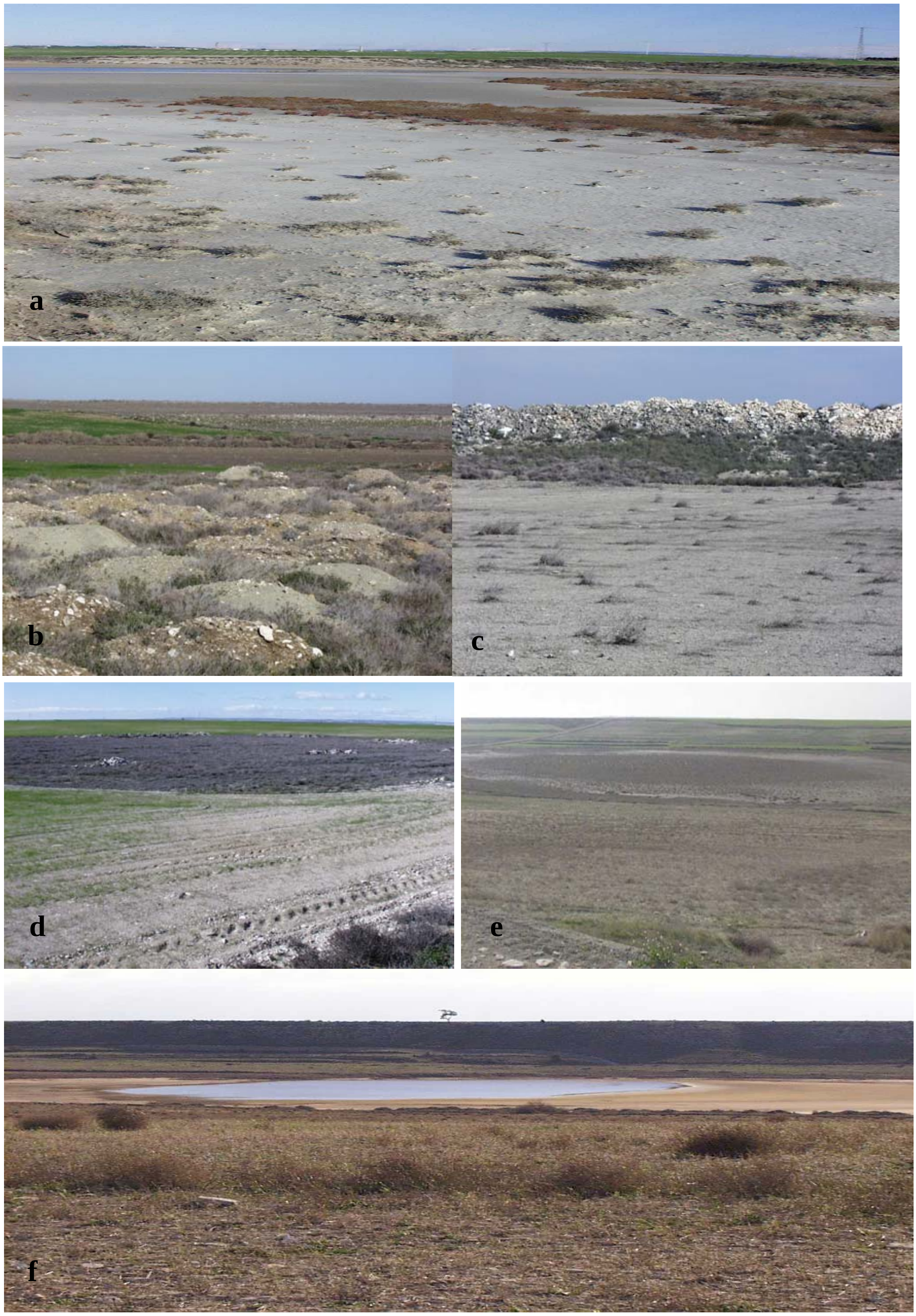

Plate 5. The Dry Bare Ground usually borders the saladas (a and f), but in the most dry depressions (b, c, d, e), this facies extends over all the bottom and it may be affected by stone dumping (b) or by farming (c, d and e).

FIGURE AND PLATE CAPTIONS

Figures:

Figure 1. Location of the Monegros playa-lakes.

Figure 2. The remotely detected saladas of Monegros that are under study, and the future irrigated area bordering them.

Figure 3. An example of a thematic map showing the facies distribution during in the wet period.

Figure 4. (a): The extent of the facies from 1985 to 2000, obtained by unsupervised classification of Landsat images, all the images are labelled by their month number on the x-axis. The lacking segment in the bar of March 2000 corresponds to the surface covered by salt efflorescence. (b to f): The facies spectral signatures in the wet season (solid line) and dry season (dashed line) represented by the medium reflectance of all the images in the period studied.

Figure 5. Boxplots of the surface extent (ha) of each facies from 1985 to 2000 for the 26 Landsat images studied. The outliers, marked with asterisk, are values higher than the upper limit defined as UL = Q3 + 1.5 (Q3-Q1), where Q1 and Q3 are the first and the third quartile of the distribution. They represent unusual observations.

Figure 6. Trend lines for each facies computed from the studied Landsat images between 1985 and 2000.

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Plates:

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