Mapping categories of gypseous lands in Mexico and Spain using Landsat imagery

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Abstract

Remote sensing is a powerful tool for thematic mapping, but its use for the discrimination of different kinds of soils has been scarce and the results variable. We demonstrate the usefulness of Landsat ETM+ images to discriminate gypseous lands in two contrasting regions, Cedral, Mexico, and Bujaraloz, Spain. We also discuss the contribution of the infrared bands, and found the bands of mid and thermal infrared to be the more useful. A supervised classification of Landsat ETM+ images enabled us to discriminate land covers related to gypseous lands in Cedral, and to locate gypsum lithologies in Bujaraloz. The thermal infrared band does not substantially improve the classification in Bujaraloz, but it does in Cedral, being best in the wet season, when the differences of temperatures among classes are relevant.

Keywords: Gypsiferous soils; Gypsum; Remote sensing; Supervised classification; Thermal band

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1. Introduction

The extent of soils with gypsic or petrogypsic horizons in Africa, Asia, Europe, the Near East, and the United States has been estimated at 207 million ha (Eswaran and Zi-Tong, 1991), and broad gypseous areas also occur in Australia, Mexico, and South America. Gypseous soils are widespread both in Mexico and in Spain. About 400,000 ha of gypseous lands occur in the state of San Luis Potosí, Mexico (Martínez-Montoya, 2005); and 1.9 million ha of gypseous lands occur in the Ebro valley, Spain (Navas, 1983). Many of these soils, occurring in dry countries, have been cropped and grazed from time immemorial (Herrero and Poch, 1998).

Gypseous soils host valuable endemisms with striking adaptations to the high amounts of gypsum, and specific management practices are needed when using gypseous lands for agriculture (Herrero and Boixadera, 2002) or for urban developments. However, no procedures are available for quick and accurate delimitation of gypseous soils.

The main advantages of satellite imaging against aerial photographs and ground survey are the synchronic coverage of large areas and the repetitivity of observations. These characteristics allow the study of dynamic phenomena and the continuous updating of thematic maps. This powerful tool has not been extensively applied to soils delineation; moreover the results have been variable as not all the potentialities have been fully explored. From the pioneer studies on the spectral signature of gypsum (Hunt *et al.*, 1971; Hunt, 1977, 1979) and its early consideration as a target for Earth surface remote sensing (Lindberg and Smith, 1973), or from the spectral data of other sources gathered by Metternicht and Zinck (2003) and the recent revision of infra-red emission of sulfate minerals by Lane (2007), the sensors of natural resources satellites such as

Landsat or Spot may be excellent for application to gypseous lands studies in dry areas. However, the literature often only states the possibility of using some satellite and sensor, or a specific region of the electromagnetic spectrum (Abd El-Hady, 1992; Younis, 1993; Mulders and Girard, 1993; Younis et al., 1997).

Goossens and Van Ranst (1998) and Goossens *et al.* (1999) report that Landsat TM images can detect gypseous soils even when the spectral differences between saline and gypseous soils are not very evident in false color compositions. These authors stress the usefulness of the thermal infrared (TIR) band for gypseous soils discrimination and conclude that gypseous soils were accurately and quickly mapped, and they attained a good separation from saline soils due to temperature difference detection both in wet and dry conditions. They agree with Crowley (1993) and with Panah and Goossens (2000) that the TIR band gives a complement to the information from visible and the near (NIR) and short wave (SWIR) bands. Opposite opinions can be found in authors like Abd El-Hady (1992), Bryant (1996), Muldavin et al. (2001), or Martínez-Ríos and Monger (2002), stating that the thermal band (TM6 or ETM+6) is not useful for gypseous soils discrimination. Some authors do not use the TIR band, as is the case of Neville et al. (2000) proposing a combination of bands TM 1, 4, 5, and 7 of Landsat 5 for surficial gypsum determination in a saline basin, or Nield et al. (2007) who propose a normalized difference ratio (TM bands 5 and 7) to identify gypsic soil areas with Landsat 7.

The aim of this article is to show the usefulness of Landsat ETM+ images for discriminating lands with geological or pedological gypsum, and to analyze the contributions of the thermal band.

For this purpose we studied two gypseous regions with contrasting characteristics, one in Cedral, San Luis Potosí, Mexico, and the other in Bujaraloz, Aragón, Spain. The

gypseous lands in Cedral, are smooth with gentle slopes; homogeneous areas $\gg 1$ ha of shallow gypsum (< 25 cm depth), gypsophilous grass or desert shrubs are common. The relief in Bujaraloz is more undulating and heterogeneous, with agricultural and shrub covers much more fragmented than in Cedral. These differences offer a good opportunity to test the use of remote sensors and to compare how they perform in two different gypseous environments.

2. Study areas

The Cedral area is located in the Altiplano Potosino, San Luis Potosí, Mexico, its surface area is 1048 km^2 , with 333 km^2 of gypseous lands corresponding to parts of the municipalities of Vanegas, Cedral, Matehuala and Real de Catorce ($23^\circ 42' 35'' - 23^\circ 55' 18''$ N and $100^\circ 34' 7'' - 101^\circ 5' 14''$ W (Fig. 1). Bujaraloz area is located in the central Ebro valley of Spain, its surface area is 1335 km^2 , and it lies between: $41^\circ 34' 48.5'' - 41^\circ 18' 10''$ N and $0^\circ 27' 20''$ W – $0^\circ 4' 32''$ E (Fig. 1). The average temperature and precipitation of these semi-arid areas are: 16.5°C and 291.8 mm for the west part of Cedral (García, 1988), 17.3°C and 373.9 mm for the east part of Cedral, and 14.5°C and 388.3 mm for Bujaraloz (Martínez-Cob et al., 1998).

Cedral landscape consists (INEGI, 1983) of llanos, lomas, bajadas and sierra, with these terms defined in Bates and Jackson (1987). Lomas, bajadas and sierra have limestone, lutite, conglomerate, sandstone, and limolite (CRM, 1992 y 1996). Alluvial deposits of gravels, sand, silt and clay are common in llano, with high contents of gypsum in the low areas (García, 1968; CRM, 1992). The Bujaraloz area is a structural platform carved by flat-bottomed valleys and close karstic depressions of high environmental interest (Castañeda and Herrero, 2008) produced by dissolution of

gypsum. According to Salvany *et al.* (1996), rocks are Miocene sub-horizontal strata, either detritic (lutite, limolite, and sandstone) or lacustrine (gypsum, limestone), and Quaternary sediments of colluvial, alluvial, and eolian origins.

3. Methods

Table 1 shows details of the satellite images used, all of them were acquired by Landsat 7 ETM+. The study area of Cedral is in the overlap (Fig. 1) of two georeferenced Landsat 7 scenes furnished by the Secretaría del Medio Ambiente y Recursos Naturales (SEMARNAT). After clipping Landsat scenes to obtain the study area sub-scenes, the thermal band of the two sub-scenes was resampled at 30 m pixel size using the nearest neighbor method with Clarke 1886 spheroid, datum NAD27 (Mexico), and UTM zone 14.

Provided that the images from Mexico were furnished with geometric correction, we did first the geometric correction and then atmospheric correction for the Spanish site in order to have the same processing in the two study areas.

In Bujaraloz, exactly the same sub-scene of each of the three available Landsat images (Table 1) was used. This subscene includes the whole study area. The three sub-scenes were geometrically corrected and georeferenced. For this purpose, about 80 control points were taken for each sub-scene on the topographic military maps of Spain (Servicio Geográfico del Ejército, 1983 and 1985) at scale 1:50,000 (Sheets 413 and 414), and a second-order polynomial transformation was applied obtaining a square mean error of less than 0.5 pixel. All bands were resampled at 25 m by the nearest neighbor method, with International 1909 spheroid, datum ED50, and UTM zone 30.

In both study areas, an atmospheric correction (Chávez, 1988) was applied to bands 1 to 5 and 7, and the digital numbers were transformed to reflectance according to Chuvieco (2002). Band ETM+6 was converted to surface temperature (°C), using the method of Sospedra *et al.* (1998) taking in to account the model of Valor and Caselles (1996) for the calculation of emissivity.

Land cover discrimination was obtained by supervised classification with a maximum likelihood classifier. Before starting the supervised classification, we performed visual interpretations of the different bands and of several of their transformations, as Tasseled Cap, IHS, principal components, and gypsum index of Neville *et al.* (2000). We find that the discrimination of gypseous lands achieved by untransformed bands was better than any of the assayed procedures.

As our computing equipment allows treating many bands, we assayed different classifications using from the three bands giving the best visual results, to a maximum of 14 bands in Bujaraloz. In Cedral each sub-scene was classified separately, whereas in Bujaraloz a multitemporal classification was achieved for the three sub-scenes.

Training areas in Cedral were taken from false color compositions RGB 647 or 746 (Appendix 1 electronic version only) using as reference information the maps of soil, vegetation, and land-use at 1:50,000 scale (CETENAL, 1972), and at 1:1000,000 scale (INEGI, 1983) together with field data about presence and depth occurrence of gypsum (Martínez-Montoya, 2005) for Cedral. The total surface of the training areas was 2.7 % of the sub-scene of gypseous area in the image 28/44, and 3.8 % in the image 28/43. The thematic classes (Table 2 and Appendix 2 electronic version only) were defined according to the map of vegetation and land use of CETENAL (1972) at scale 1:50,000, with subdivisions in the agricultural area, in the desertic shrub, and in the izotal shrub based on the greenness index from the Tasseled Cap transformation (Crist

and Cicone, 1984). Greenness index and Tasseled Cap transformation were only used as help in the visual interpretation, and for drawing training areas.

Training areas in Bujaraloz were taken from Landsat false color compositions RGB 742 or 741 (Appendix 1 electronic version only), using as reference the lithological map of Salvany *et al.* (1996) at 1:50,000 scale. The total surface of training areas for 14 classes classification was 3.25 % of the subscene. The thematic classes of Bujaraloz (Appendix 3 electronic version only) were defined based on the same map. Two more classes –irrigated lands and wetlands– were defined based on field knowledge and visual interpretations of false color compositions.

During the process of training areas designation, the spectral separability between classes was analyzed and evaluated by means of transformed divergence and Jeffries-Matusita distance. We also did a visual verification of the agreement between the obtained classification and the gypseous areas in Cedral, and the lithological map in Bujaraloz. The resulting classifications were evaluated, both in Cedral and in Bujaraloz, by means of confusion matrices taking reference areas different from the training areas used for classification. At Cedral, the reference areas totalled 2.54% of the subscene of the gypseous area in the Landsat scene 28/44, and 3.86% in the 28/43 scene. At Bujaraloz, these verification areas totalled 2.8% of the study area. As accuracy parameters we calculated the overall accuracy (OA), the kappa statistics (κ), the user's accuracy (UA), and the producer's accuracy (PA) (Congalton, 1991). The images were manipulated with ERDAS 8.4 from Leica Geosystems, and map edition was performed with ArcView 3.1, from ESRI (Redlands, CA).

4. Results and discussion

Cedral and Bujaraloz show differences in land characteristics relevant for mapping gypsum, even that bare gypsum patches are minority at the two studied sites.

A shallow gypseous soil horizon occurs in Cedral in areas of several tenths of hectares, this fact plus the monotonous gypsophilous vegetation contribute to a homogeneous landscape in terms of reflectance and thermal properties, allowing the discrimination of land covers associated with gypsum. These conditions do not occur in Bujaraloz, which gives an “advantage” to the Cedral landscape for digital classification of data from sensors having the spatial resolution of Landsat ETM+.

In Bujaraloz, most non agricultural lands bear sparse gypsophylous shrubs and soil horizons with mixed mineralogy and some organic matter. The agricultural lands show the complex and annually changing plots pattern typical of dry farming composed of winter cereals, their fallow, and plowed plots, whereas alfalfa and corn predominate at the irrigated land.

The conditions of our two study areas are far from the bare gypsum at sites like White Sands, a terrestrial analogue (Schulze-Makuch *et al.*, 2007) of Martian calcium-rich sulfate targets (Langevin *et al.*, 2005; Mangold *et al.*, 2008; Cloutis *et al.*, 2008), where the spectral signature approaches are fruitful. In the common terrestrial conditions, the abundance of gypsum in soils is mediated by specific vegetal covers or by features like water-stress in plants associated to the low water holding capacity of gypseous soil horizons. Gypsum dictates the spectral signature of soil only inasmuch as the gypseous horizon is surficial.

4.1. Cedral

Table 2 displays the 15 thematic classes discriminated by the supervised classification. In the agricultural area, class A11 is rainfed agriculture with erosion problems, whereas the other five classes have both irrigated and rainfed areas.

The two agricultural classes *no greenness* (A11) and *very low greenness* (A12) as well as the three classes of natural vegetation *gypsophilous grass* (B2), *desertic shrub with no greenness* (B11) and *with low greenness* (B12) occupy shallow soils having a horizon with 50 % or more gypsum content at a depth < 25 cm, and most of them close to 1 cm deep. A shallow gypsum horizon in the soil results in the exclusive growth of adapted plants (Meyer et al., 1992), the gypsohiles. The quick and efficient detection of desert grasslands of high biodiversity conservation value requires calibration with the substrate, along with an exploration of the temporal constraints, as pointed out by Muldavin et al. (2001).

The classes *desertic shrub with medium greenness* (B13) and *with high greenness* (B14) and the class *mesquite woodland* (B3) differ from those mentioned above by their preferential location in areas with deep gypsum (> 25 cm) according to our field observations. The three classes of *matorral-izotal* (C1, C2, and C3) do not have gypsum in the study area.

Gypseous areas of the images can be extracted by applying a mask created by delimitating these gypseous areas on the screen from the map of gypseous lands of Martínez-Montoya (2005). This mask excludes classes C1, C2, and C3, and a new classification (Fig. 2) only with the gypseous areas gives better results by decreasing the confusion between classes, with a slight increase of their separability. This achieves a more accurate classification, increasing by 14 % the overall accuracy for the classification of the wet season image, and 5 % for the dry season image, and a κ

increase of 8% and 7%, respectively. Then, the overall accuracy and the global κ of the classification in both images (wet and dry seasons) surpass 90%.

Band 6 was the most useful ETM+ band for discriminating gypseous lands in Cedral, followed by bands 5 and 7. This result agrees with the findings of Goossens and Van Ranst (1998) in the Irania desert, and with Goossens et al. (1999) in the Egyptian desert. On the other hand, our result disagrees with the works of Younis (1993) in Murcia, and García and Pérez (2001) in Madrid, both in Spain, who found TM bands 1, 2 and 3 to be the better ones. We attribute our agreement with the results in Iran and Egypt to a flatter relief, similar to Cedral, compared to the more rough relief in Murcia and Madrid together with a variety of rocks.

The TIR plays an important role in discriminating land covers. The difference of temperatures between classes is much greater in the wet season image than in the dry season image (Appendix 4 electronic version only). Four groups can be established in the gypseous area according to the temperature in the wet season: (i) very high temperatures ($> 35^{\circ}\text{C}$), *desertic shrub* either *without greenness* (B11) or with *medium greenness* (B13), and the *gypsophilous grass* (B2); (ii) high temperatures (around 30°C) with all the classes not included in the other three groups; (iii) medium temperatures (around 25°C), *mesquite woodland* (B3); and (iv) low temperatures ($< 20^{\circ}\text{C}$), crops with high and very high greenness (A22 and A23).

The inclusion of TIR in the classification improved the overall accuracy, with the greatest improvement in the wet season (Appendix 2 electronic version only) because the differences in temperatures between classes are greater than in the dry season. Using the TIR band in the classification results in a greater accuracy increase in the class *gypsophilous grass* (B2), being this class the one showing the lower accuracies in both seasons when TIR is not included (Appendix 2 electronic version only). These

accuracies increase from $\kappa < 0.15$ without TIR to $\kappa > 0.95$ if TIR is used. In the dry season, the omission error (OE) and commission error (CE) decrease from 74.2% to 20.6% and from 76.9% to 2.2%, respectively, and from 75.7% to 26.6% and 74.3% to 1.2%, respectively, in the wet season. When TIR is not used, *gypsophilous grass* (B2) is confused with the desertic shrub classes, mainly with the *high greenness desertic shrub* (B14) with OE = 25.9% and CE = 34.2% in the dry season, and OE = 68.54% and CE = 19.53% in the wet season. This confusion strongly decreases if TIR is used in both the wet (OE = 4.5%, CE = 0.2%) and the dry season (OE = 0.2%, CE = 1.0%) images, with a noticeable increase of the B2 and B14 accuracy in the two images (Appendix 2 electronic version only). The difference in temperature between B2 and B14 in the wet season is much greater than with the other desertic shrub classes (B11, B12, and B13) (Appendix 4 electronic version only), and this difference in temperature is sufficient for a substantial decrease in the confusion.

The TIR band highly improves the discrimination of the class *uncropped with low greenness* (A13) in the wet season, when this class has low user's accuracy due to the many omission errors with *desertic shrub* (OE from 3.0% to 8.5%) and *gypsophilous grass* (11.1%). These errors disappear when the TIR band is included in the classification (OE = 0%) because most of these classes have temperatures higher than A13 (Appendix 4 electronic version only). In the dry season the confusion with these classes is very low (OE from 0% to 2.7%) and the discrimination is good, irrespective of if the TIR band is included.

In contrast, the TIR band worsens the classification of the class *desertic shrub with no greenness* (B11) in the wet season because more commission errors arise (CE = 26.1% with TIR versus 11.7 without TIR), mainly from the inclusion of areas of *desertic shrub with high greenness* (B14) with a CE = 10.3% and *gypsophilous grass*

(B2) with a CE = 14.8%. This confusion can be attributed to the presence of *Larrea tridentata* as the outstanding and common component of the two classes.

The class *cropped with very high greenness* (A23) also worsens its classification when the TIR band is introduced (Appendix 2 electronic version only). This class is seldom represented in the study area (< 1%), and then the size of the samples chosen either as training areas or for evaluation of the classification were very small compared with the other classes. In spite of its low representation, this class has not been merged with the other *cropped* classes, because A23 exclusively corresponds to irrigated areas, and A23 was well classified when the TIR band was not used. This class is confused, and could be merged, with the class *cropped with high greenness* (A22). The use of the TIR band results in a decrease of the user's accuracy with an increase of commission errors from CE = 10.2% without TIR, to CE = 24.1% with TIR in dry season; and from CE = 9.0% to CE = 27.6% in wet season. The pixels erroneously included have similar temperature values in both classes, and this happens mainly in the wet season when the confusion is higher.

In summary, classification using the wet season image and including the TIR band provided the best results in Cedral (overall accuracy 0.99, and $\kappa = 0.92$). The classification from dry season imagery including the TIR band is also very good (overall accuracy 0.93, and $\kappa=0.92$). In both cases, the *desertic shrub with high greenness* (B14) and the *gypsophilous grass* (B2) are the best discriminated with $\kappa \geq 0.97$; and the agricultural class *very high greenness* (A23), with $\kappa < 0.76$, is the worst classified (Appendix 2 electronic version only). These results are comparable to those obtained by Nield et al. (2007) in San Rafael Swell, Utah, US.

4.2. Bujaraloz

In Bujaraloz we mapped lithological units, instead of landcovers associated with gypsum. The reasons were the different distribution of gypsum in Bujaraloz and in Cedral, as well as the differences in the available ground information. The heterogeneity of soils, especially in their surface horizon, is produced by the occurrence, in a surface area much smaller than in Cedral, of several kinds of rocks as shown in the names of the Lithological Units on the 1: 50 000 scale map of Salvany et al. (1996). These circumstances explain that our thematic classes (Appendix 3 electronic version only) can be composed by as much as four lithologies. At the beginning, the supervised classification produced 14 thematic classes (Fig. 3) with overall accuracy 0.60 and $\kappa = 0.55$ when the TIR band was used for classification; and overall accuracy was 0.58 and $\kappa = 0.53$ without the TIR band (Appendix 3 electronic version only).

The distinction between dry and wet seasons in Bujaraloz was not important for our purpose of image classification. In the irrigated area the soil moisture is independent of the season. In the non irrigated area the lack of natural vegetation with changes linked to season, or that most of the surface area either is plowed to earn subsidies or is planted with low input barley or durum whose development relies on irregular spring rains (Moret et al., 2007) negate seasonal weather differences.

Because of the lack of soil maps for Bujaraloz, we had to use lithological map in the classification. This map is not well suited for satellite image classification because: (i) it does not represent the soil, which is responsible of the spectral information gathered by satellites; and (ii) most of the units on this map include several lithologies not exclusive of one unit, as shown in the first column of Appendix 3. The low extent, intricate disposition, and non-pure composition of the map units, together with the lack of natural land covers, makes the Bujaraloz area unfavorable for gypseous lands discrimination with Landsat. This is the case of red lutites, outcropping as a narrow —

225 m in average— and intricate strip several km long. Such a disposition results in important confusion with *green lutite limestone* and *green lutite gypsum* thematic classes (Appendix 3 electronic version only), both of them adjacent to the *red lutites* class and containing also lutites.

The most useful ETM+ bands for gypseous land discrimination were the same as in Cedral, but with different rankings: the best was band 7, followed by 5, and then by 6.

Contrariwise to Cedral, in Bujaraloz the differences between the classification with all ETM+ bands or without the TIR band were irrelevant (Appendix 3 electronic version only). All the classes in Bujaraloz show lower temperatures in the March image, the highest in August, and intermediate values in June (Appendix 5 electronic version only). Moreover, except for *wetlands* and *irrigated lands*, the temperature for the other thematic classes is similar, making it impossible to group classes by their temperature. *Marl-limestone* shows the lowest temperatures on the three dates, while *red lutite* had the highest temperature in August.

In general, for the classes with a very good classification (*irrigated lands*, *wetlands*, *marl-limestone* and *lutite-sandstone*) or with poor classification (*gypsum*, *gypsum-depressions*, *red lutite-gypsum*) the differences in accuracy are negligible or nil when the TIR band was included in the classification procedure (Appendix 3 electronic version only). The biggest differences happened for the *alluvium*, *limestone-lutite*, *red lutite*, and *green lutite-limestone*, where the classification accuracy got worse when the TIR band was used. However, these differences were not considered relevant.

A very good discrimination of the classes *wetlands* and *irrigated land* (Appendix 3) was achieved, as they are distinctly different from all other classes, which have little or no vegetation. In other classes, *marl-limestone* was the best discriminated ($\kappa > 0.97$),

followed by *lutite-sandstone* ($\kappa = 0.92$) and by *green lutite-gypsum* ($\kappa \geq 0.80$). These last two classes had good user's accuracies from 85.1% to 97.9% but their producer's accuracies were low (Appendix 3) because of omission errors, with 38.1% of omitted pixels in the *lutite-sandstone* going mainly to *red lutite-gypsum*, 24.9%, whereas the omitted pixels in the *green lutite-gypsum*, 48.5%, were erroneously classified mainly as *gypsum* (14%).

The class *red lutite-gypsum* was the worst discriminated (Appendix 3), with 87.0% of commission error and 71.3% of omission errors. Most of the confusion happens with *lutite-sandstone* with a commission of 46.6% and *reddish lutite* with a commission of 10.7% and an omission of 14.0%, because the three classes have in common the presence of red lutite.

For the classes *gypsum* and *gypsum depressions* we also obtained unsatisfactory results ($\kappa < 0.20$). However, we realized that areas outside of the lithological units gypsum, limestone and lutite (thematic class *gypsum*) and gypsum, limestone, lutite depressions (thematic class *gypsum-depressions*), with surficial gypsum, mainly in nodular form, are well classified.

In the *gypsum* class, the amount of limestone in the surface horizon increases from west to east, being only about 5% gypsum at the east end, a fact not represented on the lithological map.

Trying to minimize the confusions, we also grouped the lithological units according to the dominant rock. Then we made a new classification where eight thematic classes (Fig. 3), i.e., six classes related to lithological units plus *wetlands* and *irrigated lands*, were discriminated with overall accuracy 0.67 and $\kappa = 0.60$ (Table 3). This accuracy increase for the *gypsum* class was not considered to be satisfactory for this class.

The results showed that the use of the lithological map as a surrogate for the soil map strongly limited the outcome in Bujaraloz. Supervised classification can be useful for discriminating gypseous lands; but in the areas lacking a soil map, these results can not be fully evaluated. In the same way, if some part of the studied region had a soil map, the ground truth used for training pixels would have less uncertainty, and then a great improvement in the results of the classification could be expected.

5. Conclusions

Supervised classification of images from Landsat ETM+ allowed discrimination of gypseous lands in Cedral, and location of gypsum lithologies in Bujaraloz. The ETM+ bands, 5, 7 and 6 (mid and thermal infrared) were the most useful for gypsum lands discrimination. The inclusion of the thermal band transformed to surface temperature in the classification improved the accuracy in Cedral, mainly in the dry season, but in Bujaraloz its contribution was not very relevant.

The classification obtained in Cedral (overall accuracies and kappas > 0.92) was very good and better than in Bujaraloz (overall accuracies and kappas ≤ 0.60), where most of the units in the map include several lithologies not exclusive of one unit. These lithological maps, the only ground data available for spectral discrimination, were insufficient in an area like Bujaraloz with highly heterogeneous soils, especially in their surface horizons.

In Cedral, the gypsophilous grass, that grows on soils with a shallow gypseous horizon (< 25 cm deep), was very well discriminated in both the dry and wet season. Overall, the image from the dry season was better for discriminating the classes related to shallow gypsum, when only the gypseous area was studied.

In Bujaraloz, the discrimination of gypsum classes corresponding to lithological units gypsum, limestone and lutite (thematic class *gypsum*) and gypsum, limestone, lutite depressions (thematic class *gypsum-depressions*) was unsatisfactory. Notwithstanding, these results are better than they appear, because field checkings showed that many areas classfyied as gypsum outside of the lithological unit gypsum actually have gypsum in the soil surface, a fact not reflected by the lithological map. The distinction between dry and wet season in Bujaraloz was not valuable for classification purposes.

The two areas studied show great disparity in extent, climate, soils, available ground information, landscape, and agricultural management. This fact suggests that the results herein presented would be useful in other gypseous lands around the world.

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Table 1.

Landsat ETM+ images used for thematic classification.

	Path/row	Date of image acquisition	Season
Cedral, Mexico	28/43	28-11-1999	End of wet season
	28/44	19-3-2000	Dry season
		17-3-2000	Wet season
Bujaraloz, Spain	199/31	21-6-2000	Dry season
		8-8-2000	Dry season

Table 2.

Thematic classes and their correspondence with the agricultural and natural vegetation classes on the maps of CETENAL (1972) and INEGI (1983) of Cedral area.

	Thematic class	Land cover
Agricultural area		
Uncropped	A11 No greenness	Ara, Air, E
	A12 Very low greenness	Ara, Pg
	A13 Low greenness	Ara
Cropped	A21 Medium greenness	Ara, Air
	A22 High greenness	Air, Ara
	A23 Very high greenness	Air
Natural vegetation		
Desertic shrub	B11 No greenness	Lt
	B12 Low greenness	Lt, Yu
	B13 Medium greenness	Hp, Cp

	Thematic class	Land cover
	B14 High greenness	Pl, Lt, Yu, Ac
Gypsophilous grass	B2	Bc, Mp, Ac, Su, Lt
Mesquite woodland	B3	Pl, Ac, Op
Izotal shrub, Yucca woodland ^a	C1 Low greenness ^b	Lt, Pl, Ag, Al, Op, Yu
	C2 Medium greenness	Ag, Ml, Al, Op, Lt, Yu, Hg, Ea
	C3 No greenness	

Table 3.

Surface extent, user's accuracy (UA%), producer's accuracy (PA%), overall accuracy (OA%), kappa by class (κ), and general kappa (κ^*) attained by the multitemporal supervised classification with TIR band Landsat ETM+ of Bujaraloz, Spain.

Thematic class	Surfaces		Accuracy		
	ha	%	UA	PA	κ
Green lutite–limestone	10994	8.21	48.08	58.00	0.41
Green lutite–gypsum	16359	12.22	86.72	56.39	0.82
Gypsum II					
(Gypsum + Gypsum–depressions)	16314	12.19	24.82	31.38	0.18
Limestone II					
(Limestone + limestone–lutite	31029	23.18	57.51	79.17	0.51
Marl–limestone	7966	5.95	95.76	97.92	0.95
Red lutite II					

Thematic class	Surfaces		Accuracy		
	ha	%	UA	PA	κ
(Red lutite + Reddish lutite + Red lutite–gypsum + Lutite–sandstone)	41324	30.87	68.90	68.29	0.58
Wetlands	763	0.57	100.00	99.80	1.00
Irrigated land	8805	6.58	100.00	97.54	1.00
Total

Fig. 1. Location of the two study areas in San Luis Potosi, Mexico, and in Bujaraloz, Spain. The study area in Mexico is enclosed in an irregular polygon resulting from the overlap of two consecutive Landsat scenes in the same path. The study area in Spain is shaded, and matches the lithological map coverage.

(a)

(b)

Figure 2. Map of thematic classes in the gypseous area of Cedral in the dry (a) and in the wet (b) seasons.

Fig. 3. Map of thematic classes in Bujaraloz obtained by multitemporal classification with: (a) 14 classes and (b) 8 classes.