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The Efficiency of Landsat TM and ETM$^+$ Thermal Data for Extracting Soil Information in Arid Regions

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ABSTRACT

A knowledge of soil surface conditions, especially desert crust, salt crust and desert varnish is useful for improving classification of remotely sensed data. Desert crust can generate high levels of reflectance, similar to those areas with high salt concentration and non-saline soil. Therefore, soil surface crusts might bias thematic remote sensing of soils. In this study, we evaluated the efficiency of the Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM$^+$) reflective and thermal bands in detecting crusted surfaces and soil salinity conditions. The study areas were Ardakan, Damghan, Lut Desert, Qom, and Abarkooh which are located in arid regions of Iran. To assess the Landsat TM thermal data for detecting land cover types, the following steps were taken: 1) determination of correlation coefficients between TM wavebands, 2) assessment of the relationship between TM thermal and TM reflective bands on land cover types, 3) assessment of the relationship between soil salinity and TM Digital Numbers (DN), 4) two dimensional Feature Space (FS) analysis of the training samples, 5) field sampling, 6) image classification and accuracy assessment, and 7) comparison of surface reflectance of different soil surface types. The results show that the trend of correlation coefficients of TM6 with reflective bands is completely different from the correlation between reflective bands. The behaviour of the thermal band on gypsiferous soils is completely different from that on saline soils. Moreover, with an increasing correlation between soil salinity and reflective bands, the correlation between soil salinity and the thermal band decreases. In image classification, the thermal band improved the separability of the crusted and gravely classes. Therefore the TM/ETM$^+$ regions of the electro-magnetic spectrum have complementary capabilities for spectral separability of gravely and crusted surfaces. In general, selection of the TM/ETM$^+$ thermal band combination is an important step for classifying the remote sensing data and for securing class separability of gravely and crusted surfaces in arid regions. We also concluded that TM/ETM$^+$ thermal bands may contain information complementary to the TM/ETM$^+$ reflective bands and therefore this combination of the TM/ETM$^+$ thermal and reflective bands provide a viable method for soil salinity studies in arid regions.

Keywords: ETM$^+$, Remote sensing, Soil salinity, Temperature, TM.

INTRODUCTION

In the future, more dry lands will be put into use for agricultural production because of increasing population pressure. This will mainly be achieved through irrigation and will thus expand the hazard of salinization. Furthermore, salinity also affects other major soil degradation phenomena, such as soil dispersion, increased soil erosion, and engineering problems. Soil, water and vegetation all have the ability to conduct heat directly

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through themselves (thermal conductivity) onto another surface and to store heat (thermal capacity). Some materials and soil surface features respond to changes in temperature more rapidly or slowly than others (thermal inertia). These thermal properties are very important, because they have an impact on our ability to sense remotely thermal information about various types of materials (Jensen, 2000). Thermal remote infrared sensing offers the possibility of monitoring the surface energy budget on regional and global scales (Norman *et al.*, 1995). However, the limited success associated with the use of thermal remote sensing may arise from: 1) the presence of numerous variables that can affect surface temperature, 2) difference between thermal properties and surface reflectance and 3) the difference between the spatial resolution of thermal and reflective bands. To date, the majority of research effort has been focused on the wavebands visible to short-wave infrared. There are three reasons for this focus: 1) global coverage and the availability of multi-spectral visible to short-wave infrared Images, in particular the Landsat TM data, 2) well understood data sets, and 3) the commercial off-the-shelf software for ingesting and analysing the data (Simon *et al*., 1999). But this will gradually change in the future by working with the available data set of Advanced Spaceborn Thermal Emission Reflectance Radiometer (ASTER) which provides multi-spectral and high-spatial resolution thermal data. In addition, other new airborne instruments are being designed with multi-spectral and hyperspectral thermal infrared capabilities and thus are likely to improve the efficiency of thermal infrared data. Therefore, the wider use of thermal data is expected in the near future. However, a better understanding of the behaviour of thermal wavelength regions on materials and soil surface conditions may increase the efficiency of the study of land cover types. The application of thermal remote sensing is increasing in different fields, such as mapping land cover types and terrain analysis (Prakash, 2000). For example, the TM thermal band has proved useful for mapping depositional environments on playas in Tunisia (Millington *et al*., 1989) and Ardakan playa in Iran (Alavi Panah *et al*., 2002). The discrimination between the salty and sandy soils of the Indo-Gangetic alluvial plain in India on the TM False Colour Composite (FCC), has posed problems. However the problem of spectral similarity was resolved through integration of thermal data with TM FCC (bands 2, 3 and 4) interpretation (Verma, 1994). Ehsani and Alavi Panah (2002) compared the most informative colour composites of the Damghan playa that were obtained from the Optimum Index Factor (OIF). They concluded that colour composite of ETM^+ bands 6-4-2 in RGB are very useful in discriminating between salt crust and silty clay soils.

Silicate minerals and non-silicate molecular units give rise to spectral features in the thermal infrared. These include carbonates, sulphates, oxides, and hydroxides, which typically occurs in sedimentary and metamorphic rock. Many studies have shown the spectral feature of carbonate minerals characterised by a sharp feature around 11.2 µm. This feature moves to slightly longer wavelengths as the atomic weight of the cation increases (Liese, 1975; Lyon and Green, 1975; Van Der Marel and Beutel Spacher, 1976), providing a very useful property for remote identification. Desert soil and desert crust are also collections of minerals such as carbonates, silicates, sulphates, oxides, and their spectra are composites of the individual spectrum of the constituent minerals. Since some phenomena, such as desert crust, salt crust, polygon crust, desert pavement and puffy soil are common in Iranian deserts; we have studied the capability of TM and ETM^+ bands in soil discrimination. Lee and Tylor (1988) concluded that the TM thermal band is a useful band for discriminating between some soil types, in spite of its low spatial resolution. That may be due to the non-silicate effect of the strong vibration molecular reflectance peak centred between 8-14 µm. Goossens and Van Ranst (1996) have shown the possibility of detecting different soil types, especially gypsiferous soils, by choosing the thermal band. They argued that the role of the thermal band in detecting these soil types is due to their surface temperature differences. Due to the problems associated with the similarity of some soil surface reflectances, we have investigated the surface contribution to the reflectance condition.

The main purpose of this study is to evaluate the efficiency of TM/ETM^+ thermal data in the study of soil surface and soil salinity conditions in desert regions of central Iran. To this end, the selected areas of desert regions with a wide range of soil surface conditions have been studied.

MATERIALS AND METHODS

Study Areas

To assess the information content of TM/ETM^+ bands in a desert region, five areas were selected. These areas are: 1) Ardakan, 2) Damghan, 3) Lut Desert (yardang area) 4) Abarkooh and 5) Qom in arid regions (Figure 1). The selected areas appear to have suitable conditions for remote sensing applications for the following reasons: a) absence of vegetation or poor vegetation cover, b) clear skies, c) low surface soil moisture contents or a high moisture contrast between wet and dry conditions. In this study, the main attention was focused on Ardakan area located in the central part of Iran. The Ardakan area is located between latitudes 32° 5'-32° 34° N and longitudes, 53° 45'-54° 14' E. This area is situated to the north of the city of Yazd and to the south of Ardakan playa. The study area has an elevation varying from 965 m MSL in Ardakan Playa and 1939 m MSL in the Harish Mountain in the Northeast.

The Lut Desert has an elevation varying from 4000 m MSL in Kerman Mountain and 200 MSL in the deepest depression in the interior part the desert. In this study, most attention has been focused on the sub-area of yardangs which cover about 120×70 Km. *'Yardang'* is a Turkman word (Heiden, 1903), now used in geomorphology for the wind-abraded ridges of cohesive materials. The yardang region is characterised by an extremely arid climate, with excessive summer heat, winter temperatures below freezing and an annual rainfall of less than 50 mm.

The Damghan playa has an elevation varying from 2340 m MSL in the Chah Shirin Mountain to 1055 m MSL in the deepest depression of Hajaligholi Kavir. The selection of the Landsat satellite images was based on the quality of the images, the preferred season and the date and availability of the images for the purposes of this study. The selected areas are located in the central Iranian deserts (Figure 1).

In this study, Landsat TM/ETM^+ thermal and reflective data with the following image characteristics were used.

Methods

This research was performed on the basis of the approach indicated in the flowchart (Figure 2) for the evaluation of thermal bands for soil salinity classification (Alavi Panah, 1997). So, for soil salinity studies the TM data recorded from the Ardakan area in Septamber were chosen because the late summer is the most suitable time for soil salinity investigation. This is due to the maximum evaporation, the most extreme conditions of soil salinity, a clear sky and a more pronounced difference between the dry surface and wet zone conditions. To calculate the relationship between soil salinity and the TM Digital Number (DN), 201 soil salinity observations (dS m^{-1}) at the upper layer (0-50 cm of each profile) were derived from a digitised and rasterized soil salinity map. The TM bands were georeferenced towards the Universal Transverse Mercator (UTM) co-ordinate system. The TM and NDVI were resampled to 30×30 m pixel size and resampling was performed using the nearest neighbour approach. To study the difference in the spectral characteristics of

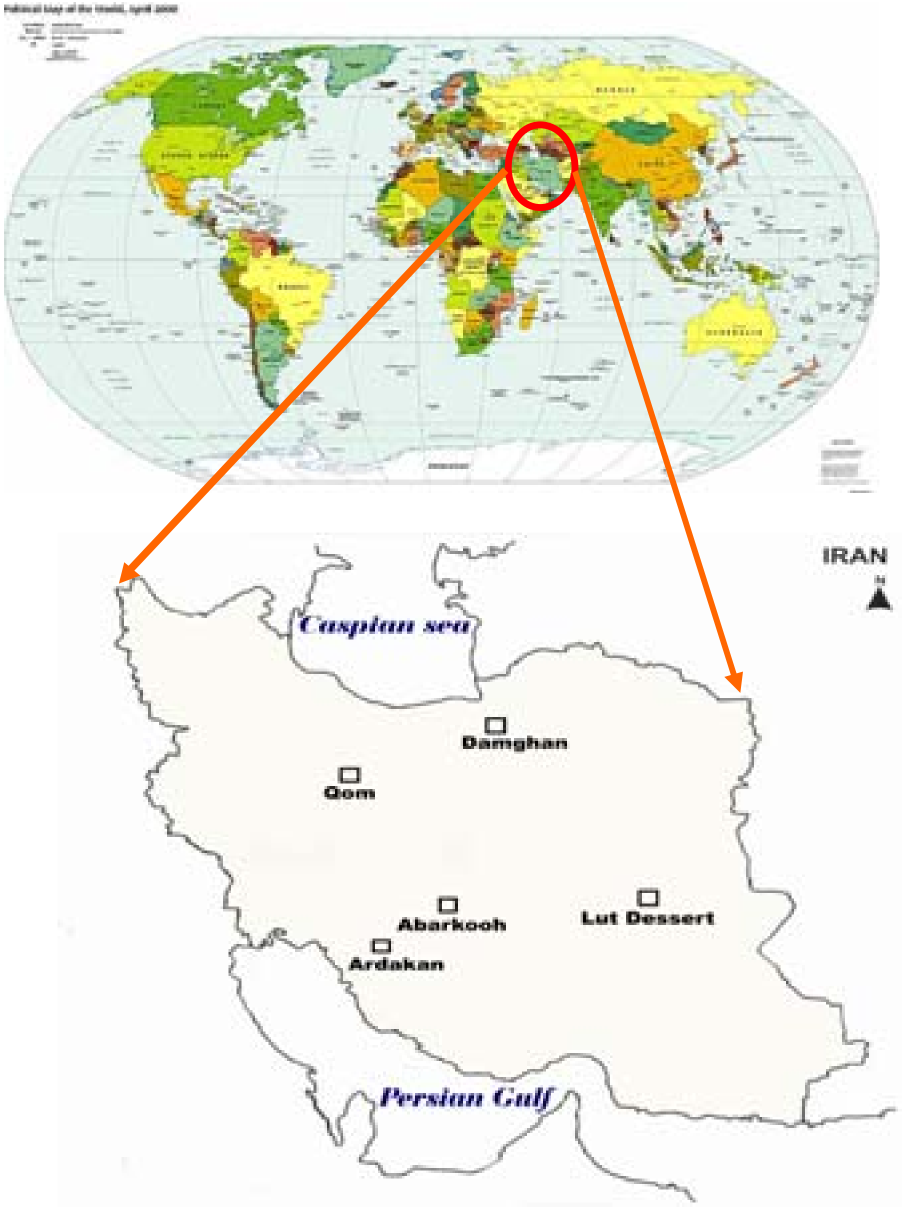

Figure 1. Geographic locations of the study areas.

saline soils and gypsiferous soils, the soil salinity observations were categorised into saline and gypsiferous soil. For image classification of the Ardakan area, fieldwork, as one of the most important steps, was carried out in June-July 1996. In order to choose representative training sites and to overcome the problems of time and season differences between the fieldwork done in June-July of 1996 and the time of data recorded by Landsat, the following steps were included:

1. The playa surface conditions were carefully studied paying attention to the stabilised crusted surface, the region vulnerable to erosion, disturbed/non disturbed and the presence of coarse particles. The playa surface which is stabilised by salt crust and desert pavement was identified on the basis of 17 years of local knowledge of the study area, aerial photos

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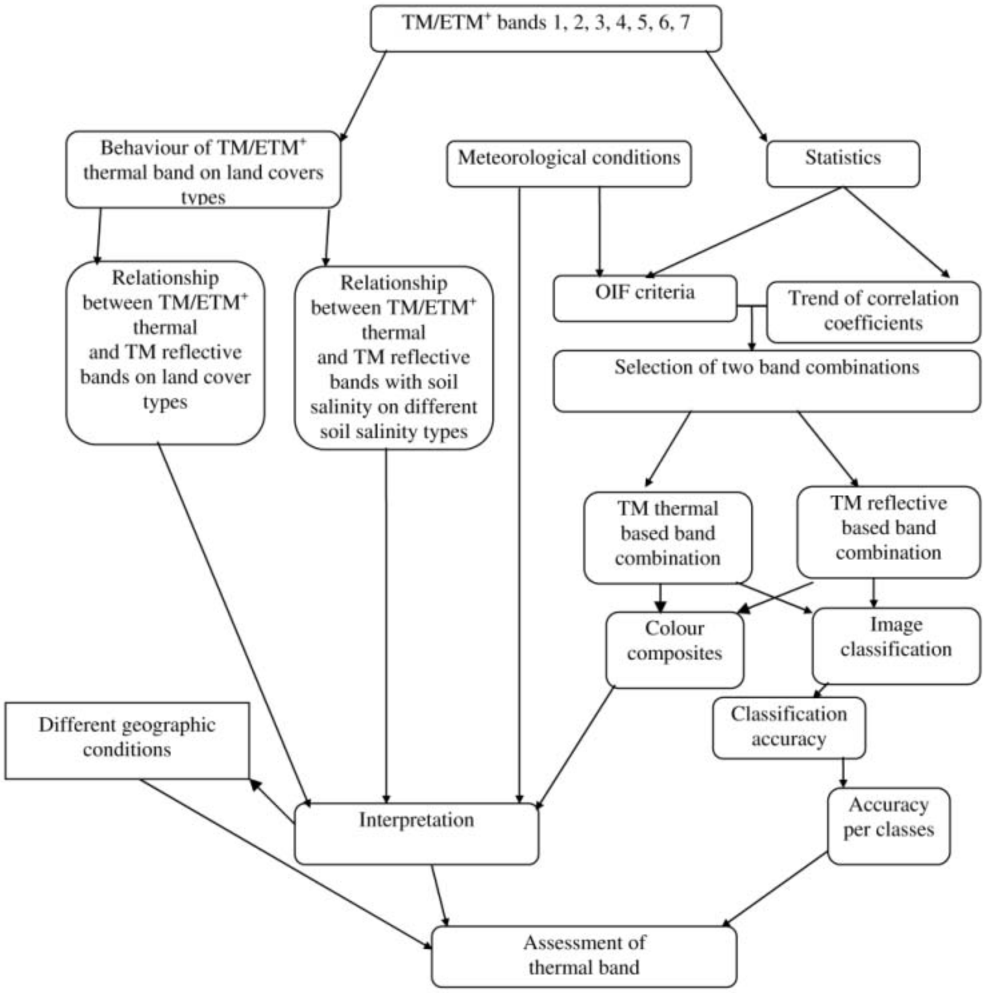

Figure 2. Flowchart of the proposed approach for evaluation of thermal band for soil salinity classification.

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(1:20,000), a wind erosion sensitivity map (1:250,000), other forms of field data such as a geological map (1:100,000) and soil/soil salinity maps (1:50000), topographic maps (1:50,000), an underground water table map (1:50,000) and confirmation of the accuracy of field data by members of the team (Alavi Panah, 1997; Alavi Panah, 2001). Extensive field observations for training sites and several extra field reconnaissances for other soil salinity studies were conducted in summer 1979, September 1989, August 1990 etc.

2. Other sources of data with respect to the time of recording data and the land use map were used. Due to a wide range of soil salinity conditions broad classes of non- to slightly saline soils were trained.

Valuable sources of information such as soil/soil salinity maps with 201 soil salinity observations, explanatory reports with 38 soil salinity observations corresponding to the time of Landsat recorded data and inter-

Table 1. Some characteristics and quality of the images used.

Area	Sensor	Mission	Path	Row	Date	Cloud coverage
Ardakan	TM	4	162	38	900911	0
Lut	TM	4	159	39	890724	0
Damghan	ETM^+	7	162	35	000720	0

views with farmers were used to improve the field knowledge. As a result, due to the heterogeneity of the land cover, 26 classes needed to be trained in order to improve the classification results (Table 2). Based on the results obtained from the Optimum Index Factor (OIF) and Feature Space (FS) analysis, the band combinations of TM 3, 4, 5, 7 and TM 3, 4, 5, 6 were selected to classify the whole TM scene of the Ardakan area by the maximum likelihood classifier. Then the classified images were compared based on the classification accuracy per classes.

3. The yardang region in Lut Desert, which is covered by the available frame of Landsat TM, was selected.
4. The relationship between the TM thermal and TM reflective bands on some broad land cover types was determined. This relationship was used to understand how the studied land cover types are dependent or independent from each other. These studied land cover types are: 1) vegetation, 2) bare land and 3) salt crust. The results of the relationships between the TM thermal and TM reflective bands in different land cover categories were discussed.

Table 2. The training classes based on field observations, maps and reports.

Land cover	Class no.	Class symbols	Class no.	Class symbols
	1	Veg-salt (salt affected vegetation)	10	S4-1(very severe saline soil 1)
	3	Veg-sparse (Sparse vegetation)	24	S4-2 (very severe saline soil 2)
Vegetation	15	Pist-1 (pistachio)	6	S4-lowg (very severe saline soil with low gravely surface)
	18	Pist-2 (affected pistachio)	11	Gr (desert pavement)
	14	Healthy-veg (healthy vegetation)	17	Gr-gyp (soil with gypsum that gypsum occur very close to the surface)
	8	S0-1 (non saline soil)	13	S4-gr1(soil with gypsum that gypsum occur in the sub surface)
	12	S0-DC (non saline soil with covered by desert crust)	16	Salt-crust (whitish colour salt crust)
	9	S0-ER1 (eroded non saline soil)	20	Dark crust (dark colour salt crust)
Non to slightly saline soil	19	S0-ER2 (highly eroded non saline soil)	2	Alluv-2 (alluvial fan 1)
	23	S0-2 (non saline soil 2)	5	Alluv-1(alluvial fan 2)
	26	S0-3 (non saline soil 3)	7	Neogene
	21	S1 (slightly saline soil)	25	Mountain
Severe saline soil	22	S3 (severe saline soil)	4	Urban

Phenomenology

Knowledge of soil surface conditions, especially desert crust, salt crust and desert varnish is useful for understanding some of the physico-chemical properties of soils. In fact, soil surface can not only be masked by vegetation, snow, but also by desert crust. Therefore phenomenology of some surface crusts and, consequently, a discussion of soil reflectance may improve the interpretation of satellite imagery. In this investigation, the following soil surface conditions, such as a) desert pavement, b) desert crust, c) salt crust, and d) puffy soil will be discussed.

Desert Pavement

Vast areas of arid soils contain coarse fragments in their surface. Coarse fragments are particles larger than 2 mm and smaller than 25 cm; this excludes stones and boulders (Soil Survey Staff, 1993). Coarse fragments in and on the surface are an important phase criteria in identifying and naming map units in soil surveys. However, the variability of the gravel coverage which can be of substantial practical importance has rarely been recorded. In Saudi Arabia, five different pavement types were classified according to their particle size, density, stability characteristics, potential for storing mobile sediments and degree of abrasion and varnishing.

Many of the gravels found throughout the study areas are heavily coated with desert varnish (Alavi Panah, 1997). The laboratory reflectance spectra of varnished quartzite indicate that the emmisivity minimum is smaller and occurs at a longer wavelength as the amount of varnish becomes greater than unvarnished quartzite (Cheristansen and Harrison, 1993). Many physical and chemical characteristics of minerals, soils and rocks influence spectral emission. The surface layers of Aridisols typically contain carbonate, very fine quartz, and abundant clay. Salisbury and Aria (1992) showed spectral reflectances (8-14 μm) of a wide range of the representative soil surface types. This result shows the separability of different soil types in terms of their reflectance spectra in the range of (8-14 μm). Potter and Rossman (1979) stated that the desert varnish which is composed of manganese and ferric oxides commonly coats the surface of rocks in a desert environment. Bartholomew *et al.* (1989) have shown that the spectra of varnished samples contain a value of 9.7 μm that does not occur in the spectrum of the unvarnished sample. They also concluded that the weathered surface of the rocks and minerals shows appreciable spectral characteristics which can be exploited by remote sensing.

Desert Crust

The presence of surface crust is an observable phenomenon in many Iranian deserts. The formation of crusts seems to be indicative of soil degradation. The effects of crusting are mostly negative, however some positive effects such as protection against wind erosion and water harvesting are also present (Sombroek, 1984). There are wide differences among soils in their susceptibility to crusting. Crusting is a function of the physical properties of the soil and the amount of soil particles. According to studies of soils in Brabant and Flanders in Belgium, crustability decreases with the increase in the amount of clay and organic matter. Thus loams and sandy loams are most vulnerable to crust formation (Morgan, 1995). Coarse particles are more resistant to detachment, because of their weight and clay content. The dispersal of fine particles from the soil causes the filling of the pores. The thickness of the surface crusts with bright surfaces is usually up to 3 to 5 mm (Figure 3). Goldshleger Ben-Dor, Benyaminim Agasi, and Blumber (2001) stated that desert crust changes the soil colour significantly. The soil aggregates are destroyed during the process of crust formation and the finer soil particles form a seal or crust at the surface, leading to increase of the overall reflectance

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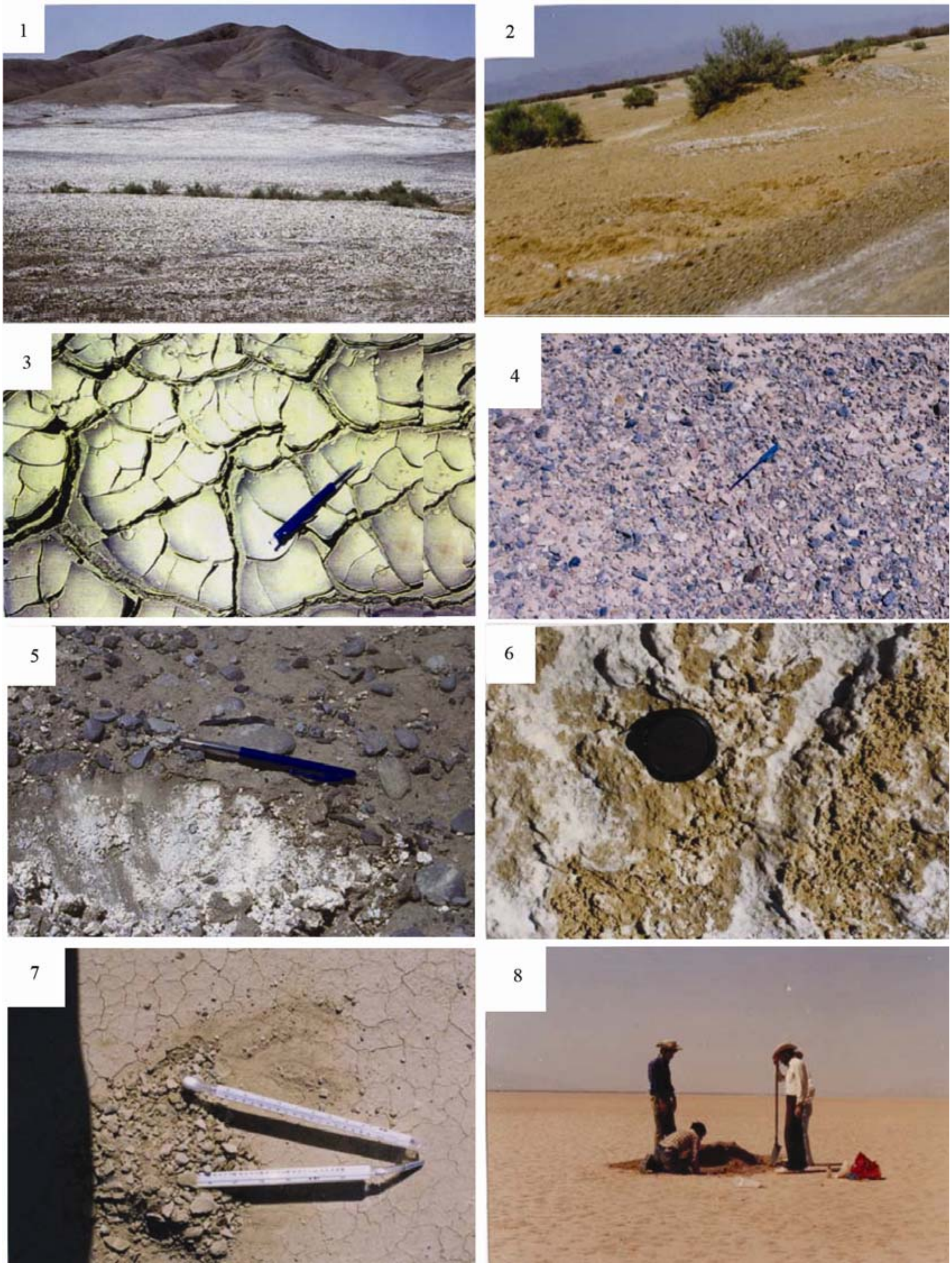

Figure 3. Surface conditions of training classes: (1) Salt crust; (2) Puffy soil; (3) Polygon crust; (4) Gravely soil; (5) Gravely soil with gypsum; (6) Saline soil affected by calcium and magnesium chloride; (7) Sealing, (8) Very severely saline soil.

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of a soil (De Jong and Epema, 2001). Goldshleger *et al.* (2001) reported that these crusts cause an overall increase in reflectance (e.g. up to 12 percent). Goldshleger *et al.* (2001) found spectral information to be related to changes in particle size distribution and texture at the soil surface, suggesting the crust might bias thematic remote sensing of soils.

The desert crusts have a very smooth surface which overlays darker coloured soils (Figure 3). In this area the colour and thickness of the desert crusts vary in each field. For example, a desert crust in the study area with a thickness of about 2-3 mm appears as a dull colour (7.5 YR 6/4) (Munsell colour, 1975) and the colour of the layer beneath that appears brown (7.5 YR 4/6). The regenerated desert crusts are thinner and appear as a dull brown colour (7.5 YR 5.5/4) in this area.

Desert crust can generate high levels of reflectance, similar to those of areas with a high salt concentration and non-saline silt-rich soil. Desert crust causes spectral confusions because of their its similarity to salt related features (Metternicht and Zinck, 2003) (Figure 4) and non-saline soil (Alavi Panah, 1997).

Goossens and Van Ranst (1996) reported that the places with intact desert crust are characterised by a very high reflection and, as the desert crust is eroded, the reflection of the original underlying soils will become dominant and this will lower the degree of reflection.

Salt Crust

Two important types of salt crusts have been recognised in the study area:

a) Efflorescent, a very fragile crystalline crust that grows from the evaporation of saline ground water discharging to the surface which appears like a snow cover

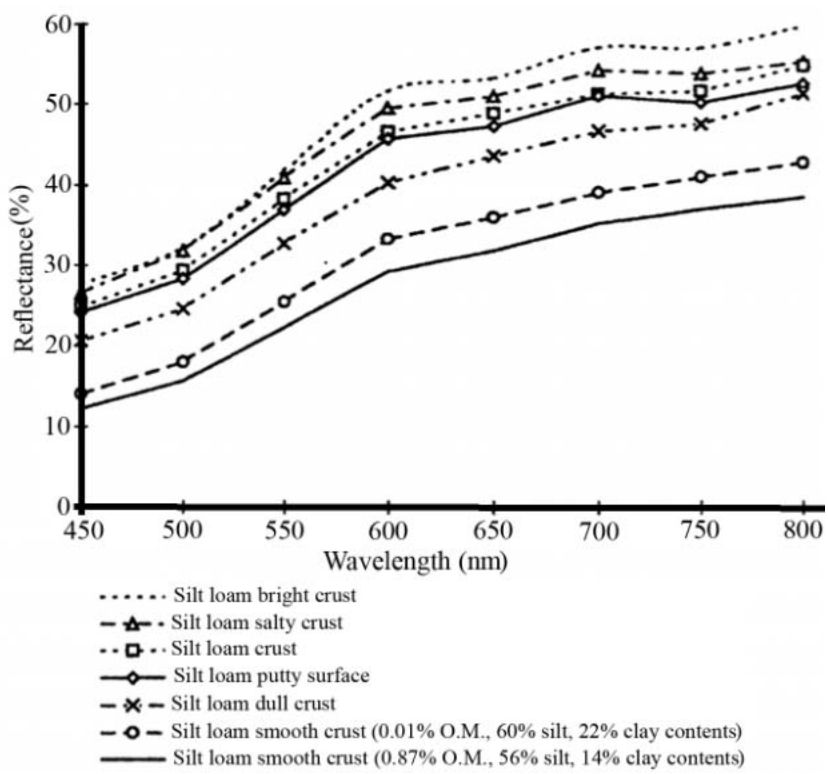

Figure 4. Influence of soil properties on the reflectance of saline and non-saline crusts (Metternicht and Zinck, 2003).

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(Figure 3).

b) A salt-silt-clay crust which is massive, relatively hard, whitish grey to greyish-white and it usually has a rough surface.

Mougenot *et al*. (1993) indicated that the quantity and mineralogy of salts, salt crust, puffy soil and salt crystals are the main factor affecting the visible and near infrared reflectance. Salts with a low moisture content have high reflectance, especially in the blue region of the spectrum (Metternicht and Zinck, 1995). The low reflectance in the middle-infrared bands is attributed to the presence of hygroscopic water in salt minerals or the high moisture content of fresh salts (Everitt *et al*., 1988). Metternicht and Zinc (1995) showed that incorporation of the TM thermal band in image classification was decisive for salt and sodium detection. They argued that this was attributable to the predominance of sulphates, chloride and small amount of carbonates of sodium and calcium. Sulphate anions have an absorption band near 10.2 µm causing internal vibrations in water molecules (Siegals *et al*., 1980; Mulder, 1987). The spectral signature of saline soils can be due to salt itself, or other chromophores related to the presence of salt (e.g., particle size distribution and pore space). For example, in the puffy soil the porosity and the air content of the soil increases and the soil surface reflectance will vary accordingly. Iron-, hydroxyl-, water-, sulphate-, and carbonate bearing minerals display spectral features in the wavelength region 0.4 to 2.5 µm. By contrast, some minerals such as quartz, gypsum and hematite exhibit spectral features in the thermal infrared and can be detected in the atmospheric window between 8 and 12 µm. Therefore, data from the visible to short-wave infrared complement data from the thermal infrared (Simon *et al*., 1999).

Puffy Surface

Characterisation of the soil salinity type may be useful in interpreting soil salinity conditions based on remote sensing images. The type of salt can be a factor affecting soil structure and soil colour. For example, accumulation of Na_2SO_4 gives rise to puffed Solonchaks, characterised by a fluffy surface layer containing a mixture of soil particles and needles of Na_2SO_4, 10 H_2O (Buringh, 1960). These crystals are formed overnight when air moisture is relatively high. Their needle shape disturbs the soil particles which consist mainly of fine crumb aggregates. According to Buringh (1960) saline soils with a high percentage of hygroscopic salts (especially $CaCl_2$ and $MgCl_2$) with an-always moist surface layer exist in Sebkhas. Andriesse (1968) stated that their loose puffed nature is caused by the hygroscopicity of calcium and magnesium chloride. During the night, when air humidity is high, they attract water from the air and form a moist, dark coloured surface. It is remarkable to see in the summer a completely wet surface layer during the early morning in dry and hot areas. This daily alteration gives a loose fine crumb structured "puffed" surface. Andriesse (1968) also found that salts in hygroscopic surfaces are mainly of NaCl, but the uptake of water, however, is mainly due to $MgCl_2$ and $CaCl_2$. This causes the dark colour. The puffy, sodium sulphate-rich crusts seem to respond more to the influence of silt than to salt content, as the curve shape (Figure 4) and the level of reflectance are similar to those of the bright silt loam crust. Figure 4 reveals the spectral confusions between salty crusts and bright silt loam structural crusts in the blue and green regions of the spectrum. Surface brightness due to high silt content determines higher reflectance than that of puffy or smooth salty crusts. A clear decrease in reflectance is observed as the crusts become non-saline, together with the lower content of silt and clay.

Factors Affecting Surface Temperature

Daily Course of Soil Temperature

The typical diurnal temperature variations for wet soil, dry soil, rock, water and vegetation are different. If all of the variations of surface temperatures were the same, then

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thermal remote sensing would be of no value. The results obtained from the ATLAS mission that was flown over a large sandbar in the Mississippi river at 5.00 A. M. and 10.30 A. M., reveals a dramatic difference in the temperature properties of sand and gravel on the sandbar.

Coarse Fragments

Lutz (1952) showed the effect of coarse fragments on the soil temperature, and he found that removal of coarse fragments would decrease the temperature of the soil. Temperature for those soil surfaces covered by coarse fragments rises earlier in the spring and is higher in the summer unless it is shaded by a foliage canopy or litter.

Soil

The soil surface temperature is influenced by both internal and external factors. The internal factors are thermal conductivity and heat capacity. Thermal conductivity is a measure of the rate at which heat passes through a material. The thermal conductivity of soil depends on soil physical properties such as, soil particles, air, moisture and porosity. Thermal capacity determines that how well a material stores heat. A high amount of quartz and some heavy minerals, such as hematite, may have an important role in temperature rise on the soil surface. The external factors which influence the surface temperature are meteorological conditions such as, solar radiation, air temperature, relative humidity, wind speed and cloudiness. There are various factors affecting soil temperature inducing a great difference between the maximum and minimum temperature of the soil.

Soil Moisture

The behaviour of moisture in the soil is conditioned not only by the dimensions and shapes of the soil pores but also by the properties of the water itself. The following three categories of soil water differ in their physical and chemical properties: a) bound water, b) capillary water, and c) gravitational water. The diurnal oscillations of temperature in a moist soil are less than those in a dry soil (Fitgerald, 1974).

Soil Texture and Structure

The size of soil particles has a considerable influence on heat transfer in the soil (Myers *et al.*, 1968). Experiments show a great variation in thermal conductivity of three kinds of soils. They also showed that, the greater the content of clay particles relative to sand, the smaller the conductivity of the solid phase. The more soil is dispersed, the lower its thermal conductivity. As the porosity of the soil increases, the air content also increases, and the soil conductivity decreases. Since the thermal conductivity of the air is lower than that soil, of the influence of soil porosity on conductivity will not be as great as that of particle size and soil moisture.

Soil Salinity

When dissolved salts are in the soil solution, the thermodynamic activity of the water is reduced (Taylor, 1958). Consequently, water in the soil is rendered less available to plants. A reduction in the rate of water uptake by roots, and a decrease in the water content of stalks causes a reduction in the plant transpiration rate (Elhing and Gardner, 1963). The relationship between cotton leaf temperature to the salinity of the soil is presented by Myers (1970). He stated that remote sensing of plant temperature is most successful when some physiological moisture stress is present. Hence, differences in temperature range between salt affected and non-salt affected vegetation would be more evident if measurements were delayed for a week or more following heavy rain or irrigation, and if the measurements were made around noon or in the early afternoon, when the incident solar radiation and air temperature are near their maximum.

Salt mineralogy (e.g. carbonates sulphates, chlorides) determines the presence (or absence) of absorption bands in the electromagnetic spectrum. For example pure halite (NaCl) is transparent and its chemical composition and structure preclude absorption in the visible and near to thermal infrared bands (Hunt, *et al*., 1971). On the contrary, carbonates present absorption features in the thermal range (between 11 and 12 µm) due to internal vibrations of $CO3^{-}$group, whereas sulphate anions have an absorption band near 10.2 µm caused by overtones or combination tones of internal vibrations of constitutional water molecules, are reported by Mulders (1987) and Siegal and Gillespie (1980).

RESULTS AND DISCUSSION

Variation of Correlation Coefficients

The variation of the correlation coefficients between ETM^+ and TM wavebands for the Damghan area was plotted over 7 wavebands respectively (Figures 5a and b). The trend and amount of these correlation coefficients of the area reveal;

1. The trend of both ETM^+/TM thermal curves in comparison to that of the ETM^+/TM reflective bands is identical. This means that lower spatial resolution of TM thermal band (120 m), in comparison to the higher spatial resolution of the ETM^+ thermal band (60 m), does not affect on the trend of the correlation coeffi-

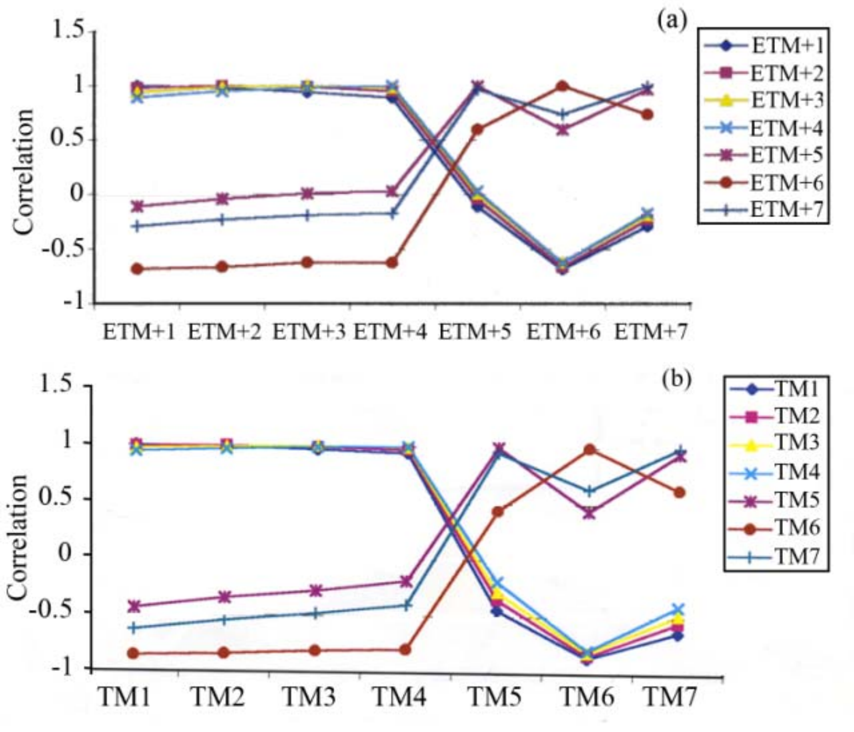

Figure 5. The plot of the correlation coefficients between; (a) 7 ETM^+ and, (b) TM wavebands of Damghan area.

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cient, but affects the amount of correlation coefficients. Therefore, we can select the TM thermal and reflective bands the same as ETM+ thermal and reflective bands.

2. The graph in Figure 5 clearly shows a negative correlation between the thermal and the reflective bands TM1/ETM+1-TM4/ETM+4 while a positive correlation between the thermal and the reflective bands TM5/ETM+5 and TM7/ETM+7 were found. This shows that the information content of TM5/ETM+5 and TM7/ETM+7 are more comparable to the thermal band than to TM1/ETM+1-TM4. The curves indicate a difference in behaviour between the ETM+/TM thermal band and the ETM+/TM reflective bands. The result obtained from the correlation of the ETM+/TM thermal and ETM+/TM reflective bands suggests that the information content of the two different thermal and reflective bands may be complementary. As in thermal remote sensing we measure the emitted radiation, it may prove to be complementary to other remote sensing data and even unique in contributing the identification of surface materials and features. Thus, though still not fully explored, thermal remote sensing reserves potentials for a variety of applications.

The correlation matrix in Figure 5b can be explained by the two most common spectral variables found in desert soils. The slope of soil spectra in the visible bands varies from soil to soil because of variations in the ferric oxide coating common on soil grains. Soil spectra vary in TM bands 5 and 7 due to variations in the strength of water, hydroxyl, SO4, and CO3 absorption bands (the water bands are typically due to water of hydration bands in minerals, not to free water as soil moisture and, while the water bands themselves are outside the TM bands, their continuum absorption affects the slope of the spectral curve).

Relationship between TM Thermal and Reflective Bands

In this study, the relationship between the TM thermal and TM reflective bands for bare soil, vegetation and salt crust land cover types of the three regions (Qom,

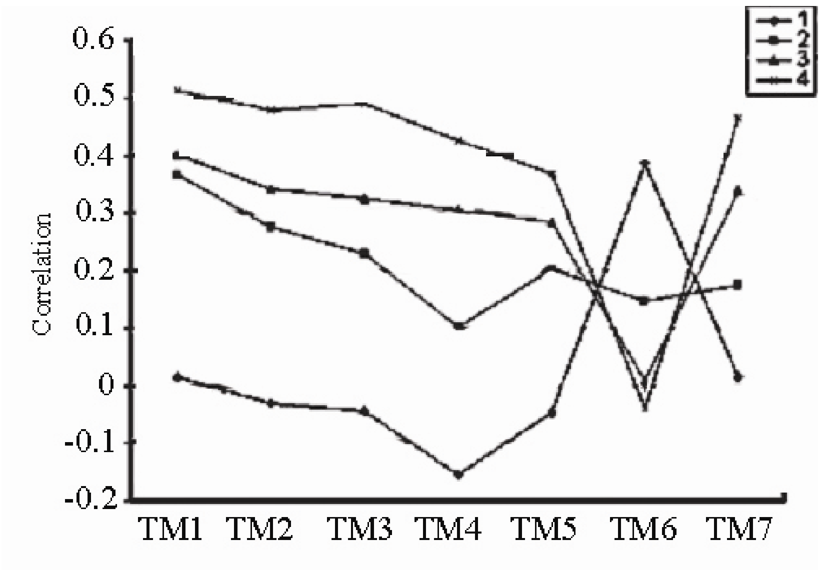

Figure 6. The plot of the correlation coefficients between the following soil salinity classes and DN values over TM bands of the Ardakan area: (1) Gypsiferous soils; (2) Total area (including non-saline, saline and gypsiferous soils); (3) Non-gypsiferous soil, (4) Non-gypsiferous soils with salinity conditions.

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Abarkooh and Ardakan areas) was determined. The results of these correlations are shown in Tables 3 and 4. Based on the results obtained, the highest positive correlation was found on the vegetation class and the lowest negative correlation was found on the salt crust class. The correlation coefficient range between TM bands varies from -0.93 for bare soil in the Qom area (correlation between TM1 and TM6) and +0.81 (correlation between TM5 and TM6) for the vegetated area in the Ardakan region. Curran (1983) concluded that, against a given background of soil or senesced vegetation, VIS reflectance of green vegetation is determined largely by chlorophyll absorption and, hence, leaf area index. Smith and Choudhary (1991) showed a close relationship between VIS and radiant surface temperature and they then concluded that, in a mixed forest and agricultural land use, visible reflectance is a more general index of green vegetation cover than NDVI over South East Australia. A similar conclusion is also indicated for semi-arid and arid shrub lands (Musick, 1984). The range of leaf temperature can be associated with variations in physiological moisture stress, plant density, soil background, irrigated trees or soil moisture, etc. The intermediate correlation coefficients are related to bare soil conditions. Based on the wide range of correlation coefficients between the TM thermal and TM reflective bands which were found in different land cover types, we can conclude that TM thermal and TM reflective bands behave differently on some land cover types. This means that the relationship between TM thermal and TM reflective bands greatly depends on the vegetation cover and salt crust. The results indicate that the relationship between the TM6 and other TM bands may depend on land cover/land use types. The results of the relationship between TM thermal band and TM reflective bands are as follows:

1. There was no significant correlation between the TM thermal band and TM reflective bands on soil class (Tables 3 and 4). This means that the TM thermal and TM infrared bands are decorrelated or independent of each other on soils with different surface conditions. Therefore, it might be said that many physical and chemical characteristics of soils, minerals and gravels may influence thermal emission.
2. The results show that, in the vegetated area, TM reflective bands are an indicator of thermal data as surface temperature.

Relationship between Soil Salinity and TM DN Values

Table 3. Correlation coefficients between the TM thermal and TM reflective bands on bare lands.

Study areas	TM band 1	TM band 2	TM band 3	TM band 4	TM band 5	TM band 7
Qom	-0.93	-0.92	-0.90	-0.89	-0.42	-0.27
Abarkooh	-0.69	-0.72	-0.71	-0.71	-0.69	-0.69
Ardakan	0.27	0.18	0.17	-0.13	-0.14	0.28

Table 4. Correlation coefficients between the TM thermal and TM reflective bands on three land cover types of Ardakan playa.

Land cover types	TM band 1	TM band 2	TM band 3	TM band 4	TM band 5	TM band 7
Vegetation	0.81	0.79	0.81	0.54	0.81	0.8
Soil	-0.08	-0.05	-0.07	-0.12	-0.08	-0.07
Salt crust	-0.69	-0.58	-0.65	-0.75	-0.62	-0.67

Figure 7 shows the variation of the correlation coefficients between soil salinity and TM DN values over the TM wavebands. The results of the correlation between the soil salinity data and the DN values show that, in the case of gypsiferous soils, no significant correlation is found between the soil salinity and the DN values of the TM reflective bands; but a significant correlation is found between soil salinity with the TM thermal band on gypsiferous soils (Figure 6). This figure reveals the behavior of the TM thermal band on the gypsiferous soils that is completely different from the behavior of saline soils. This means that, with an increasing correlation between soil salinity and TM reflective bands, the correlation between soil salinity and the TM thermal band decreases. In case of gypsiferuos soils the TM thermal band behaves totally differently from TM reflective bands. This suggests that valuable information about gypsiferous soils could be found in the TM thermal band that could not be found in the TM reflective bands. This result confirms the results obtained by Metternicht and Zinc (1995) that showed the incorporation of the TM thermal band was decisive for salt and sodium detection. They argued that this was attributed to the predominance of sulphates, chloride and a small amount of carbonates of sodium and calcium. Sulphate anions have an absorption band near 10.2 µm caused by internal vibrations of constituent water molecules (Siegals *et al*., 1980; Mulder, 1987). The reverse correlation of TM thermal and the TM reflective bands on the saline and gypsiferous soils suggest that the information content of the TM thermal and the TM reflective bands are complementary.

Image Classification

Based on the results obtained from the OIF, the band combinations of TM 3, 4, 5 and 6 have the first rank and TM 3, 4, 5 and 7 have second rank and are therefore the most informative bands used to classify the whole TM scene of Ardakan area by the maximum likelihood classifier.

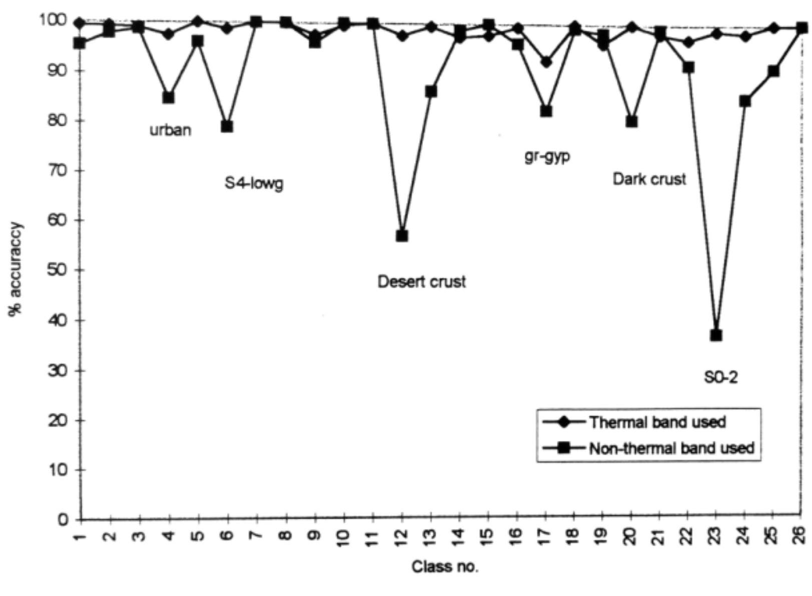

Figure 7. Comparison between the classified accuracy using TM included and TM excluded band combinations.

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Table 5. Descriptions of the effective training classes in improving classification accuracy by including TM thermal band.

Class no.[a]	Class symbol	Description
4	Urban	Build up with the roofs which are mostly covered by the raw soil, parcel and sparse trees including mainly *Almus sp., Pinus radiata, Prosopis spicigera, Tamarix sp.*, and *Fraxinus axelcior.*
6	S4-lowg	Very severe saline soil, less than 1% vegetation coverage, light soil surface texture (sand, sandy loam), low gravely surface, This class located in the north of the study area close to the Ardakan playa.
11	Gr	Saline soil, gently sloping area with less than 3% overall slope, light soil surface texture (sand, sandy loam), high gravely surface, gypsum layer in the subsurface, different species of shrubs especially in the gullies. Maximum vegetation cover is 5-6%.
12	S0-DC	Non saline soil, bare soil, formation of a surface crust of a few millimetres thick with usually a bright surface. They are mainly located near the vegetated area.
16	Salt-crust	Generally hard and dry layer, high surfaces roughness and irregularities, diversity and differences in the portion of white and grey brown to brownish Colour. This class is located in low land. Depth of ground water table is about 1.5 m
17	Gr-gyp	Very severe saline soil, gypsiferous soil, sandy loam soil surface texture, gypsum exposed on or very close to the surface (gypsiferous soil), they are mostly located alongside the S4-gr class and partly alongside the river wash.
20	Dark crust	Dark and dry salt crust, water table depth at about 1.2 m depth, drainage water with salinity of 20 dS/m, clay layer at depth of about 3 m, the crusted layer with dominant portion of dark brown colour, weak drainage conditions, vegetation cover is less than 5-10 % including *Tamarix sp., Atriplex lentiformis* and *Alhaji cameleron,* irregular roughness. This class is mainly located in a small depression near the Meybod area.
23	S0-2	Non saline soils, maximum vegetation covers of 10-15%, mostly located between the cultivated areas and are in fallow vegetation, commonly silty loam-loam soil surface texture.

[a] Class number.

Then, the classified images were compared based on classification accuracy per class (Figure 7). The overall accuracy of this classified image is high (92%), and is nearly comparable with the overall accuracy (99.6%) resulting from the classified image in which TM thermal band is included. Although the overall accuracy is high, this figure clearly shows that some training classes have a low accuracy in the non-TM thermal based image. The lower accuracy in some non-TM thermal based classified images is due to confusion with some other classes.

From the above results, we may generalise the effect of TM thermal band in improving the classification accuracy of;

a) Gravely surface (gypsic soil and saline soil),

b) Crusted soil surface,

c) Urban areas.

The result obtained from the gravely surface classes indicates that some information on gravely surface are dormant in TM reflective DN values while, in this respect, the TM thermal band can provide extra useful information. It seems that gypsum may have a role in lowering the surface temperature of the gr-gyp class. The more soil that is dispersed, the lower its thermal conductivity. As the porosity of the soil increases, the air content increases and the soil conductivity decreases. This is due to the fact that the thermal conductivity of the air is lower than that of soil. However the influence of soil porosity will not be as great as that of particle size and soil moisture (Chudnovskii, 1962). Allen *et al.* (1996) showed that the TM thermal band is a very useful tool for separating gypsum from other lithologies. Goossens and Van Ranst (1996) showed that the TM thermal band has a key role in separating saline soils from gypsiferous soils in Egypt. They also found that the TM thermal band is important for separation of gypsiferous soils in dry and wet conditions, resulting from temperature differences. An important factor affecting temperature rise of the dark crust class may be due to its location in a depression. This situation may cause the capturing of more radiation and retention of

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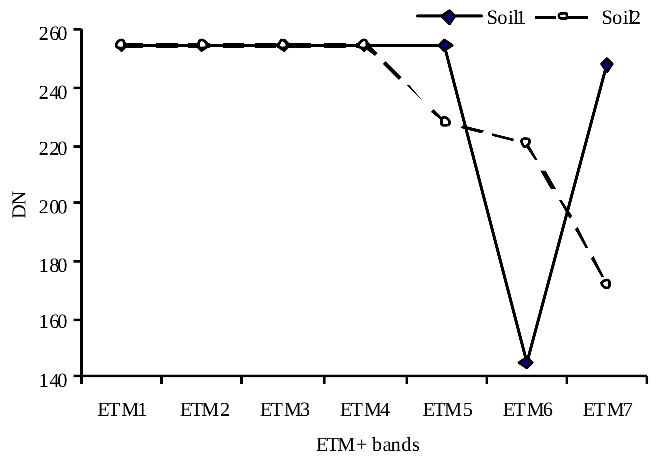

Figure 8. The plot of two types of soil surface reflectance over ETM$^+$ bands in the Damghan playa margin.

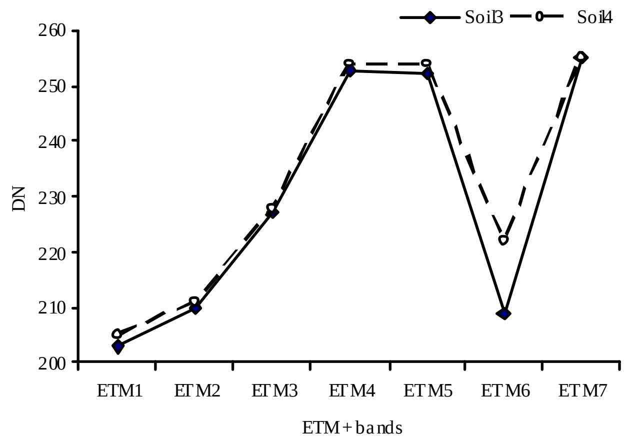

Figure 9. The plot of two types of soil surface reflectance over ETM$^+$ bands in the Damghan playa margin.

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more temperature. Almost all the roofs of the building in the study area are coveredby soil (soil and straw). Sparse vegetation, lack of any industrialised area, lack of metallic roves, and the effect of shadow at 9:45 A. M. at the time of satellite overpass, might be reasons for the low temperature of the urban areas. The composition and structure of the canopy have a significant impact on the thermal behaviour of the urban environment. In other words, apart from the properties of urban construction materials, the layout of buildings and pavements within an urban landscape can also affect the appearance of the urban heat island (Goward, 1981). Nichol (1994) has successfully utilised TM thermal infrared data, to derive surface temperature data for some housing estates in Singapore.

In the Ardakan area gravely saline soils cannot be separated from some other classes by TM reflective bands. That can be due to the fact that gravels on the soil surface may hinder the soil surface reflectance. Basedon the results obtained we concluded that soil salinity studies are not completely possible by using only the TM reflective band. We also concluded that this problem could mainly be solved by including the TM thermal band for supervised classification. We also concluded that the role of the TM thermal band in separating some land cover types could be related to temperature difference. Of course, further research is necessary to evaluate the precise effect of gravels in different land cover types. This is because types of coating, mineral constituents and soil matrix are factors which may affect the temperature rise in desert area. From the result obtained we may also conclude that, for mapping soil salinity of the Ardakan area based on satellite TM images, various classes must be trained. This is not possible unless a strong, careful, and more detailed field observation can be carried out. Obviously, soil salinity mapping based on TM satellite images of the Ardakan playa without a careful field observation, or a well established sampling plan is impossible. In other words, soil salinity classification in the playa margin with various types of surface conditions is not a simple task.

Spectral Signature Evaluation of ETM$^+$ Bands

The mean spectral reflectances of two soil surface types that were obtained from ETM$^+$ bands over the Damghan playa margin were compared (Figures 8 and 9). As these figures show, the mean and the trends of these types of soil surface reflectance (soil 1 and 2) are the same from the blue (ETM$^+$ band 1) to infrared (ETM$^+$ band 5) bands but, at the ETM$^+$ band 7 and, especially at ETM$^+$ thermal band, there is a big distance between the mean reflectance of these two soil types. This comparison shows that the TM/ETM$^+$ thermal band can separate these two soil classes from each other well. Interestingly, the separability of soil class no. 1 (surface gypsum) and soil class no 2 (polygon crust) by TM/ETM$^+$ thermal band suggests that gypsum, on the one hand, or polygon crust, on the other, may play a role in temperature difference. It has been known for sometime that the presence of buried objects (subsurface soils) can be detected by observing the temperature variations on the surface of the soil, which has been exposed to solar radiation (Deans *et al.*, 2001). Polygon crusts are brown soil with a very hard surface, the diameter of polygons is about 20 cm and the dominant colour dark brown (7.5 YR4/4). For a more accurate and precise interpretation, further research is needed. The results obtained from spectral signatures confirm the results obtained by Ehsani and Alavi Panah (2002). They showed that ETM$^+$ thermal has a significant effect in improving the classification accuracy of some saline soil classes. As Figure 10 shows, the spectral reflectances of soils 3 and 4 are also much comparable from blue (ETM$^+$ band 1) to near infrared (ETM$^+$ band 4) but, at the ETM$^+$ band 5 and especially at the ETM$^+$ thermal band, a large difference in the mean of DN values can be seen. This comparison shows that the TM thermal band can separate these two classes (polygon crust and salt crust) from each other well. This result confirms that desert crust causes spectral confusions because of their spectral similarity with crust features or because desert crust can generate high levels of reflectance, similar to those of areas with high salt concentration and non-saline silt-rich soil. This result also confirms the results obtained by Metternicht and Zinc (1995) and Alavi Panah (1996) that showed that the incorporation of the TM thermal band was decisive for the study of soil salinity conditions.

CONCLUSION

The TM and ETM$^+$ bands offer valuable information necessary for the soil salinity conditions in desert regions. Based on the results obtained from TM image classification, we may generally conclude:

1. The main land cover and soil surface conditions can be classified on the basis

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of Landsat TM images,

2. The TM reflective bands may not be sufficient for classifying different soil types and surface conditions but, by including the thermal band, these problems might be resolved.

Based on the results obtained from this study, the TM thermal band is important for improving the classification accuracy of gravely saline soil and crusted soil surface. Based on the results obtained from the relationship between TM bands and soil salinity values we concluded that the TM thermal and TM reflective bands behave completely differently in land cover types. This means that the relationship between TM thermal and TM reflective bands greatly depends on the vegetation cover, bare soil and salt crust. We may also conclude that thermal data, as a surrogate of surface temperature, is a fundamental thermodynamic quantity that can be used to classify the image. The TM thermal band contains information complementary to the TM reflective bands and this combination of the TM thermal and the TM reflective bands provides a strong tool for land cover classification. The reason that the TM thermal band is most often excluded from soil analysis is usually due to its low spatial resolution. But, from the result obtained we can conclude that, in determining the nature of a vast areas, spatial resolution might not be so important and more detailed spectral information relevant to the physical and chemical composition may be obtained.

The result of spectral signature evaluation of the TM/ETM^+ thermal and reflective bands may improve our knowledge and interpretation of different soil salinity and surface conditions; in particular, it may provide an opportunity for delineating salt crust and desert crust. Based on the results obtained from playa margins in arid regions we may conclude that hyper arid climatic conditions might be ideal for detailed mapping of land cover types and understanding the behavior of the TM/ETM^+ thermal and TM/ETM^+ reflective bands.

In salt affected desert areas, spectral confusions between different surface features of gravely surface and crusted surfaces are common. This hampers the spectral separability of salt affected areas. Therefore, on the basis of the results obtained from this investigation, the thermal range improved the separability of the crusted and gravely surfaces because of the greater promise of the TM thermal band than the TM reflective bands on sub-surface conditions. We may conclude that, for sometime, the soil properties of sub-surface soils can be detected by observing the temperature variations on the surface of the soil, which has been exposed to solar radiation. Therefore the TM regions of the electro-magnetic spectrum have complementary capabilities for spectral separability of gravely and crusted surfaces. Selection of the TM thermal in band combination is an important step for evaluating the remote sensing data and securing class separability of gravely and crusted surfaces.

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کارایی داده‌های حرارتی لندست TM و ETM^+ برای استخراج اطلاعات خاک در مناطق خشک

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چکیده

کسب اطلاعات از ویژگیهای سطح خاک بویژه پوسته بیابانی، پوسته نمکی و جلای بیابانی، برای بهبود طبقه‌بندی داده‌های سنجش از دوری مفید می‌باشد. هدف از این تحقیق ارزیابی کارایی باندهای انعکاسی و حرارتی سنجنده‌های نقشه‌برداری موضوعی (TM) و نقشه‌بردار پیشرفته موضوعی (ETM^+) برای تعیین وضعیت سطوح پوسته‌ای و شور خاک می‌باشد. مناطق مطالعه شده عبارت بودند از اردکان، دامغان، بیابان لوت، قم و ابرکوه. برای ارزیابی داده‌های حرارتی سنجنده TM برای تعیین انواع پوشش اراضی، مراحل زیر انجام گرفت: ۱-تعیین ضریب همبستگی بین باندهای TM؛ ۲-تعیین ارتباط بین باندهای حرارتی و انعکاسی TM در انواع پوشش اراضی؛ ۳-تعیین رابطه بین شوری خاک و درجات روشنایی (DN) سنجیده TM؛ ۴-تجزیه و تحلیل پدیده‌ها در فضای دو بعدی (FS) با استفاده از نمونه‌های تعلیمی؛ ۵-مطالعات میدانی؛ ۶-طبقه‌بندی باندهای سنجنده و براورد صحت طبقه‌بندی و ۷-مقایسه بازتاب سطحی خاکهای مختلف. نتایج نشان می‌دهند که روند ضریبهای همبستگی TM6 با باندهای انعکاسی TM نسبت به روند همبستگی بین باندهای انعکاسی TM کاملاً متفاوت است. همچنین رفتار باند حرارتی TM در خاکهای حاوی گچ کاملاً با رفتار آن در خاکهای شور متفاوت باشد. بعلاوه با افزایش همبستگی بین شوری خاک و باندهای انعکاسی TM، همبستگی بین شوری خاک و باند حرارتی TM کاهش می‌یابد. باند حرارتی قابلیت تفکیک‌پذیری کلاسهای پوسته‌ای و گراولی را بهبود بخشید. بنابراین محدود حرارتی طیف الکترومغناطیسی می‌توانند به‌طور مکمل جهت تفکیک‌پذیری طیفی سطوح گراولی و پوسته‌ای مورد استفاده قرار گیرند در مجموع انتخاب ترکیبی از باندهای انعکاسی و حرارتی TM/ETM^+، قدم مهمی برای ارزیابی داده‌های دور سنجی و نیز تفکیک‌پذیری کلاسهای سطوح پوسته‌ای و گراولی در مناطق خشک می‌باشد. همچنین باندهای حرارتی TM/ETM^+، ممکن است شامل اطلاعات مکمل با باندهای انعکاسی TM/ETM^+ باشند و بنابراین ترکیب باندهای انعکاسی و حرارتی TM/ETM^+ یک روش متداوم را برای مطالعات شوری خاک در مناطق خشک فراهم می‌کند.

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