# Optical remote sensing of salt-affected soils

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**Abstract**

Soil salinization as a result of natural or human-induces processes is a serious global-scale problem. Numerous studies and efforts in assessing and controlling soil salinity have been made. Nearly sixty percent of the salt-affected soils around the world are in irrigated farmlands, and this trend is increasing. Salinization is a major reason for degradation of soil resources and decline of soil fertility. From an ecological and economic point of view it is extremely important to establish both the occurrence and distribution of soil salinization as well as the intensity of the process. Remote sensing techniques are widely used in soil surveys to detect and map salt-affected areas. However, many constrains in monitoring and evaluating the spatial and temporal variability of the salinization process have been found out. Difficulties also arise in applying remote sensing to the assessment of slightly affected soils. The goal of this paper is to examine the spectral reflectance properties of soils with different degree of salinization and the feasibility of using spectral indicators derived from Vis/NIR data as detectors of salt-affected soils and quantitative estimators of soil salinity level.

### Дистанционни изследвания на засолени почви в оптичния дипазон

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Ключови думи: дистанционни изследвания, спектрални отражателни характеристики, засолени почви, спектрални индекси

**Резюме**

Почвеното засоляване е най-често срещаната причина за деградация на земите. Този процес се е превърнал в световен проблем поради бързото нарастване на засегнатите площи във всички климатични области. Засоляването се отразява неблагоприятно върху плодородието на почвите и застрашава устойчивото земеделие. Дистанционните методи широко се използват за изследване на почвените ресурси, в това число на засолуени почви. От екологична и икономическа гледна точка е изключително важно да се наблюдава появата и раазпространението на почвеното засоляване, както и динамиката на прозеса. Целта на настоящата работа е да представи някои методи за анализ на спектралните отражателни свойства на засолени почви и използването на спектрални индикатор за количествена оценка на степента на засоляване.

## Introduction

Today the world faces unprecedented set of environmental problems many of which are related to ecosystem depletion and destruction. At present, conservation of natural resources is a fundamental and crucial ecological issue all over the planet. Soil cover is an essential component of the natural environment. It resembles the relationships between the other environmental components (rocks, water, climate, vegetation, human activities) and is an indicator of the ecological status of the landscape. Soil salinization is nowadays a world-wide problem relevant to the global concern of natural resources preservation. Based on the statistics concluded in 2008, more than 77 million hectares (5% of cultivated lands) in the world are affected by excess salt. Salt-spoiled soils constitute more than half of all irrigated lands. Every day for more than 20 years, an average of 2,000 hectares of irrigated land in arid and semi-arid areas across 75 countries have been degraded by salt. Increased salinization of arable land will cause 50% land loss by the middle of 21st century [16].

On the other hand, the concepts of precision and sustainable agriculture are turning, at present, into operational practices [5, 15]. These concepts are often characterized as an evolutionary step in agriculture. Precision farming is the use of information technologies to achieve site-specific management of farmlands.

Site-specific management accounts for the within-field variability of factors that influence yield, identifies the causes of this variability and effectively modifies crop farming practices. Such a factor is soil salinization which harmfully affects the fertility of soils by nutrient decline, thus threatening the sustainability of agricultural production.

Soil studies and particularly detecting deterioration of land quality and monitoring the results of remediation and revitalization measures benefit considerably from the new informational capabilities provided by remote sensing. Soil recourses are with no doubt among the priorities of earth observations [4, 8, 11, 12]. A lot of effort has been put into detection and mapping salt-affected areas by remote sensing techniques [2, 3, 6, 7, 9, 10, 13, 14, 17, 18]. The objective of this paper is to examine the spectral reflectance properties of soils with different degree of salinization and the feasibility of using spectral indicators derived from Vis/NIR data as detectors of salt-affected soils and quantitative estimators of soil salinity level.

## Background

Land degradation has become recently a global and urgent environmental issue considered a high priority. One of the main and most common reasons leading to soil degradation is salinization. The process of salinization depends on environmental and anthropogenic factors such as high temperatures, poor drainage, increased mineralization of groundwater, intensive irrigation and over-fertilization. Secondary salinity due to human activities has significantly increased the extent of the problem.

Salinization is a major reason for the decline of soil fertility and continuous loss of arable land. It is one of the most severe environmental factors limiting the productivity of agricultural crops. Most crops are sensitive to high concentration of salts in the soil. Agricultural losses caused by salinity are expected to increase with time. Secondary salinization of agricultural lands is particularly widespread in arid and semi-arid environment where crop production requires irrigation schemes. According to global statistics, salinization affects nearly 10% of the soil resources and 50% of all irrigated land in the world. In Bulgaria salinization accompanies the most fertile soils used for intensive agriculture (Sliven, Burgas, Plovdiv and Veliko Tarnovo regions). In Bulgaria saline soils (solonets and solonchak) cover 35,000 ha, accounting for 0.6 percent of the arable land and 2.4 percent of irrigable land.

Soil salinity is one of the biggest problems worldwide related not only to “wearing out” of soil resources but to the loss of biodiversity in both terrestrial and aquatic ecosystems. Besides being unsuitable for agricultural use saline soils are pollutants for the surrounding areas. From an ecological and economic points of view it is extremely important to establish both the occurrence and distribution of soil salinization as well as the intensity of the process, i.e. to detect the presence and quantify the extent and rate of salinization.

A dramatic example of a serious environmental problem, especially when resulting from human activity, is soil salinization is the disappearance of the great basin of the Aral Sea and the expansion of large areas of salt-affected soils. Up until the third quarter of the 20th century the Aral Sea was the world’s fourth largest saline lake. Its salinity was approximately 10g/l. The water level in the Aral Sea started drastically decreasing from the 1960s onward as a result of the implications of water-intensive agricultural practices. By 1989 the Aral Sea had receded to form two separate parts, each of which had a salinity almost triple that of the sea in the 1950s. Even re-watering those lakes did not compensate for the increased salinity over the years. In 1998, water level was down by 20 m. By the end of the 20 th century the Aral had receded into three separate lakes. The level of salinity rose to often more than 100g/l in the remaining Southern Aral. The new desert Aralkum in Uzbekistan and Kazakhstan that has appeared on the seabed once occupied by the Aral Sea is nearly 60,000 km$^2$ of sandy, salty soil, most of which is contaminated with fertilizers remnant (Figure 1). A sharp increase in salinization of lands is one of the most negative consequences of Aral Sea crisis. Salinization of soils accelerated the desertification process as it accompanied the sharp decline in groundwater level and the drying of subsoils. This eventually lead to soil erosion, one of the primary reasons for extensive fertilizer use. In turn, these abusive fertilizing practices further deteriorated soils and created pollution. Landsat satellite imagery in Figure 2 shows the visible changes and disappearance of the Aral Sea [19].

Remote sensing techniques have been widely used in soil surveys for detection and monitoring of the spatial-temporal distribution of salt-affected soils. These techniques include aerial photo survey, multispectral and hyperspectral satellite imaging, airborne electromagnetics, infrared thermography, active and passive micro-

**Fig. 1 Spreading of salt-affected soils over large areas in Uzbekistan and Kazakhstan**

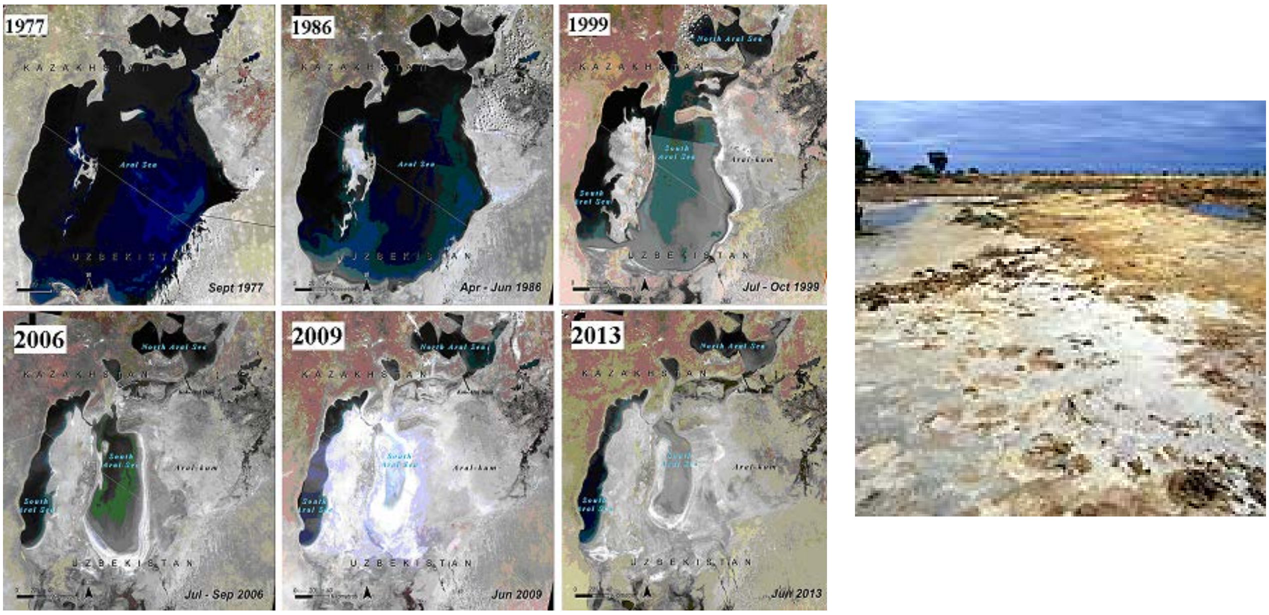



**Fig. 2 Progressive disappearance of the Aral Sea (source: USGS/NASA)**

wave radiometry [2, 9]. All they exploit soil reflective and emissive properties to identify saline areas and discriminate soil salinity classes. For instance, microwave observations make use of the sensitivity of the dielectric constant and brightness temperature to soil salinity level. Optical sensing tries to find distinctive spectral features of salinized soils in the visible and infrared parts of the spectrum. Data has been acquired from various airborne and spaceborne sensors. Different processing methods have been proposed to analyze these image and non-image data for deriving soil salinity information and developing predictive models.

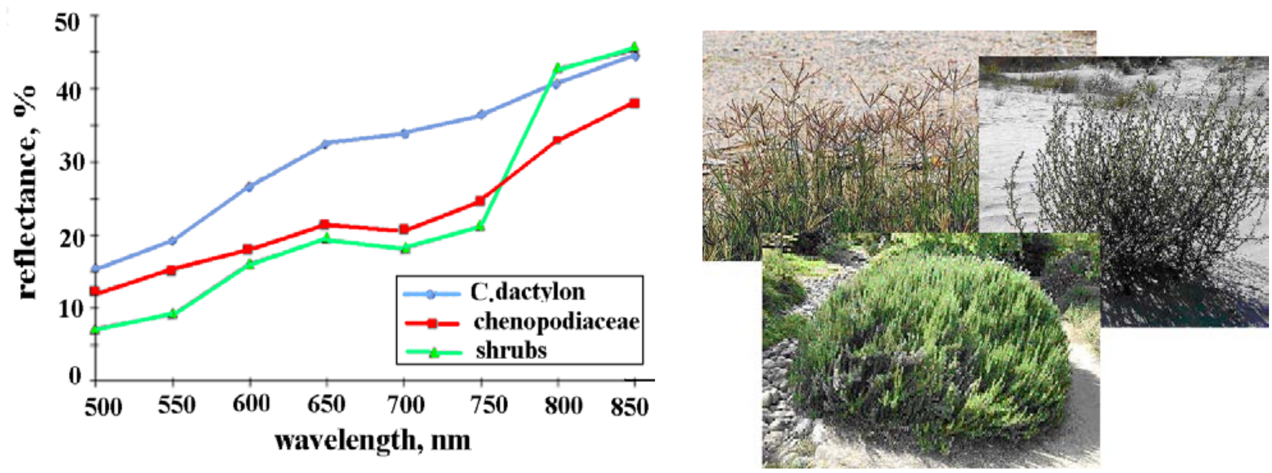
Numerous publications are devoted to usimg a variety of spectral data to describe soil salinization [3, 6, 7, 10, 13, 14, 17, 18]. Most of them point out difficulties associated with the complexity of the process, its dynamic nature and the interrelated factors on which salinization depends (inherent soil properties, climate conditions, and agricultural activities). Difficulties also arise in applying remote sensing to the assessment of slightly affected soils. Constrains in monitoring and evaluating the spatial and temporal variability of the salinization process have been found out.

Soil salinity can be perceived from remotely sensed data either on bare soils or through the biophysical properties of vegetation as these are affected by salinity. A frequently utilized approach is to use plant indicators since plant species have different tolerances to soil and water salinity [6, 10, 16].

Salt-sensitive species exhibit inhibited growth depending on the salt levels and the particular species. In saline areas vegetation becomes dominated by more salt-tolerant plant species that can be possibly considered salinity indicative. Since plant species vary in their sensitivity to salts, some species will be affected by low concentrations, while others will tolerate high salt concentrations. As so, an indicator of slightly saline soils will be plant inhibited growth, while for high salt-containing soils such an indicator will be the presence of halophytes (Figure 3).

**Fig. 3 Pictures of different halophytes**

Usually, attempts are made to identify and distinguish between various salt-tolerant and salt-sensitive plants on the basis of multispectral data. The spectral properties of salt-tolerant species, however, depend on plant type. In Figure 4a the reflectance curves of three halophytic species (Figure 4b) are plotted which illustrate the significant differences of plant spectral behaviour. There are many uncertainties in using plant indicators of soil salinity. Some species grow vigorously in both on-saline and saline environments. Besides, salt-tolerant species vary from region to region.




**a)** **b)**

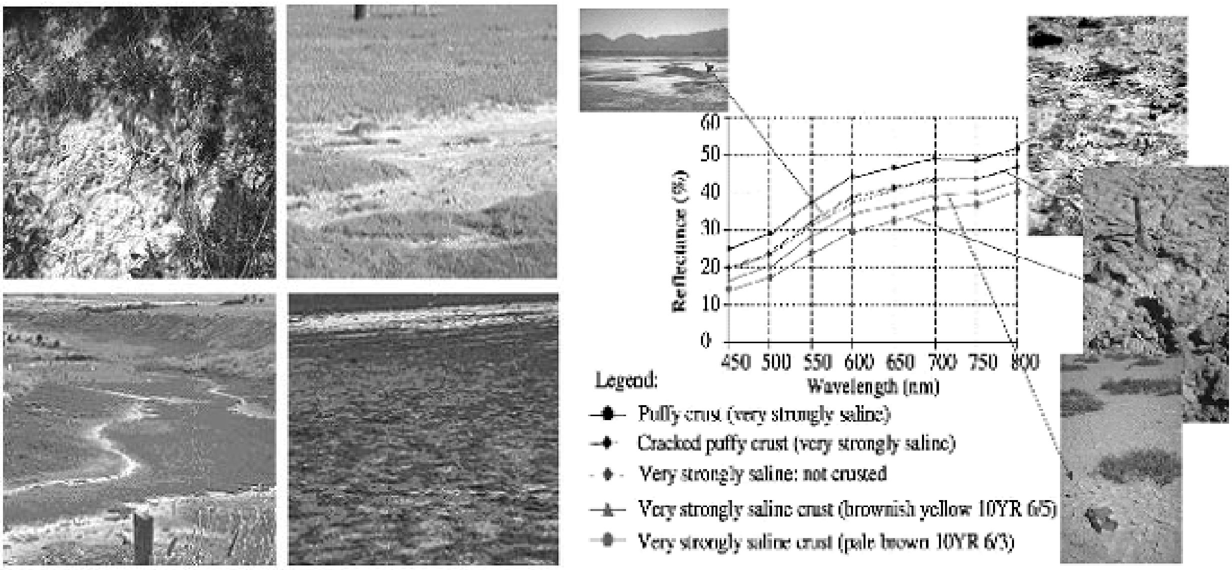
**Fig. 4 Spectral reflectance curves (a) and pictures (b) of three salt-tolerant species: Cynodon dactylon, chenopodiaceae and shrubs**

Their presence at a particular location is influenced by seasonality, climate conditions, and other factors. The use of such secondary indicators for monitoring and mapping salinized areas by remote sensing is limited to medium and low salinity where tolerant plants grow fairly well.

A commonly applied technique for assessment of salt-affected soils is the analysis of soil multispectral and hyperspectral reflectance signatures. Soils tend to accumulate salts in the surface layer with local concentration and deposits of light-colored crust, whitish and whitish-grey salt patches, stripes or crystals (Figure 5a). That is why saline soils are characterized by high reflectance in the optical range. Color is a dominant factor affecting optical properties of soils. It is greatly determined by the humus content which could be higher in solonetz soils and alkaline saline soils. The concentration of organic matter leads to pronounced variations of soil reflectance patterns. For example, the reduction of two color-difference units of the Munsell Scale causes reduction of soil reflection in the whole spectral range.

Besides, saline soils differ in their structure varying from smooth to rougher as well as in color from white to light grey and darker. This leads to great variability in spectral reflectance and causes difficulties for the interpretation of the acquired remote sensing data. Figure 5b presents the spectral reflectance curves of highly saline soils with different color [14].

Another approach of using remotely sensed data to detect and characterize saline soils is the implementation of empirically derived relationships between soil spectral features and in situ measurements of soil electrical conductivity. The electrical conductivity is a soil property that can be associated with the level of soil salinity




**a)** **b)**

**Fig. 5 Different salinity manifestation on the soil surface - salt crust, patches, strips and dark alkali solonetz (a); reflectance spectra of highly saline soils with different color (b)**

[3, 6]. Many papers indicate the ability of remote sensing data to differentiate between highly saline and unsalted soils and no success in distinguishing low and moderate salinity levels [3, 6. 7, 13]. It is worth mentioning also that the synergetic use of measurements in different spectral ranges (visible, infrared, thermal, microwave) might enhance the assessment of soil salinity [14, 17, 18].

## Material and methods

Ground-based and airborne reflectance measurements in the visible and near infrared range of the electromagnetic spectrum were carried out over soils with varying salinity. Different data processing methods were applied to identify salt-affected soils and to examine the performance of soil multispectral response in serving as a quantitative indicator of the salinization degree.

Due to the dry climate and poorly drained conditions, strong salinization is observed in the surrounding areas of many saline lakes (endorheic basins) such as the Adjinour lake (20 000 hectares of salt-affected soils) on the territory of Azerbaijan where a part of our research encompassing ground-based and airborne experiments has been carried out (Figure 6). Soil salt content on the sites was 15-20%. Multispectral was acquired also over moderately saline soils (6-8%) in Mongolia (natural solonetz, meadow solonchak), and less saline soils (1-3%) in Bulgaria, Belozem (meadow solonetz, solonchak-solonetz).

Soil spectral reflectance signatures in the visible and near infrared band (400-820 nm) were measured with multichannel spectrometric systems from airborne platforms (aircraft, helicopter) and in situ. The field and remotely sensed datasets were analyzed statistically. Different spectral indicators were examined for their ability to resemble distinctive reflectance feature of salt-affected soils and enhance soil salinity discrimination. Such spectral indicators were reflectance factors for selected wavelengths, linear combinations and band ratio indices, slopes of the spectral reflectance curves within different portions of the spectral range, clustering by a two-dimensional space representation, regressions, and others.

**Fig. 6 Ground-based and airborne spectral measurements of saline soils in the region of Adjinour Lake, Azerbaijan**

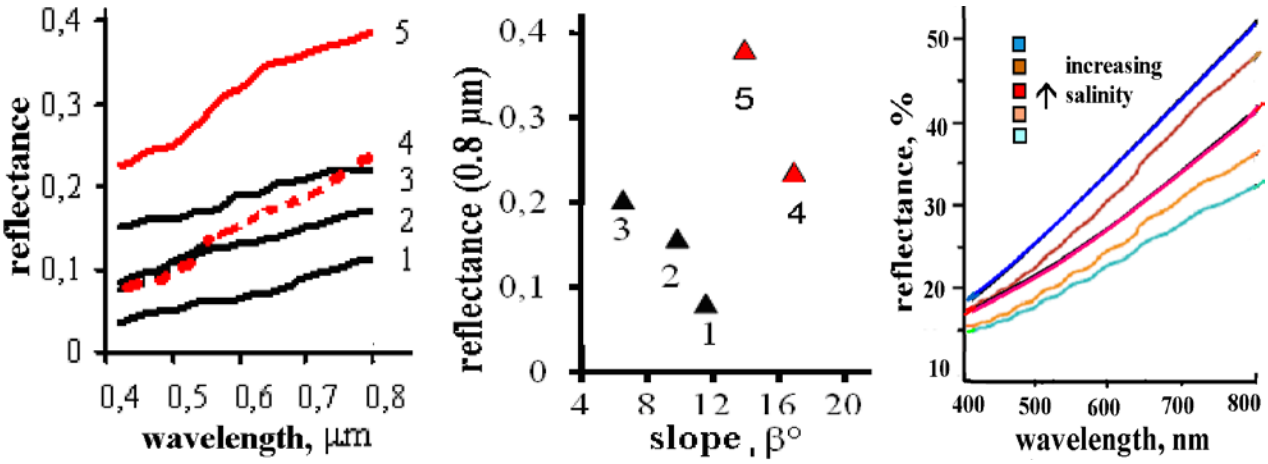
Soil spectral reflectance signatures in the visible and near infrared band (400-820 nm) were measured with multichannel spectrometric systems from airborne platforms (aircraft, helicopter) and in situ. The field and remotely sensed datasets were analyzed statistically. Different spectral indicators were examined for their ability to resemble distinctive reflectance feature of salt-affected soils and enhance soil salinity discrimination. Such spectral indicators were reflectance factors for selected wavelengths, linear combinations and band ratio indices, slopes of the spectral reflectance curves within different portions of the spectral range, clustering by a two-dimensional space representation, regressions, and others.

## Results and discussion

Herein some results obtained from Vis/NIR spectrometry studies of saline soils are presented. The main objective of the study was to empirically investigate the relationship between soil spectral reflectance and salinity level, and to examine the ability of various spectral indicators to identify salt-affected areas and assess soil salinity degree.

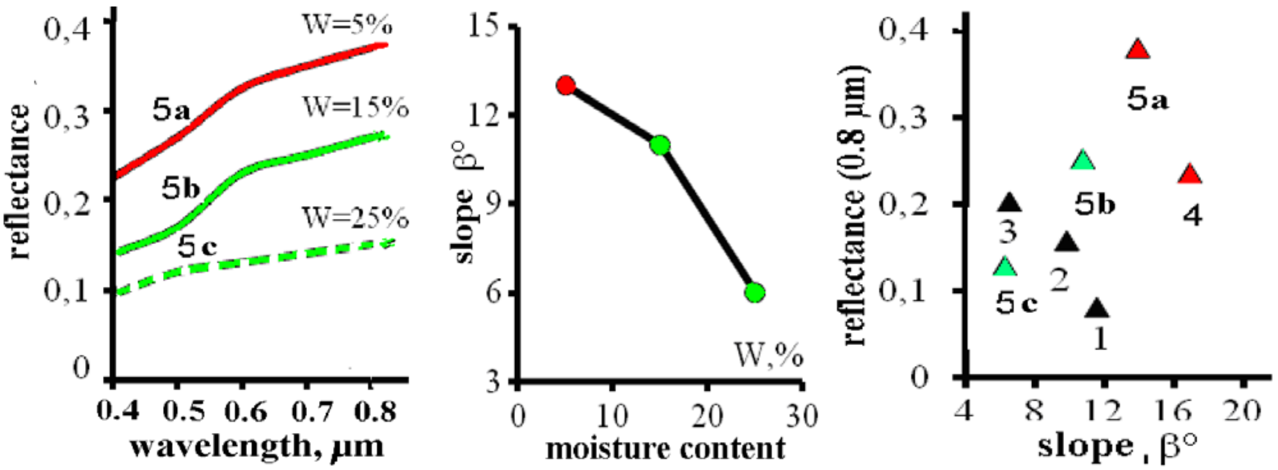
Soils are characterized by increasing reflectance in the wavelength range under consideration. In Figure 7a the spectral characteristics of various soil types are plotted. The reflectance curves differ greatly and the values of the reflectance factors can serve as a classification feature. Another potentially usable characteristic is the overall slope of the reflectance curve which increases as samples become more saline. Salt-affected soils (4 and 5) are distinguished by their higher brightness and steeper slope. Using these two features saline soils were confidently identified and separated from non-saline soils. This is illustrated in Figure 7b where the soils from Figure 7a are presented in a two-dimensional space of the spectral curves slope (the angle $\beta^o$) and the reflectance values at 0.8 μm. Similarly, in Figure 7c, soils with different salt content exhibit higher reflectance and steeper slope.

Soil physicochemical properties such as moisture content, organic matter, texture, color and surface roughness highly affect the spectral reflectance of soils. For example, crusted saline soil surface is generally smoother than a non-saline surface and exhibits high reflectance at Vis/NIR wavelengths. Crust color, however, can range from pure white to grey, pale brown, and darker. and affects the reflectance of salinized soils. The importance to account for soil surface condition is illustrated below using experimental data. In Figure 8a the spectral reflectance of the moderate saline soil 5 from Figure 7a is shown for three values of soil water content (5%, 15% and 25%). With increasing moisture, and consequently, darkening color, the reflectance in the entire spectral range decreases, more noticeably to longer wavelengths. The latter leads to smaller slope of the curves 5b and 5c (Figure 8b). These two effects dramatically change the position of the soil in the two-dimensional space of NIR reflectance and slope as evident from Figure 8c In this case, it is not possible to discriminate between the saline (5b and especially 5c) and non-saline soils using NIR reflectance data and slope values. Detection and assessment of saline soils is more reliable during dry periods.




a) b) c)

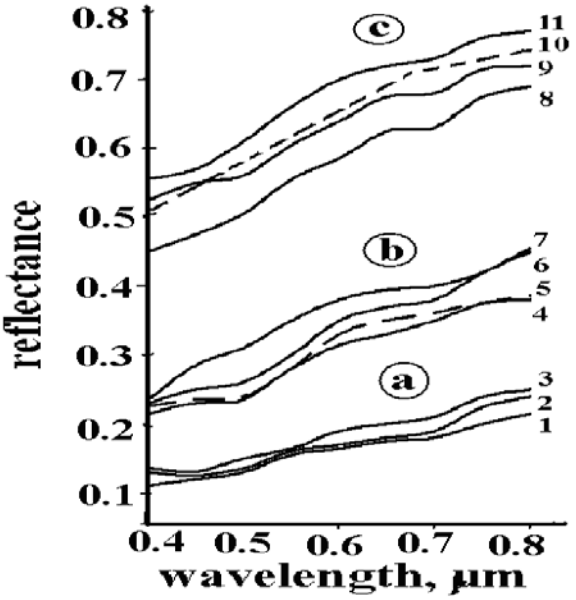
**Fig. 7 Spectral reflectance signatures of different soil types (a): 1 - leached black soil chernozem, 2 - brown forest soil, 3 - alluvial-meadow soil, 4 – lightly saline meadow solonetz, 5 – moderately saline solonchak; soils location in the two-dimensional space of the slope of the spectral curves and the values of the reflectance factors at 0.8 µm (b); decreasing overall soil reflectance with salinity increase (c)**



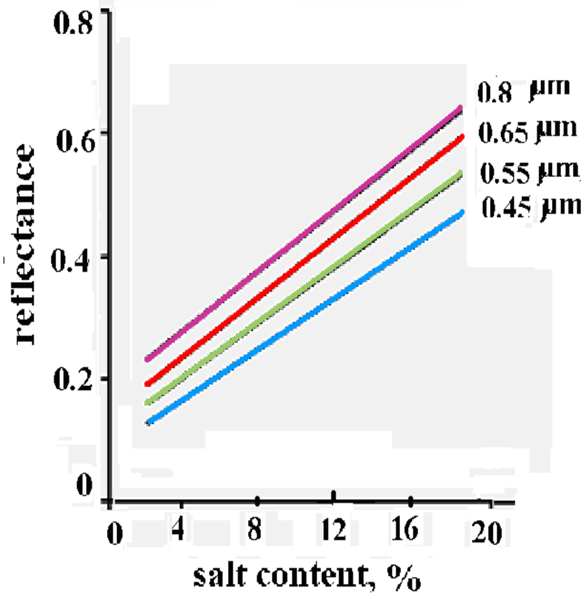

a) b) c)

**Fig. 8 Reflectance curves of solonchak with different surface moisture (a); soil representation in a two-dimensional space of reflectance curve slope and reflectance value at 0.8 µm (b)**

In Figure 9 the spectral reflectance characteristics of soils with different salt content (as described in the previous section) are presented. The ground-based reflectance measurements are shown with solid lines and the dotted lines refer to airborne data. As it can be seen from Figure 9a, according to the reflectance values the soils are distinctly grouped by the salinity level into low (a), medium (b) and highly (c) saline. Increased reflectance associated with higher salinity is observed in the whole wavelength range. The established dependences of the spectral reflectance factors at different wavelengths on the salt concentration in the soil are plotted in Figure 9b for the blue, green, red, and near infrared bands. The reflectance values differ 2-3 times for the different levels of soil salinity which here varies from 1-3 % (group “a”) to 6-8 % (group “b”), and 18-20 % (group “c”). In this case, the reflectance factors can be confidently used as spectral indicators of soil salinity level.



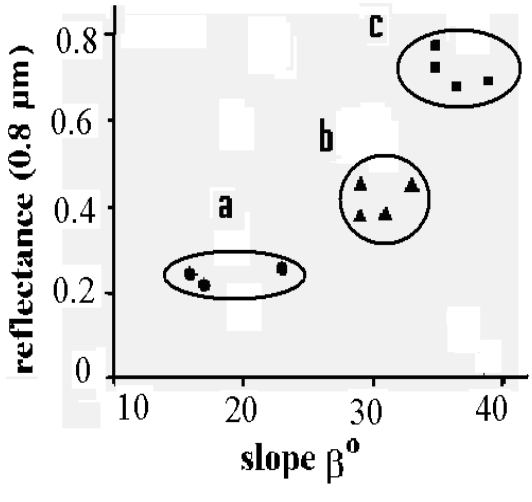

a)



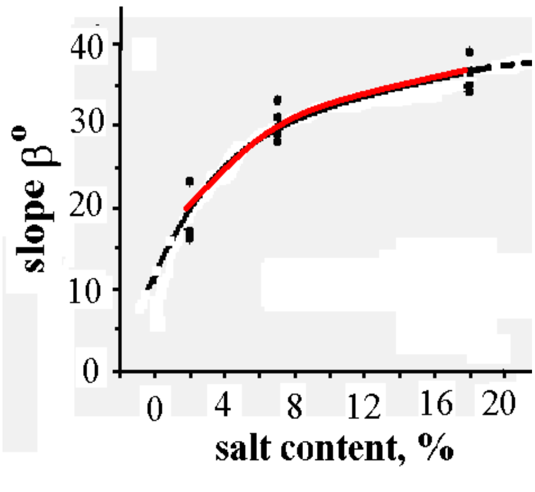

b)

**Fig. 9 Spectral reflectance signatures of saline soils with different salt content (a):**
**a – 1-3% (meadow solonetz, Bulgaria), b – 6-8% (solonchak, Mongolia), c – 16-20% (crusted solonchak, Azerbaijan); dependence of the reflectance factors at different wavelengths on the salinity level (b)**

In Figure 10a these three groups of salt-affected soils are presented in a two-dimensional space of the reflectance at 0.8 μm and the slope β° of the spectral curves. The reflectance goes up and steeper with the increased salt content. The soils form three non-overlapping clusters. This means that the soils can be reliably distinguished by these two classification features. Data analysis in a two-dimensional space allows better detection and differentiation of saline soils specifically in cases when this is not possible using only one feature. In Figure 10b the statistical relationship (derived by regression analysis) between the gradient β° of the reflectance curves and the salt content in soils is presented. It shows the steeper-slope trend with increasing salinity. The practical use of such empirical dependencies for identification and characterization of saline soils requires extensive and more detailed experiments particularly over low-salinity soils.



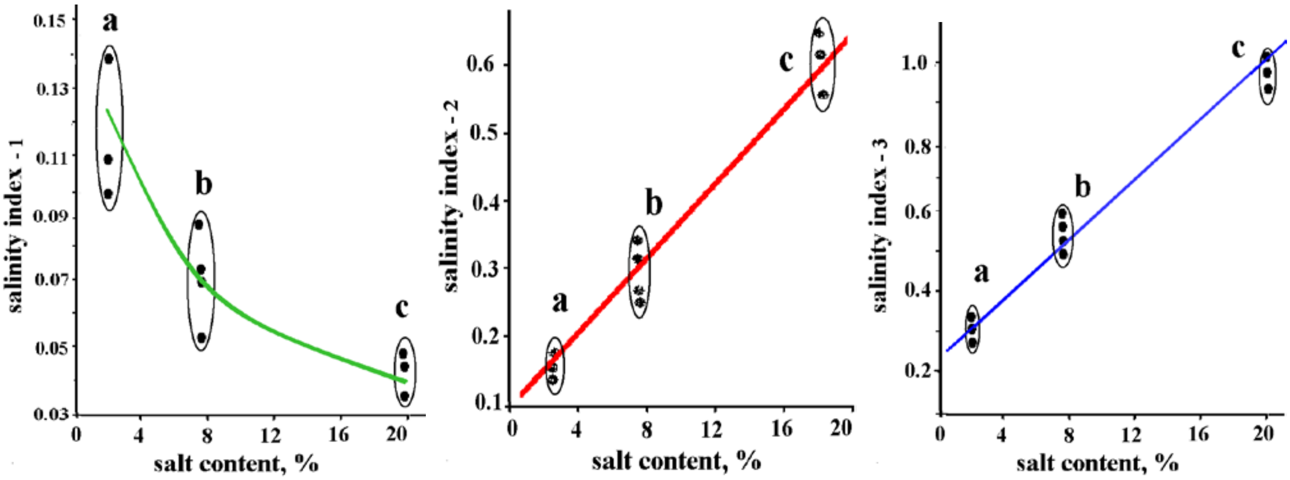

a)




b)

**Fig. 10 Representation of salt-affected soils (from Figure 9a) in a two-dimensional space of the slope (angle β°) of the spectral curve and the reflectance values at 0.8 μm (a); dependence of the spectral curve slope on the soil salinity (b)**

Another approach which we used to statistically analyze of the relation between soil multispectral reflectance and salinity content was the implementation of different transformations of the acquired spectral data. The performance of various spectral indices. Most commonly these indices are linear combinations and pair-wise or multiple-band ratios of reflectance values at different wavelengths. Suchlike transformations enhance the




a) b) c)

**Fig. 11 Empirical relationships between salt content in soils and salinity indices**

discrimination between soils and the statistical discrimination of soil properties. Our goal was to find spectral attributes with high correlation with soil salinity in order to use them as quantitative salinity indicators. The relationship between soil salinity and multispectral data was determined through regression analysis. Herein, results are presented for the following band combinations: SI-1 = $(BxR)^{-2}$, SI-2 = (NIR-R)/(NIR+R) and SI-3 = $(R^2+NIR^2)^{-2}$, where SI-1, SI-2 and SI-3 denote the spectral indices and the abbreviations B (blue – 400 nm), R (red – 650 nm) and NIR (near infrared – 800 nm) denote the spectral bands and wavelengths for which soil reflectance factors have been measured. The calculated for each soil sample indices were regressed against the soil salinity. In Figure 11 the empirically derived relationships between the salt content and the salinity indices are shown. It was found that these spectral indices were strongly correlated with the observed soil salinity data and, the best result achieved for SI-3. Consequently, we can consider them good salinity indicators and direct spectral predictors of the salinization level.

## Conclusions

Soil salinization is a multifactor phenomenon whose heterogeneity, spatial dynamics and seasonal dependence complicate surveys both with conventional field methods and remote sensing techniques. Soil surface condition: texture, roughness, color, mineral composition, organic and moisture content, also are causes for significant variations of soil spectral reflectance properties. The application of remotely sensed data for recognition and characterization of saline soils requires detailed knowledge of soil spectral behaviour as a multifactor function of the salinity level, type of salinization and other physicochemical properties. In-situ study of the spectral properties of salt-affected soils and especially of soils with lower salinity is an important work, for it is the basis of airborne and satellite monitoring of the salinization process. The results presented in our paper illustrate the feasibility of soil salinity assessment from visible and near infrared reflectance data. But, in general, the right way to obtain more reliable information about soil salinization is the synergetic use of multisensor data and different data processing approaches.

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