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ASSESSMENT OF SOIL SALINITY PROBLEMS IN AGRICULTURAL AREAS THROUGH SPATIAL AND TEMPORAL REMOTE SENSING

By

Mohammed Saifeldeen Abd-Elwahed

A Dissertation Submitted to the Faculty of the

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WITH A MAJOR IN SOIL SCIENCES

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As members of the Dissertation Committee, we certify that we have read the dissertation

prepared by *Mohammed Saifeldeen Abd-Elwahed*

entitled *ASSESSMENT OF SOIL SALINITY PROBLEMS IN AGRICULTURAL AREAS THROUGH SPATIAL AND TEMPORAL REMOTE SENSING*
and recommend that it be accepted as fulfilling the dissertation requirement for the

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College.

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STATEMENT BY AUTHOR

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ABSTRACT

This study is aimed at addressing the capability of using remote sensing data in detecting and tracking soil salinization variability using a series of experimental methodologies. In a controlled experiment, the spectral reflectance changes associated with salt crust formation on soil surfaces were tracked in order to detect the optimum moisture levels for salinity detection and recognize the influence of soil texture on salinity-induced spectral changes. In another experiment, lettuce plants were utilized to assess plant biophysical responses to moderate salinity levels with canopy-level reflectance data. An FR-ASD spectrometer was used to collect reflectance data in the 400-2500 nm spectral region. Finally, MODIS satellite data were employed to analyze the temporal profiles of selected high (8-11 dS/m), moderate (4-6 dS/m) and none (1-3 dS/m), salt affected sites in the Nile Delta, Egypt. The analyses of spectral data revealed that the use of remote sensing data to discriminate salinity levels in soils is highly affected by moisture content and texture. At low moisture contents, salts have high reflectance in the VIS-NIR spectral region but low reflectance in SWIR region. Spectral ambiguity with soil salinity was found across soil texture types.

Significant relationships were found between plant chlorophyll content and the REP index (R^2 =0.97), and dry biomass with SAVI values (R^2 =0.94) under different salinity treatments. The spectral vegetation indices (VI's), SAVI and REP, and water indices (WI's) were found to be effective in discriminating between plants growing under moderate conditions of soil salinity and a non-saline condition. The combination between VI's and WI's was found to be useful in improving the ability to assess salinity stressed

plants from non-stressed plants. Finally, MODIS results showed separability between canopy seasonal growth under high saline (HS) and non-saline (NS) conditions based on phenology. Canopies growing under HS conditions had lower VI and WI values in the green-up period. It may be concluded that using plant biophysical response to detect soil salinity could be useful in detecting early stages of salinity. Also using the combination between VI's and WI's using MODIS data is a useful to discern between high saline and none saline areas.

INTRODUCTION

Global environmental change, one of the most important issues for human beings at the moment, is certainly linked with agricultural activities, because it greatly affects food production and because agricultural activities sometimes result in negative impacts on their environments. One of these negative impacts is that agricultural environments are unstable and degrading and this degradation is taking place so fast that many countries will not be able to achieve sustainable agriculture in the future. Soil salinization, which considers a major form of this environmental degradation in agricultural areas, adversely affects biological functions in ecosystems and causes degradation of soil and water resources. Remote sensing techniques are potentially very useful for detecting, monitoring and the eventual control of soil salinization. Soil salinity can be perceived from remotely sensed data either on bare soils, with salt crust, or through the biophysical properties of vegetation as these are affected by salinity.

The reflectance spectra of the salt crusted on the top of soil is affected by many factors, such as soil water content and soil physical characteristics. In the first chapter we assessed the effect of both water content and soil texture on the spectral reflectance of salt crusted on soil surfaces and how this may affect the ability of remote sensing to detect soil salinity from bare soil surfaces. Also, a study of the optimal water content level appropriate for salinity detection was a primary goal of the first chapter. The second chapter analyzes the changes associated with canopy spectral reflectance as affected by salinity stress. Relationships between canopy characteristics (biomass and chlorophyll

concentration) and spectral parameters (vegetation indices, water indices and “red edge position” (REP)) were analyzed to test the effectiveness of these indices as well as the combinations between them in discrimination between salt stressed and non-stressed canopies. The third chapter analyzes seasonal patterns of 3 different agricultural study sites, highly saline, moderately saline and non saline, in the Nile Delta, Egypt using MODIS 8-day data at 500m resolution. The objective is to determine if MODIS captures the temporal differences between canopies growing under such conditions and to see if the vegetation indices (VIs) and water indices (WIs) can be used to extract useful information that can be used to detect soil salinity.

PRESENT STUDY

The methods, results, and conclusions of this study are presented in the chapters appended to this dissertation. The following is a summary of the most important findings in this document

I. SUMMARY

Specific objectives and hypotheses are outlined for the three chapters as follows:

Chapter 1: Spectroradiometric study of salt treated soils

Objectives

1.1 To detect the optimum and range of soil moisture content levels for salinity detection on bare soils using remote sensing data.

[Hypothesis: In saline soils the reflectance characteristics are very much dependent on moisture conditions. Saline soils usually have high concentrations of salt in soil solutions. These salts, upon evaporation, form salt crusts with efflorescence on the soil surface. Soil moisture content is a limiting factor in this salt crust formation. Moisture also greatly influences the reflection of shortwave radiation from soil surfaces in the VIS-NIR (400–1100 nm) and SWIR (1100–2500 nm) regions of the spectrum. Detecting soil salinity on bare soils using remote sensing depends on the appearance of this salt crust on the soil surface. This work was conducted to determine spectral characteristics of salt crusts while it is forming on the soil surface and detecting the optimum soil moisture levels for salinity detecting on the bare soil surfaces.]

1.2 To recognize the influence of soil texture on salinity-induced spectral changes.

[Hypothesis: In nature, natural soil properties as well as conditions such as surface roughness, soil texture, and illumination condition govern their spectral response. Soil texture is one of the most important factors that affect the spectral reflectance of the soil. The presence of different soil fractions of sand, silt or clay influence the spectral signature of saline soils, which affect the ability of remote sensing to detect the salts when it shows up at the top of soil surface.]

Chapter 2: Studying the response of lettuce plants to soil salinity stress using reflectance spectrometry

Objectives

2.1 To assess plant biophysical response to moderate salinity levels with canopy-level reflectance data.

[Hypothesis: Plants under salinity stress often show biophysical changes. Plant responses could provide a more estimation of salinity because measurements of growth characteristics at one point in time integrate the cumulative effect of salinity. Relating salinity-induced canopy reflectance characteristics to plant biochemical properties, which are also sensitive to salinity stress; consider a more mechanistic approach of applying remote sensing to detect the low to moderate salinity levels. Plants under salinity stress often exhibit water deficit symptoms and at the same time the chlorophyll content is decreasing. Canopy reflectance in the VIS-NIR domain is highly affected by plant chlorophyll content. Reflectance in the SWIR region (1300–2500nm) largely depends on

the water concentration in the tissues. Using canopy reflectance data in the 400-2500 nm region could be useful to assess moderate salinity levels and detect salinity in early stages of development.]

2.2 To investigate the ability of multiple and combined spectral indices to improve salinity stress detection using plant responses.

[Hypothesis: Spectral indices respond to the change in plant chlorophyll content and the amount of biomass and water status. Since salinity stress affects all of these canopy biophysical properties, the SAVI (soil adjusted vegetation index) and REP (Red edge position) indices were used to extract the chlorophyll concentration and biomass information. The WBI (water band index), NDWI (Normalized difference water index) and LSWI (land surface water index), on the other hand, will extract moisture content information. We therefore assessed the relationship among these indices to improve salinity stress detection using remote sensing.]

Chapter 3: Soil salinity assessment in the Nile Delta using MODIS data

Objectives

3.1 To assess the response of the MODIS bands and spectral vegetation and water indices in detecting and monitoring local scale soil salinity in the Nile delta in Northern Egypt.

[Hypothesis: The phenology of canopies growing in salinity stress areas in the Nile Delta differ from that growing under moderate and non saline conditions. Such differences are measurable with MODIS temporal vegetation and water indices data sets

and can be used to distinguish canopies growing under different salinity levels as well as to monitor salt affected areas.]

3.2 To investigate if the combined spectral indices, vegetation and water indices; improve upon the detection saline soils using MODIS data.

[Hypothesis: Vegetation indexes respond to the change in vegetation cover, biomass and chlorophyll content. Water spectral indices are sensitive to the change in the moisture content levels. Both the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) will extract the salinity induced changes in canopy biomass and chlorophyll information. The normalized difference water index (NDWI) and land surface water indices (LSWI) will extract salinity induces changes in canopy water content. We therefore assessed the relationship between VI's and WI's, under different soil salinity levels, using MODIS data over the Nile Delta, Egypt.]

II. CONCLUSION

In Chapter 1, we examined the spectral reflectance of soils treated with NaCl saline solution. A wide range of low to moderate salt contents was examined, varying between 1.3 and 9.27 dS/m. Spectral reflectances were measured while the soils were drying on three different soil textures (clay, silt loam and fine sandy loam). The measurements were done with an FR-ASD spectrometer in the 400-2500 nm spectral region. The spectral analyses revealed that using remote sensing data to distinguish between soils with different salinity levels is highly affected by the soil moisture content of the soil. With low moisture content, salts have high reflectance in the VIS-NIR (400-1300) region but low reflectance in the SWIR region. For the soil with high clay content,

a water holding capacity (WHC) of 35% was the threshold limit above which there was difficulty to identify saline soil from non saline soil using remote sensing data. On the other hand, for the silt loam texture soil, a WHC of 50% was the threshold limit.

In Chapter 2, of this study, we evaluated the impact of soil salinity, using 4 irrigation treatments of fresh water, 0.1%, 0.25% and 0.5% NaCl saline solutions on lettuce. The relationships between canopy characteristics (biomass and chlorophyll concentration) and spectral parameters (vegetation indices and "red edge position" (REP)) were analyzed. Reflectance measurements were done using an FR-ASD field-Spec 350-2500 nm spectroradiometer. Results revealed that soil salinity had an apparent impact on plant characteristics. Significant relationships were found between plant chlorophyll content and the REP ($R^2 = 0.97$), dry biomass, and spectral vegetation index SAVI ($R^2 = 0.94$) under different salinity treatments. The spectral indices, SAVI, REP and water indices were found to be effective in discriminating between plants growing under moderate conditions of soil salinity and a non-saline condition. The combination of vegetation indices and water indices was found to be useful in improving the ability to discern between plants growing under salinity stress and non-stressed plants which could be used to evaluate the potential of current and future remote sensing systems in detecting and monitoring moderate conditions of soil salinity in vegetated areas.

In chapter 3, we found the MODIS time series data are generally valuable in distinguishing between crops planted under highly saline conditions and non saline conditions. Crops growing under highly saline conditions had lower VI values in the green-up peak compared to the crops that growing under moderate or non saline

condition. The results also showed that VI-LSWI scatterplots could be useful in detecting the salinity stress under high salinity levels but not with moderate levels. LSWI used MODIS 2130 nm band (Band 7) has higher sensitivity to retrieve canopy water content conditions under stress when it is plotted against either NDVI or EVI. At the same time we found that using MODIS data to discern between crops growing under moderate saline and non saline conditions was not possible.

APPENDIX A

SPECTRORADIOMETRIC STUDY OF SALT TREATED SOILS

I. INTODUCTION

Environmental land degradation has recently become a global, urgent issue and is now being considered with high priority, especially in the developing countries, to meet food and fiber demands of accelerated population pressure with the limited available resources. Secure balance in the global supply and demand for food has forced humans to develop agriculture in semi-arid to arid lands, which are generally less suitable for agriculture and sensitive to environmental changes.

There are two main types of salinity; Natural salinity and man-made salinity. Saline soils occur naturally in arid and semiarid climates from weathering of indigenous minerals and evaporation (El-Ashry, *et al*., 1985; Tanji, 1990) but are more important economically where irrigation is practiced to produce crops (Ghassemi *et al*., 1995). Man-made or Irrigation salinity refers to an accumulation of salt in the plant root zone or on the soil surface, commonly as a result of saline groundwater rising within two meters of the ground surface. Salinity problem arise when the volume of irrigation water exceeds evaporation and transpiration by plants. The excess water percolates into groundwater (termed recharge) causing water tables to rise.

Recently, Dehaan and Taylor (2002) stated that soil salinization is caused by number of factors, the most significant of which is the rise of saline groundwater to where it approaches the ground surface. Capillary rise causes the direct precipitation of saline minerals in surface soils. Local topography, rainfall history, seasonal effects,

drainage, farming practices, soil composition, and vegetation cover greatly influence the extent to which the effects of salinization are observed at ground surface. Indicators of increasing salinization at the surface are therefore likely to be varied because of these factors.

Studies of salinization using remote sensing often concentrated on severely saline soils neglecting the slightly affected areas, which must actually be just the target when dealing with the soil degradation and desertification. The detection and assessment of lower levels of salinity are difficult, mainly because of the nature of remote sensing data, which do not allow getting information on the third dimension of the 3-D soil body. It is also because the impact of salinity on electromagnetic properties needs to be further explored to understand how it can be derived from remotely sensed information (Vidal *et al*., 1997). Most of the published investigations based on remote sensing distinguish only three to four classes of soil salinity, after consulting geomorphologic or soil degradation maps or by means of conventional time consuming and laborious field surveys. Current sensors and interpretation algorithms do not allow the detection of intermediate to medium salinity levels.

This work was conducted to 1- detect the optimum and range of soil moisture content levels for salinity detection on bare soils using remote sensing data; 2- recognize the influence of soil texture on salinity-induced spectral changes.

II. REVIEW OF LITURATURE

Remote sensing performs the detection, collection and interpretation of data from distance by mean of sensors. The sensors measure the reflectance of electromagnetic radiations from the features at the earth surface. The radiated energy is transmitted through space in waveform. The electromagnetic spectrum ranges from gamma rays, with wavelength of less than 0.03 nm, to radio energy with a wavelength of more than 30 cm. In remote sensing applied to land resources surveys, wavelengths between 0.4 and 2.4 nm are commonly used. The presence of salts at the terrain surface can be detected from remotely sensed data either directly on bare soils, with salt efflorescence and crust, or indirectly through vegetation type and growth as these are controlled or affected by salinity (Mougenot, *et. al.* 1993). Ben-Dor and Banin, (1995) mentioned that the reflectance spectroscopy has the ability to provide nondestructive rapid prediction of soil physical, chemical, and biological properties in the laboratory.

Advances in portable spectrometers, digital photography, and high-resolution satellite imagery continue to improve the speed, portability, scope, and cost-effectiveness of salinity detection. A variety of remote sensing data has been used for identifying and monitoring salt-affected areas, including aerial photographs, video images, infrared thermography, visible and infrared multispectral and microwave images (Metternicht and Zinck, 2003).

The results of Verma *et al*, (1994); Metternicht and Zinck, (1997); Dwiviedi and Sreenivas, (1998) demonstrated the value of remote sensing techniques in soil salinity studies. Metternicht and Zinck, (1997) reported that the main cause of spectral confusion

which mask different salinity degrees were the topsoil cover, the topsoil textures, and mixtures of topsoil properties under field conditions. In general, reflectance increases with increasing quantity of salts at the land surface. This is particularly true for the blue band; In contrast, reflectance decreases and salts are difficult to identify with increasing moisture, the presence of ferric oxides and the inclusion of clay. Similarly, the presence of water and OH^- groups in crystal lattice contributes to decreasing the reflectance in middle and near-infrared bands (Epema, 1990; Mougenot, 1993).

Saha *et al*. (1990) used the spectral signatures (spectral responses in different bands) to differentiate the wasteland categories (salt-affected and waterlogged) and other land use features in India. They observed that the spectral separability was greater in TM bands 4, 5 and 7 for all the wasteland categories. This implies that the spectral region between 1.5 and 2.5 μm is suitable to the presence of salts.

Hick and Russel (1990), using Geoscan—a 24-channel instrument that approached hyperspectral imaging capabilities, concluded that vegetation vigor, as shown by near-infrared reflectance (NIR), is the best indicator of the impacts of increasing soil salinization. Using Hymap airborne sensor that has 128 bands between 450 - 2500 nm spectral range, Taylor and Dehaan (2000) mapped saline areas characterized by salt scalds, halophytic vegetation, and soils with different salinity levels. Using spectral unmixing, they found that saline endmembers presented a pronounced high reflectance at 800 nm, a shallow and wide hydroxyl feature at 2200 nm, and broad absorption features at 1450 and 1900 nm. Ben-Dor *et al*. (2002) report successful results in using the

hyperspectral DAIS-7915 sensor and the Visible and Near-Infrared Analysis (VNIR) approach to produce quantitative soil surface maps soil salinity.

Under laboratory conditions spectroradiometer analysis and using surface soil samples Csillag *et al*. (1993) used a modified stepwise principal component band selection method to separate 13 classes of the soil salinity status. They reported that the importance of high spectral resolution in recognition accuracy of salinity status decreased from 91, 90, and 88 % as bandwidth increased from 10, 20, and 40 nm, respectively, over both locations. They identified six spectral ranges characterizing the salinity status of the soils exposed to different salinization and alkalinization processes, including the visible (0.55–0.77 μm), near-infrared (0.9–1.3 μm) and middle-infrared (1.94– 2.15, 2.15–2.3, 2.33–2.4 μm) bands.

The variability of the soil surface conditions and changes in bare soil surface conditions complicate the reflectance of the soil. Although spectral signatures play a central role in detecting, identifying and analyzing earth surface materials, the spectral world is full of ambiguity. Radically different materials can have great spectral similarity making differentiation difficult. To use remote sensing data effectively, one must know and understand the spectral characteristics of the particular features under investigation. A better understanding of the behavior of different wavelength regions on different soil salinity based upon remote sensing (Hunt and Salisbury, 1976).

Surface salinity is a highly dynamic process, causing identification constraints derived from the spatial and temporal variable nature of drying soil (precipitated salts). Salt detection is easier at the end of the dry season, since salts will dissolve during the

rainy season, and upon drying. Alavi Panah and Goossens (2001) reported that Salt-affected soils in arid regions, especially when a salt crust (whitish color) is formed; show a high reflectance, the soil structure, which is the result of chemical and physical properties of the soil, may alter the reflectance. The water content of soil causes a decrease in the soil reflectance through the visible and near infrared spectrum. Structural conditions of the soil surface have an influence on reflectance. Some other investigations in the reflectance spectra may not be attributed to a single soil salinity property. In fact the spectra of soil surfaces are full of ambiguity.

(Ben-Dor *et al.* 2002) have successfully demonstrated the use of advanced spectroscopy techniques in the quantitative retrieval of soil properties based on their spectral absorption features, employing a 'Visible and Near Infrared Analysis' (VNIRA) methodology to predict soil chemical constituents. The VNIRA approach assumes that a concentration of a given constituent is proportional to the linear combination of several absorption features, and is capable of generating empirical models for predicting soil properties using laboratory wet chemistry and spectral measurements on representative sets of "calibration" samples.

General information and data regarding the extent of soil salinization and the resulting impacts are poorly understood. Lack of broad guidelines for assessment and monitoring of soil salinization, including early warning indicators, have disadvantaged effective soil salinization monitoring and detection programs. Using remote sensing data has been significantly used as starting point for monitoring, identification, and change detection of soil salinity. In contrast, Metternicht and Zinck, (2003) reported that lack of

specific absorption bands of some salt types like halite (NaCl); occurrence of spectral confusions with other terrain surface features; vertical, spatial, and temporal variability of salinity in the soil layer; soil properties (e.g. soil texture, soil surface texture, soil color), and low spectral resolution of satellite bands are the most important factors that restrict the use of remote sensing data for salinity monitoring purposes. Howari (2003) indicated that the main factors affecting the reflectance or the signals gathered by the sensor are mostly the moisture content and roughness as well as, salt quantity, and mineralogy.

It is clear that most of the published investigations based on remote sensing distinguish only two to three classes of soil salinity. In general, moderately to highly saline areas are easily detected, while low salinity levels and the initial stages of salinization are more difficult to discern.

III. METHODOLOGY

A controlled tray experiment was conducted to track the different salinity crusting stages on different soil textures types. It is not simple to do such treatments (wide range of salts and different soil textures) and follow the different crusting stages spectrally under field conditions.

The experiment was conducted using trays (50X35X8 cm); each tray contained a 5 cm thickness of soil. Four replications were used.

Three different types of soils were used: a light texture soil (fine sandy loam), heavy texture soil (clay) and medium texture soil (silt loam). The soil characteristics are shown in table (1). These soils were treated with 5000 ppm saline solution. Sodium chloride (NaCl) was used as a source of salinity. The solution was sprinkled on the soil surfaces until the soil was deemed at the water holding capacity for each soil (table 1).

One day before starting the reflectance measurements, one tray from each soil was placed on a balance and splashed with water until the water holding capacity (WHC) was achieved. The time was measured until the soil mass returned to its initial value. It required 110 minutes for the sandy loam soil, 122 minutes for the silt loam soil and 140 minutes for the clay soil to return to the initial mass value. A 140 minutes period was used for the three different soils as a drying period during the reflectance measurements.

A. Reflectance measurements

On cloudless days, measurements were made from 1030 to 1330 MST. The reflectance spectra of the simulated salty soils was recorded over the 350-2500 nm region in 10nm nominal wavelengths, 1 nm increments**,** using a Full Range Analytical Spectrum

Device (FR-ASD) instrument with 8° field of view. The surfaces were viewed vertically from a height of 0.5 m. Spectral measurements were then collected repeatedly (every 20 minutes) until the soil mass returned to its initial value (after ~140 minutes). These steps were repeated for 6 cycles (sprinkling saline solution and scanning while the soils were drying). The whole experimental period took 6 consecutive days.

The average temperature was 101°F during the whole study period. For each tray, triplicate readings were made, preceded by and followed by a spectral response reading from a white Spectralon panel.

The root mean square deviation of the three triplicate measurements on each tray was fairly constant and averaged ± 0.11% reflectance.

Soil samples were collected, after each drying stage, from each tray to measure the electric conductivity (EC) according to Rhoades (1982).

The main objectives were (1) to investigate the optimum water content levels to which the simulated salty soils can be distinguished spectrally, (2) determine what wavebands would be valuable and sensitive in detecting and monitoring low to moderate soil salinity levels on bare soil surface, and (3) evaluate the influence of soil texture on salinity-induced spectral changes.

IV. RESULTS AND DISSCUSION

The spectral reflectance curves of the clay texture soil are plotted in Figures (1 and 2) at different soil moisture contents and salinity levels. A general observation is that the higher the salinity, the higher the reflectance across the whole spectral region. All spectral curves at varying salinity levels also maintained a similar shape as the control soil (ECe = 1.37), but higher reflectivity level. The same pattern was observed in the medium texture soil (silt loam soil) reflectance curves (figures 3-4) .These results agree with the results of Everitt *et al.* (1988) who found that well-developed saline efflorescence and crusts are always associated with high reflectance in the visible and near-infrared spectra. Their study indicated that crusted saline soil surfaces are generally smoother than non-saline surfaces; giving higher reflectivity. A simple investigation of these figures, especially with the lowest water content figures, illustrates that there is also a relationship between increasing salt content of the soil between the two SWIR regions (1400-1800 nm) and (2100-2300 nm).

On the other hand, the salt influence was not very clear in the fine sandy loam soil (figures 5-6) which is brighter than the other two soils. The figures also demonstrate that the reflectance decreased with increasing moisture content for all studies soils.

The spectral curves do not change in appearance with increasing salt content and the ratio of salt-treated soils to non-treated soil (1.37 dS/m for clay soil, 1.29 dS/m for silt loam soil and 1.16 dS/m for the fine sandy loam soil) reflectance remains fairly constant in the visible, and NIR spectra for clay soil (figures 7-8), silt loam soil (figures 9-10) and for the fine sandy loam soil (figures 11-12). On the other hand, the reflectance ratio

between salt-treated and non-treated soils decreases significantly in the SWIR region for both the clay soil and the silt loam soil. The fine sandy loam soil showed the same trend but the decrease in the SWIR region was small compared to the other two soils. The presence of water and OH^- groups in the salt crystal lattice contributes to decreasing the reflectance in the shortwave infra-red region (Epema, 1990; Mougenot, 1993). From these figures we can state that Even at WHC, there is a salt influence, although lower (~15-20%) than the influence at lower moisture contents (~ 40%). Salinity influence is low at SWIR2 and high in VIS-NIR.

Four different wavelengths were chosen to represent the VIS, NIR and SWIR parts of spectrum. The reflectance at 650, 860, 1650, and 2130 nm as a function of soil EC are shown in figures (13a through 13d) for clay soil and (14a through 14d) for silt loam soil. The reflectance exhibited a general linear response to increasing soil salinity. The effect of salinity on the reflectance is almost not evident with high soil water content (WHC) values. Sensitivity to salinity levels was greatest at intermediate soil moisture levels (9-12.5%) and for EC > 3 dS/m levels. sensitivity to salinity was also high at lower moisture levels (6-8%) but only for EC > 4 dS/m values.

On the other hand, with the lower water content values, while reflectance exhibited only negligible increases (lower slope) below EC ~ 3.7 dS/m for clay soil and EC ~ 4.26 for silty loam soil, the reflectance values showed higher sensitivity for salinity changing (higher slop) beyond this EC value either in visible or longer wavelengths. Since the saline soil have been defined by the USDA Salinity Laboratory as having an

ECe of 4 dS/m or more, the sensitivity of VIS and SWIR reflectance at these intermediate EC levels is potentially important.

The equivalent figures for the light texture soil, fine sandy loam, spectral reflectance at 650, 860, 1650, and 2130 nm are shown in figures (15a through 15d). The reflectance values were almost constant with increasing soil EC values under different soil water contents.

Figures (16 and 17) represent the soil reflectance at 650, 860, 1650, and 2130 nm as a function of soil moisture content for clay soil and silt loam soil respectively. Visibly, the reflectance decreased with increasing soil moisture content under the four studied wavelengths and under the whole studied salinity levels. Higher sensitivity for moisture content was found with water content lower than 19% for the clay soil and 24% for the silty loam soil.

The same relationship for sandy loam soil is shown in figure (18). The same inverse relationship between soil reflectance and soil moisture content was obtained under the different studied wavelengths. There was no difference between the different salinity levels.

V. CONCLUSION

In general increasing quantity of salt at the soil surface provides a higher reflectance in the visible and NIR spectral regions. There is a relation between the existence of salts in the soil surface and the difference between VIS-NIR and SWIR reflectance.

Identifying salted soils varies with water content. The presence of high water content prevent the formation of salt crust on the soil surface which leads to reduce the ability of remote sensing to detect the saline soils on bare soils. For the soil that has high clay content 35% of the water holding capacity (WHC) was the water content limit below it there was a difficulty to identify saline soil from non saline soil using remote sensing data. On the other hand, for the medium texture soil (silt loam) 50% of WHC was the limit.

Many salt-affected soils can be identified by a white salt crust that form on the soil surface; thus, these soils tend to have higher visible and NIR reflectance. This spectral response cannot always be used to identify saline soil, because soils with high sand contents have visible and NIR spectral properties similar to salt-crusted soils. The dull white tone of salt crust on the soil surface and the sandy soils post problems in their discrimination by remote sensing data. The main causes of spectral confusion, on the bare soil the presence of large amount of silt and sand. Surface brightness due to high sand content determines higher reflectance that makes spectral confusion between the white salt crusts and high content sand.

In general remote sensing data could be used as a tool for discriminating between saline soils and non-saline soils on the dark soils that have high clay content but not with soils that have high sand content. The low soil salinity and early stages of salinization lower than 4 dS/m, is hard to be detected on bare soil using remote sensing.

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Table 1: Pre-salinity treatment application soil test analyses.

Unit / Soil	*pH	*EC	**WHC	*Texture*		
		dS/m	w/w%	%Clay	%Silt	%Sand
Fine sandy loam	7.1	1.16	18.5	3.04	28.10	68.66
Clay	7.7	1.37	34.8	57.75	22.31	19.94
Silt loam	7.3	1.29	31.2	12.16	53.02	34.82

* pH obtained from 1:1 water extract

* EC obtained from 1:5 water extract

** Water Holding Capacity

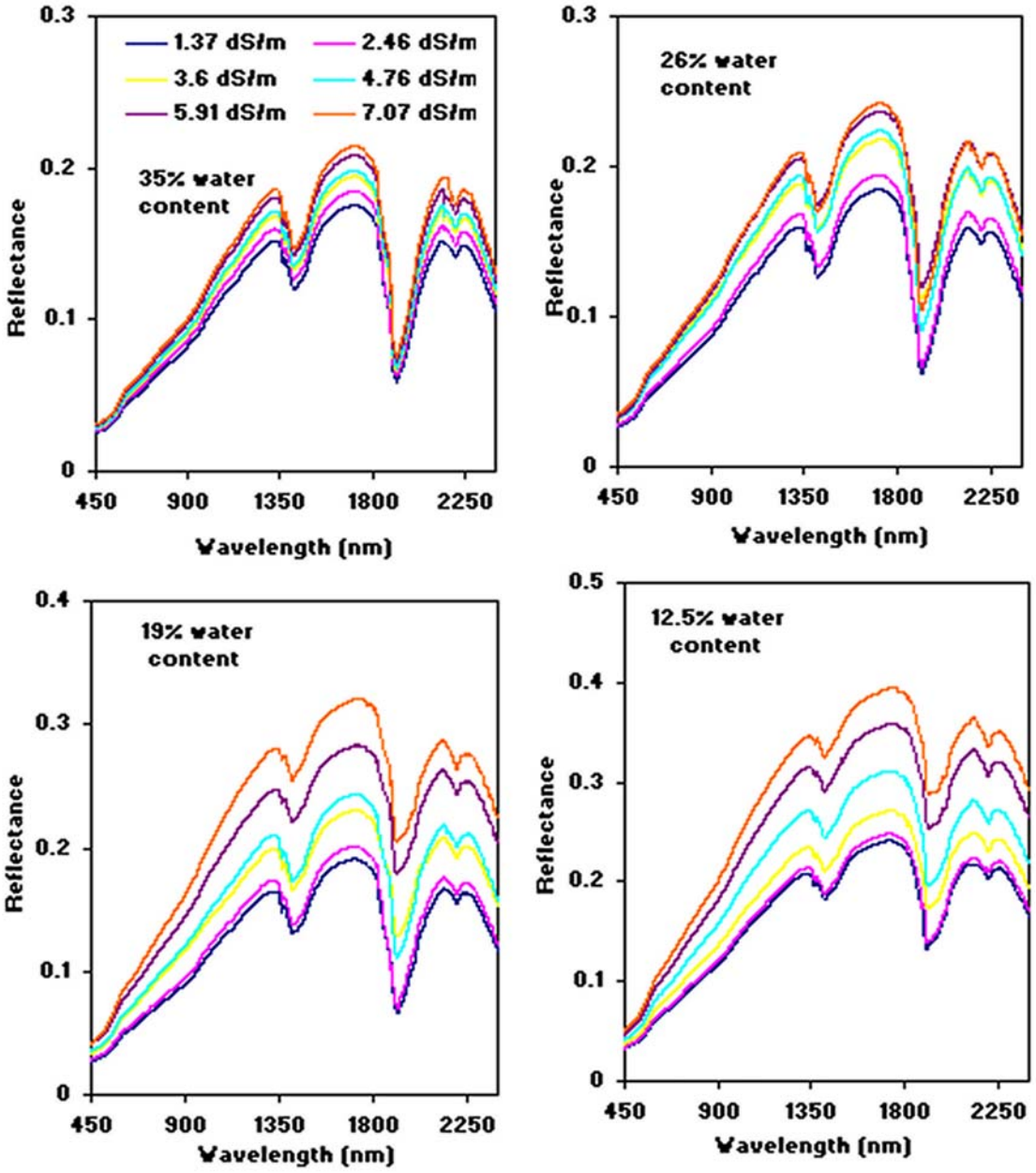

Figure 1: The effect of soil salinity level (EC) on clay soil spectral reflectance under four different soil moisture contents 35%, 26% 19% and 12.5%.

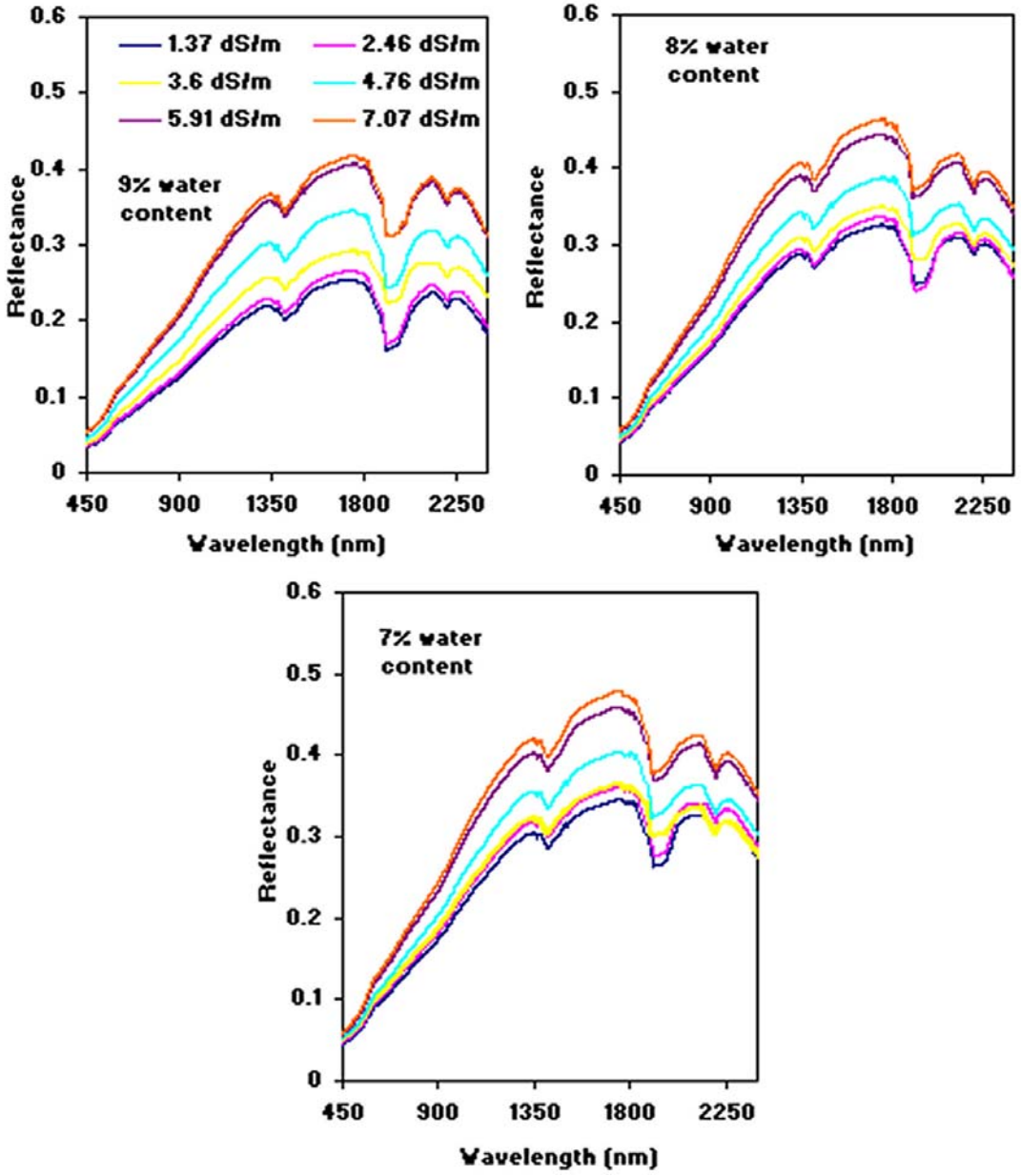

Figure 2: The effect of soil salinity level (EC) on clay soil spectral reflectance under three different soil moisture contents 9%, 8% and 7%.

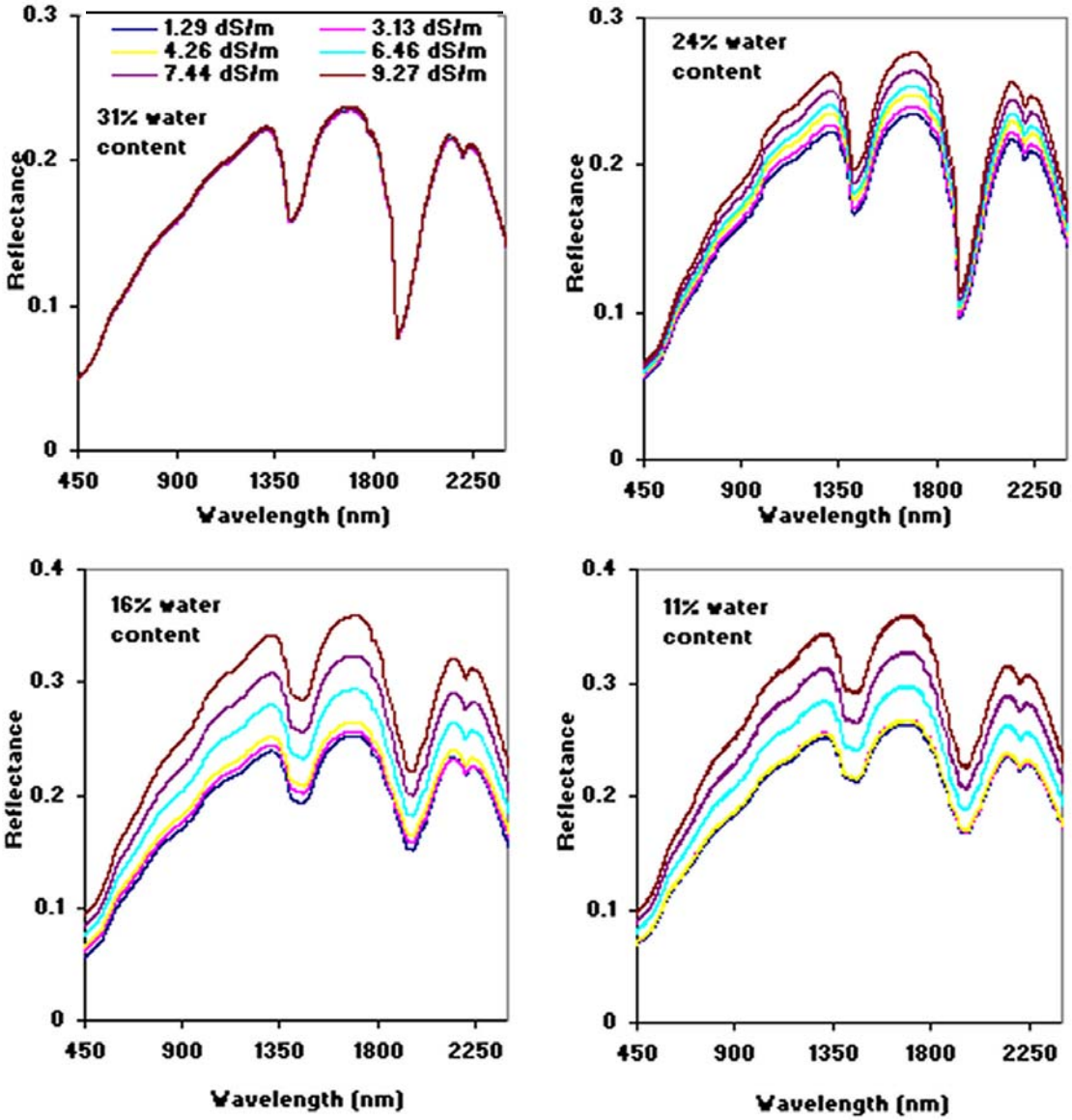

Figure 3: The effect of soil salinity level (EC) on silt loam soil spectral reflectance under four different soil moisture contents 31%, 24%, 16% and 11%.

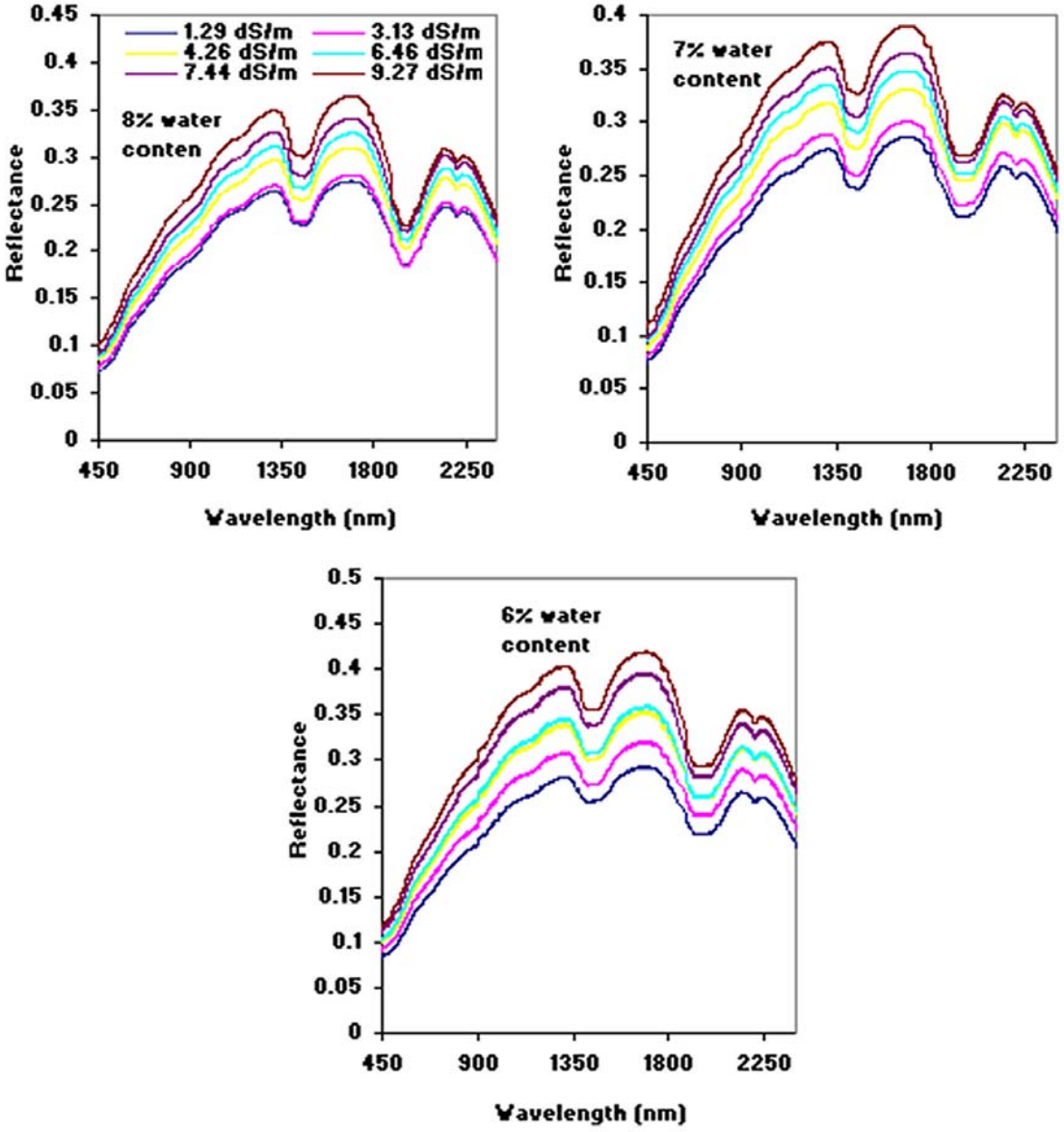

Figure 4: The effect of soil salinity level (EC) on silt loam soil spectral reflectance under three different soil moisture contents 8%, 7%, and 6%.

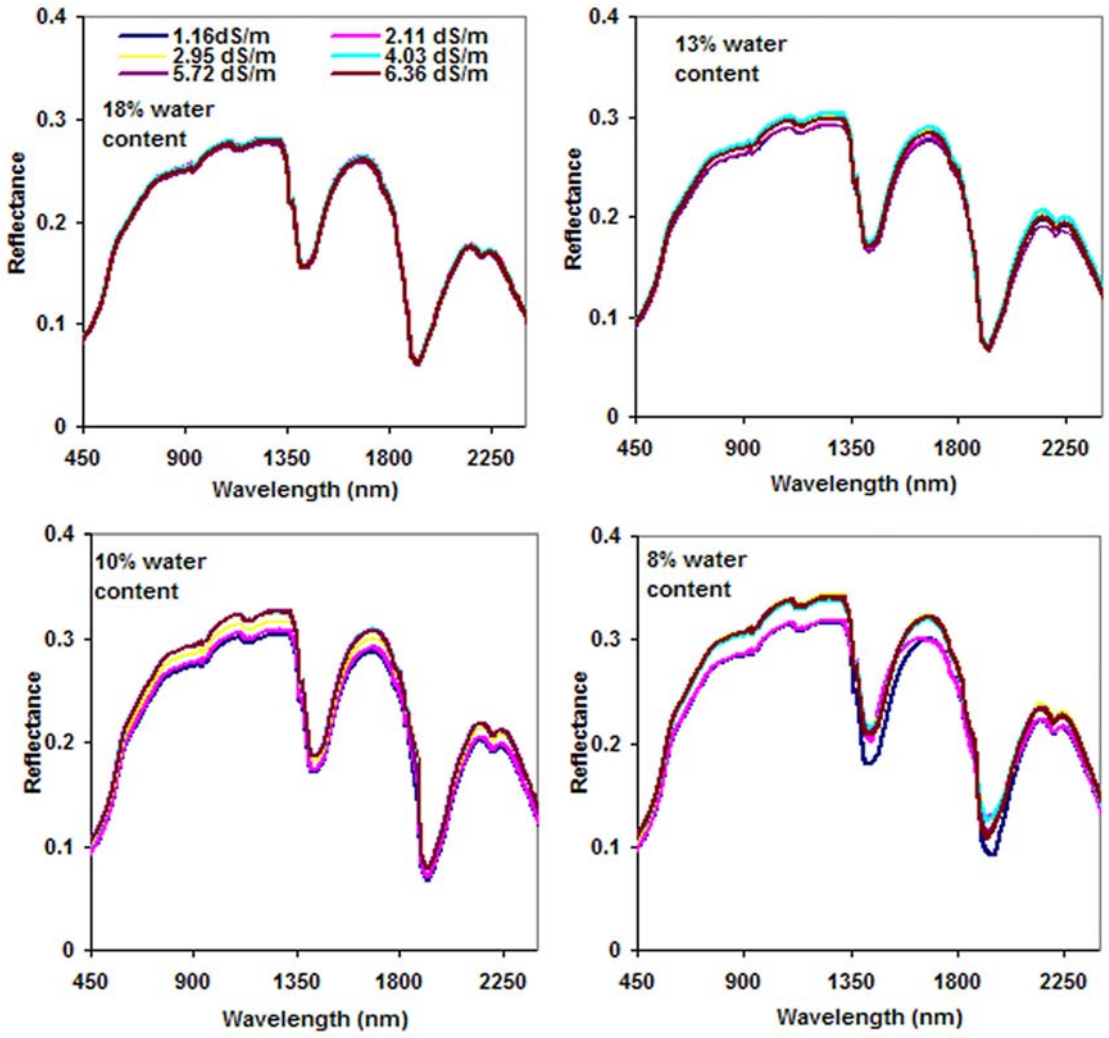

Figure 5: The effect of soil salinity level (EC) on sandy loam soil spectral reflectance under four different soil moisture contents, 18%, 13%, 10% and 8%.

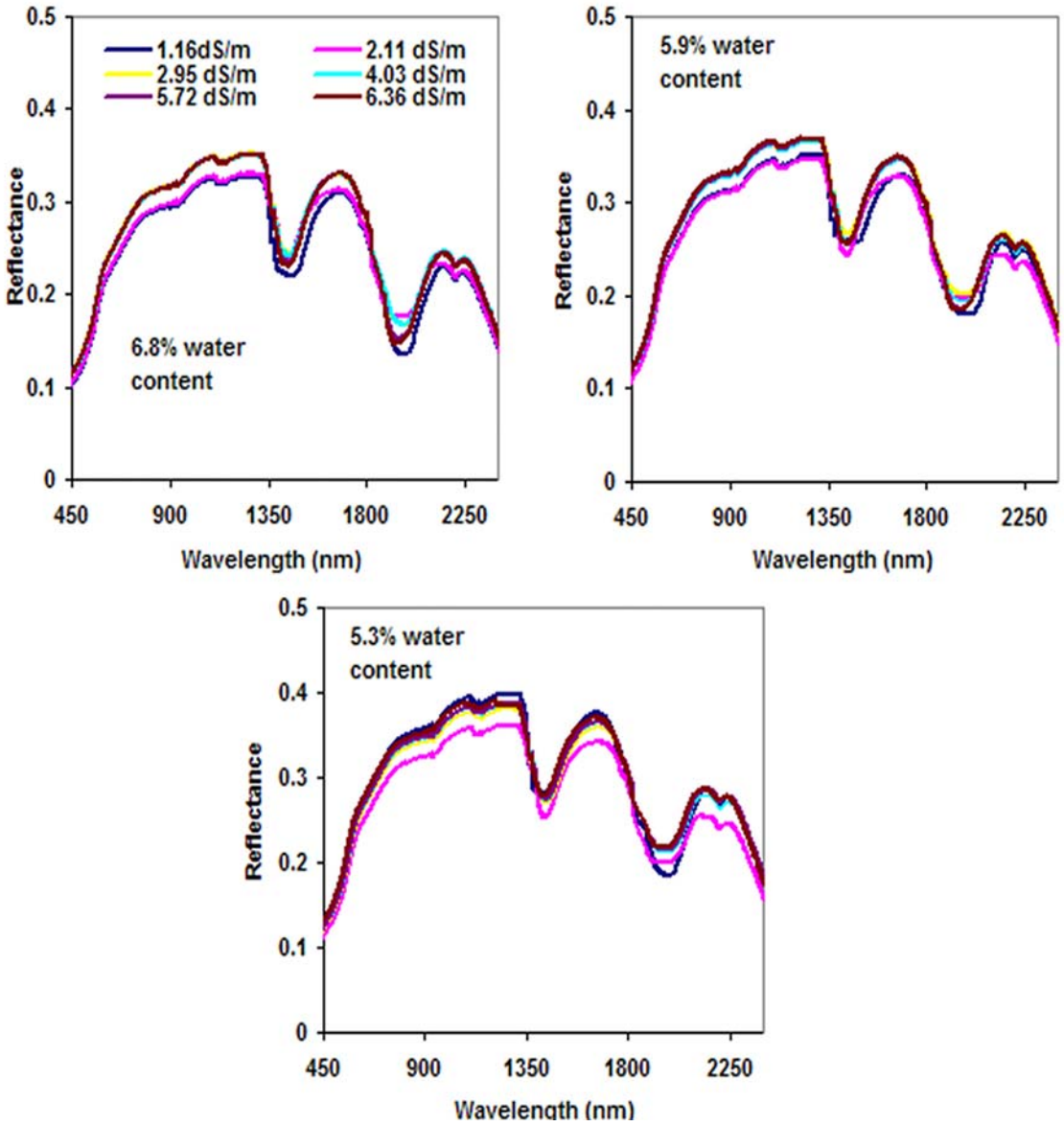

Figure 6: The effect of soil salinity level (EC) on sandy loam soil spectral reflectance under three different soil moisture contents, 6.8%, 5.9% and 5.3%.

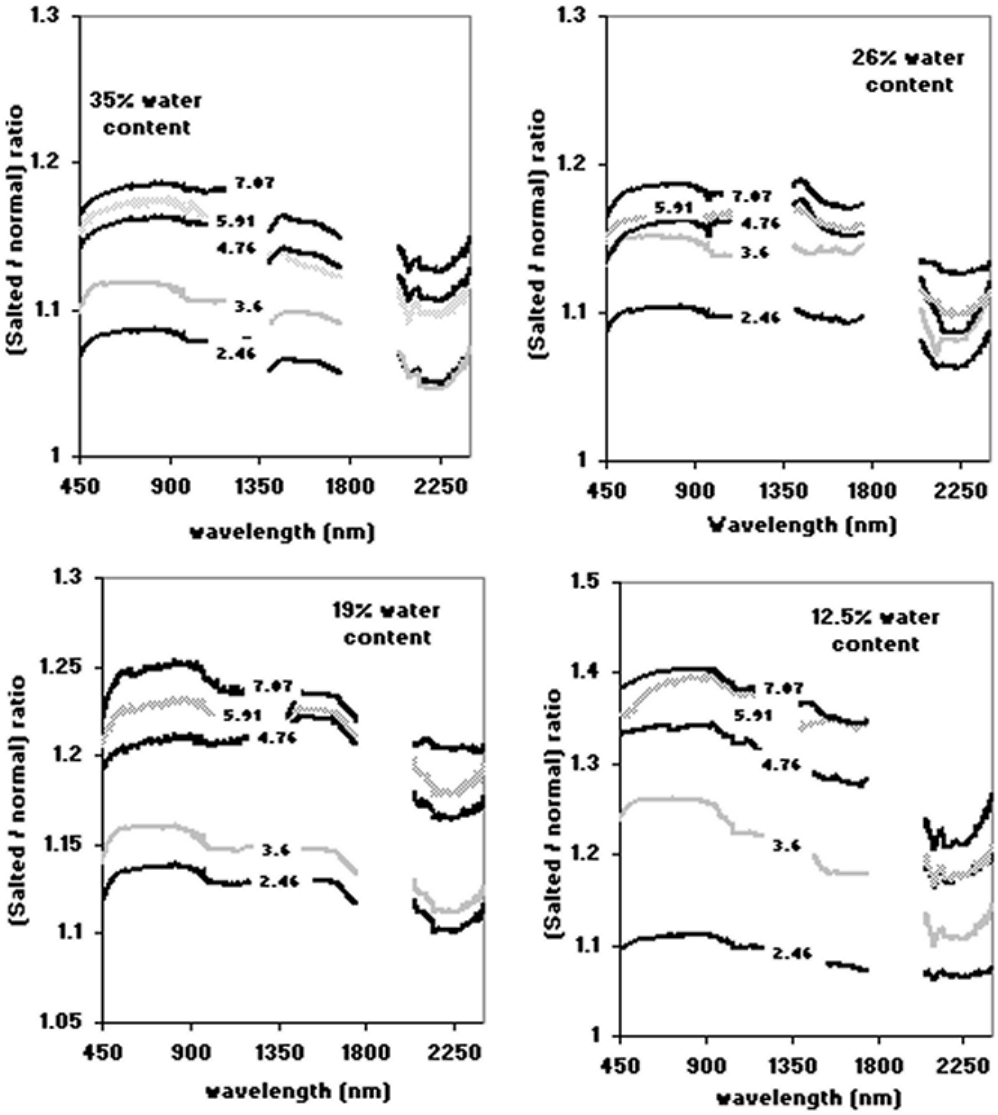

Figure 7: The salted to non-salted clay soil reflectance ratios under four different soil moisture contents, 36%, 26%, 19% and 12.5%.

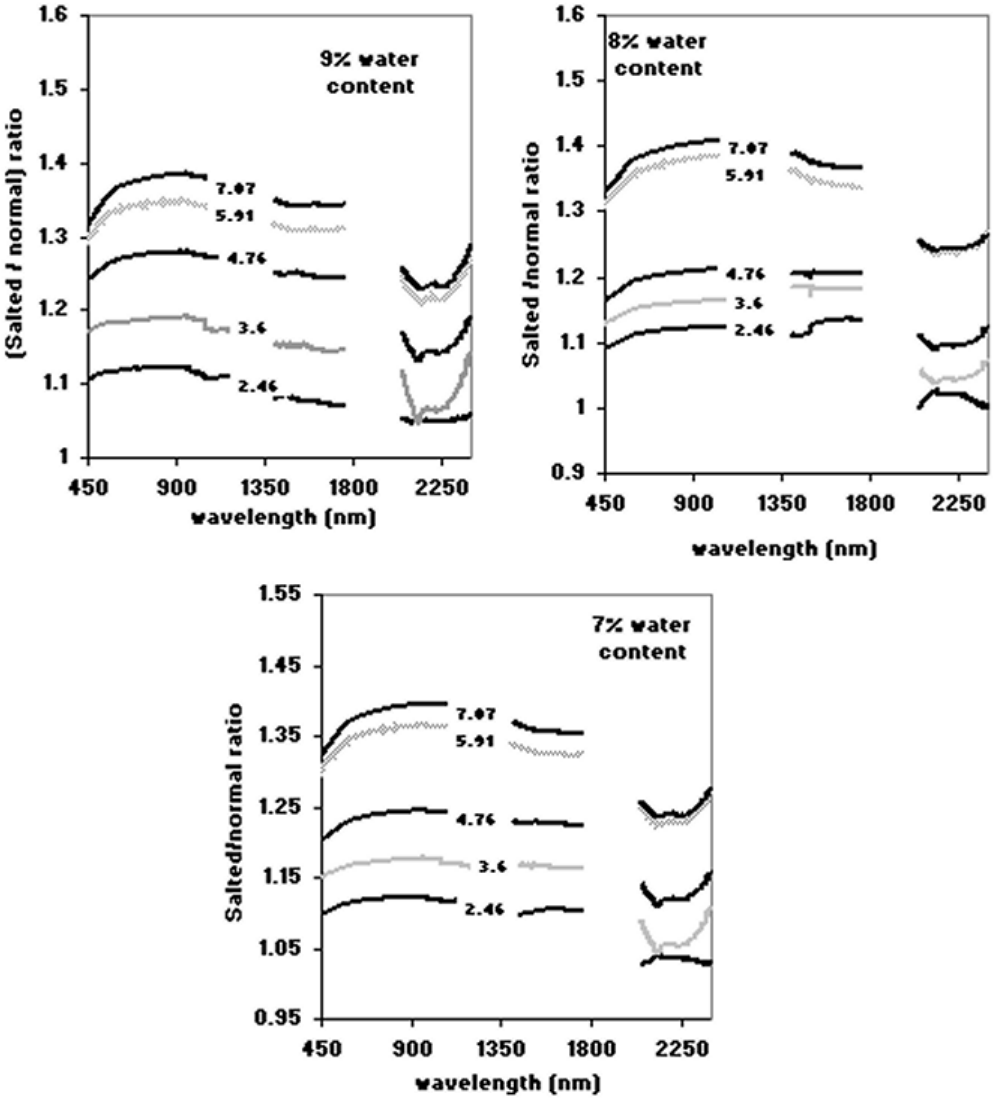

Figure 8: The salted to non-salted clay soil reflectance ratios under three different soil moisture contents, 9%, 8%, and 7%.

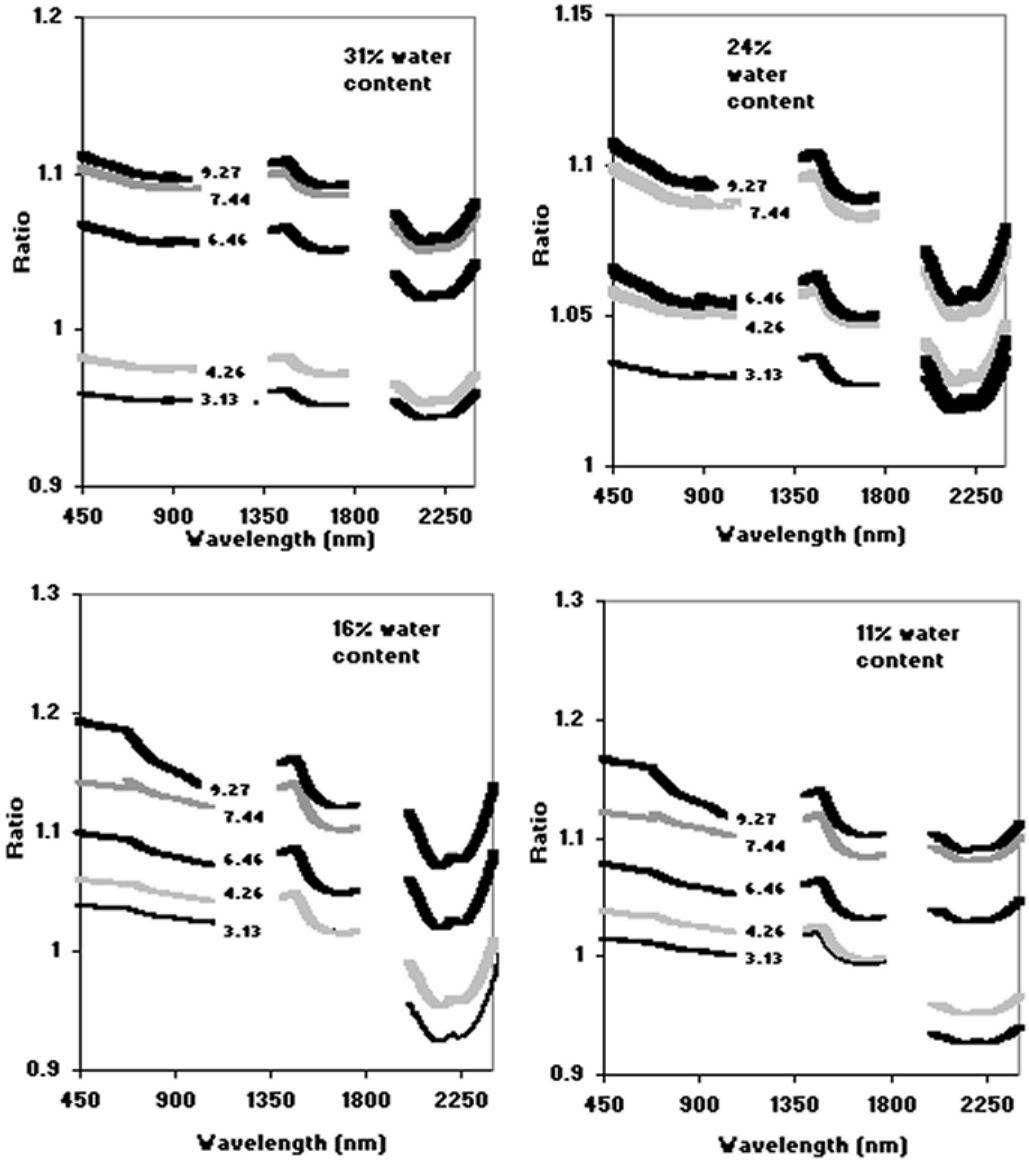

Figure 9: The salted to non-salted silt loam soil reflectance ratios under four different soil moisture contents, 31%, 24%, 16% and 11%.

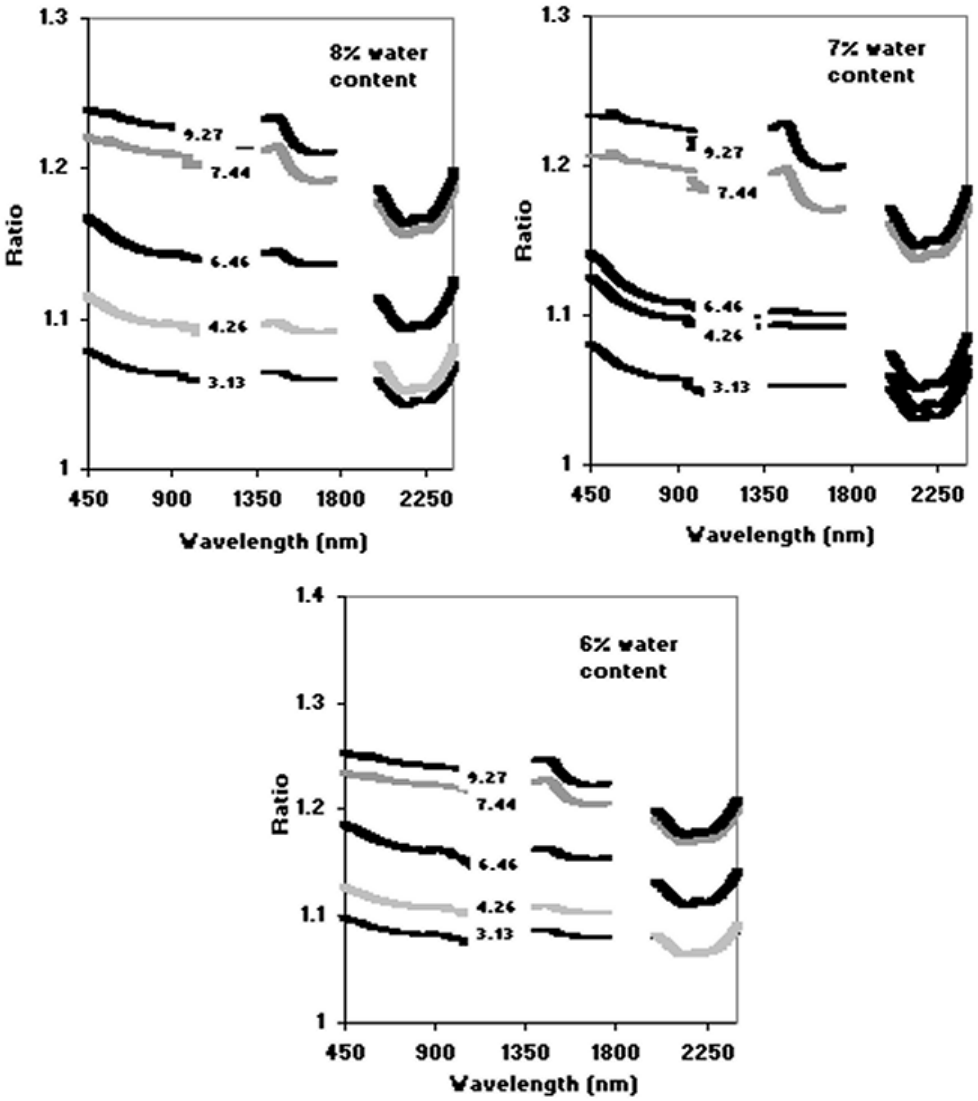

Figure 10: The salted to non-salted silt loam soil reflectance ratios under three different soil moisture contents, 8%, 7%, and 6%.

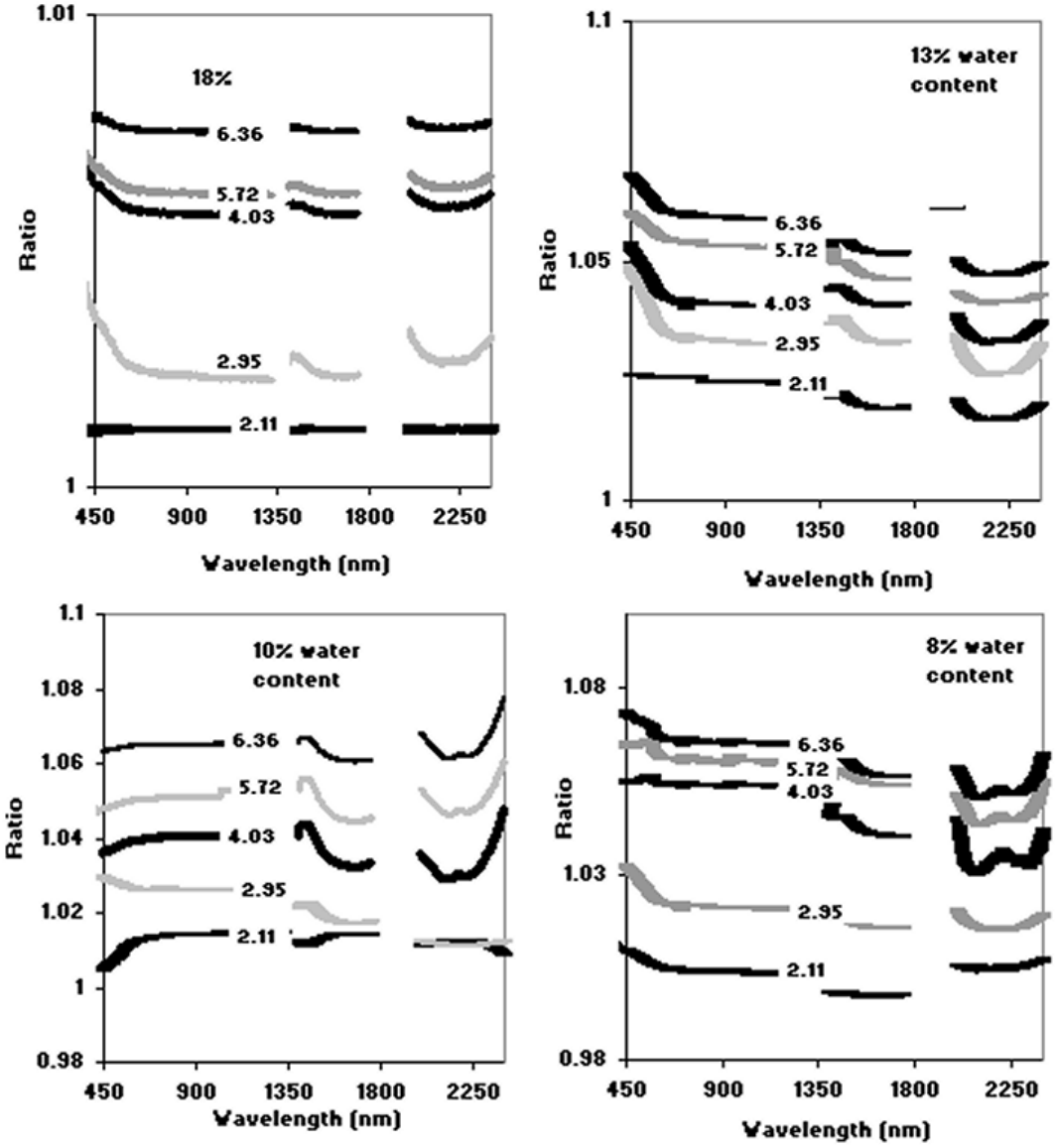

Figure 11: The salted to non-salted sandy loam soil reflectance ratios under four different soil moisture contents, 18%, 13%, 10% and 8%.

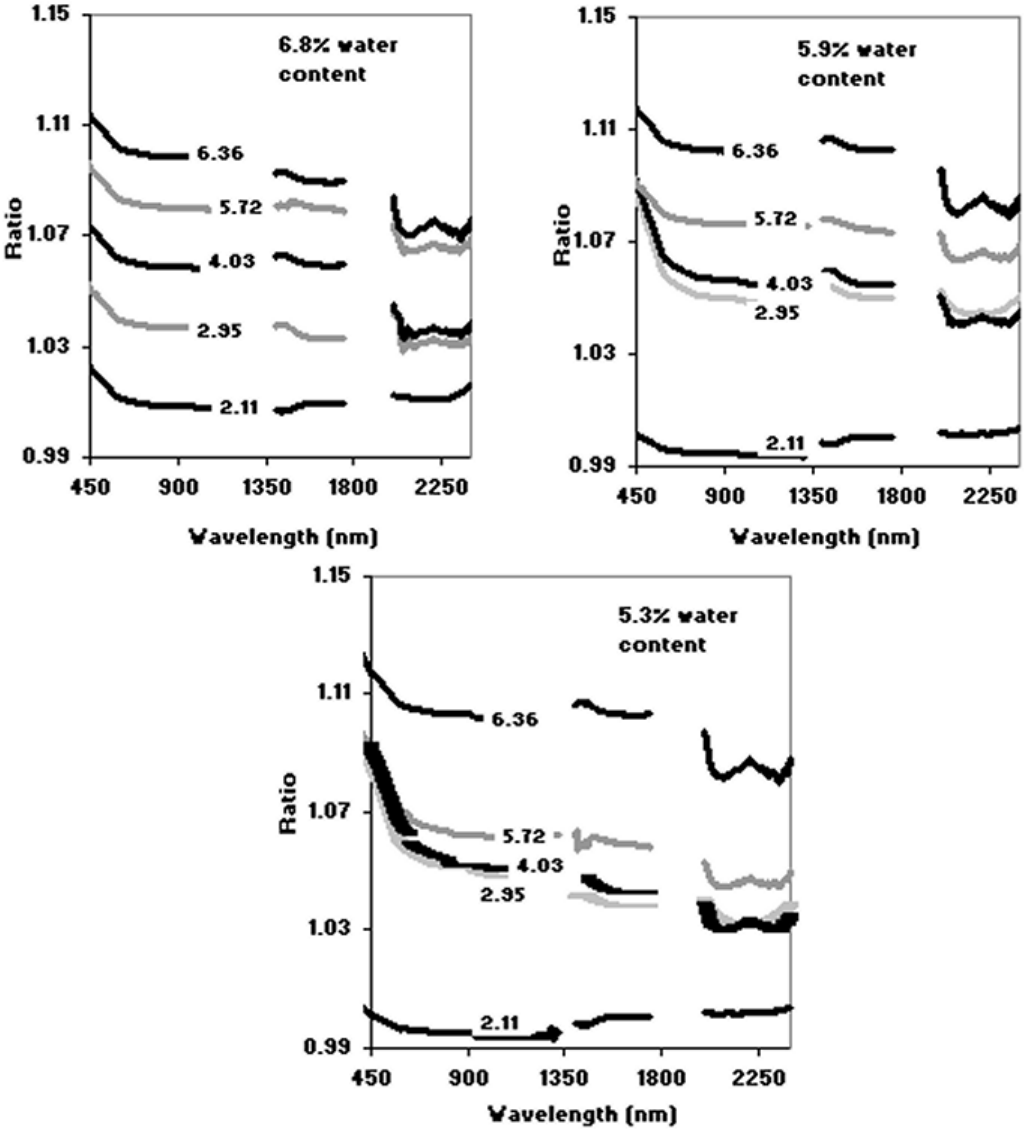

Figure 12: The salted to non-salted sandy loam soil reflectance ratios under three different soil moisture contents, 6.8%, 5.9%, and 5.3%.

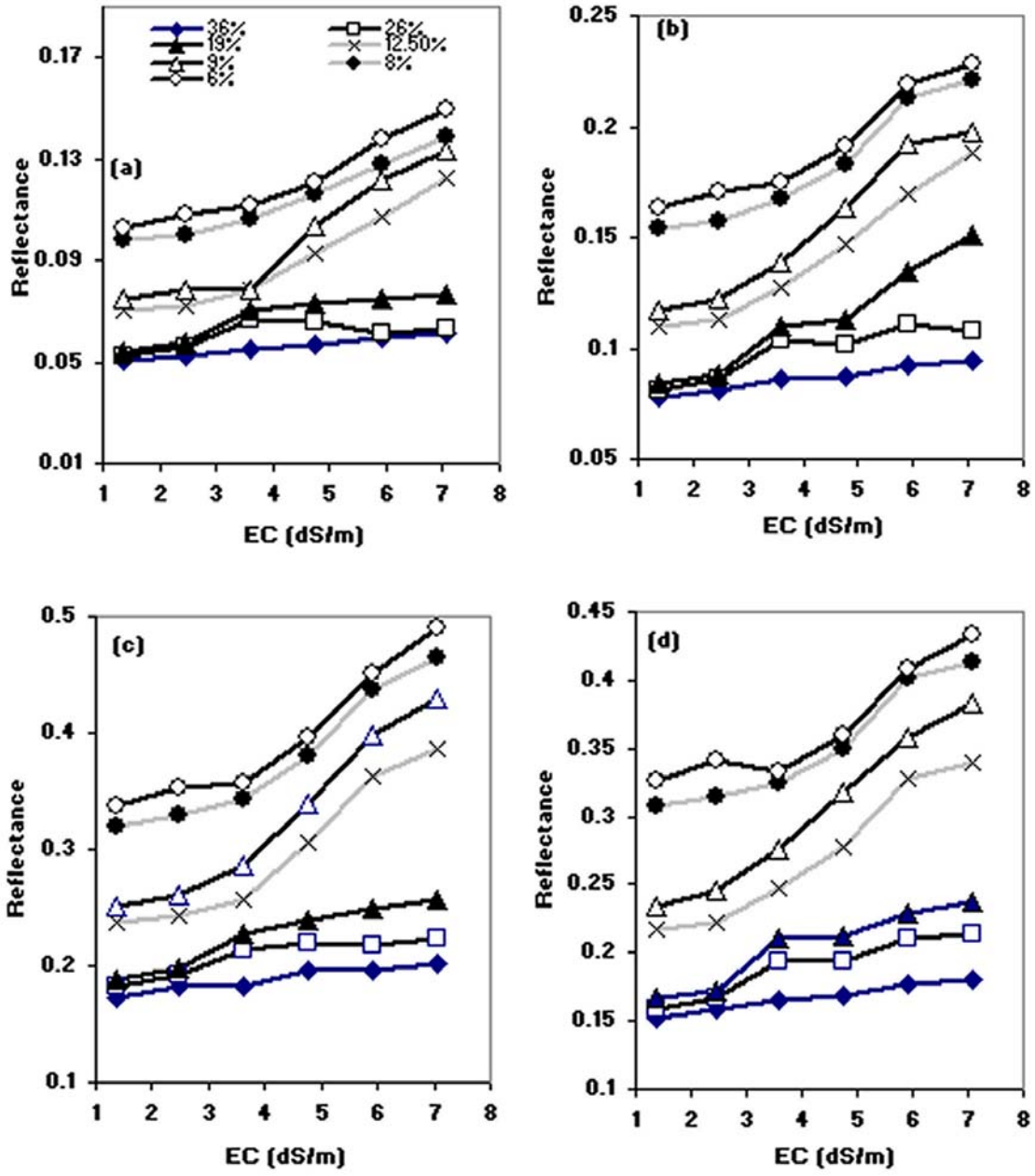

Figure 13: Changes in clay soil reflectance as affected by the soil salinity under seven different soil moisture contents at (a) 650 nm, (b) 860 nm, (c) 1650 nm and (d) 2130 nm.

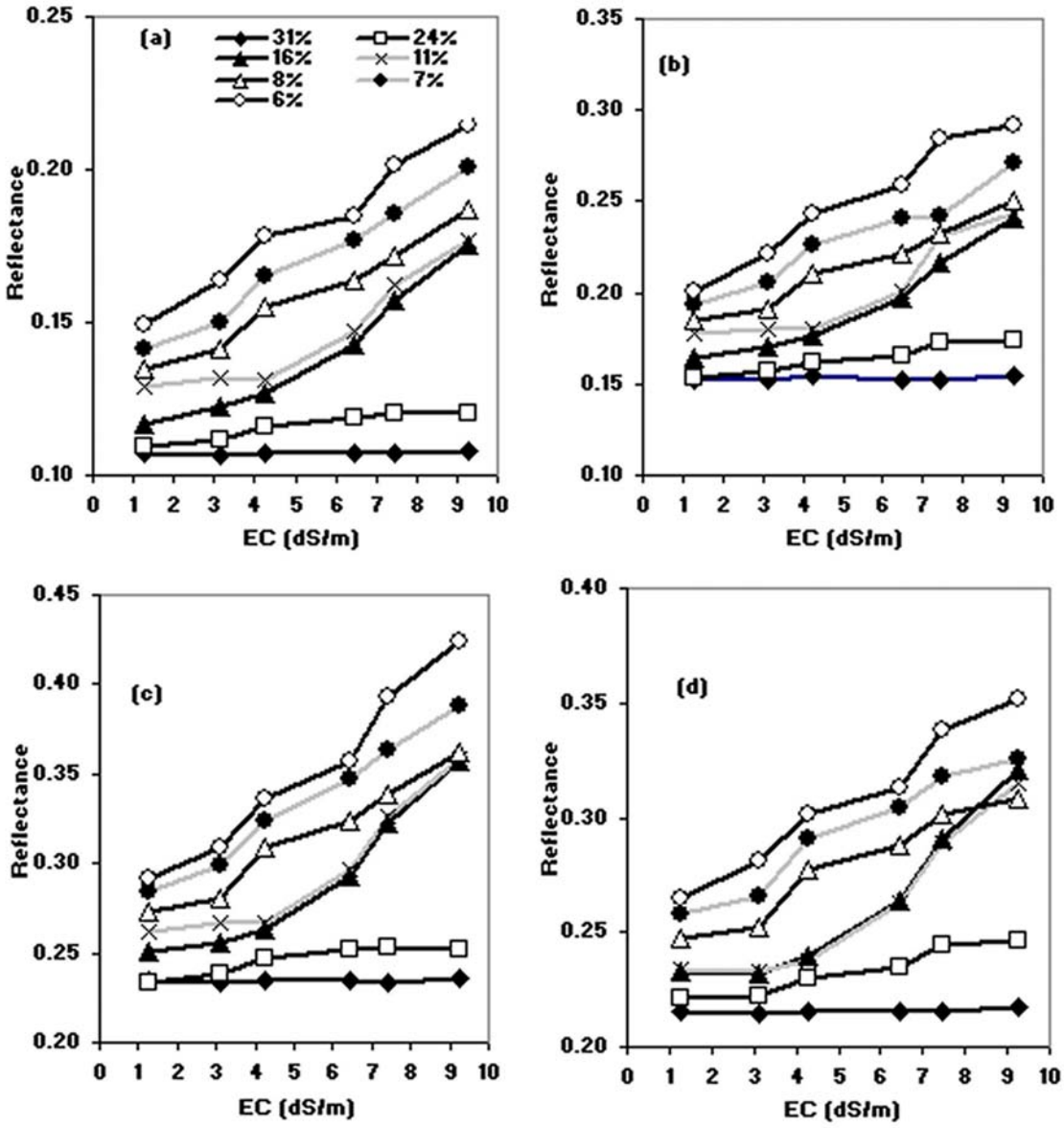

Figure 14: Changes in silt loam reflectance as affected by the soil salinity under seven different soil moisture contents at (a) 650 nm, (b) 860 nm, (c) 1650, and (d) 2130 nm.

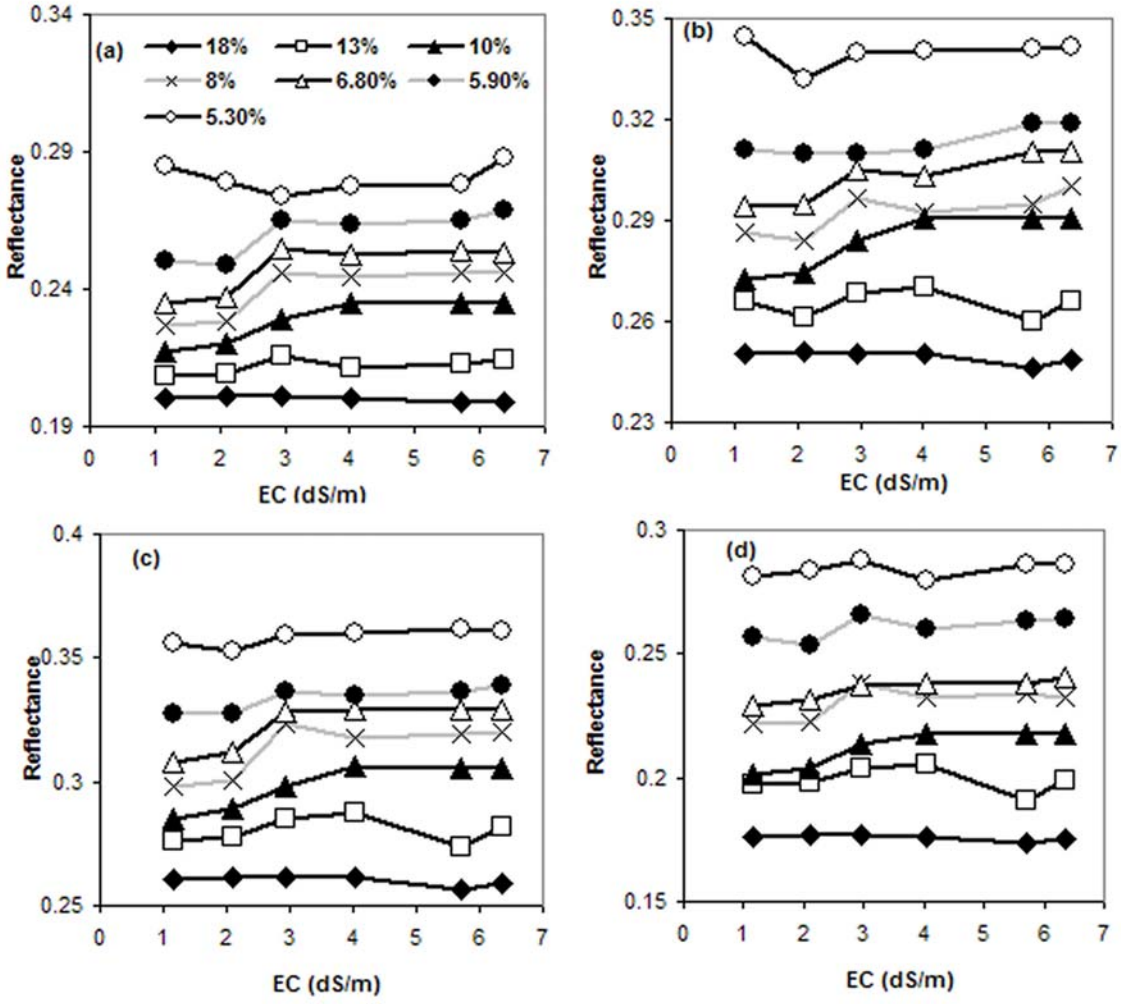

Figure 15: Changes in sandy loam soil reflectance as affected by the soil salinity under seven different soil moisture contents at (a) 650 nm, (b) 1650 nm, and (c) 2130 nm.

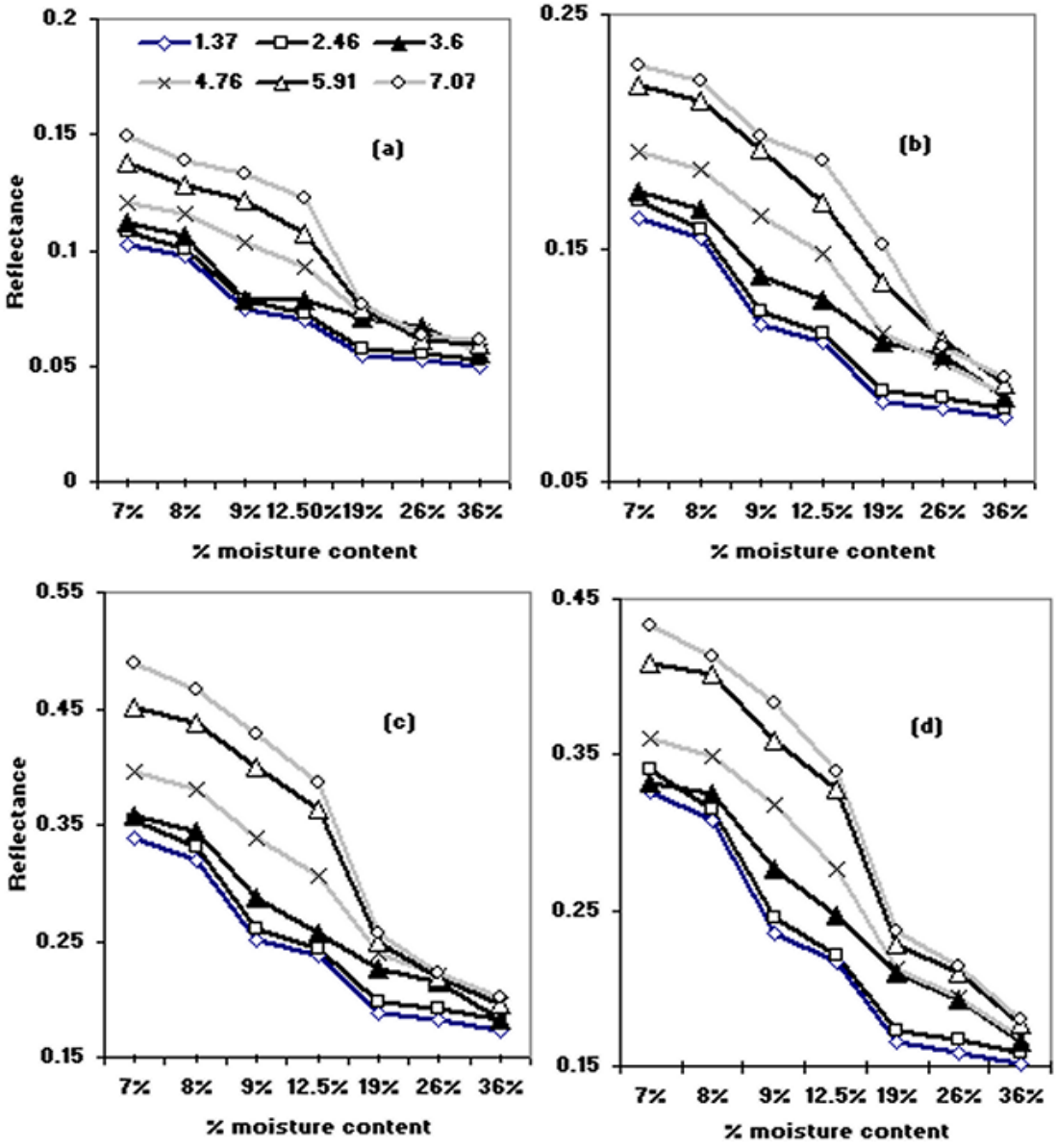

Figure 16: Changes in clay soil reflectance as affected by soil moisture content under six different soil salinity levels at (a) 650 nm, (b) 1650 nm, and (c) 2130 nm.

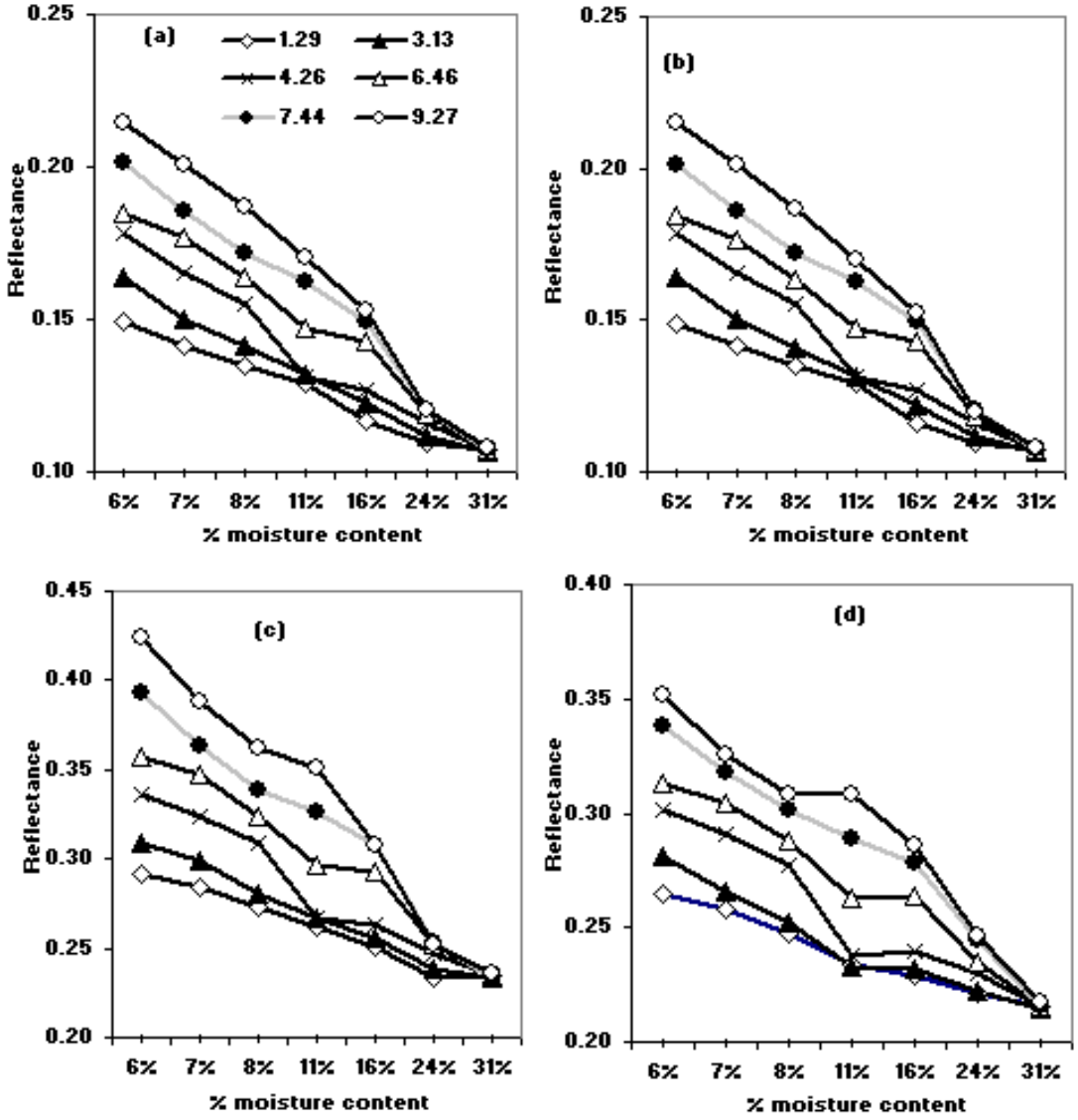

Figure 17: Changes in silty loam soil reflectance as affected by soil moisture content under six different soil salinity levels at (a) 650 nm, (b) 1650 nm, and (c) 2130 nm.

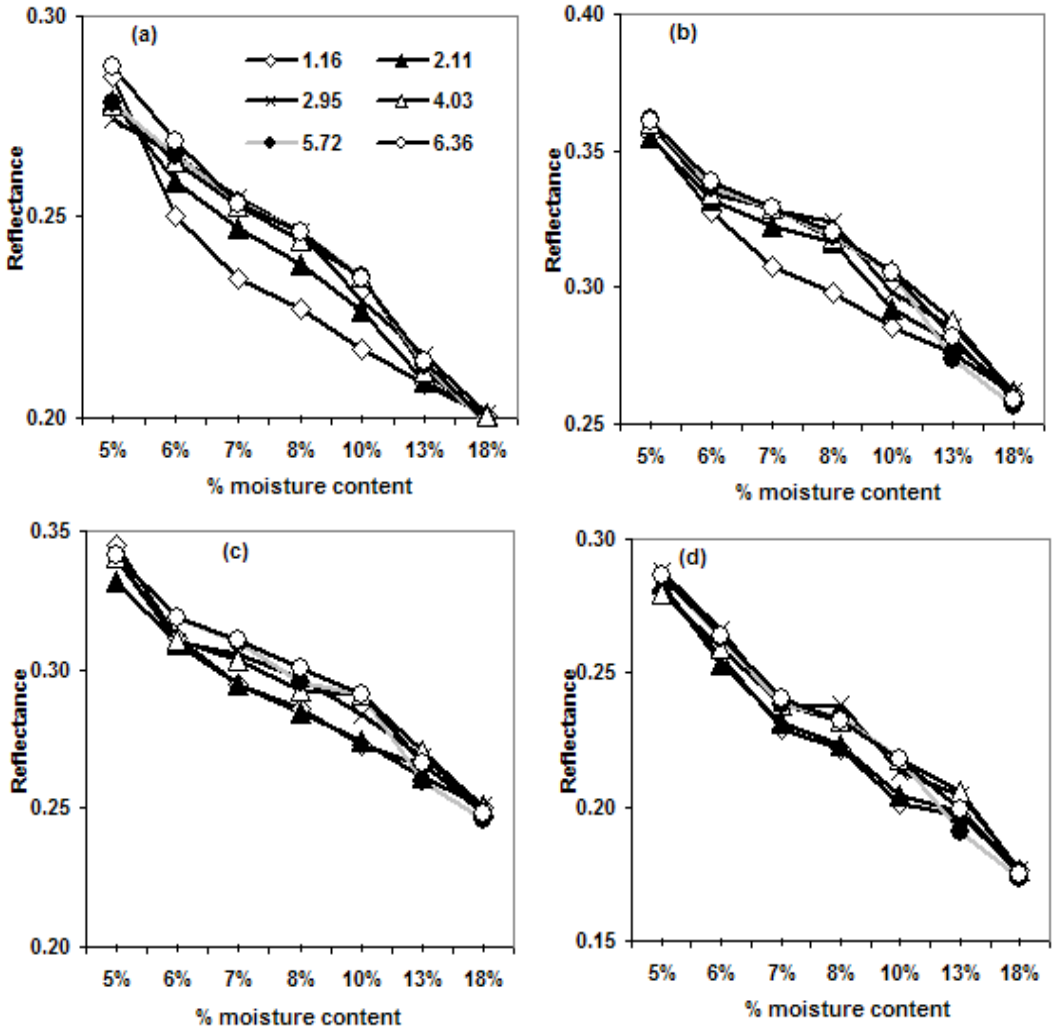

Figure 18: Changes in sandy loam soil reflectance as affected by soil moisture content under six different soil salinity levels at (a) 650 nm, (b) 1650 nm, and (c) 2130 nm.

APPENDIX B

STUDYING THE RESPONSE OF LETTUCE PLANTS TO SOIL SALINITY STRESS USING REFLECTANCE SPECTROMETRY

I. INTRODUCTION

Salinity is one of the most important environmental factors limiting crop production of agricultural soils in many parts of the world. Salinity effects on plants include ion toxicity, osmotic stress, mineral deficiencies, physiological and biochemical perturbations, and combinations of these stresses (Munns, 1993, 2002; Yeo, 1998; Hasegawa *et al*., 2000).

One-third of the land being irrigated worldwide is affected by salinity, but salinity also occurs in non-irrigated land (Allen *et al*., 1994). In agricultural fields, the salt levels fluctuate seasonally and spatially, and variation will occur due to the circumstances influencing each particular plant. This variability makes research difficult. The uptake of ground water by plant roots can increase the salinity of ground water or the soil around the roots due to the exclusion of salt (Niknam and McComb, 2000). On the other hand, it has been found that excess soluble salts in the root zone restrict plant roots from withdrawing water from the surrounding soil, effectively reducing the plant available water (Bauder, 2001; Bauder and Brock, 2001; Hanson *et al*., 1999; USDA, Natural Resources Conservation Service, 2002). Basically, water is both held tighter to the soil in saline environments and is also less available for plant uptake due to osmotic forces. This leads to reduced water uptake and increased plant stress.

Sustainable agricultural progress in regions with current or potential salinity problems implies the development of appropriate techniques for the prediction, detection and monitoring of salinization processes and their impact on vegetation from global to local scales (Menenti and Chanduvi, 1998).

Scattered vegetation or a lack of vegetation on highly salt affected soil surface makes it possible to directly detect salts on surface. Improvements are necessary in the detection and mapping of moderate salinity, and on the effects of salinity on vegetation (Mougenot *et al*., 1993). One possible alternative to the direct salinity measurement is to use plant responses to saline environments as an index of soil salinity. It is suggested that plant responses may provide a more comprehensive assessment of salinity because plant roots generally penetrate deep in the soil profile and measurements of growth characteristics at one point in time integrate the cumulative effect of substrate salinity. Remote sensing of the plant canopy is particularly useful in this respect. For example, Penuelas *et al.* (1997) found that canopy reflectance of barley was lower in the near infrared (NIR) and higher in the visible spectrum region with increasing salinity. To characterize salinity effects on cotton, Wiegand *et al*. (1992) found that the yield and plant cover were correlated to vegetation indices derived from remote sensing measurements using either multispectral video images or reflectance data from the SPOT satellite.

Relating salinity-induced canopy reflectance characteristics to plant biophysical and biochemical properties, which are also sensitive to salinity stress, consider a more mechanistic approach of applying remote sensing to determine salinity effects on plant

growth or eventual salinity assessment. One of the primary biochemical parameters that affect canopy reflectance in the visible domain is the concentration and total amount of leaf chlorophyll. Salinity has been shown to have some decreasing effects on leaf chlorophyll content of chickpea (Datta and Sharma 1990), and sunflower (Santos, 2004).

Remote sensing studies have also been conducted on developing algorithms of using vegetation indices to infer plant chlorophyll content (Chappelle *et al*. 1992, Gitelson and Merzlyak 1997, Blackburn 1998 and Barnes *et al*., 2000). However, no information can be found in the literature on interrelations between salinity, canopy reflectance, and leaf chlorophyll.

Lettuce plants were used in this research. It is considered a moderately tolerant species to soil salinity (United States Salinity Laboratory Staff, 1954).

II. REVIEW OF LITERATURE

A. Plant tolerant mechanisms under salt stress

All plants are subjected to a multitude of stresses throughout their life cycle. Depending on the species of plant and the source of the stress, the plant will respond in different ways. When a certain tolerance level is reached, the plant will eventually die. When the plants in question are crop plants, then a problem arises. The two major environmental factors that currently reduce plant productivity are drought and salinity (Serrano, 1999), and these stresses cause similar reactions in plants due to water stress. These environmental concerns affect plants more than is commonly thought.

The response of plants to salt stress is based on the transcriptional action of many defense proteins, and research has not discovered the basis for them all (Serrano, 1999). Osmotic stress and ion toxicity are the problems stemming from salt stress, and the resulting decrease in chemical activity causes cells to lose turgor (Serrano *et al*., 1999). Cell growth depends on turgor to stretch the cell walls, and lack of turgor implies danger for cell survival. The plant's defense against this salinity attack requires osmotic adjustment, and, to a certain degree, this can be done through synthesis of intracellular solutes (Serrano *et al*., 1999). Salinity creates the specific problem of ion toxicity, because a high concentration of sodium is bad for the cells. High salt concentrations inhibit enzymes by impeding the balance of forces controlling the protein structure (Serrano *et al*., 1999). The toxic effects of salt can occur at relatively low concentrations, depending on the plant species, so the homeostasis of sodium is important for the

tolerance of organisms to salt stress. The stress caused by ion concentrations allows the water gradient to decrease, making it more difficult for water and nutrients to move through the root membrane (Volkmar *et al*., 1998). In turn, the water uptake slows, and as the osmotic effect spreads from the root membrane to the internal membranes, the ion concentration inside the plant alters the solute balances (Volkmar *et al*., 1998). Once high concentrations of salt have reached the inside of the plant, tissue and organs development is altered. The salt causes a slower rate or shorter duration of expansion of cells and this compromises the size of the leaves (Volkmar *et al*., 1998). The overall effect of salinity on plants is the eventual shrinkage of leaf size, which leads to death of the leaf, and finally the plant. Salinity may also cause reduced ATP and growth regulators in plants (Allen *et al*., 1994).

There is a wide spectrum of salinity tolerance among higher plants (Robinson *et al*., 1997), but there is also variability in salt tolerance occurring in plants with lower salt tolerance, suggesting that there is the potential for improvements to be made in these plants (Allen *et al*., 1994).

Lettuce is a vegetable of intermediate salt tolerance (Resh, 1995). A study done on the effects of salinity and lettuce growth reported that lettuce was more sensitive to tip burn and growth stunting after exposure to saline water (Pascale 1995). Further studies have revealed a reduction in overall seedling and vegetative growth when spinach and lettuce were exposed to high salinity levels (Kaya 2002).

B. Plant spectral properties and soil salinity

Both the optical properties of leaves and soil background affect the spectral reflectance of vegetation canopies. Variations in soil salt concentration induce changes in plant characteristics, which are expected to be spectrally evident in the region between 350 and 2500 nm.

Relatively little incident visible radiation (350–700nm) is reflected or transmitted in healthy green leaves due to absorption by chlorophyll and other leaf pigments. Changes in leaf reflectance in the visible portion of the spectrum indicate pigment development such as chloroplasts, developed concurrently with mesophyll cell enlargement (Leech 1985).

Plant reflectance in the near infrared (NIR) region (700 – 1300 nm) is relatively high and strongly influenced by cellular structure and refractive index discontinuity within the leaves (Gausman, 1985). Absorption by water is quite weak between 700 and 1300 nm, however, two minor water absorption bands are present near 970 and 1200 nm, the shape and depth of which have been related to hydration state of leaves (Gausman, 1985).

Water concentration in the tissues consider an important factor affecting the canopy reflectance in the short wave infrared (SWIR) region (1300–2500nm) (Tucker, 1980; Gausman, 1985), although leaf cell structure, morphology and tissue constituents also influence reflectance in this region (Wessman *et al.*, 1988). In particular, the wavelengths at 1530 and 1720 nm seem to be most appropriate for assessing vegetation water (Fourty and Baret, 1997), but water also significantly absorbs in the intermediate

regions between them. Therefore, when water is lost from leaves, absorption decreases and reflectance tends to increase in the entire 1300 – 2500 nm region.

Plants under salinity stress frequently show symptoms of water deficit, especially under conditions of high evaporative demand (Blum, 1988). As previously mentioned, leaf/canopy water content can be directly determined (and then related to salinity status) by looking at the specific spectral absorption bands of the water molecule in the NIR and SWIR. The SWIR region responds to both vegetation water content and soil surface moisture, the weaker 1240 nm, water absorbing region has been shown to respond to canopy moisture status only and be insensitive to surface soil moisture. The Normalized Difference Water Index (NDWI) uses two reflectance bands in the high NIR reflectance plateau of vegetation canopies, at 860 nm and 1240 nm wavelengths (Gao 1996), NDWI = (ρ860nm – ρ1240 nm) / (ρ860nm + ρ1240nm). Penuelas *et al* (1997) observed that the ratio between the reflectance at 970 nm and the reflectance at a reference wavelength, 900 nm, where there is no absorption by water concentration but that is affected in the same way with respect to sample structure, was increased in response to increasing salinity and was thus related to crop water status response to salinity. They called this ratio the water band index (WBI = ρ900nm/ρ970nm). Also as the short wave infrared (SWIR) spectral band is sensitive to vegetation water content and soil moisture, a combination of NIR and SWIR bands have been used to derive water sensitive vegetation indices (Ceccato *et al*., 2001, 2002a,b; Xiao *et al*., 2004). Another water index was calculated as the normalized difference between the NIR (0.78–0.89 μm) and SWIR (1.58–1.75 μm) spectral bands, here it is called ‘‘Land Surface Water Index (LSWI)’’

(Xiao *et al*., 2002, 2004), LSWI = (ρ860nm – ρ2130 nm) / (ρ860nm + ρ2130nm) or (ρ860nm – ρ1640 nm) / (ρ860nm + ρ1640nm). As leaf liquid water content increases or soil moisture increases, SWIR absorption increases and SWIR reflectance decreases, resulting in an increase of LSWI value.

Spectral vegetation indices are linear combinations and/or ratios of spectral bands designed to enhance the vegetation signal of spectral measurements. Significant relationships have been found between these indices and green biomass (Baret and Guyot, 1991). NDVI [Normalized Difference Vegetation Index] [(ρ_{NIR} - ρ_R) / (ρ_{NIR} + ρ_R)] is one of the most frequently applied vegetation indices. Relationships between NDVI and biomass production under different salinity levels in barley field trials were investigated by Penuelas *et al*. (1997). They observed that, in low salinity plots, VIS reflectance decreased and NIR reflectance (and therefore NDVI) increased with increasing biomass. The one used in this research was the soil adjusted vegetation index (SAVI). Huete (1988) proposed the Soil-Adjusted Vegetation Index (SAVI) to minimize the effects of soil background on the quantification of greenness by incorporating a soil adjustment factor (L) in the basic NDVI equation. This factor is determined by the relative percentage of vegetation and whether the soil is light or dark; L is added to the denominator and L+1 is multiplied by the numerator. For Huete's (1988) study, L was given a value of 1.0 for emergent crops, 0.5 for the intermediate stage, and 0.25 for the final, pre-tassel stage:

$$SAVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED} + L}(1 + L)$$

Where:

- ρ_{NIR} = Reflectance in the near infrared
- ρ_{RED} = Reflectance in the red band

L = Soil constant and equals 0.5 as an average value for most soils.

Many problems of quantitative analysis may be tackled in a more effective way than vegetation indices, using the technique of derivatives. The derivative of a spectrum is its rate of change with respect to wavelength. In remote sensing, the first derivative has mostly been used so far to facilitate the location of critical wavelengths such as the "red edge", corresponding to the wavelengths between 690 and 740 nm in the reflectance spectra. Characteristics of leaf reflectance spectra are determined by the surface properties of the leaf, as well as internal structure and biochemical components. One example of this is the distinctive ''red edge,'' which occurs as a sharp increase in reflectance around 700 nm. The red edge exists because of the strong chlorophyll absorption band centered around 670–680 nm, coupled with scattering of near-infrared reflectance within the leaf, which causes large reflectance above 700 nm (Curran *et al*, 1990; Gitelson and Merzlyak, 1996).

The red edge may shift to shorter wavelengths under stress or senescence as a product of decreases in chlorophyll (Curran *et al*, 1990) or may shift to longer wavelengths due to the increasing in chlorophyll concentration, which leads to stronger chlorophyll absorption often referred to as "red-shift" (Horler *et al*, 1983; Curran *et al*, 1995). Many studies demonstrated the influence of chlorophyll concentration on the REP

(Filella and Penuelas, 1994). Taking all this into account, the “red-edge” position is expected to be a good indicator of the impact of soil salinity on crop conditions.

The overall objectives of this study were to assess plant biophysical response to moderate salinity levels with canopy-level reflectance data.; study the relationship among reflectance, chlorophyll concentration and biomass production under different salinity levels using an experiment performed on lettuce plants and to investigate the ability of combined spectral indices to improve salinity stress detection. Relationships between canopy characteristics (biomass and chlorophyll concentration) and spectral parameters (SAVI, WBI, NDWI, LSWI and REP) were analyzed. The significance of observed changes in spectral variables was then evaluated with respect to soil salinity.

III. MATERIALS AND METHODS

A. Experimental setup

The experiment was carried out inside the greenhouse in the Environmental Research Lab (ERL), University of Arizona. On August, 16th, 2003 lettuce were planted in pots (diameter = 25 cm and height = 25 cm) filled with 15 kg of alluvial silty clay loam soil.. Table (1) and Figure (1) show the chemical and optical properties of this soil. Two healthy lettuce (*Bibb*) seedlings, 4 weeks old and of uniform height per pot were used for this experiment (Figure 2).

The pots with lettuce plants were kept in the greenhouse according to a completely randomized design with four replicates. Four treatments were considered for the experiment: 1) control treatment (S_0) irrigated with fresh water (EC_w =0.4 dS m^{-1}); 2) saline treatment ($S_{0.1}$) irrigated with a saline solution (EC_w =1.41 dS m^{-1}) obtained by adding 0.1% sodium chloride salt (NaCl) to irrigation water, 3) saline treatment ($S_{0.25}$) irrigated with saline solution (EC_w =3.9 dS m^{-1}) obtained by adding 0.25% sodium chloride salt (NaCl) to irrigation water and 4) saline treatment ($S_{0.5}$) irrigated with saline solution (EC_w = 7.8 dS m^{-1}) obtained by adding 0.5% sodium chloride salt (NaCl) to irrigation water. Irrigation water was applied twice a week. Irrigation solutions were applied to maintain field capacity of the soil. The amount of irrigation water varied between 3.24 to 3.86 liters per pot per week. On average a total of 3.5 l of solution per irrigation per pot was applied using graduated beaker along one side of the pot as a surface irrigation. The irrigation water did not have any direct contact with plant leaves at the irrigation time.

B. Measurements

1. Reflectance measurement

Spectral measurements were made biweekly, one measurement every other week, from 1030 to 1230 MST on clear cloud-free days. The measurements were started after 2 weeks of transplanting (DOY 245). The reflectance spectrum of each pot was recorded over the 350-2500 nm region in 10nm nominal wavelengths, 1 nm increments, using a Full Range Analytical Spectrum Device (FR-ASD) instrument with 8° field of view. All spectral measurements were made with the ASD pointed vertically downward (nadir) from 0.5-m height. Plant components filled the instrument's field of view. For each pot, triplicate readings were made, preceded by and followed by a spectral response reading from a Spectralon white panel. The three reflectance measurements recorded at each time were averaged in order to reduce high frequency instrument noise. The measurements were made while the soil was dry just before applying the irrigation treatments.

2. Soil and vegetation measurements

On the last day of the spectral measurements, November, 6th, 2003 (DOY 310), the above ground plants were harvested for the determination of chlorophyll content fresh weight and dry biomass. Three leaves for each plant were used to determine the total chlorophyll content; leaves were enclosed in polyethylene bags immediately after cutting, and then refrigerated with ice for transport for the laboratory. The chlorophyll was extracted by grinding the plant leaves in 80% acetone followed by centrifugation. The chlorophyll concentrations were determined by measuring absorbance at 652 nm (Arnon, 1949). The chlorophyll concentration was defined as follows: chlorophyll concentration

(milligram per gram of fresh tissue) = (OD_{652}/36) x Ve (milliliters)/W (grams), with OD_{652} being the absorbance of chlorophyll at 652 nm, Ve being the volume of the extraction solution, and W being the fresh weight of tissue. For each measurement, four samples were prepared and the mean of their chlorophyll concentration was determined. The above ground part of each plant was dried in the oven at 105°C, and then weighted to determine the dry biomass.

Soil samples were collected at the end of experiment in 16 different pots irrigated with water at different salt concentrations. The treatments were the S_0, $S_{0.1}$, $S_{0.25}$ and $S_{0.5}$ described above. Four replications were done for each treatment. For each soil sample, electrical conductivity (EC) was measured on saturated soil past extract using a laboratory EC-meter (Rhoades, 1982).

IV. RESULTS

Figure (3) shows the effect of soil salinity on the above ground dry biomass of lettuce plants at the end of experiment. Soil salinity, measured by EC, had a clear impact on crop growth (R^2 =0.96). Other investigators have reported similar findings, with various bean cultivars and a number of other crops (Pessarakli and Huber, 1991; Al-Rawahy *et al*., 1992 Cachorro *et al*., 1994). The decreasing response of dry weight to increasing salinity stress may be attributed to decreased leaves number. Figure (4) demonstrates the effect of the four studied salinity treatments on the lettuce leaf number during the whole study period. The leaves number increased with time progress under the different treatments and up to the end of experiment. The salinity stress started to affect the leaf number after DOY 277. The differences between treatments were not significant before DOY 277 (Table 2). On the other hand, after DOY 277 the negative effect of salinity on leaves number increased significantly with time progress.

Figure (5) demonstrates the effect of soil EC on the total chlorophyll concentration of lettuce plants treated with different salinity levels. The figure shows that increasing soil salinity, represented as EC, decreases the total plant chlorophyll content with the highest sensitivity observed between 1.6 and 3 dS/m; that is changes of chlorophyll content were big at low EC and smaller at higher EC values. Photosynthetic capacity of many plant species is reduced in the presence of salinity which is associated with stomatal closure. Salinity can seriously change the leaf-chlorophyll concentration, as well as photosynthetic efficiency (Seemann and Critchley, 1985). The induced decrease

of chlorophyll content in NaCl stressed plants is mainly due to limitations of chlorophyll synthesis (Santos, 2004).

The relationship between soil salinity and the percent of water content, [(Fresh weight – dry weight)/fresh weight] * 100, is shown in figure (6). The general trend of this relationship was similar to the relationship between chlorophyll concentration and soil salinity showed in figure (5). The highest sensitivity was found between EC values 1.6 and 3 dS/m. the sensitivity decreased force values above 3 dS/m.

Figure (7) shows the effect of increasing irrigation water salinity level on the dry biomass and the chlorophyll concentration of the lettuce plants. Both dry biomass and total chlorophyll concentration declined with increasing NaCl concentrations in the irrigation solution. The highest salinity treatment 0.5% induced 67% and 55.6% decrease, compared with control treatment, in dry biomass and total chlorophyll content respectively.

These data shows that soil salinity had a clear impact on the lettuce plants, it remains to be demonstrated whether measurements of reflectance spectra can be used to detect and monitor the impact of moderate soil salinity on the plants.

At the end of the experiment differences in reflectance spectra (Figure 8) and in their first derivative (Figure 9) were evident among the four irrigation treatments. During the growing cycle, these differences become progressively significant and were reflected in the spectral indicators derived from reflectance spectra; SAVI, red edge position (REP) and water indices. Figure (8) shows that irrigation water salinity is associated with both increased reflectance in the reflected red spectral region, and decreased reflectance in the

reflected NIR spectral region. These effects could be attributed to the effect of salinity on plant chlorophyll content. Accumulation of excess Na^+ may cause metabolic disturbances in processes where low Na^+ and high K^+ or Ca^{2+} are required for optimum function (Marschner 1995). Chlorophyll breakdown is associated with increased Na^+ concentrations (Krishnamurthy *et al*. 1987). High concentrations of Cl^- in leaf tissue may disrupt photosynthetic function through the inhibition of nitrate reductase activity (Xu *et al*. 2000).

As previously stated the 'red edge position', REP, can be obtained from the first derivative of the reflectance spectrum and could be used as an indicator of plant stress. Figure (9) shows that increase the irrigation water salinity resulted in shifting in the REP, for the lettuce plants, towards the shorter wavelengths. Increasing the irrigation water salinity from 0, 0.1, 0.25 then 0.5% moved the REP from 720, 715, 712 then 710 nm respectively. This means that there is a negative relationship between the REP and salinity stress level. This figure also shows that the amplitude of the first derivative (FD amplitude) was affected by salinity treatments. Increasing the applied water salinity from 0 to 0.5% decreased the amplitude from 0.012 to 0.0038.

Figure (10) demonstrates the relationship between the above ground dry biomass of lettuce plants, grown under different salinity levels, and SAVI values. It is evident that there is a slightly non-linear relationship exists between the SAVI and lettuce dry biomass. The decrease of biomass in the lettuce plants under salinity stress (Figure 3) resulted in a decrease of SAVI (R^2 =0.93). The best fitting function between SAVI and biomass was ln function.

The relationship between the chlorophyll concentration and SAVI is shown in figure (11). The relationship between the plant chlorophyll concentration and SAVI was similar to the relationship found between dry biomass and SAVI. The best fitting function was ln with R^2 value 0.9.

As expected, a positive linear relationship was found between the red edge position (REP) and chlorophyll content of lettuce plants (R^2 =0.92) as shown in figure (12). Salinity stress, which results in lower overall leaf chlorophyll concentration, causes increasing reflectance in the entire visible region and narrowing of the main chlorophyll absorption band (680 nm) in the red region (Wang *et al,* 2000).

Figure (13) shows the effect of increasing irrigation water salinity levels on SAVI, REP averages and the amplitude of the first derivative during the whole study period. Increasing the applied salinity level decreased SAVI REP and FD amplitude values. The three spectral indices were decreased by increasing salinity stress. The decreasing trend for both REP and FD amplitude were logarithmic decrease with R^2 vales 0.95 and 0.96 respectively. Conversely, SAVI decreased linearly with increasing salinity stress (R^2 = 0.97).

Figure (14) illustrates the trend of SAVI with time progress under the four studied salinity treatments. Under control treatment (S_0), SAVI increased with time progress until the end of the experiment (DOY 310). On the other hand, SAVI decreased with time in plants irrigated with 0.1 % ($S_{0.1}$), 0.25% ($S_{0.25}$) or 0.5% ($S_{0.5}$) NaCl saline solution. The higher salt treatment ($S_{0.5}$) had the worst effect on SAVI compared with the other two treatments ($S_{0.1}$ and $S_{0.25}$). Consequently, the differences between the SAVI mean values

under these 4 different treatments also increased and become significant from the sixth week of treatment applications (DOY= 277) towards the end of the growing cycle (Table 3).

The trend of the red edge peak position (REP) mean values showed a clear tendency to move increasingly with time towards the shorter wavelengths in $S_{0.1}$, $S_{0.25}$ and $S_{0.5}$ treatments (Figure 15). Differences between REP men values for salt treated plants ($S_{0.1}$, $S_{0.25}$ and $S_{0.5}$) and non-treated plants (S_0) increased progressively with time. Statistical analyses shown in table (4) show that no significant differences were observed for the measurements made after two weeks of salinity application (DOY =245). On the other hand, starting from the fourth week (DOY =262) and up to the end of the growing cycle, differences between S_0 and the other treatments become significant.

Figure (16) represents the relationship between the four studied water indices (WBI, NSWI, LSWI_1640 and LSWI_2130) and the lettuce plant water content under the different studied salinity treatments. A positive linear relationships was found between All studied water indices and the plant water content. The R^2 values were very close (0.92, 0.91, 0.91, and 0.89) respectively.

Figure (17) shows the trend of the different water indices (WBI, NDWI, $LSWI_{2130}$ and $LSWI_{1640}$) mean values of the lettuce under the previously mentioned 4 salinity treatments with time progress. The four water indices had the same trend with time progress with different absolute values. The water indices were always higher in plants irrigated with fresh water (S_0 treatment) than in those plants irrigated with any of the other 3 saline treatments ($S_{0.1}$, $S_{0.25}$ and $S_{0.5}$). The indices values increased progressively

with time progress under S_0 and $S_{0.1}$ treatments. On the other hand, the two higher salinity treatments ($S_{0.25}$ and $S_{0.5}$) had an observable impact effect on the water indices with time progress. The NDWI values also did not become positive until DOY 277 (6 week old plants) for the three salinity treatments. Under the fresh water treatment, the NDWI values became positive after DOY 262, which means that this index is limited to a green cover boundary.

Based on the previous results, only the LSWI will be used as a water index along with SAVI and REP to analyze the ability of the combined remote sensing indices for detecting the salinity stress in low to moderately salinity levels using plant responses.

Tables (5 and 6) represent statistical comparison derived from t-test of the land surface water index ($LSWI_{1640,}$ and $LSWI_{2130}$) as affected by the different salinity treatments. No significant differences were observed for the measurements made after two weeks of salinity application (DOY =245) for either $LSWI_{1640}$ or $LSWI_{2130}$. On the other hand, starting from the DOY =262, and up to the end of the growing cycle, differences between S_0 and the other treatments become highly significant. The difference between $S_{0.25}$ and $S_{0.5}$ treatments were not significant till DOY =293. Starting from DOY =293 and up to the end of the growing period the differences were highly significant between these two treatments for both studied LSWI (1640 and 2130).

For comparing purposes figure (18) was created to compare the behavior of the two LSWI and SAVI with time progress under each of the studied salinity treatments. Control (S_0) and $S_{0.1}$ treatments showed a similarity between water indices and SAVI general trend. They increased with time until DOY 293 and started to show consistency

with time progress. On the other hand, under the other two treatments (S0.25 and S0.5) SAVI started to adversely affected earlier than the water indices. SAVI values started to decrease at DOY 277 but both $LSWI_{1640}$ and $LSWI_{2130}$ did not show this tendency to be decreased until DOY 293. That means that the plant water content is affected by salinity stress latter than the plant biomass and chlorophyll concentration do.

Figure (19) shows the relationship between SAVI and REP for the lettuce plants irrigated with four different water salinity treatments; during the whole growing period. A linear relationship was found between SAVI and REP in the same DOY with increasing salinity application (Figure 19a). Both SAVI and REP decreased with increasing salinity application from the control treatment (S_0) to the highest treatment ($S_{0.5}$). The slope of the linear relationships decreased from 80.2 at DOY 245 to 46.63 for DOY 310. Plants irrigated with fresh water had almost constant REP values, around 720 nm, (Figure 19b) at the same time SAVI values for this treatment increased with time advancement. Conversely, increasing salinity from 0.1% to 0.5% resulted in lower SAVI values and also shifted the REP towards the lower wavelengths from 720 to 707 nm. From this figure also we can state that both the salinity increment and the time progress had an adverse effect on the relationship between SAVI and REP.

Figure (20a) represents the SAVI-$LSWI_{1640}$ plot for the lettuce plants under the different salinity treatments. A strong positive linear relationship between SAVI and LSWI was found for control treatment. On the other hand under the $S_{0.1}$ treatment the linear relationship was found till DOY 277 then SAVI values became constant while $LSWI_{1640}$ increased till DOY 310. Under both $S_{0.25}$ and $S_{0.5}$ treatments the relationship

between SAVI and $LSWI_{1640}$ was linear till DOY 277 then a hock shapes show up due to decreasing the SAVI and at the same time decreasing the $LSWI_{1640}$. The same relationship was found when using $LSWI_{2130}$ (Figure 20b).

V. DISCUSSION AND CONCLUSION

Moderate salinity stress levels affected important characteristics of lettuce plants; chlorophyll concentration, dry biomass, water content and leaf number. The negative response of dry weight to increase salinity stress may be attributed to both the decrease of leaf area expansion and leaves number, smaller amounts of radiation intercepted, and hence decreased photosynthesis. High salt concentrations inhibit enzymes by impeding the balance of forces controlling the protein structure. Salinity creates the specific problem of ion toxicity, because a high concentration of specific ions such as chlorine or sodium may have a toxic effect for the plant cells and may stunt or stop their growth (Saskatchewan, 1987). Sodium and chlorine accumulation in leaf tissues can lead to desiccation. Sodium can also reduce protein synthesis and alter hormonal activity. Plant biomass production depends on the accumulation of carbon products through photosynthesis, but elevated salinity can adversely affect photosynthesis (Lee *et al*, 2004).

The changes in plant characteristics reflected on changes in spectral reflectance parameters, indicating the potential of reflectance spectrometry as an indicator of soil salinity. Hyperspectral remote sensing data is increasingly being used to establish relationships between vegetation water absorption features and vegetation physiological status. Spectral retrievals of both chlorophyll and water contents in vegetation canopies better describe plant physiological status and provide opportunities for improved salinity stress analysis.

We found that spectral indices can provide useful information on crop response to soil salinity during the growing season. Significant relationships were found between biomass and SAVI, chlorophyll content and REP as well as plant water content and spectral water indices. The spectral parameters SAVI, REP and LSWI (either 2130 or 1640 nm) were found to be effective in discriminating between plants growing under moderate conditions of soil salinity and a non-saline condition.

The four studied spectral water indices (WBI, NDWI, LSW_{1640}, and $LSWI_{2130}$) were useful to discriminate between plants irrigated with fresh water and those irrigated with saline water, especially after two weeks from transplanting (DOY 262). WBI and NDWI were not useful for discriminating plants irrigated with 0.5% ($S_{0.5}$) and 0.25% ($S_{0.25}$) saline solution. On the other hand, we found that both LSWI could be used to discriminate between the two higher salinity treatments 0.5% ($S_{0.5}$) and 0.25% ($S_{0.25}$).

The vegetation indices SAVI and REP were affected by salinity stress faster than spectral water indices (LSWI_1640 and LSWI_2130) did indicating that applying salinity stress to plants is affecting the chlorophyll concentration and dry biomass more than affecting the plant water content; vegetation indices generally would show decreases in plant growth (or senescence) while water indices would show decreases in plant water content.

In general, the combination between vegetation indices and water indices was found to be useful in improving the ability to discern between plants growing under salinity stress and non-stressed plants.

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Table 1: Soil chemical and physical properties.

	*pH	ECe	ESP	**NO_3-N	PO_4-P	***K	Texture
Unit		dS/m	%	ppm	ppm	ppm	
	7.6	1.4	7.3	24	12	220	Silty clay loam

* pH obtained from 1:1 water extract
** NO3-N and PO4-P from Olsen bicarbonate extracts.
*** K using neutral molar ammonium acetate.

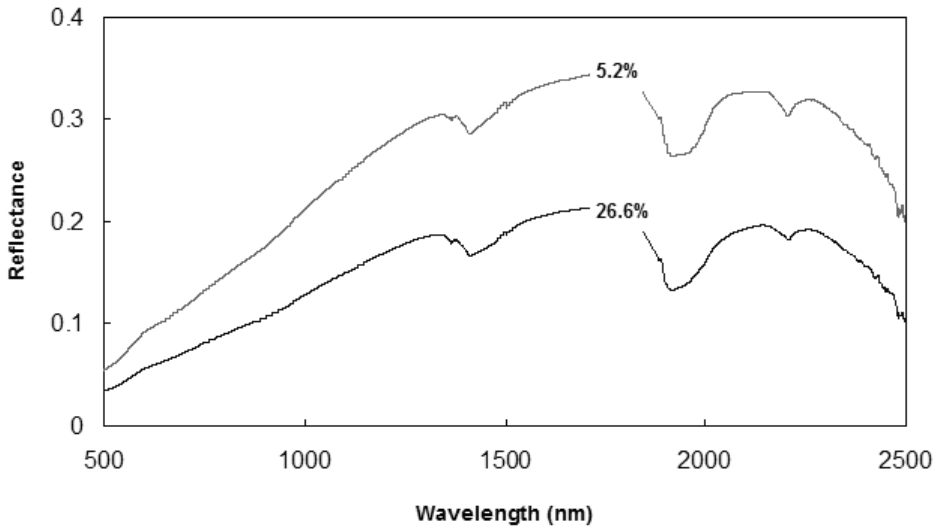

Figure 1: Pre-application optical soil properties.

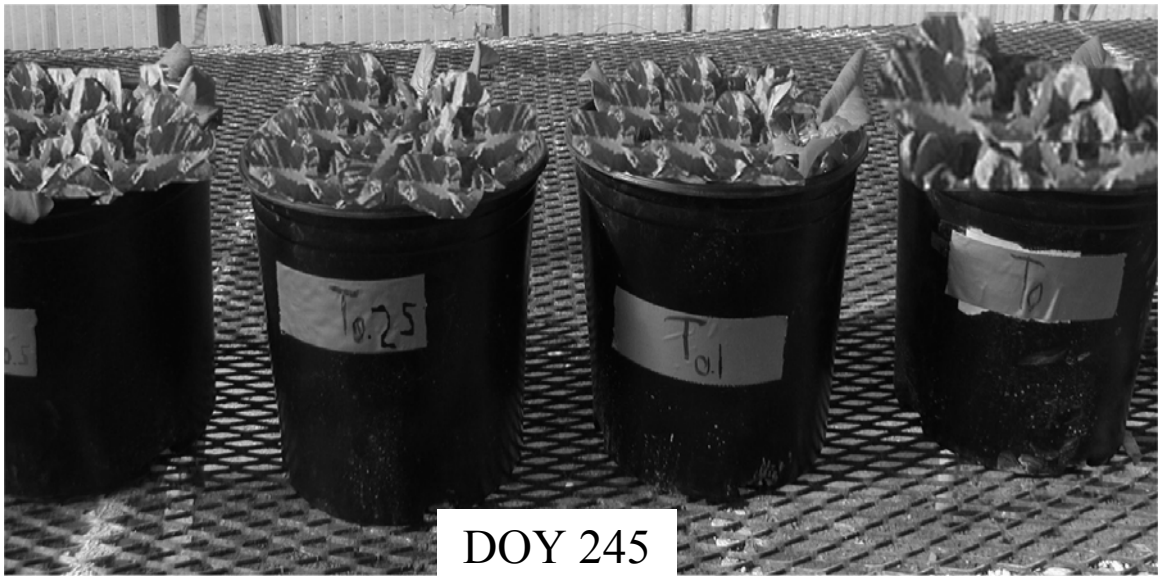

Figure 2: Lettuce plants after transplanting to the pots on DOY 245.

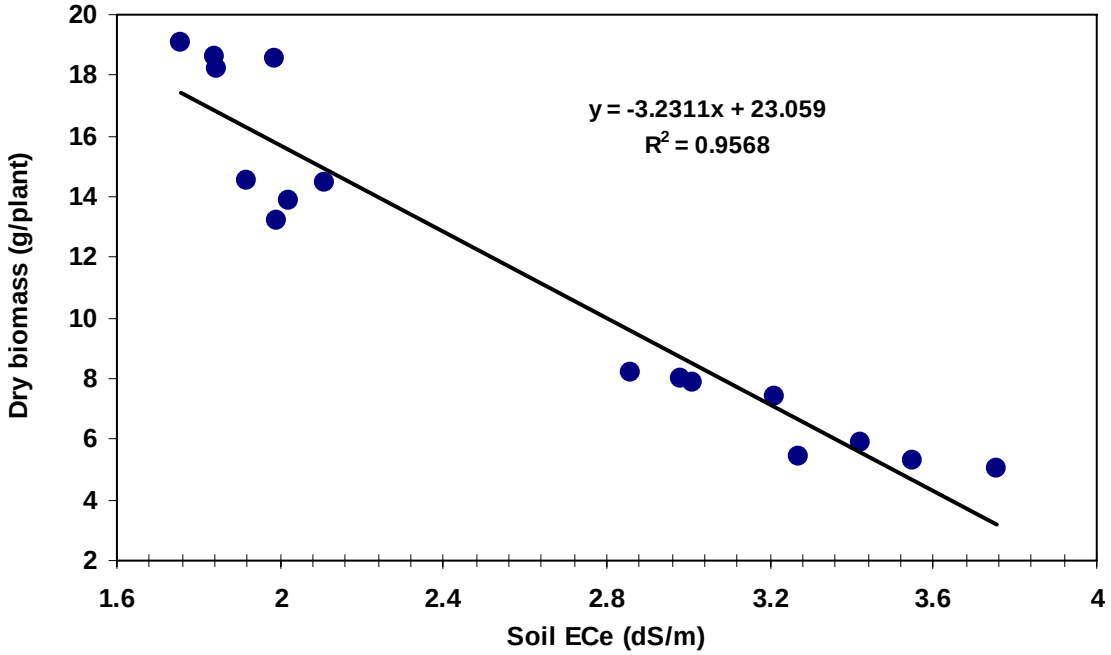

Figure 3: Lettuce above ground dry biomass as affected by soil electrical conductivity (EC).

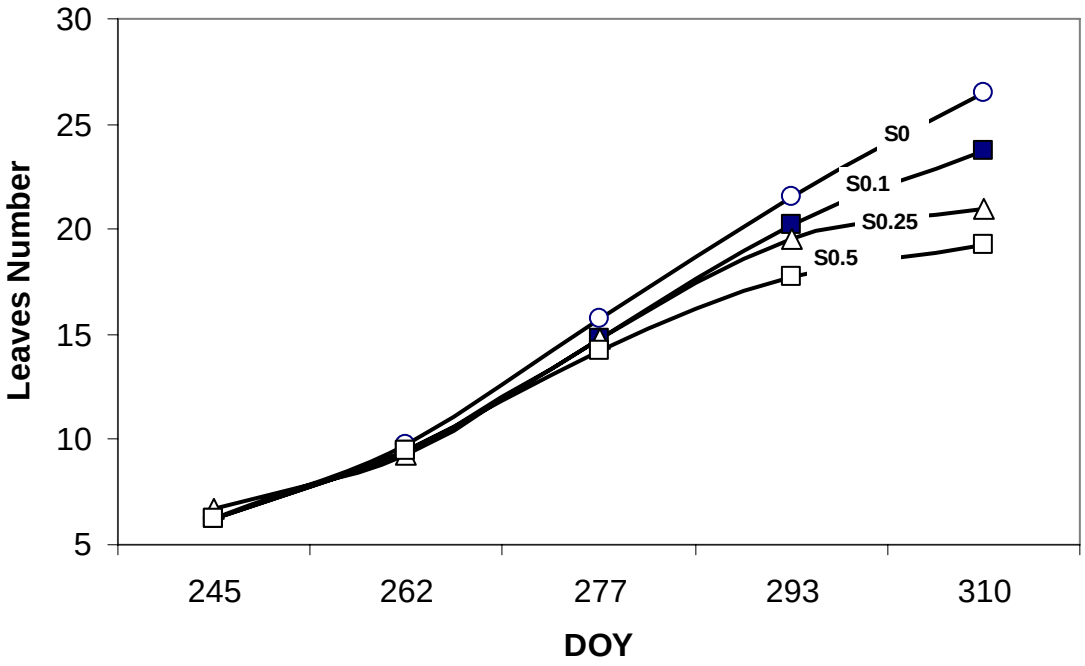

Figure 4: Lettuce leaves number as affected irrigation salinity treatments during the whole study period.

Table 2: Statistical comparison derived from t-test of the lettuce leaves number as affected by the different salinity treatments.

DOY	Statistical comparison											
	S_0 vs. $S_{0.1}$		S_0 vs. $S_{0.25}$		S_0 vs. $S_{0.5}$		$S_{0.1}$ vs. $S_{0.25}$		$S_{0.1}$ vs. $S_{0.5}$		$S_{0.25}$ vs. $S_{0.5}$	
	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.
245	0.010	NS	-1.731	NS	0.011	NS	-1.002	NS	0.001	NS	1.01	NS
262	1.002	NS	1.732	NS	0.522	NS	0.523	NS	-0.001	NS	-0.523	NS
277	1.449	NS	1.414	NS	2.196	NS	0.002	NS	0.775	NS	0.775	NS
293	2.611	*	4.899	**	7.833	**	3.001	*	8.660	**	7.016	**
310	3.667	**	19.053	**	29.01	**	3.005	*	6.971	**	7.011	**

DOY = Day of Year

NS = Not significant
* = Significant at $P < 0.05$
** = Significant at $P < 0.01$

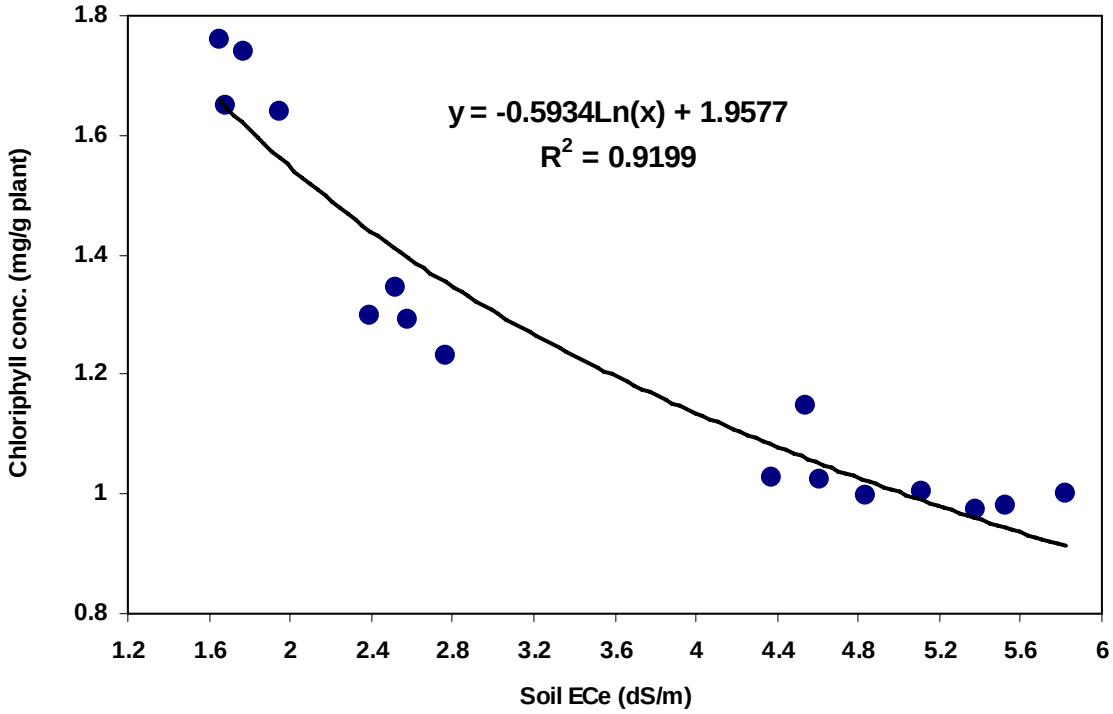

Figure 5: Lettuce chlorophyll content as affected by soil electrical conductivity.

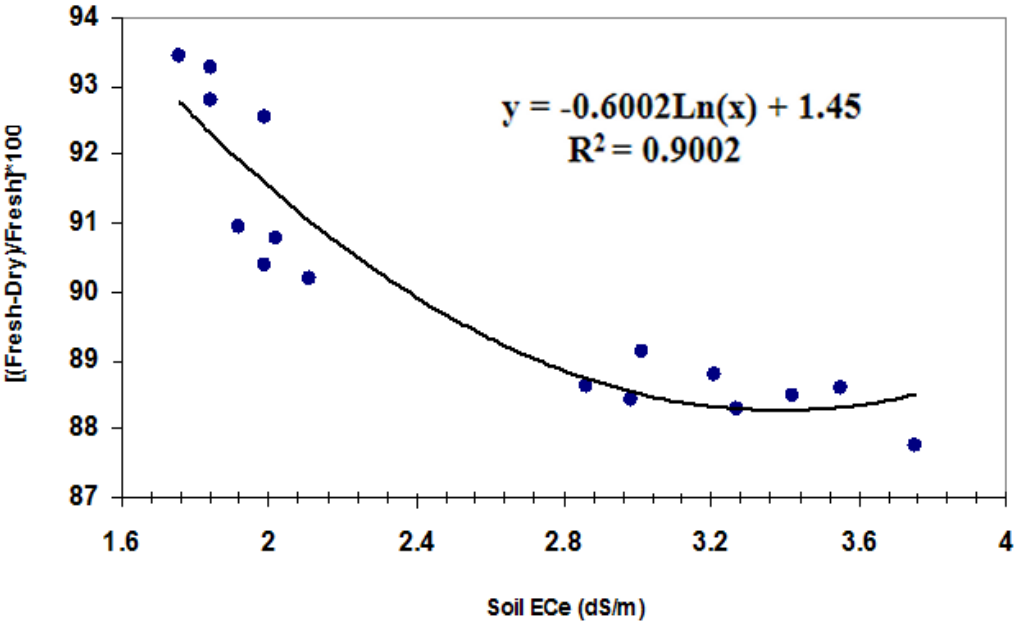

Figure 6: Lettuce water content as affected by soil electrical conductivity (EC).

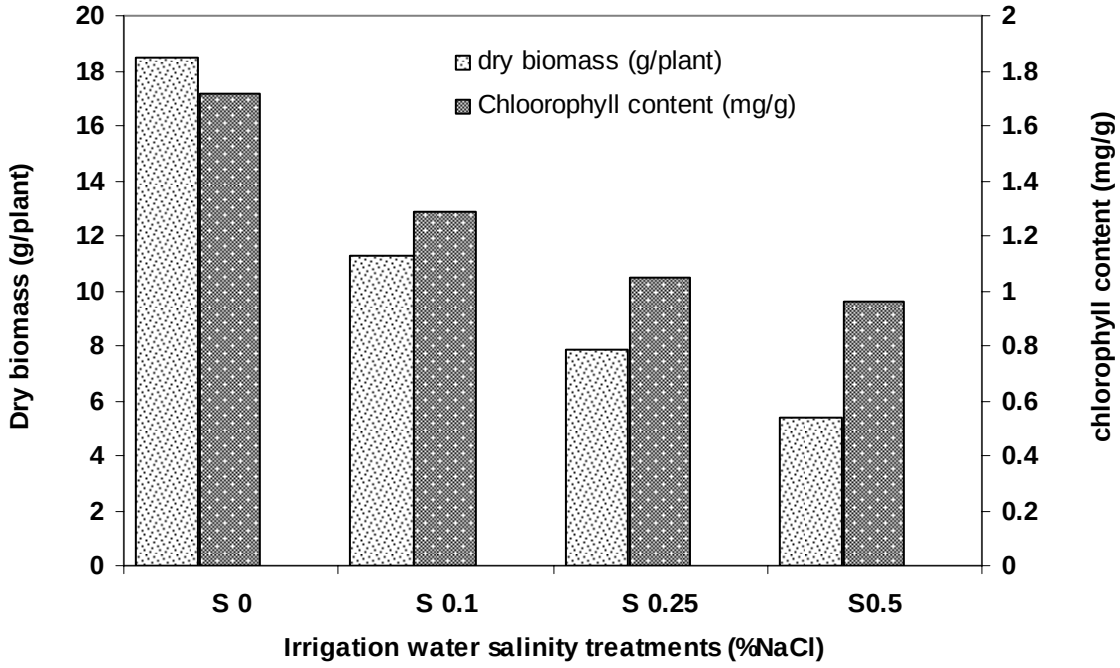

Figure 7: Effects of increasing NaCl concentration in the irrigation solutions on dry biomass and chlorophyll content of lettuce plants growing under four different salinity treatments

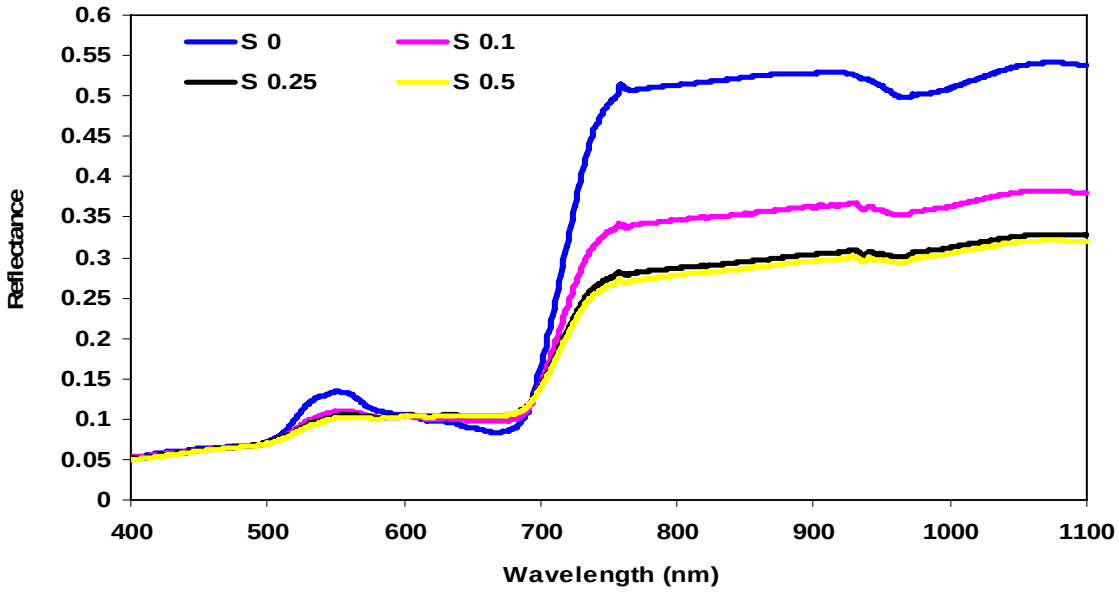

Figure 8: Average spectral reflectance of lettuce plants during the whole growing period (10 weeks) as affected by different salinity stress levels.

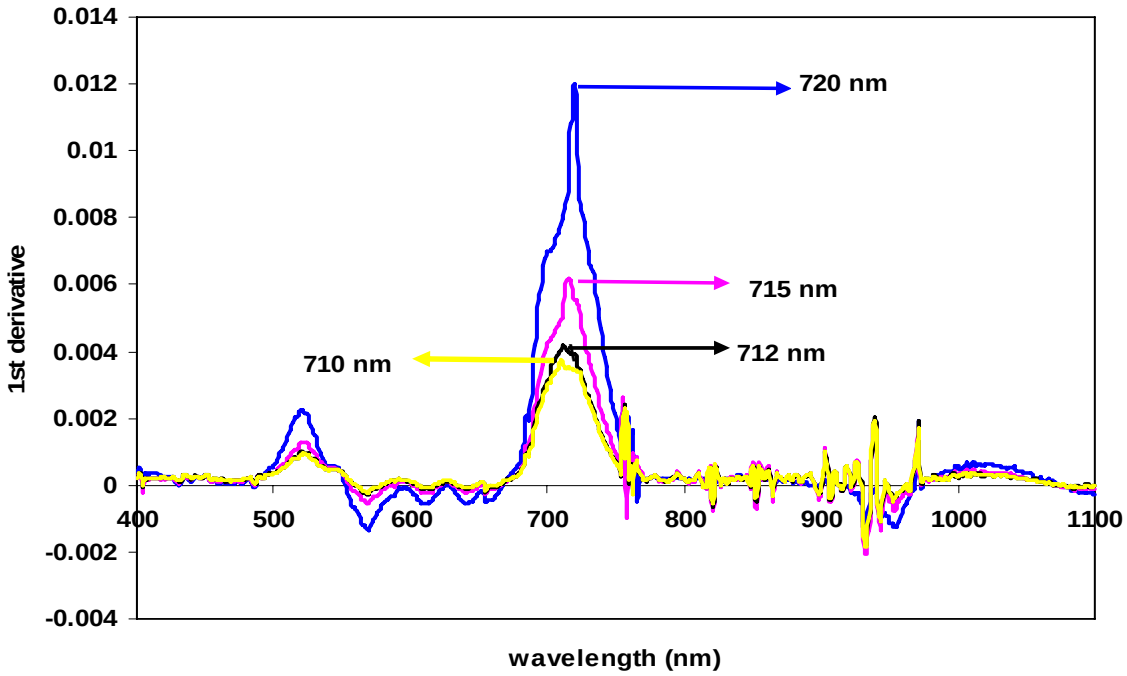

Figure 9: First spectral derivative of lettuce plants for controlled experiment as affected by different salinity stress levels.

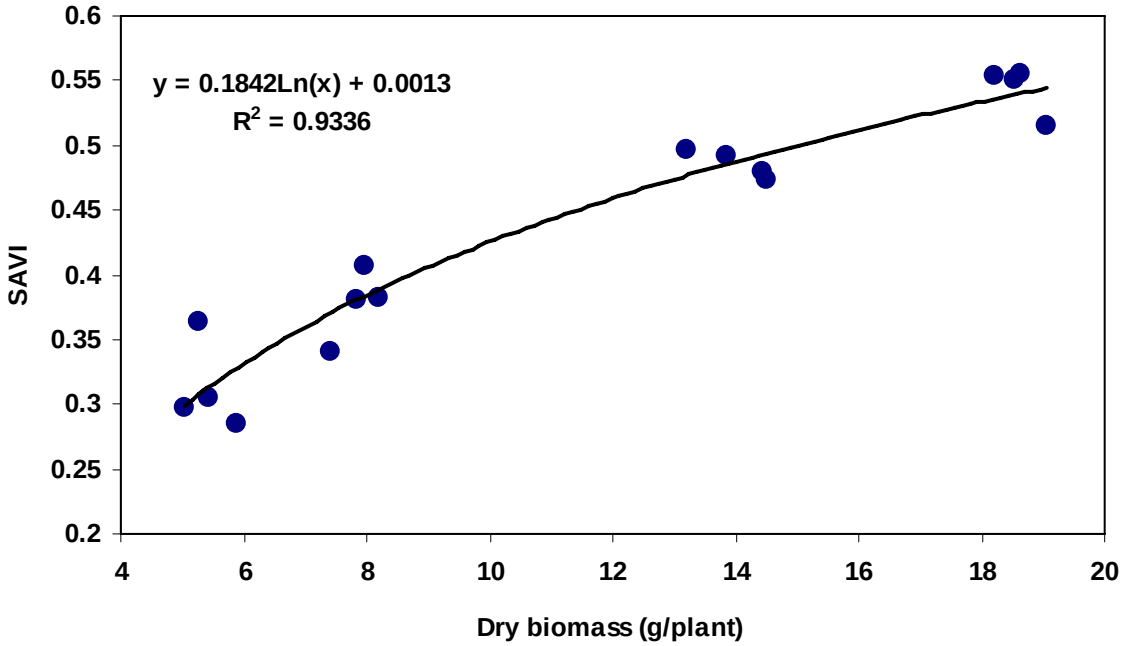

Figure 10: The relationship between soil adjusted vegetation index (SAVI) and above ground dry biomass for lettuce plants growing under different salinity treatments

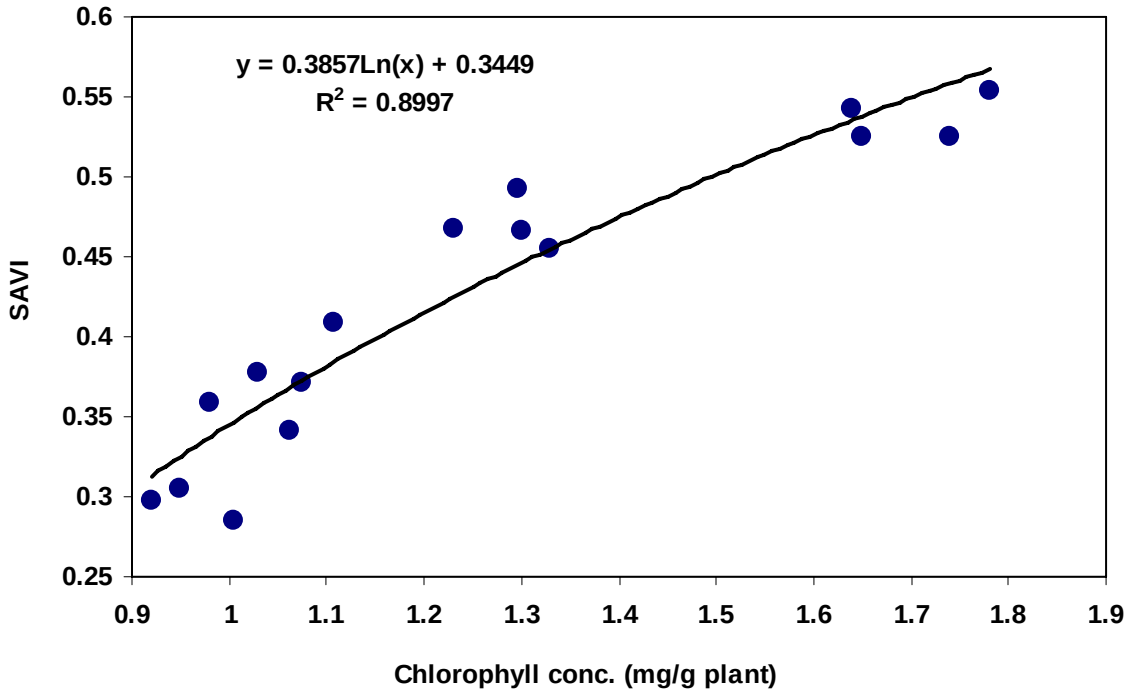

Figure 11: The relationship between soil adjusted vegetation index (SAVI) and chlorophyll concentration for lettuce plants growing under different salinity treatments.

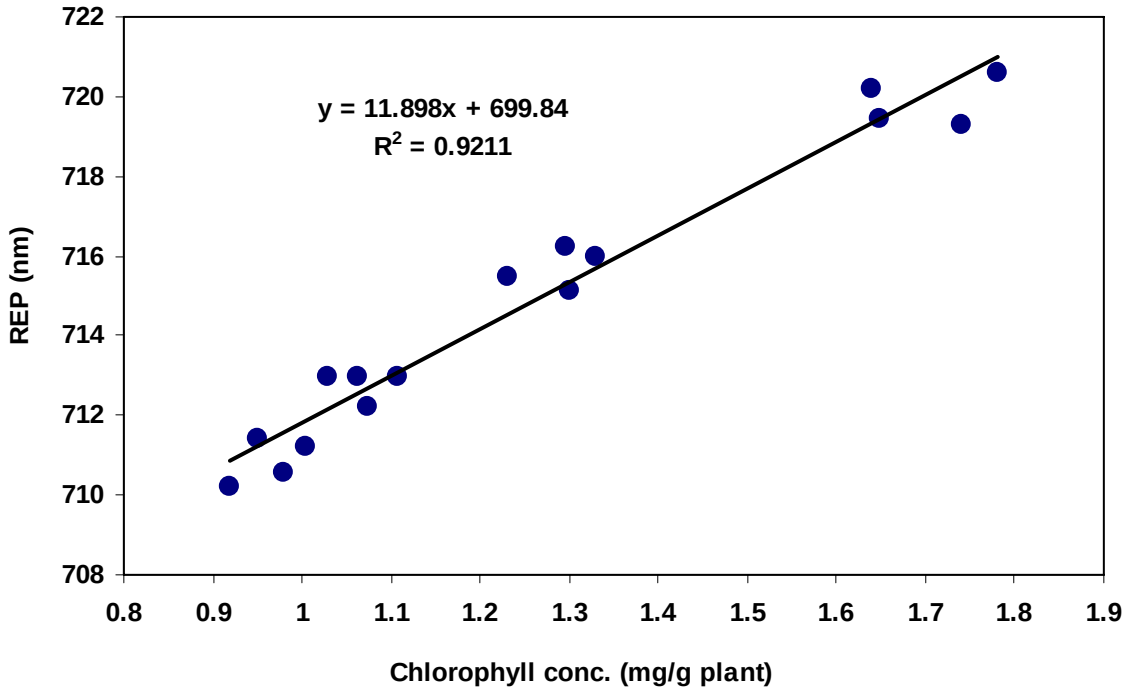

Figure 12: The relationship between the red edge position (REP) and the chlorophyll content for lettuce plants growing under different salinity treatments.

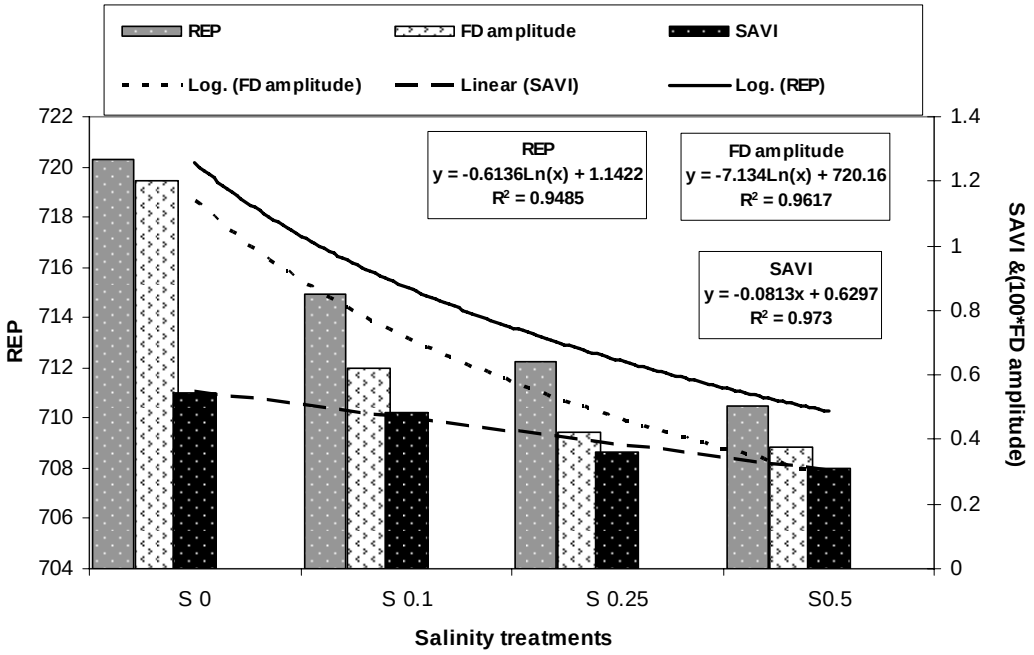

Figure 13: Effects of increasing NaCl concentration in the irrigation solutions on SAVI, REP and the first derivative amplitude (FD amplitude) of lettuce plants growing under four different salinity treatments.

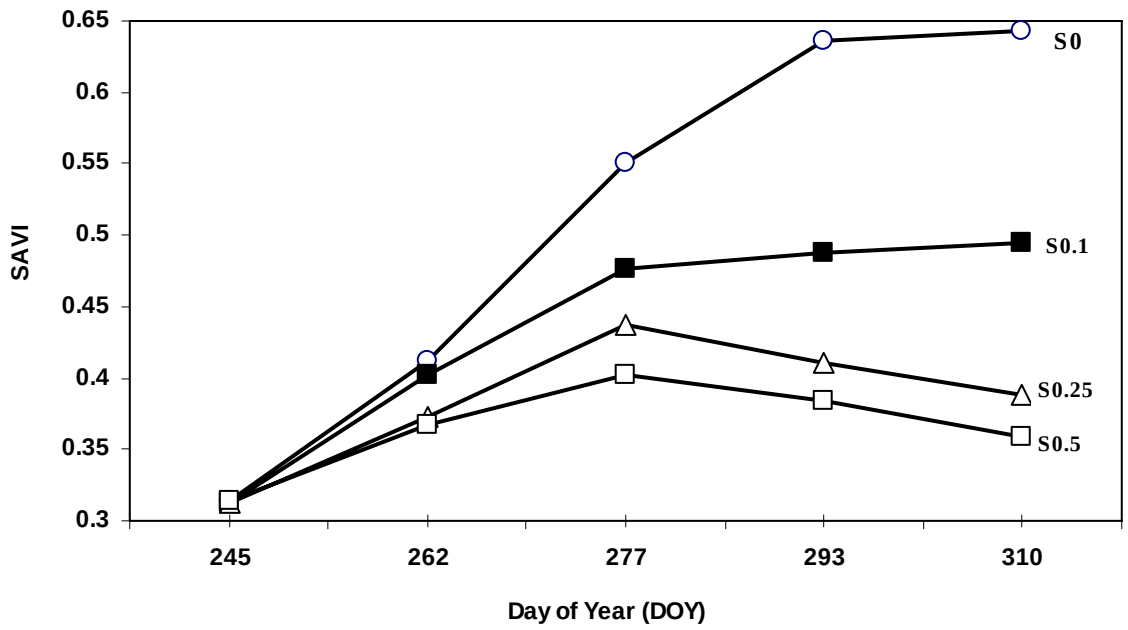

Figure 14: Trends of the mean values of SAVI for lettuce plants grown under four different salinity treatments (S0, S0.1, S0.25 and S0.5) with time progress.

Table (3): Statistical comparison derived from t-test of the normalized difference vegetation index (SAVI) as affected by the different salinity treatments.

DOY	Statistical comparison											
	S_0 vs. $S_{0.1}$		S_0 vs. $S_{0.25}$		S_0 vs. $S_{0.5}$		$S_{0.1}$ vs. $S_{0.25}$		$S_{0.1}$ vs. $S_{0.5}$		$S_{0.25}$ vs. $S_{0.5}$	
	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.
245	-1.246	NS	-0.969	NS	2.220	NS	0.149	NS	-0.274	NS	-0.349	NS
262	0.711	NS	9.310	**	13.968	**	7.604	**	7.525	**	4.983	**
277	2.569	*	8.775	**	3.011	**	10.077	**	17.333	**	9.595	**
293	28.829	**	27.589	**	3.125	*	15.579	**	24.202	**	6.436	**
310	17.314	**	20.856	**	3.512	**	8.019	**	13.497	**	2.850	**

DOY = Day of Year

NS = Not significant
* = Significant at $P < 0.05$
** = Significant at $P < 0.01$

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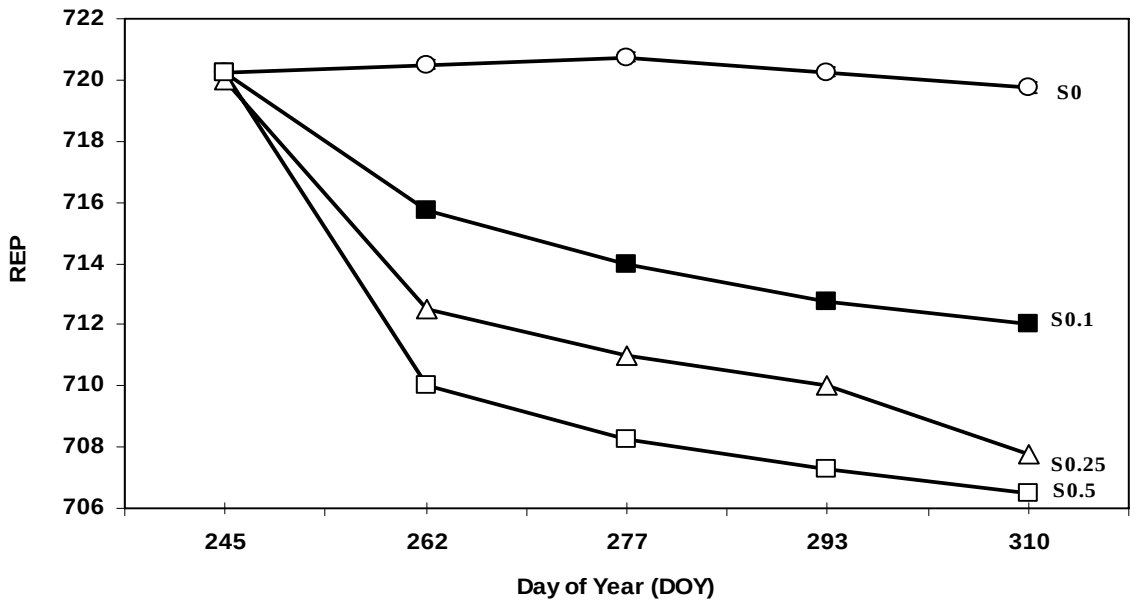

Figure 15: Trends of the mean values of REP for lettuce plants grown under four different salinity treatments (S0, S0.1, S0.25 and S0.5) with time progress.

Table (4): Statistical comparison derived from t-test of the red edge position (REP) as affected by the different salinity treatments.

	Statistical comparison											
	S_0 vs. $S_{0.1}$		S_0 vs. $S_{0.25}$		S_0 vs. $S_{0.5}$		$S_{0.1}$ vs. $S_{0.25}$		$S_{0.1}$ vs. $S_{0.5}$		$S_{0.25}$ vs. $S_{0.5}$	
DOY	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.
245	-0.756	NS	-1.342	NS	0	NS	-0.5	NS	0.756	NS	-1.342	NS
262	-1.342	NS	6.957	**	10.961	**	14.5	**	3.9	*	1.698	NS
277	10.729	**	10.961	**	11.258	**	7.348	*	5.196	**	2.774	*
293	25.981	**	14.50	**	15.922	**	4.95	**	8.5	**	5	**
310	12.318	**	29.394	**	27.672	**	6.928	**	8.573	**	5.196	**

DOY = Day of Year

NS = Not significant
* = Significant at $P < 0.05$
** = Significant at $P < 0.01$

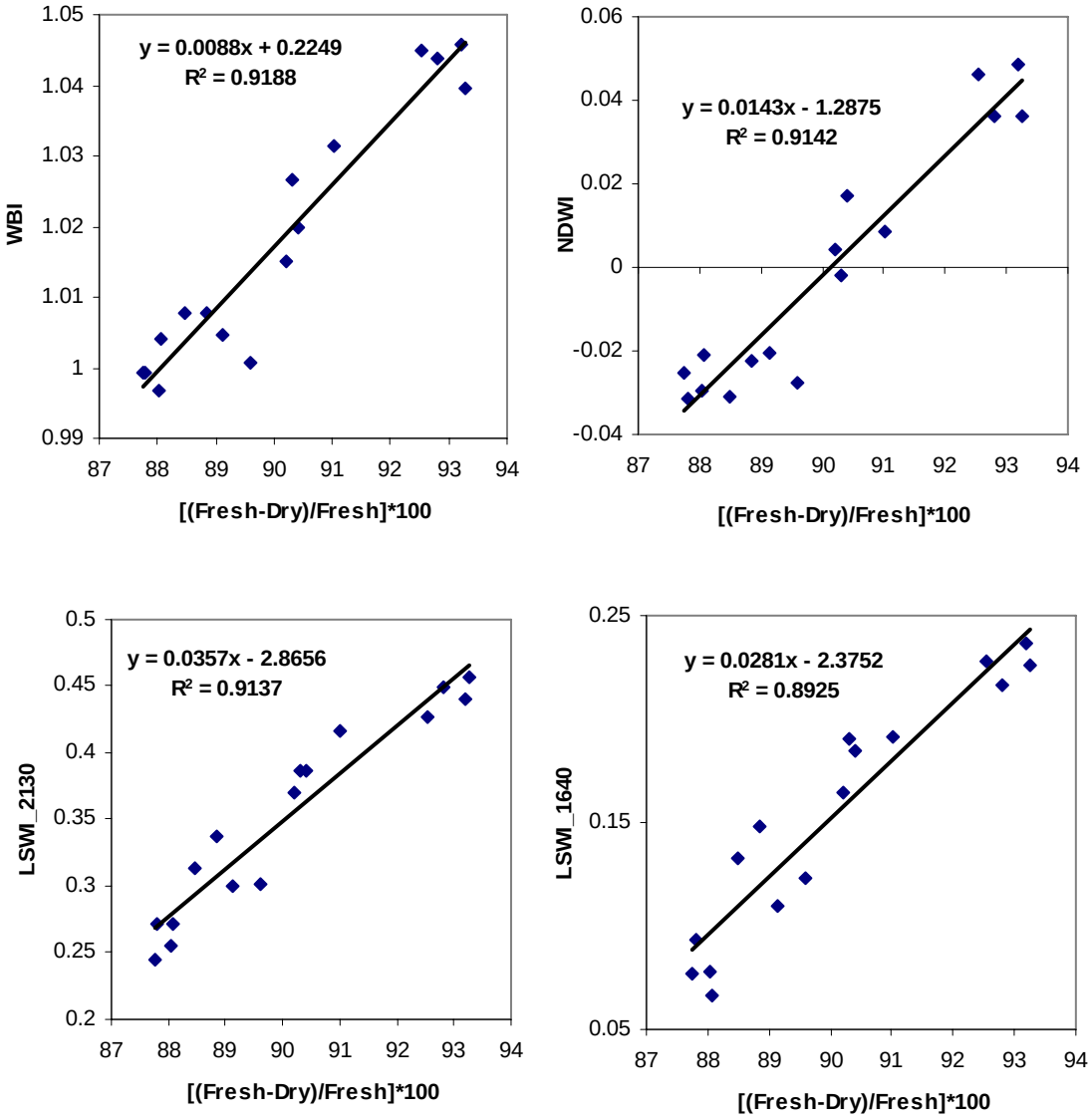

Figure 16: The relationship between the spectral water indices, WBI, NDWI, LSWI_2130 and LSWI_1640, and the water content for lettuce plants growing under different salinity treatments (S_0, $S_{0.1}$, $S_{0.25}$ and $S_{0.5}$).

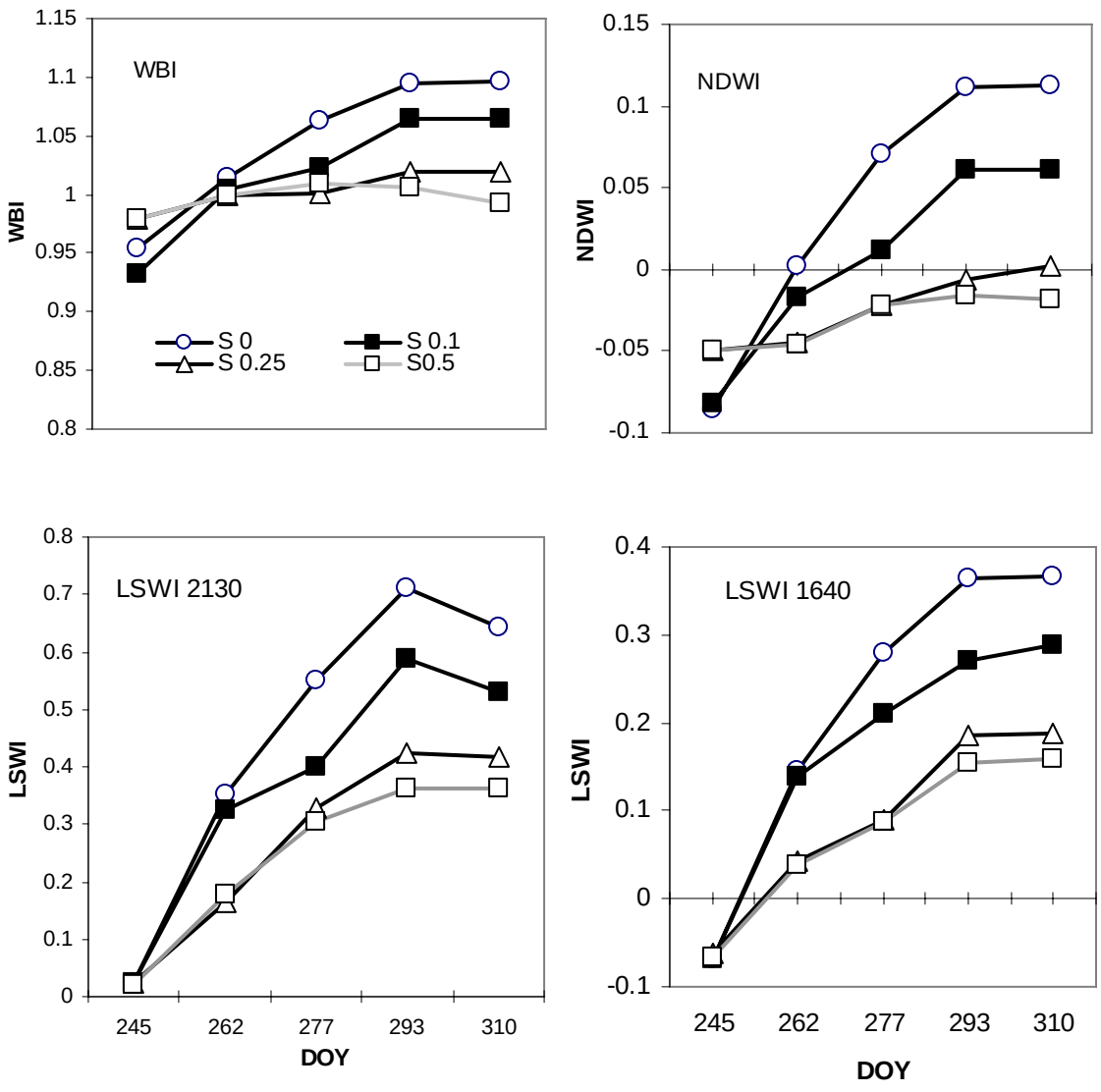

Figure 17: Trends of the mean values of WBI, NDWI, LSWI_2130 and LSWI_1640 for lettuce plants grown under four different salinity treatments (S_0, $S_{0.1}$, $S_{0.25}$ and $S_{0.5}$) with time progress

Table (5): Statistical comparison derived from t-test of the land surface water index ($LSWI_{2130}$) as affected by the different salinity treatments.

	Statistical comparison											
	S_0 vs. $S_{0.1}$		S_0 vs. $S_{0.25}$		S_0 vs. $S_{0.5}$		$S_{0.1}$ vs. $S_{0.25}$		$S_{0.1}$ vs. $S_{0.5}$		$S_{0.25}$ vs. $S_{0.5}$	
DOY	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.
245	0.004	NS	-9.27	NS	-2.51	NS	-8.52	NS	-2.44	NS	0.93	NS
262	2.96	*	11.83	**	8.56	**	2.09	*	1.54	NS	-2.53	NS
277	6.48	**	10.961	**	14.49	**	15.80	**	16.38	**	-7.16	NS
293	4.26	**	10.75	**	13.55	**	14.31	**	4.51	**	3.66	**
310	5.63	**	16.52	**	19.97	**	23.71	**	27.64	**	13.53	**

DOY = Day of Year

NS = Not significant
* = Significant at $P < 0.05$
** = Significant at $P < 0.01$

Table (6): Statistical comparison derived from t-test of the land surface water index ($LSWI_{1640}$) as affected by the different salinity treatments.

DOY	Statistical comparison											
	S_0 vs. $S_{0.1}$		S_0 vs. $S_{0.25}$		S_0 vs. $S_{0.5}$		$S_{0.1}$ vs. $S_{0.25}$		$S_{0.1}$ vs. $S_{0.5}$		$S_{0.25}$ vs. $S_{0.5}$	
	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.	T-test	Sig.
245	-0.436	NS	-2.73	NS	-2.70	NS	-2.73	NS	-2.70	NS	0.13	NS
262	2.30	*	4.04	**	18.70	**	1.39	NS	2.30	*	0.21	NS
277	3.66	**	15. 60	**	11.66	**	6.79	**	5.68	**	-7.27	NS
293	3.47	**	6.84	**	7.51	**	22.41	**	6.77	**	4.53	**
310	3.49	**	6.00	**	8.03	**	12.79	**	8.61	**	6.69	**

DOY = Day of Year

NS = Not significant
* = Significant at $P < 0.05$
** = Significant at $P < 0.01$

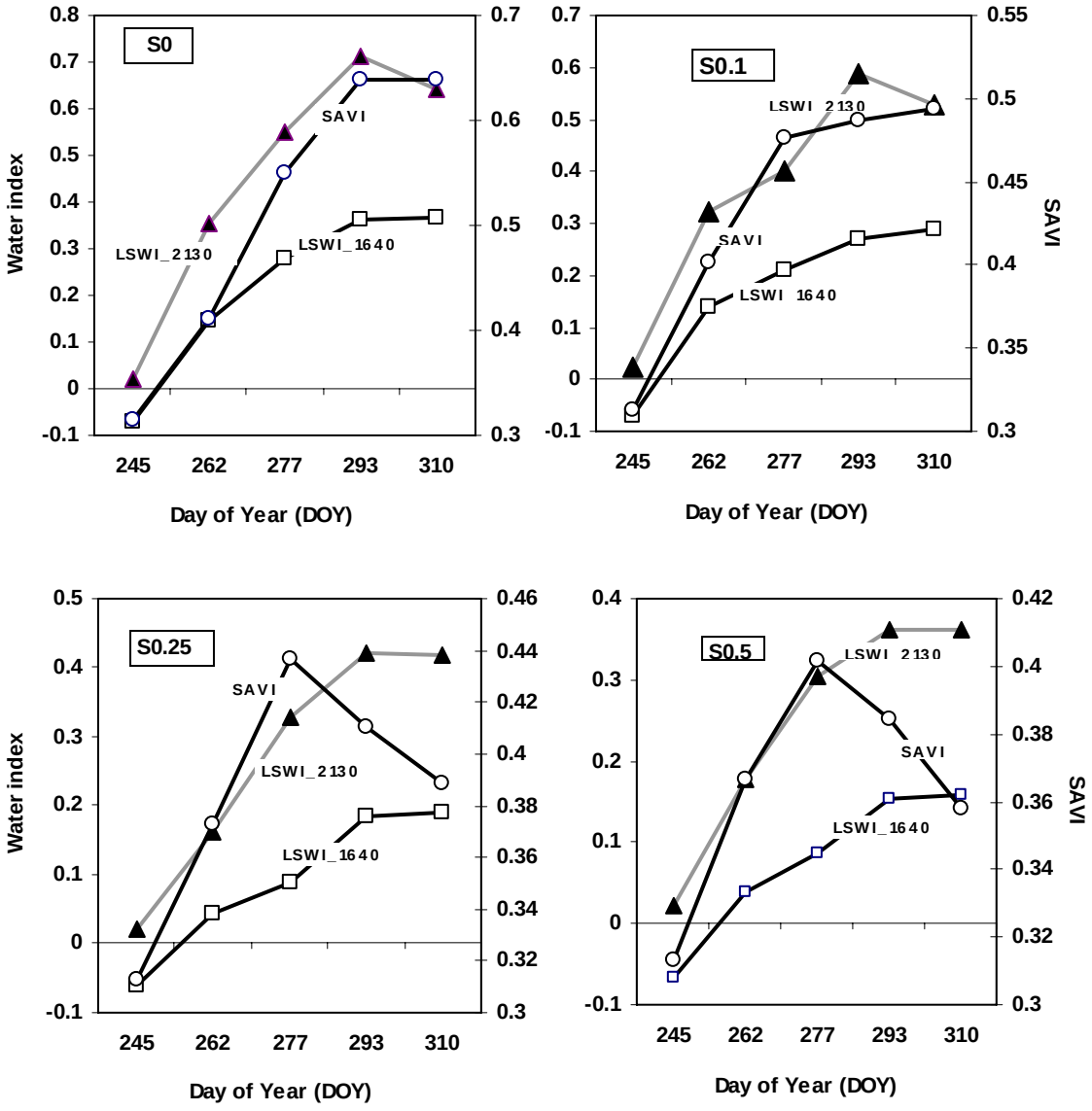

Figure 18: Trends of the mean values of SAVI, LSWI_2130 and LSWI_1640 for lettuce plants grown under four different salinity treatments (S_0, $S_{0.1}$, $S_{0.25}$ and $S_{0.5}$) with time progress.

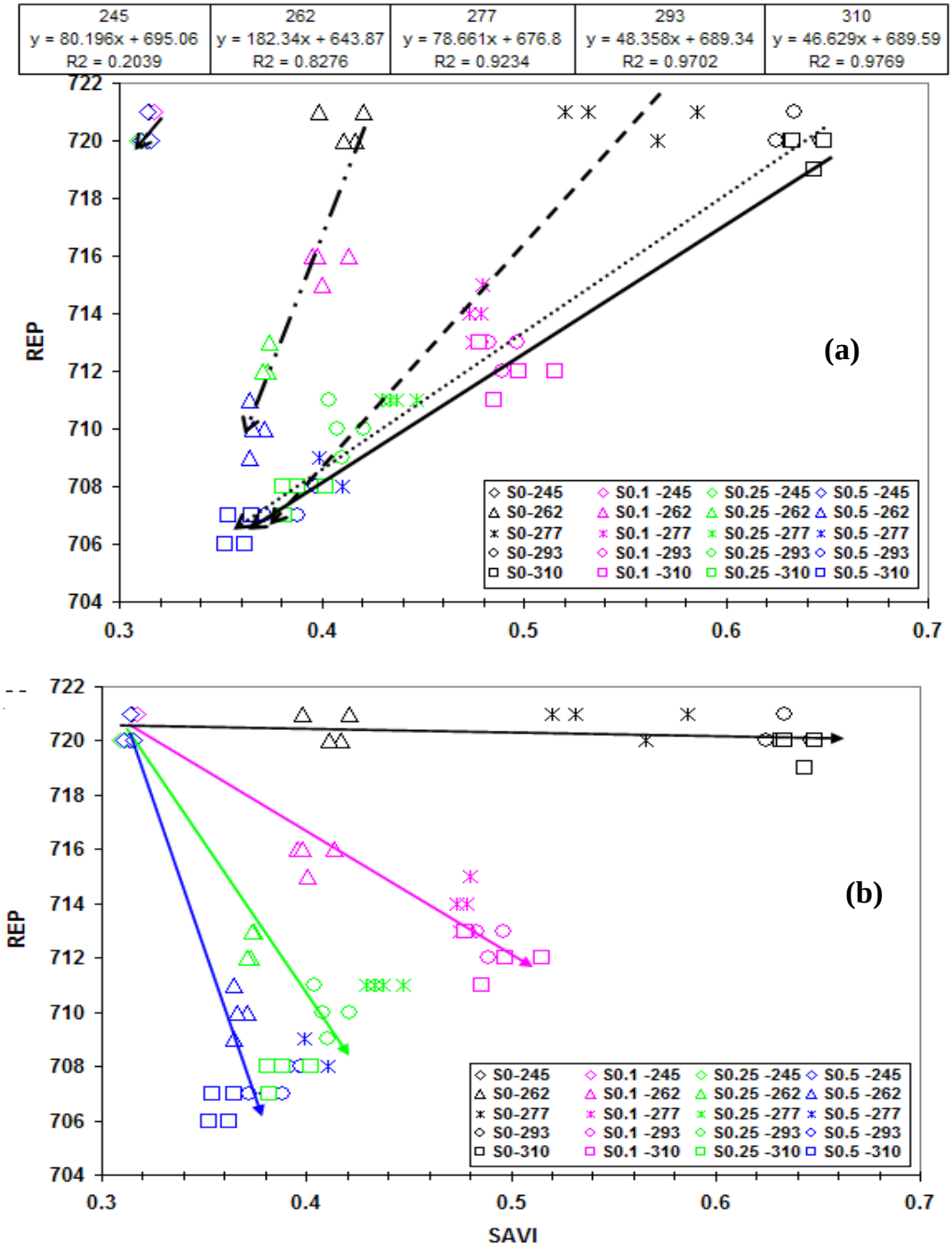

Figure 19: REP plotted against SAVI for lettuce plants grown under 4 different irrigation water salinity levels (S0, S0.1, S0.25 and S0.5).245, 262, 277, 293 and 310 represent the day of year.

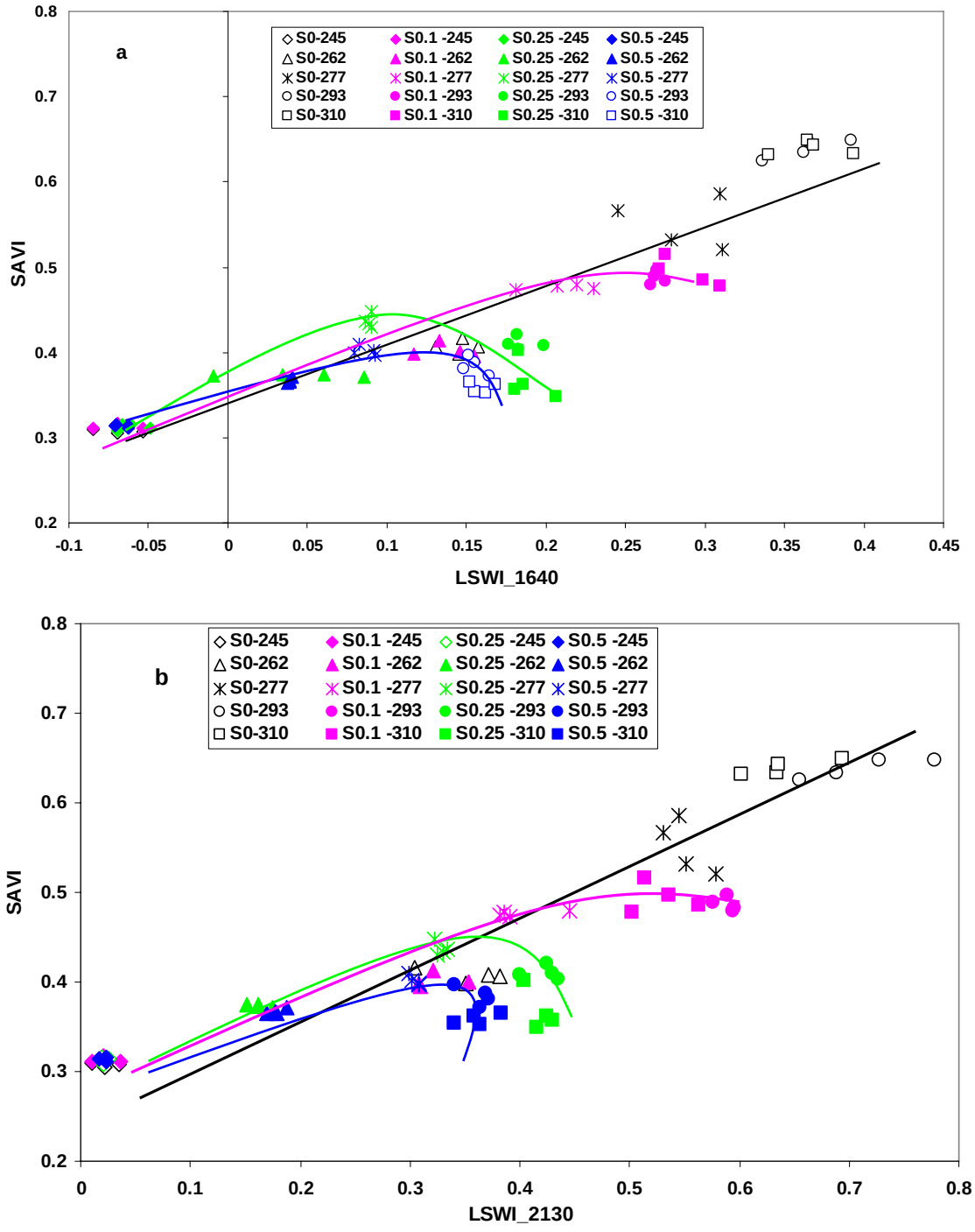

Figure 20: LSWI (a: 1640 nm and b: 2130nm) plotted against SAVI for lettuce plants grown under 4 different irrigation water salinity levels; 245, 262, 277, 293 and 310 represent the day of year.

APPENDIX C

SOIL SALINITY ASSESSMENT IN THE NILE DELTA USING MODIS DATA

I. Introduction

Salinity problems have a large impact especially in semi-arid regions since these areas with harsh climatic conditions are under high pressure to supply the required food and fiber for their rapidly increasing population. This pressure results from changes in land use, which is mainly due to the common policy of agricultural growth. Under such climatic condition, soluble salts are accumulated in the soil profile, adversely affecting soil properties and environment which cause decrease of soil productivity.

A. Soil Salinity

Soil salinity, as a term, that refers to the state of accumulation of the soluble salts in the soil. Soil salinity can be determined by measuring the electrical conductivity of a solution extracted from a water-saturated soil paste. The electric conductivity as ECe (Electrical Conductivity of the extract) with units of decisiemens per meter ($dS.m^{-1}$) is an expression for the anions and cations in the soil.

From the agricultural point of view, saline soils are those, which contain sufficient neutral soluble salts in the root zone to adversely affect the growth of most crops. For the purpose of definition, saline soils have an electrical conductivity of saturation extracts of more than 4 $dS.m^{-1}$ at 25 °C (Richards, 1954).

As salinity levels increase, plants extract water less easily from soil, aggravating water stress conditions. High soil salinity can also cause nutrient imbalances, which then result in the accumulation of elements toxic to plants, and reduce water infiltration if the

level of one salt element (like sodium) is high. In many areas, soil salinity is the factor limiting plant growth.

B. Soil Salinity global distribution

There are extensive areas of salt-affected soils on all the continents, but their extent and distribution have not been studied in detail (FAO, 1988). In spite of the availability of many sources of information, accurate data concerning salt affected soils of the world are rather scarce (Gupta and Abrol, 1990). Statistics relating to the extent of salt-affected areas vary according to authors, but estimates are in general close to one billion hectares, or 7.7% of the earth's continental extent (Ghassemi *et al*, 1995). In addition to these naturally salt-affected areas, about 77 M ha have been salinized as a consequence of human activities, with 58% of these concentrated in irrigated areas. On average, salts affect 20% of the world's irrigated lands, but this figure increases to more than 30% in countries such as Egypt, Iran and Argentina (Ghassemi *et al* 1995).

According to estimates by FAO and UNESCO, as much as half of the world's existing irrigation schemes is more or less under the pressure of secondary salinization and water-logging. About 10 million hectares of irrigated land are abandoned each year mainly because of the secondary salinization and alkalinization (Szabolcs, 1994).

Prediction of further degradation needs monitoring of the spatial and temporal changes in salinity. Timely detection of salinization assessment of its degree of severity and the extent, particularly in its start is very important. Monitoring soil salinity means first identifying the places where salts concentrate and, second detecting the changes in

this concentration. Both depend on the salt distribution at the soil surface and on the capability of the remote sensing tools to identify salts.

II. REVIEW OF LITERATURE

A. Egypt Agricultural characteristics

The importance of land in Egypt appears from the fact that The Egyptian economy has traditionally relied heavily on the agriculture sector as a source of growth and support for the non-agricultural sector.

Egypt lies in the northeastern corner of the African continent between latitudes 22° and 32° N and longitudes 25° and 36° E (Figure 1) with a total area of about 1 million km^2. The Egyptian terrain consists of a vast desert plateau interrupted by the Nile Valley and Delta, which occupy about 4% of the total country area. Most cultivated lands are located close to the banks of the Nile River, its main branches and canals, and in the Nile Delta. Rangeland is restricted to a narrow strip, a few kilometers wide, along the Mediterranean coast and its bearing capacity is quite low. No forest land exists. The total cultivated area (arable land plus permanent crops) is 3.4 million ha (2004), or about 3% of the total area of the country. Arable land was about 2.9 million ha, or 85% of the total cultivated area, and permanent crops occupy the remaining 0.5 million ha.

1. Agriculture and food security

The agricultural lands are mainly occupied with widely diversified crops throughout the year. The majority of agricultural land is cultivated twice a year, with the remaining land being left fallow during one season because the soil is saline or water-logged, or because of insufficient irrigation water. The agricultural soil in the Nile Valley

and Delta is of fine texture (medium-to-heavy clay). The clay content increases in the Nile Delta toward the Mediterranean Sea.

2. Crop rotation patterns

The major cropping seasons are the winter (November±May) and the summer (May± October) seasons. Most crops are grown both in the Delta and the Valley, with the exception of rice (Delta mainly) and sugarcane (Valley). The main winter crops are wheat and alfalfa. Minor winter crops are, amongst others, pulses, barley and sugar beet. The main summer crops are maize, rice and cotton, the latter being the most important Egyptian export crop (Ministry of Agriculture and Land Reclamation. 2002, 2003).

An early soil survey indicated that the percentages of salt-affected soils relative to total cultivated lands was 60% in the Lower Delta, 25% in the Middle Delta, 20% in the Upper Delta and Middle Egypt, and 25% in the Upper Egypt (Aboukhaled *et al.*, 1975). A rather recent inventory concluded that almost 35% of the agricultural lands in Egypt suffer from salinity, wherein the electrical conductivity of the extract from saturated soil is higher than 4 dS/m (Hamdi *et al.*, 1996).

3. The Nile Delta

Sixty percent of the cultivated lands of Northern Delta region are salt-affected, twenty percent of the Southern Delta and Middle Egyptian region and twenty five percent of the Upper Egypt region is salt-affected soils.

The majority of salt-affected soils in Egypt are located in the Northern part of the Nile Delta and on its Eastern and Western sides. In the Mediterranean coastal plains and

lower Delta, excessive rates of groundwater withdrawal have resulted in a large drop in the water table and, as a consequence, seawater intruded into the aquifers (GARE, 1992).

Basically, soil salinity problems related to irrigation with low quality (saline) water occur when salts accumulate in the crop-root zone and, consequently, the available water in soil for the crop is reduced. Another possibility, evapotranspiration leads to a salt accumulation in the top soil, where a shallow groundwater table exists and as a result of upward movement of water-containing salts. This type of secondary soil salinization is mainly attributed to poor drainage conditions. Once, proper drainage is installed and the groundwater table is stabilized at deeper depths, either the salinity problem would be controlled, or recognized as a problem of the first type, i.e. the applied irrigation water is too saline (Kotb *et al*., 2000).

B. Soil Salinity and remote sensing

As previously mentioned in chapters 1 and 2 prior efforts to identify soils with high salinity using remotely sensed data was relied primarily on two approaches. First, saline soils can be identified through assessment of bright salt-crusted soils. Second, the presence of saline soil can be inferred by its effects on the spectral response of vegetation. (Mougenot *et al.,* 1993 and Lenney *et al.,* 1996).

1. Detection of soil salinity on bare soil

Saline distribution is rather dynamic, and methods for accurately and rapidly mapping potential seasonal saline spots are seriously needed. Remote sensing data and techniques have been widely used to monitor and map such these areas (Hunt and Salisbury, 1976; Hick and Russell, 1990; Mougenot *et al*., 1993; Verma *et al*., 1994; Ben-

Dor *et al*., 2002; Dehaan and Taylor, 2003). The presence of salts at the terrain surface can be detected from remotely sensed data either directly on bare soils, with salt efflorescence and crust, or indirectly through vegetation type and growth as these are controlled or affected by salinity (Mougenot, *et al,* 1993).

The potential of remote sensing in the study of salt-affected soils and in particular slightly to moderately affected areas is usually restricted (Metternicht and Zinck, 2003; McGowen and Mellyon, 1996).

The space-borne sensors have provided the global coverage of the earth's surface conditions at different spatial and temporal resolutions. In general, they are sensitive to reflected solar energy (400 to 2500 nm), to emitted thermal energy (8000 to 14000 nm) or radiation at longer wavelengths known as microwaves.

Basically, the radiation reflected from soil surface can vary depending on the soil constitutes and wavelengths (Csillag *et al*., 1993). Soil elements have characteristic features mostly occurring in narrow wavelength regions. In general, such detailed spectral signatures are masked when the bandwidths are wide and/or the spectral bands are limited (Cloutis, 1996). This is the case with broad-bands sensors such as Landsat TM, SPOT and ASTER that average the reflectance over a wide range. Most of the studies using conventional remote sensing data are focused on mapping severely saline areas or successfully differentiating between saline and non-saline soils (e.g., Hick *et al*., 1984; Mougenot *et al*., 1993; Dwivedi and sreenivas, 1998). That is partially due to higher spectral reflectance of severely saline soil as compared to non-saline soils (Rao *et*

al., 1990). The advantage of the space-borne data is their high temporal resolution since salt concentration in soil changes, at least seasonally.

Remote sensing has repeatedly been used as a promising tool to obtain information regarding soil properties, land degradation processes and canopy biophysical properties (Dehaan and Taylor, 2002; Van der Meer *et al*., 1999). Thousands of medium to high-resolution imageries from the earth surface are available, which can be used to detect and monitor salinization/ alkalinization spatially and temporally (Escadafal, 1994).

McGowen and Mallyon (1996) report significant overestimation of saline areas when using Landsat TM data and a maximum likelihood classification. The reasons were attributed to different reasons including land management practices, native vegetation and soil types present across the study area. The problem was resolved by combining multitemporal imagery of different cropping periods.

In the context of salinity remote sensing observations have often concentrated on severely saline soils neglecting the slightly affected areas, which must actually be the target when dealing with soil degradation. This concentration is basically related to the complex nature of the salinization process and its influence on different soil properties, both physical and chemical (Csillag *et al*., 1993).

2. Detection of soil salinity using vegetation responses

Changes in the concentration of salts in soils induce changes in plant characteristics, which, to a certain extent, are expected to be spectrally detectable. Salinity stress results in lower overall leaf chlorophyll content (Wang *et al*, 2000). Another early response of plants reacting to salt that has reached their leaves is to exclude

it from the cytoplasm (Volmar *et al*., 1998). One method is allowing the salt to build up outside the cells, in the intracellular space. This leads to a gradient of water moving out of the cells to accommodate the change in ion concentration, and eventually too much water leaves the cell and the cell becomes dehydrated (Volmar *et al*., 1998).

Spectral vegetation indices (VIs) are physiologically related to canopy chlorophyll content and absorbed photosynthetically active radiation (Tucker and Sellers 1986). Thus, VIs generally would show decreases in plant growth (or senescence) caused by salinity stress rather than lower water contents. On the other hand, water indices employing the 1240 nm, 1640 nm, or 2100 nm wavelengths have recently been used as vegetation measures related to canopy moisture condition. A combined VI-WI approach may potentially provide a related display of remotely sensed measurements that might help in distinguishing plants growing under different salinity stress levels.

The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the *Terra* platform was launched on 18 December 1999 as part of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS). MODIS provides a major advance in remote sensing of the Earth. MODIS was designed to support global studies and thus has high temporal resolution but relatively coarse spatial resolution. It is being used operationally to make global maps of surface parameters such as Leaf Area Index (LAI), land cover, and fractional forest cover (Myneni *et al*., 2002; Friedl *et al*., 2002; Hansen *et al*., 2002). MODIS also has the potential to help local studies. For example, the strong seasonal pattern of irrigated agricultural lands associated with the

onset of irrigation, growth, and harvest, can be tracked using a time series of MODIS data, acquired frequently throughout the growing period.

The primary objectives of this research were to assess the potential of temporal Moderate Resolution Imaging Spectroradiometer (MODIS) data to detect and monitor the local scale soil salinity in the Nile delta in Northern Egypt (Figure 1) and to investigate if the combined spectral indices, vegetation and water indices can be used upon the detection of saline soil.

III. DATA AND METHODS

A. Study area description

The Nile Delta is one of the oldest intensely cultivated areas on earth. It is very heavily populated, with population densities up to 1600 inhabitants per square kilometer. The low lying, fertile floodplains are surrounded by deserts. The Nile delta is situated almost in the middle of the Egyptian Mediterranean coastline (Figure 1), which extends about 1,000 km (16% of the total Mediterranean coast). It connects to the Mediterranean Sea through its two branches surrounding the delta, the Damietta in the east and the Rosetta in the west.

Hot dry summers and mild winters characterize Egypt's climate. Rainfall is very low, irregular and unpredictable. Annual rainfall ranges between a maximum of about 200 mm in the northern coastal region to a minimum of nearly zero in the south, with an annual average of 51 mm.

Due to the lack of rain, the whole area is served by irrigation canals that reach all the fields by gravity. All the fields are irrigated by the flood method.

B. MODIS Data

In this study, we used the MOD09A1 product, with 7 of the 36 MODIS 500 m bands. The MOD09 is 8-day composite computed from MODIS level 1B land bands 1–7 (centered at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm). Each 8-day composite is an estimate of the surface reflectance for each band at 500-m spatial resolution as it would have been measured at ground level if there was no atmospheric scattering or absorption (Vermote *et al*., 2002).

MODIS products are organized in a tile system with the Sinusoidal (SIN) projection grid, and each tile covers an area of 1200 km by 1200 km (approximately 10° latitude by 10° longitude at equator). In this study, we downloaded MOD09A1 data 2 years (2003–05) of MODIS 8-day composites. We hypothesized that the MODIS data would be able to discern canopies growing under salinity stress conditions from those growing under non-saline conditions.

C. Methods

The analysis strategy was achieved through combined vegetation and water indices were used to discriminate the variations on vegetation water and chlorophyll contents associated with salinity stress.

For this study, nine different sites were selected at the Nile Delta (Figure 1) representing various levels of soil salinity. These 9 sites were chosen depending on two main factors; EC values and the canopies planted in these areas. The 9 sites were cultivated with the same winter canopies and the same summer canopies during the period 2003–05, (Table 1). The 9 sites were selected also to represent 3 different soil salinity levels; non-saline (NS), moderately saline (MS) and highly saline (HS) sites (Table 1).

For each 8-day composite, a number of different vegetation and water indices were extracted, over 9 different sites, a widow of 1x1 was used over each site, for growing season and time series analyses. The indices that were used in this study are shown in Table (2).

Both the spatial and temporal relationships between vegetation indices and water indices were analyzed in consider to soil salinity.

For the water index calculations, MODIS SWIR bands (band 5, 6 and 7) along with the NIR band (band 2) were used. Normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) (Huete *et al*, 1994 and Huete *et al*, 1997) were used as vegetation indices to investigate the relationship between VI's and WI's.

V. RESULTS AND DISCUSSION

A. Spectral vegetation indices temporal profiles.

Figure (2) shows the vegetation indices (NDVI and EVI) temporal profiles over the 9 study sites during the 2003–2005 period. The nine examined areas exhibited well-pronounced seasonal NDVI and EVI profiles with the highest values in the winter season, February and August, and lowest VI values in June and October. Both moderately salt affected (MS) and non salt affected sites (NS) had the highest VI values throughout the year while the highly saline affected sites (HS) showed intermediate to low VI values. The moderately salt affected sites had VI values similar to non-salt affected sites during the peak growing season. On the other hand, the highly salt affected sites had lower VI values, during the peak growing season.

Figure (3) shows vegetation indices (NDVI and EVI) temporal profiles after averaging each 3 similar sites (HS, MS, and NS). The highest VI values during the peak growing season were obtained in the winter seasons (November-May) compared to summer season (June – September). These highest values in the NDVI profile varied from 0.8 in the summer season peak to 0.88 in the winter season; EVI highest values were 0.58 in the summer season peak to 0.63 in the winter season.

To further investigate the differences among the study sites, we averaged the two annual cycles of VI data into single seasonal profiles for each site. The NDVI values of the normal soil and the moderately-saline affected soil sites were easily discriminable from the highly saline-affected sites during the green-up peak either in the summer or in

the winter season, but were not as well discriminable in the end of each season (October –November) (Figure 4 a.).

Overall, NDVI variations among the different salinity level sites were greatest in the winter season (November-May) and minimal in the summer season (June-September) (Figure 5a). In contrast, EVI showed more variations between the highly salt affected sites and the other two sites (normal and moderately salt affected) in the green peak of the winter season, with values ranging from ~ 0.4 (highly saline) to ~ 0.64 (the other two sets of sites) (Figure 5b). On the other hand, either the NDVI or EVI values of the normal soil sites were not discriminable from the moderately salt affected sites in both the summer season and winter season.

The cumulative VI response curves integrate VI temporal variations over the whole growing cycle, for summer season and winter season, are shown in Figure (6). In general, the profile shapes were similar. There was no difference between the two summer seasons (2003 and 2004) under the three different study sites. Similar to the summer curves there was no difference between the two studied winter seasons. The summer season curves reflected a slowdown in growth during the month of July through the growing season (Figure 6). The more salt stress (HS) yielded the lower magnitude cumulative VI profiles, indicating lower productivities in comparison with the lower salt stress (MS and NS). The NS site had the highest values, followed by the MS sites. The summer season plot using EVI is the only one that showed ability to discern between MS soil and NS soils. This might due to that the summer temperature is higher than winter so

the effect of salt stress in moderately saline areas become bigger due to high temperature affecting the plant growth and yield.

B. Spectral water indices temporal profiles.

To investigate differences among the water indices, we compared the NDWI (1240 nm) and the LSWI (1640 nm and 2130 nm) formulations over the 9 different study sites. The temporal profiles of these spectral water indices are shown in figure (7). The three WI had a similar general trend with different absolute values. The variations among the different salinity level sites were similar to the NDVI variation trend. The greatest variation was in the winter season (November-May) and minimal in the summer season (June-September).

The averaged profiles of the three studied water indices (Figure 8) show that the highest contrast between peak growing and the end of the growing season was shown in the LSWI_2130 profile, varied between 0.15 to 0.65 for either non-salt or moderately salt affected sites and 0.14 to 0.44 for highly salt affected areas.

The cumulative WI response curves are shown in Figure (9). The general profile shapes were similar for the three studied WIs with different absolute values; either in summer or winter season curves. On the other hand, the variation in the NDWI cumulative magnitude under highly saline condition (HS) was negligible either during the summer season or the winter season. A clear difference between cumulative WI under HS conditions from one side and under either MS or NS from the other side. Summer season curves showed a separabilaty between the moderately saline areas (MS) and none saline (NS). This seprability did not appear in the winter season cumulative curves. This could

be due to the high summer temperature which affects the water status in the canopy and in the soil which leads to increase the effect of stress on the plants in summer season compared to the winter season.

C. Vegetation and water spectral indices combinations

To investigate the behavior of the relationships between VI's and WI's of the crops planted under different salinity stress levels (HS, MS, and NS), 1 pixel was extracted over each site (3 sites for each level of salinity).

The relationship between NDVI and three water indices; NDWI, LSWI_1640, and LSWI_2130 for the three study sites is shown in Figure (10). The three water indices positively correlated with NDVI. The slope of this positive relationship increased from NDWI to LSWI_2130. It is hard to discern between the three study sites; highly saline, moderately saline and non-saline, using this relationship between NDVI and NDWI or LSWI_1640. The slope values of these relationships were very close for the three study sites; for NDVI-NDWI relationship the slopes were 0.251 (highly saline, HS), 0.260 (moderately saline, MS) and 0.266 (non-saline, NS). For the NDVI-LSWI_1640 relationship the slope values were 0.572, 0.649, and 0.633 for HS, MS, and NS respectively. Using the LSWI_2130, the difference in slope values between HS site on one hand, and both MS and NS on the other hand were evident. The slopes were 0.706, 0.855, and 0.891 for HS, MS, and NS respectively. At the same time this figure shows that differentiation between MS and NS using this NDVI-LSWI_2130 relationship is hard.

Figure (11) shows the relationship between enhanced vegetation index (EVI) and the three water index (NDWI, LSWI_1640, and LSWI_2130) at the three study sites HS, MS, and NS. Similar to NDVI, the three water indices are positively correlated with EVI. The slope values for the three study sites were very close to each other using EVI-NDWI scatter plot. On the other hand, using the other two water LSWI indices we found that distinguishing between highly saline site and the other two sites (MS and NS) is possible. The slope of EVI-LSWI_1640 relationship at the highly saline site (0.822) was larger than the moderately saline site (0.728) and the non saline site (0.737). Using LSWI_2130 the slope at the HS was 1.12 and 0.939 for the MS and 0.985 for NS site.

Figure (12) shows NDVI-NDWI scatterplots and EVI-NDWI scatterplots for the three different studied sites; HS, MS and NS, during the greening-up and the drying-out periods for winter season. For the three study sites the relationship was linear and the trend for either greening up or drying out period was similar. A slight difference between greening up and drying out periods was shown when salinity stress increase for both NDVI and EVI. The same linear relationship was found during the summer season (Figure 13) under the three different saline areas. The difference between greening up and drying out periods, under both MS and HS condition, was greater than in winter season. These variations were more evident using EVI than NDVI. The equivalent scatterplots using LSWI_1640 are represented in figure (14), for winter and figure (15) for summer season. For summer season (Figure 15) the relationship was similar to VI-NDWI relationship. On the other hand, In winter season (figure 14) the same linear relationship was found under the NS and MS sites but under high salinity levels, using

either NDVI or EVI, in the greening up period the best fitting equation that describes this relationship was the exponential relationship whereas the same relation was linear while the canopy was in the drying out period. Per unite of water content there is more chlorophyll (higher VI value) in greening up curve compared to the drying out one, this means that salinity stress adversely affect the water crops content in the early growing stages more than the chlorophyll content and the dry biomass. This was similar to the VI-LSWI_2130 relationships, which is shown in figure (16) for winter season and figure (17) for summer. Under moderately saline condition (MS) for winter season there was a separation between greening up period and drying out using LSWI_2130 this separation did not show up when using LSWI_1640 or NDWI.

VI. CONCLUSION

We found the MODIS time series data are generally valuable in distinguishing between crops planted under highly saline conditions and non saline conditions. All of the study sites at the Nile Delta; highly saline (HS), moderately saline (MS) and non saline (NS) sites, showed strong VI seasonal profiles representing seasonal trends in photosynthetic activity. The VI seasonal profiles had well-pronounced seasonal variations with high vegetation activity in the growing seasons; winter season (November to February) and summer season (June to August) and decreasing VI values during the drying out phases; winter (February to May) and summer (August to September). The crops growing under highly saline conditions had lower VI values in the green-up peak compared to the crops that growing under moderate or non saline conditions. The early growing stages (greening up periods) are affected by salinity stress more than the late stages (drying out).

The results also showed that VI-LSWI scatter-plot could be useful in detecting the salinity stress under high salinity levels but not with moderate levels. LSWI used MODIS 2130 nm band (Band 7) has higher sensitivity to retrieve canopy water content conditions under stress when it is plotted against either NDVI or EVI.

In summary, we found that moderate resolution satellite remote sensing, such as MODIS, offers valuable information for discriminating between crops growing under highly saline conditions and non saline. Although there were limitations, much information on phenology and seasonal dynamics were retrievable from the seasonal time series MODIS data. The suitable solution for assessing saline soils in cultivated areas

using MODIS sensor data were the combination between vegetation indices, either NDVI or EVI, and water indices, LSWI 2130. The greening up period is the best for distinguishing between salt stressed and non stressed crops. The main difficulty in retrieval of salt-affected areas from MODIS satellite data is to distinguish between moderately saline areas and non saline. This is rather difficult because of low spectral resolution of MODIS satellite bands. The best monitoring results can be obtained by detecting the areas under salinization risk using MODIS and then integrating finer resolution satellite with field and laboratory.

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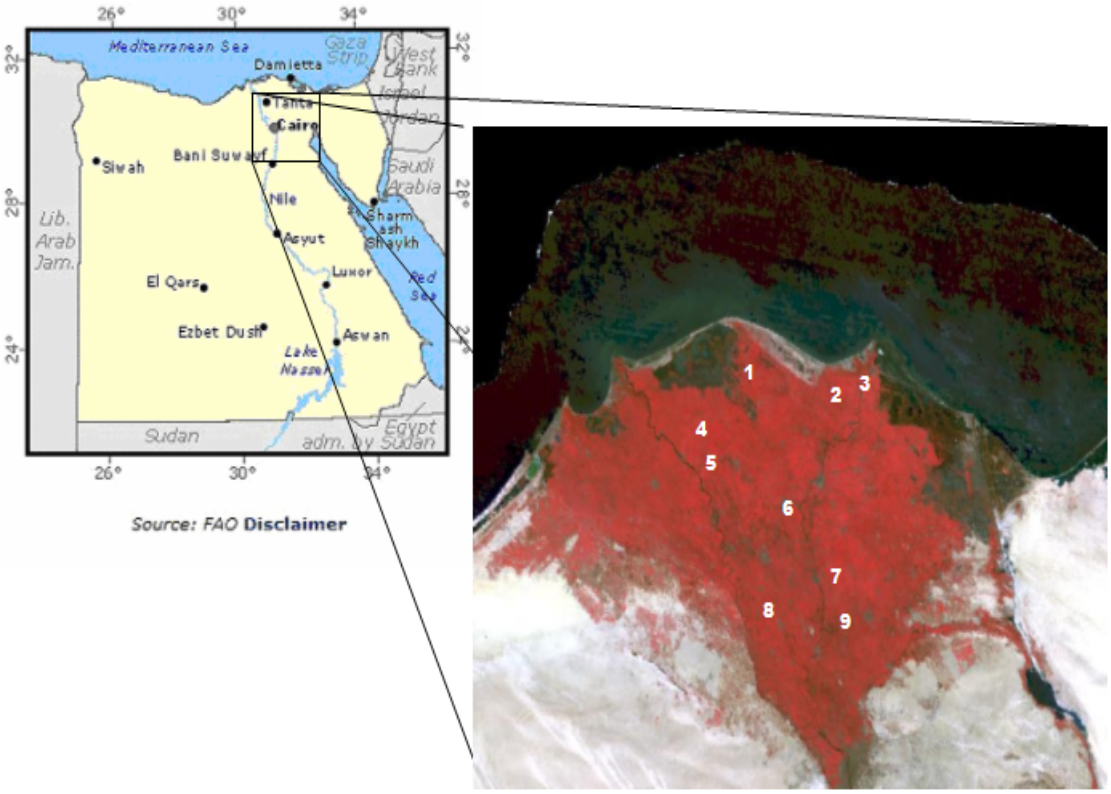

Figure 1: Study location, The Nile Delta, Egypt.

Table 1: Studied spectral indices using MODIS bands.

Index	Formula	Reference
NDVI	(ρ858.5 – ρ645)/(ρ858.5 + ρ645)	Tucker, 1978
EVI	((ρ858.5 – ρ645)*2.5)/ (ρ858.5+6* ρ645-7.5* ρ469+1)	Huete, 1996
NDWI	(ρ858.5 – ρ1240)/(ρ858.5 + ρ1240)	Gao, 1996
$LSWI_{1640}$	(ρ858.5 – ρ1640)/(ρ858.5 + ρ1640)	Xiao, 2004
$LSWI_{2100}$	(ρ858.5 – ρ2130)/(ρ858.5 + ρ2130)	

***Wavelengths are based on MODIS center wavelength**

Table 2: Study locations in the Nile Delta

Site	Location	Lat.	Long.	Salinity Status	Crops	
					Summer	Winter
1	El-Hamoul	**31' 30" 00 N.**	**31' 12" 55 E.**	Highly Saline (9.7-10.2 dS/m)	Clover & wheat	Cotton & rice
2	East North delta	**31' 26" 30 N.**	**31' 43" 11 E.**	Highly Saline (8.77-11.31 dS/m)	Clover & wheat	Cotton & rice
3	East North delta	**31' 28" 15 N.**	**31' 47" 35 E.**	Highly Saline (9.52-11.52 dS/m)	Clover & wheat	Cotton & rice
4	Shbeen Elkom.	**30' 47" 0 N.**	**31' 08" 18 E.**	Mod. Saline (5.09-5.88dS/m)	Clover & wheat	Cotton & rice
5	Kafr El-sheikh	**31' 08" 0 N.**	**30' 49" 05 E.**	Mod. Saline (4.91-5.76) dS/m)	Clover & wheat	Cotton & rice
5	Kafr El-sheikh	**31' 08" 0 N.**	**30' 49" 05 E.**	Mod. Saline (4.91-5.76) dS/m)	Clover & wheat	Cotton & rice
6	Blkas	**31' 16" 59 N.**	**31' 20" 54 E.**	Mod. Saline (54.44-6.05 dS/m)	Clover & wheat	Cotton & rice
7	Berket Elsaba	**30' 46" 15 N.**	**31' 18" 27 E.**	Non-Saline (2.40 -2.61dS/m)	Clover & wheat	Cotton & Maize
8	Berket Elsaba	**30' 38" 45 N.**	**30' 58" 34 E.**	Non-Saline (2.11-3.0 dS/m)	Clover & wheat	Cotton & Maize
9	Meet Ghamr	**30' 37" 30 N.**	**31' 21" 42 E.**	Non-Saline (1.91-2.61 dS/m)	Clover & wheat	Cotton & rice

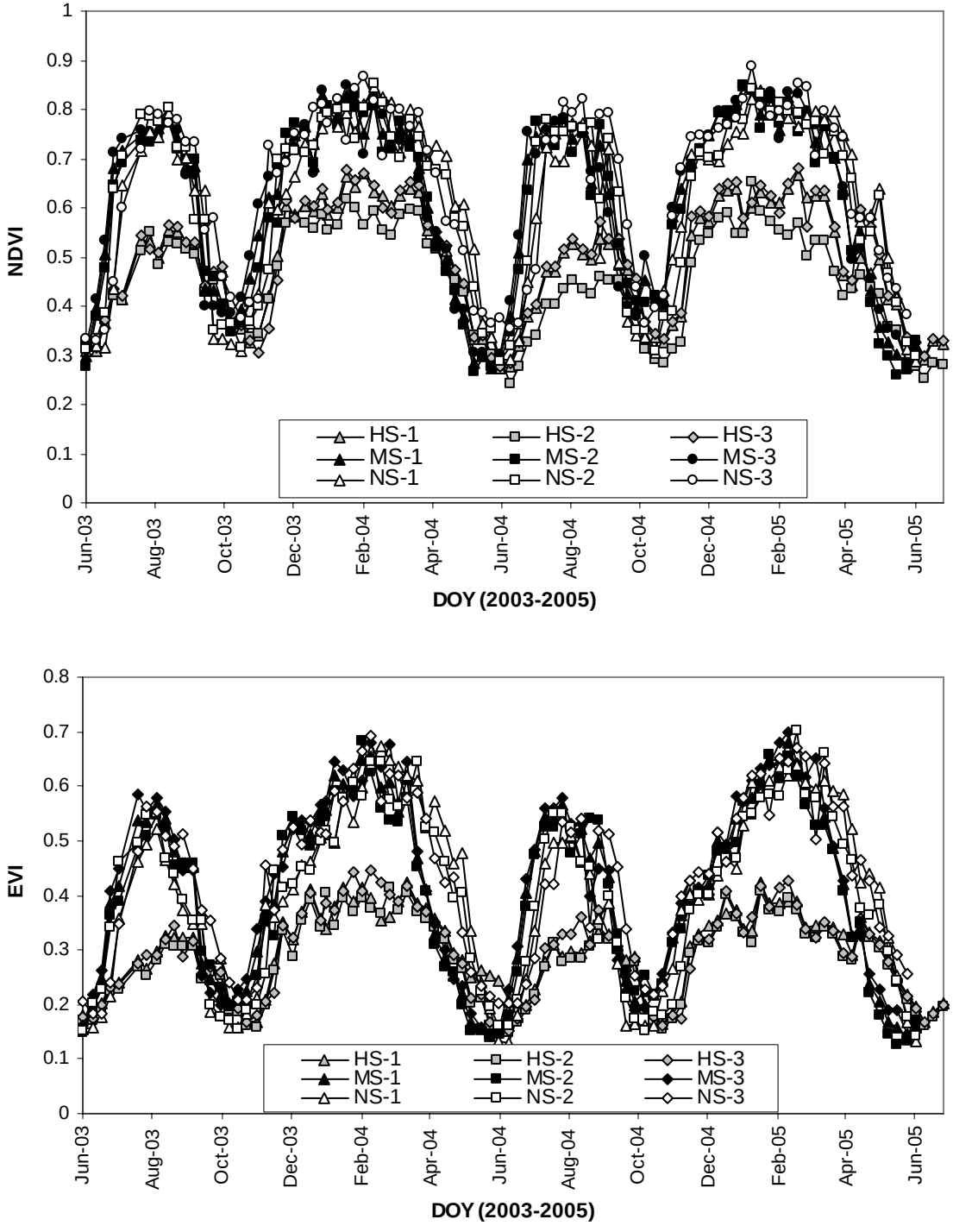

Figure 2: The VI temporal profiles of the nine studied sites. HS is highly saline MS is moderately saline and NS is non saline.

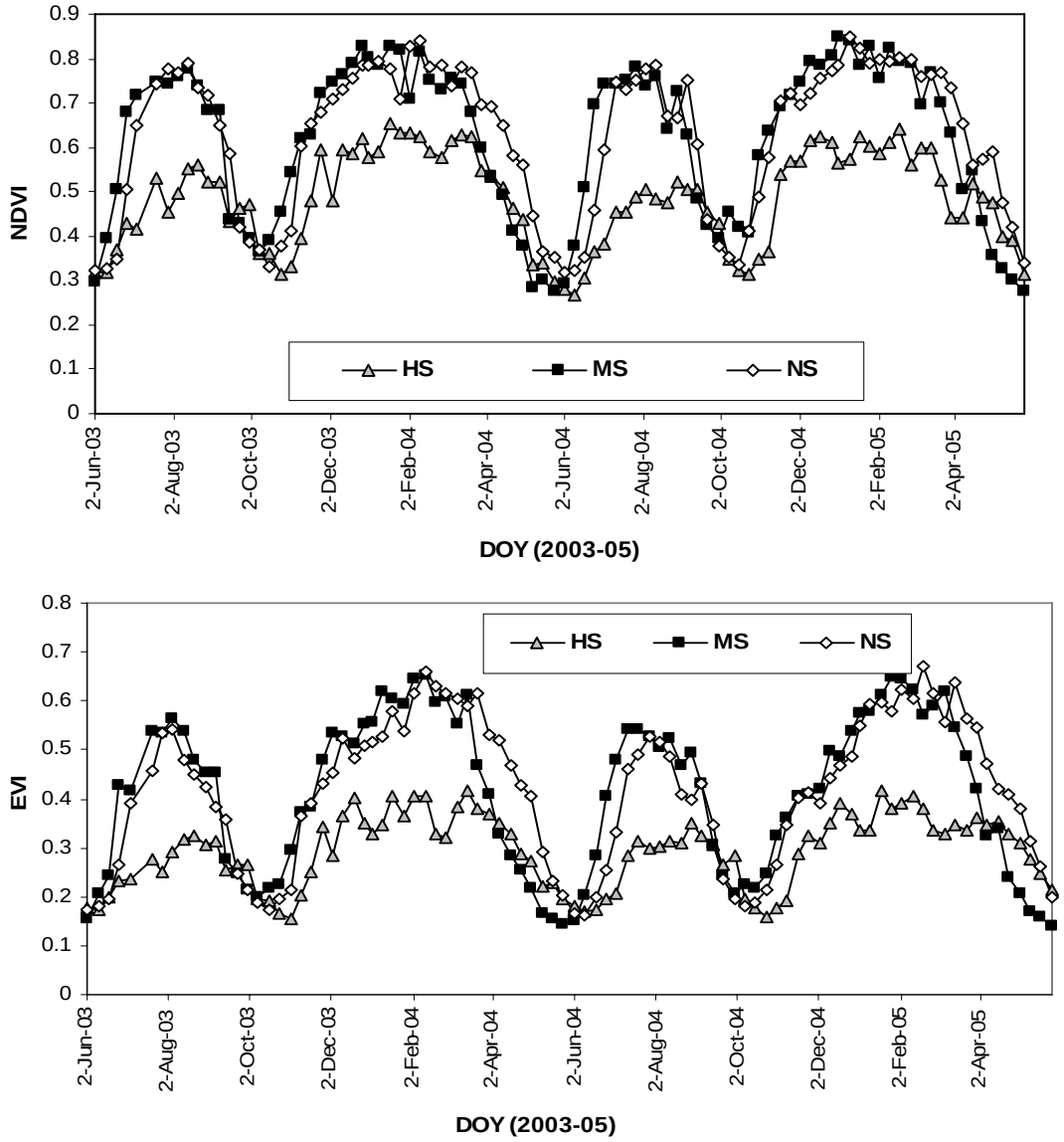

Figure 3: The average VI temporal profiles of the studied sites. HS is highly saline MS is moderately saline and NS is non saline.

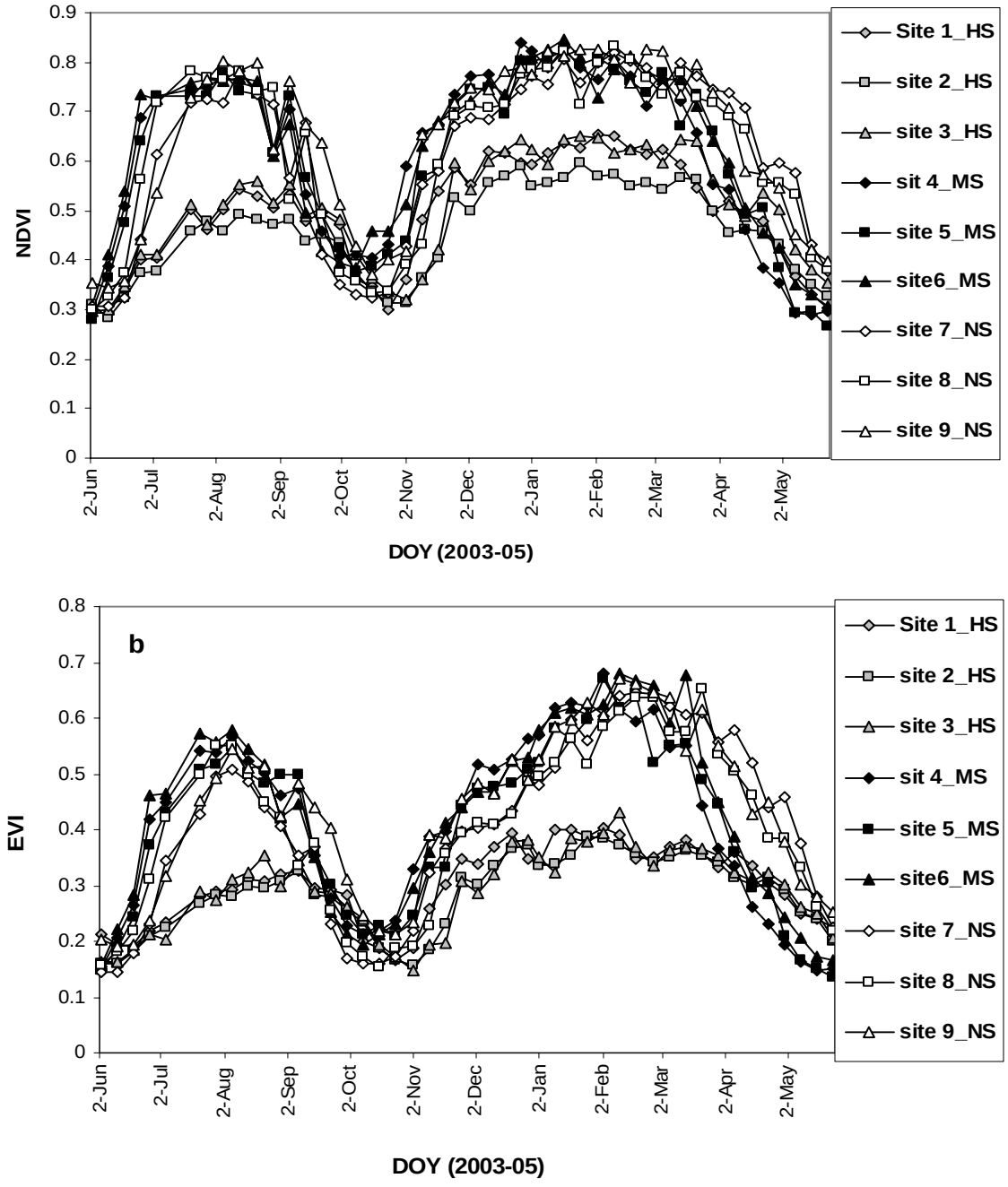

Figure 4: The average seasonal profiles of years 2003–05. (a) NDVI and (b) EVI at 9 different sites in the Nile Delta.

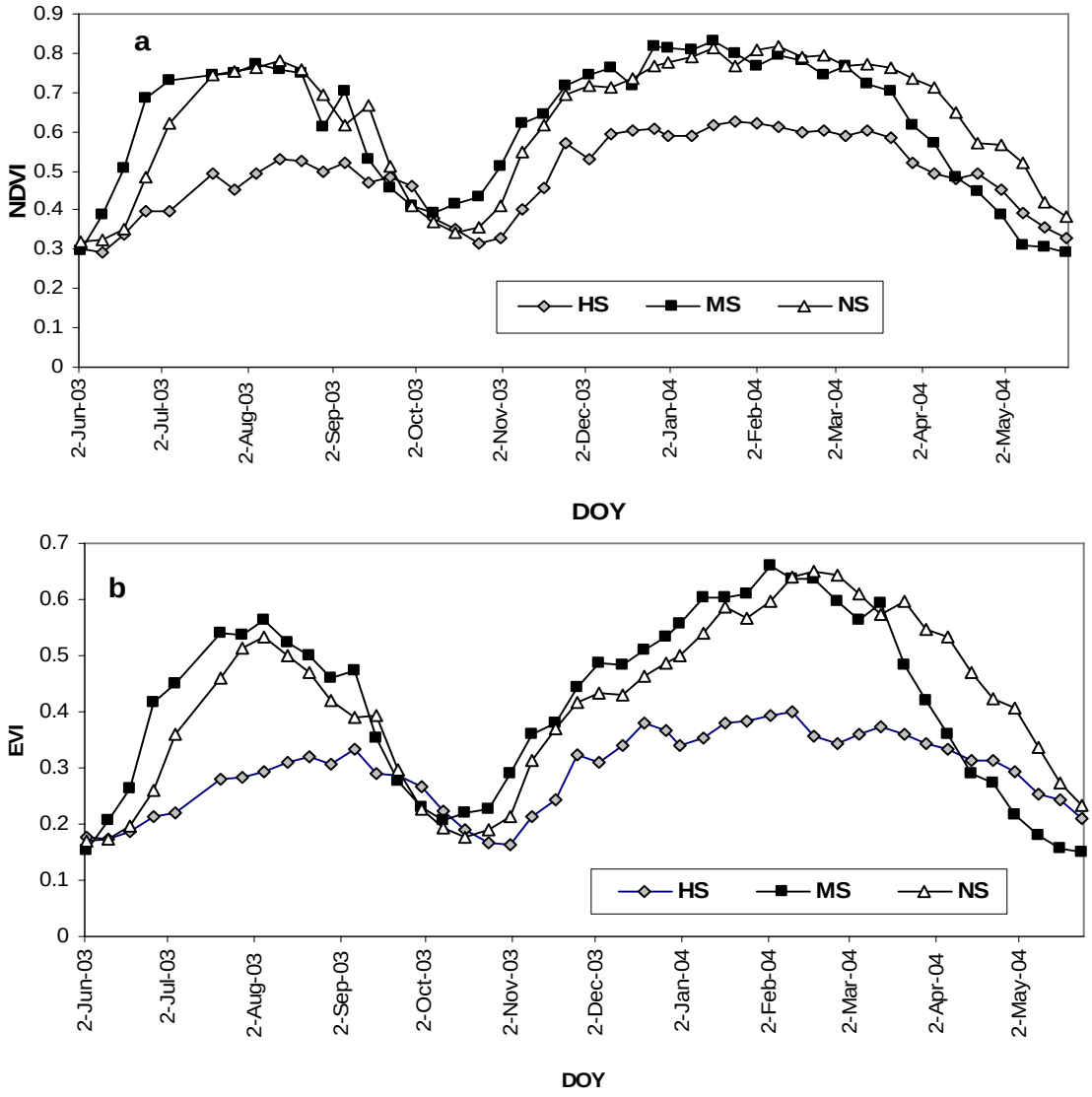

Figure 5: The verage seasonal profiles of years 2003–05 (a) NDVI and (b) EVI at the HS MS, and NS.

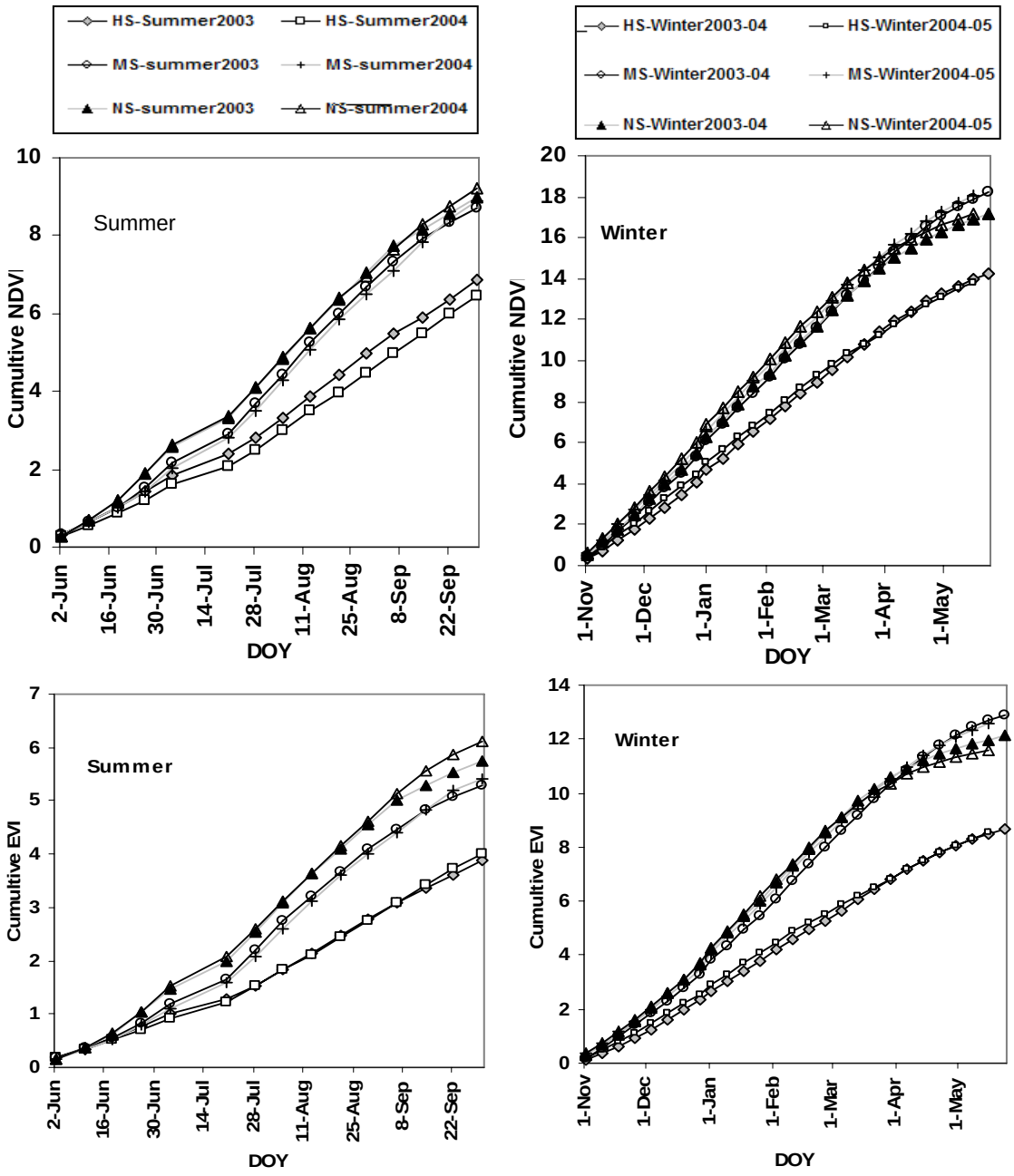

Figure 6: The cumulative response curves of (a) NDVI and (b) EVI for highly saline (HS) moderately saline (MS) and none saline (NS) for summer and winter seasons (2003-05).

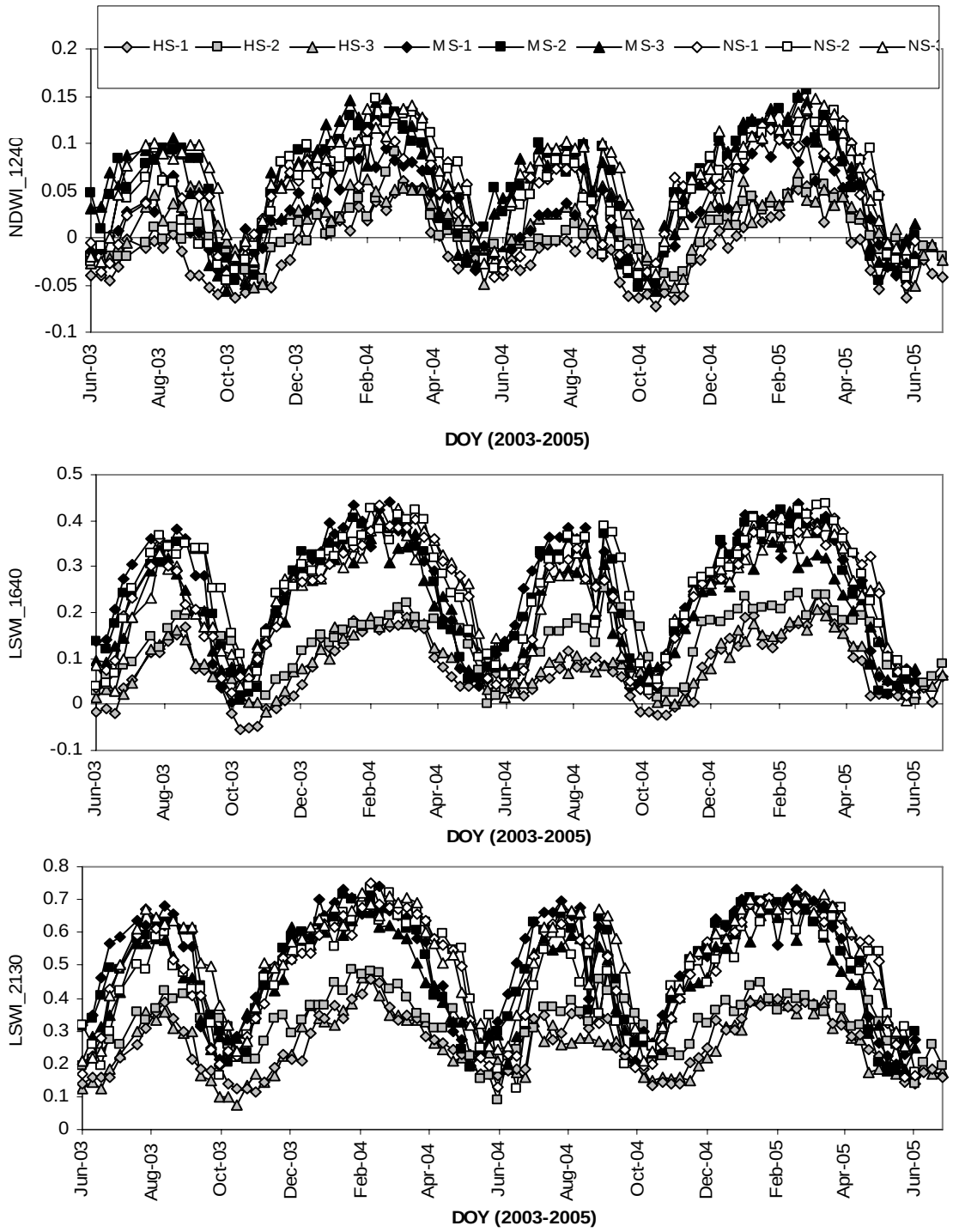

Figure 7: The WI temporal profiles of the nine studied sites. HS is highly saline MS is moderately saline and NS is non saline.

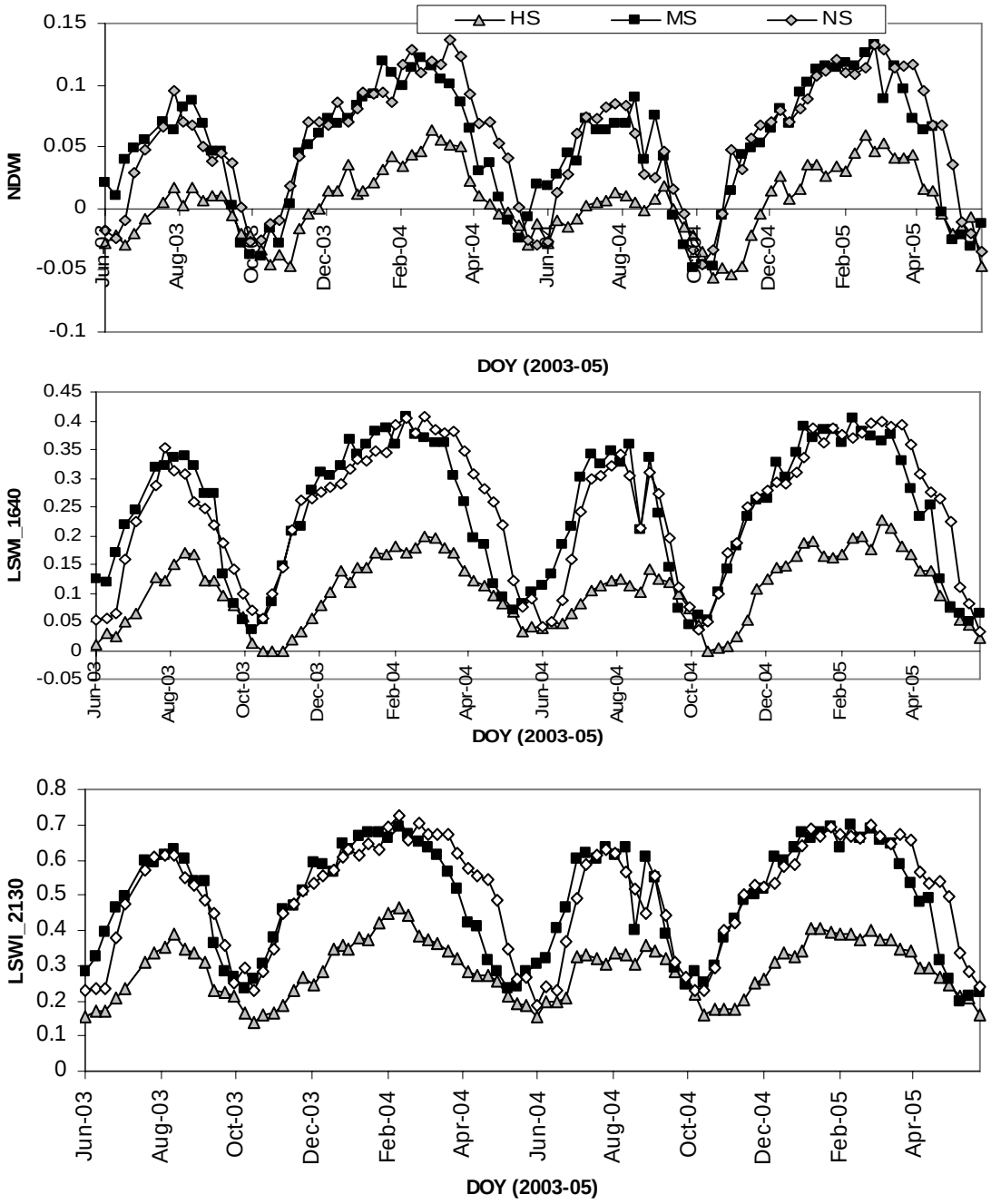

Figure 8: The average WI temporal profiles of the studied sites. HS is highly saline MS is moderately saline and NS is non saline.

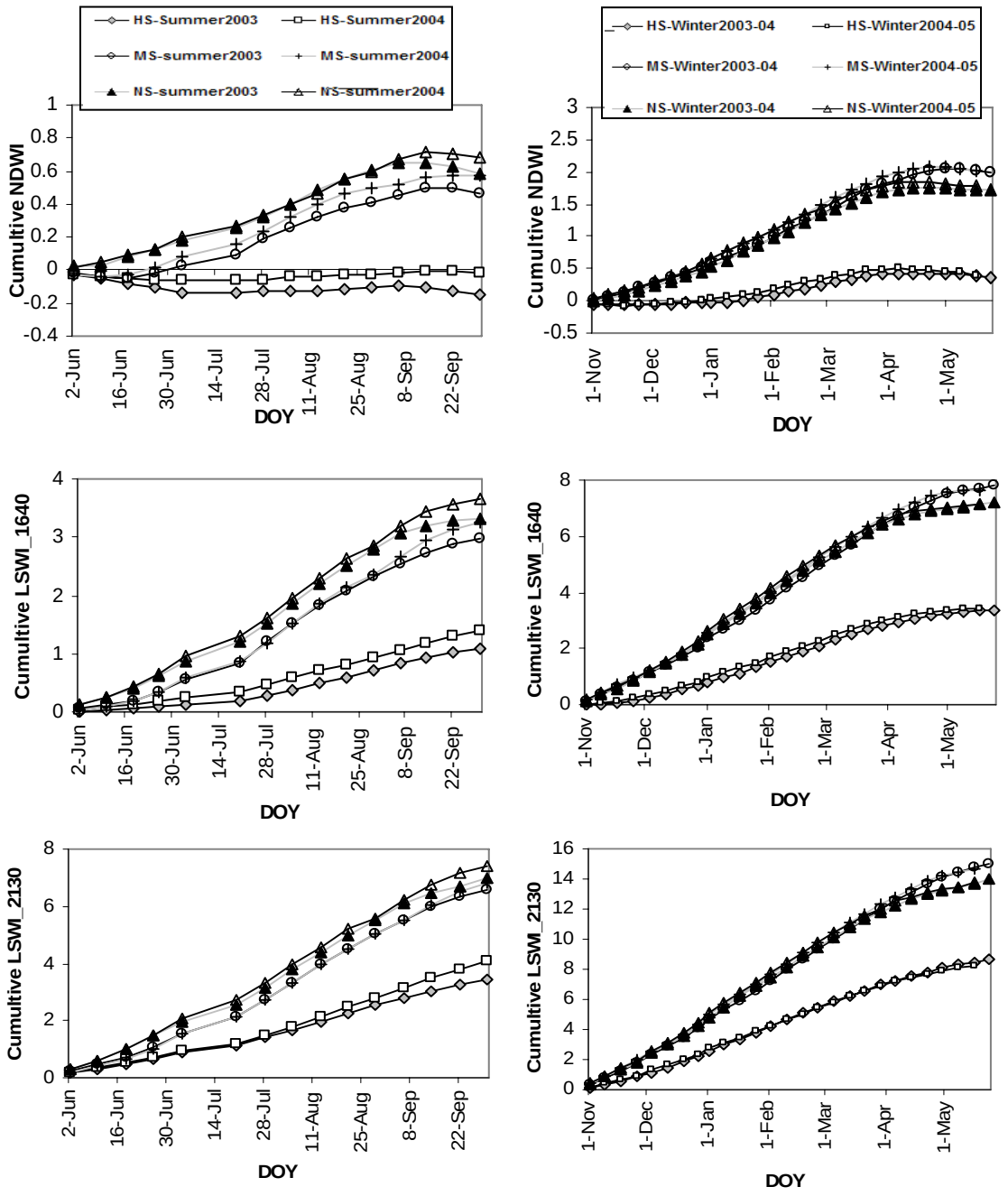

Figure 9: The cumulative response curves of (a) NDWI and (b) LSWI_1640, and LSWI_2130 for highly saline (HS), moderately saline (MS) and none saline (NS) for summer and winter seasons (2003-05).

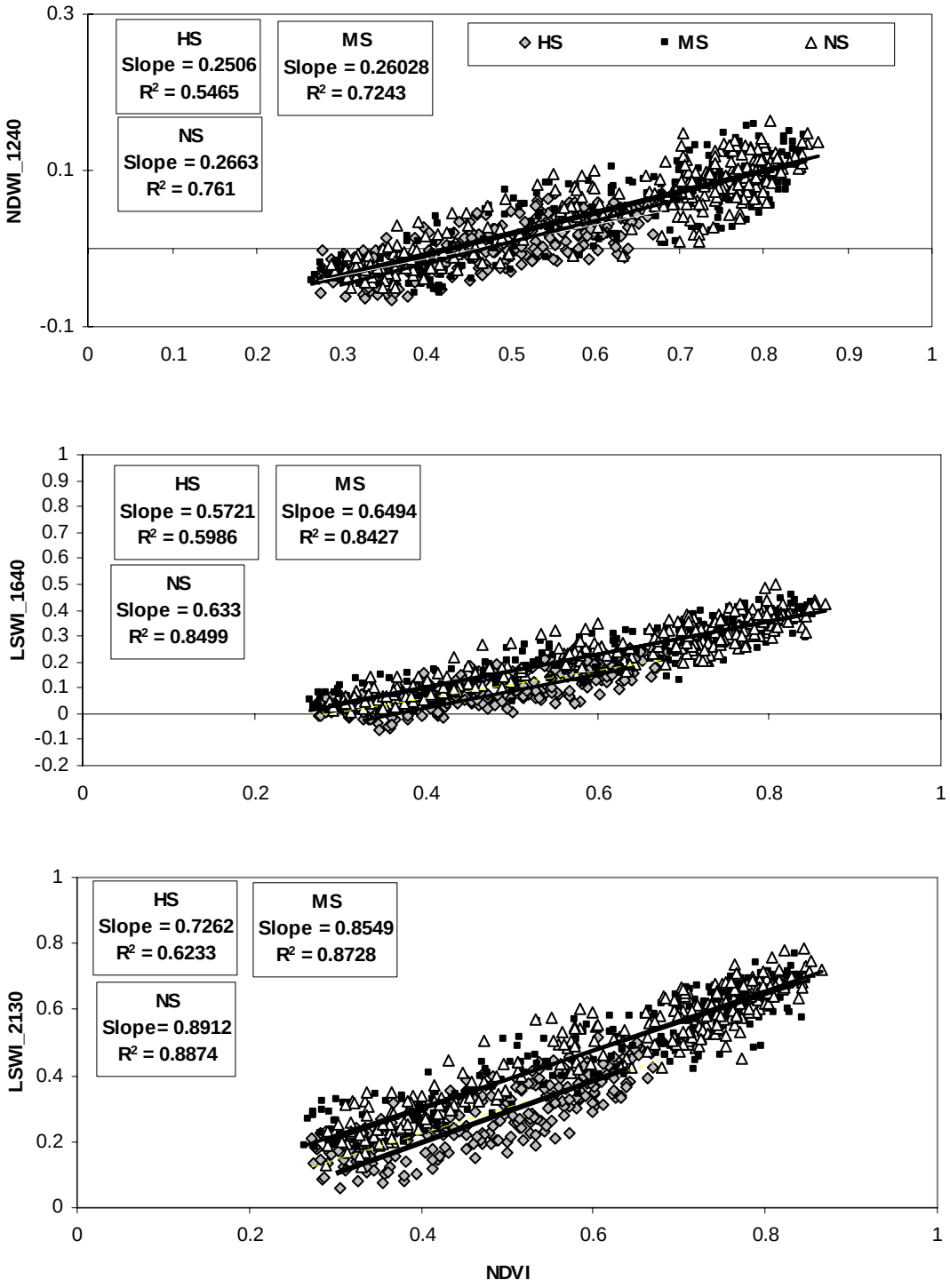

Figure 10: NDVI-WI's scatterplots over 3 different sites; highly saline (HS) moderately saline (MS) and non saline (NS).

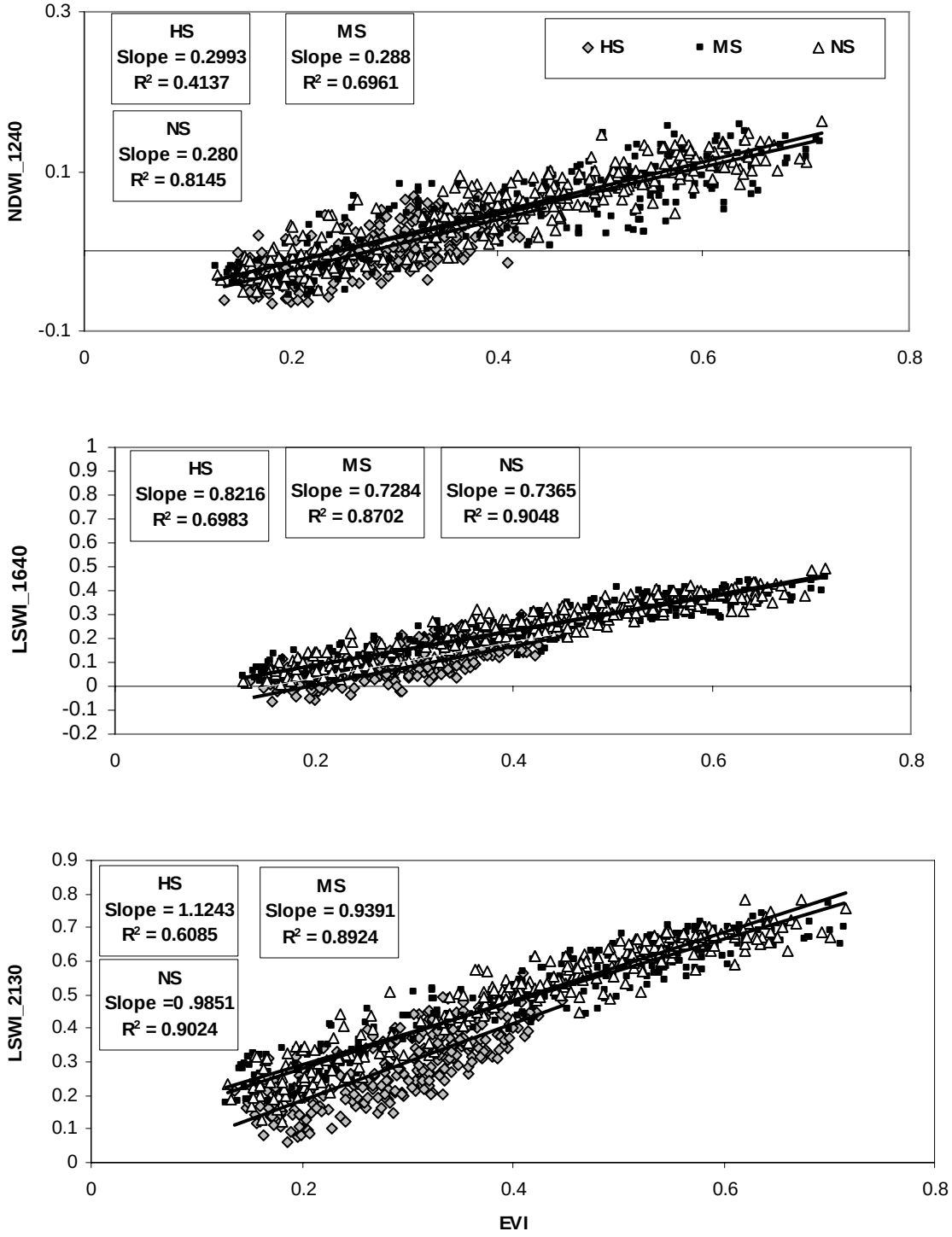

Figure 11: EVI-WI's scatterplots over 3 different sites; highly saline (HS) moderately saline (MS) and non saline (NS).

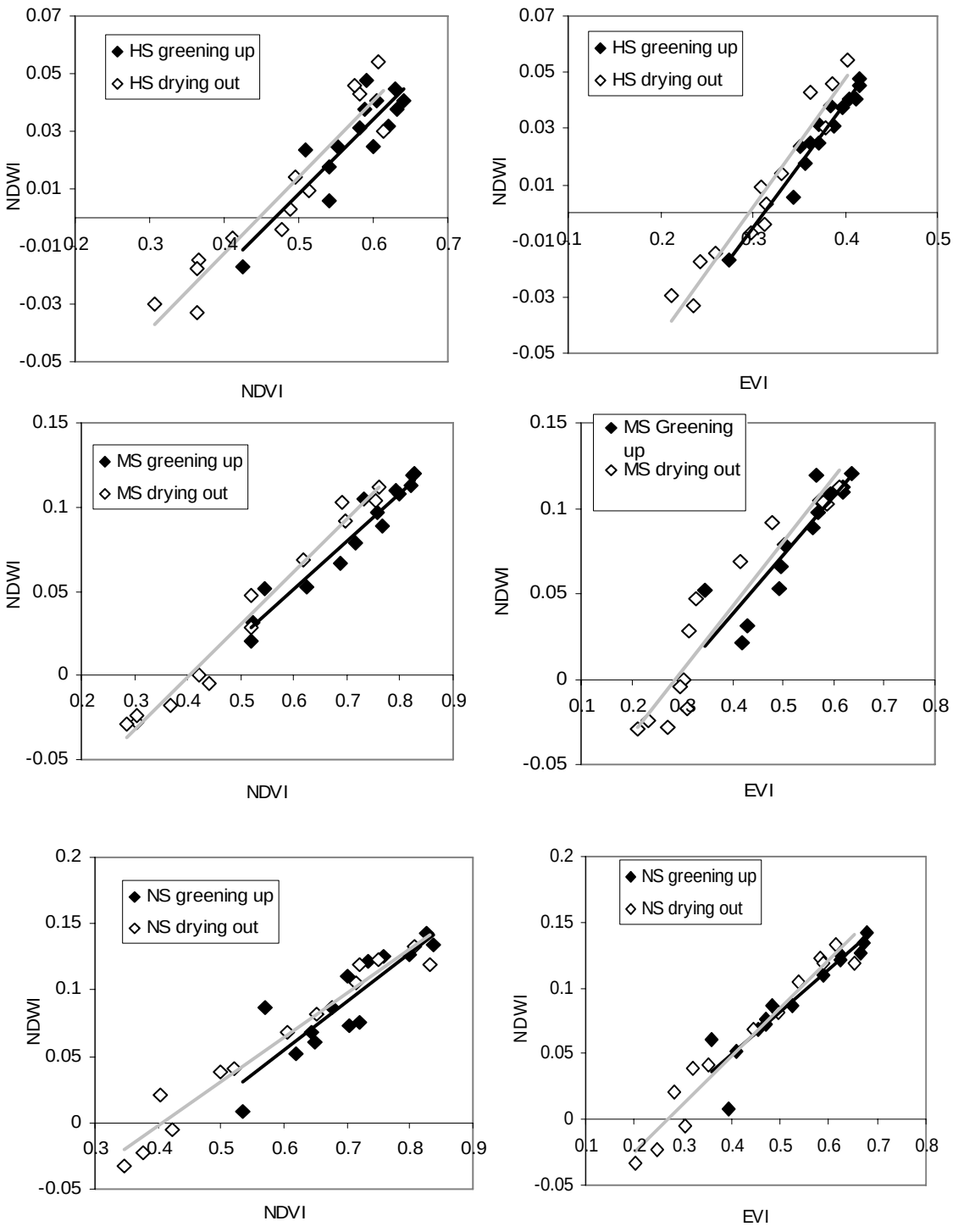

Figure 12: VI-NDWI scatterplots over 3 different sites that have different salt contents during the greening up and drying out periods in winter season.

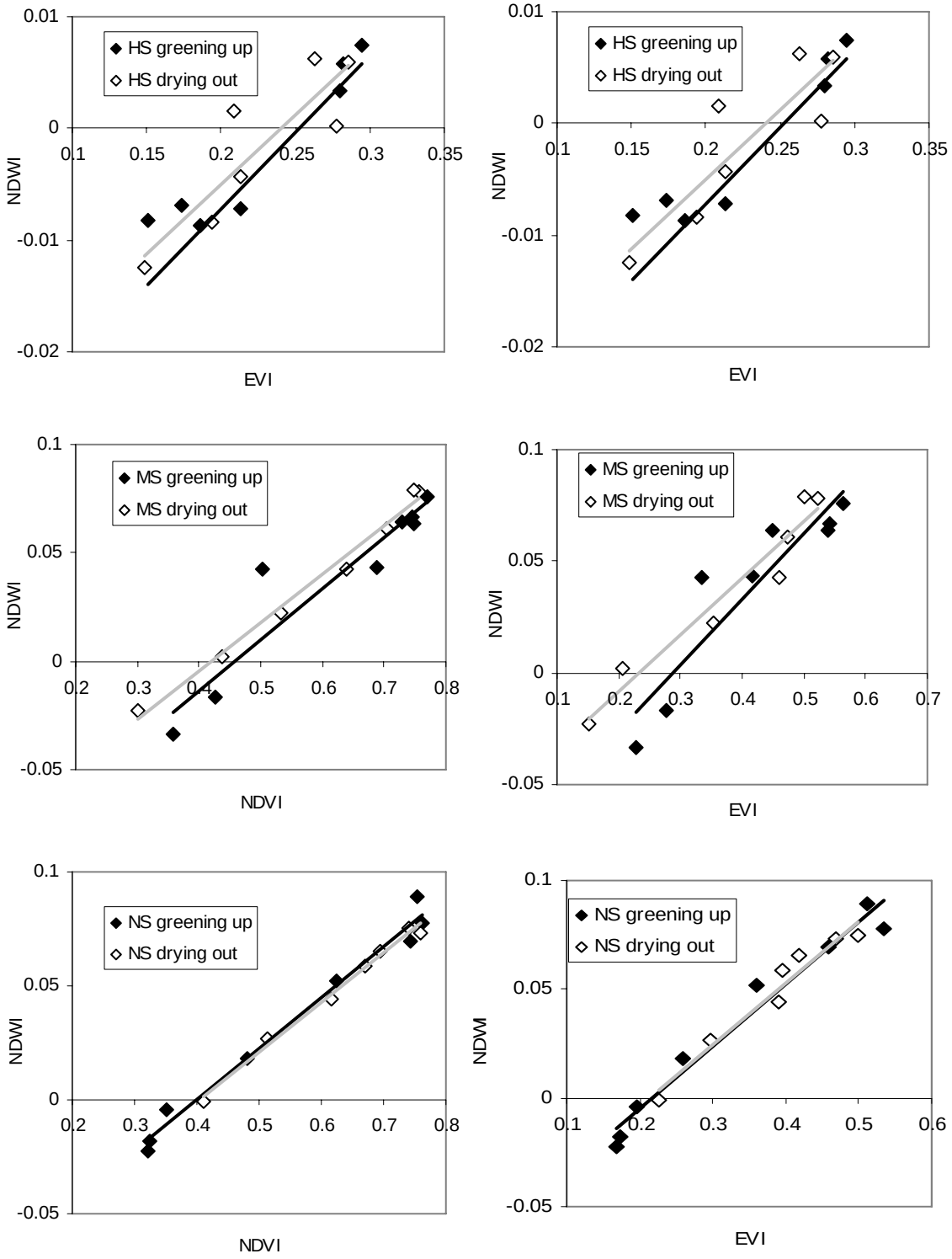

Figure 13: VI-NDWI scatterplots over 3 different sites that have different salt contents during the greening up and drying out periods in summer season.

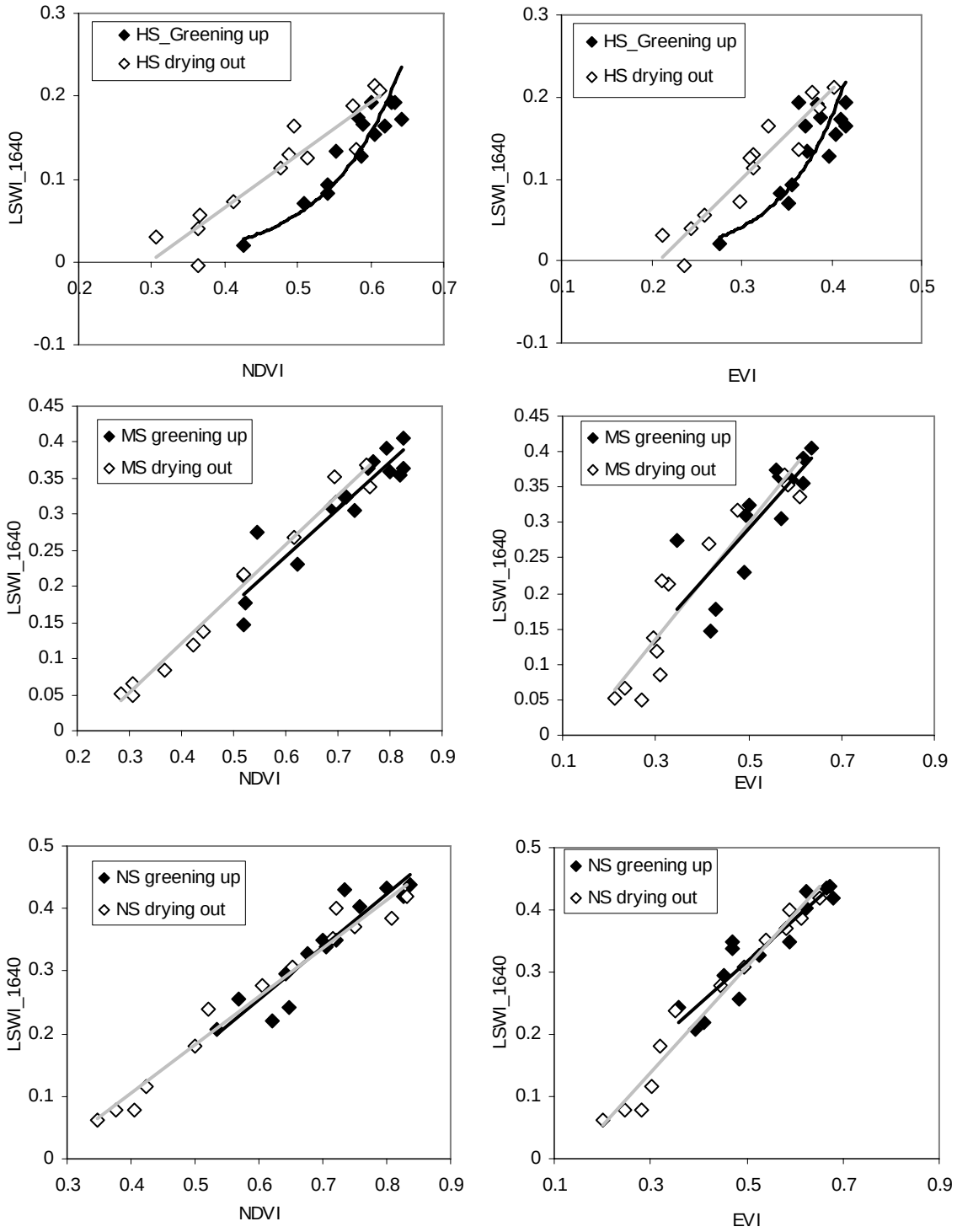

Figure 14: VI-LSWI(1640) scatterplots over 3 different sites that have different salt contents during the greening up and drying out periods in winter season.

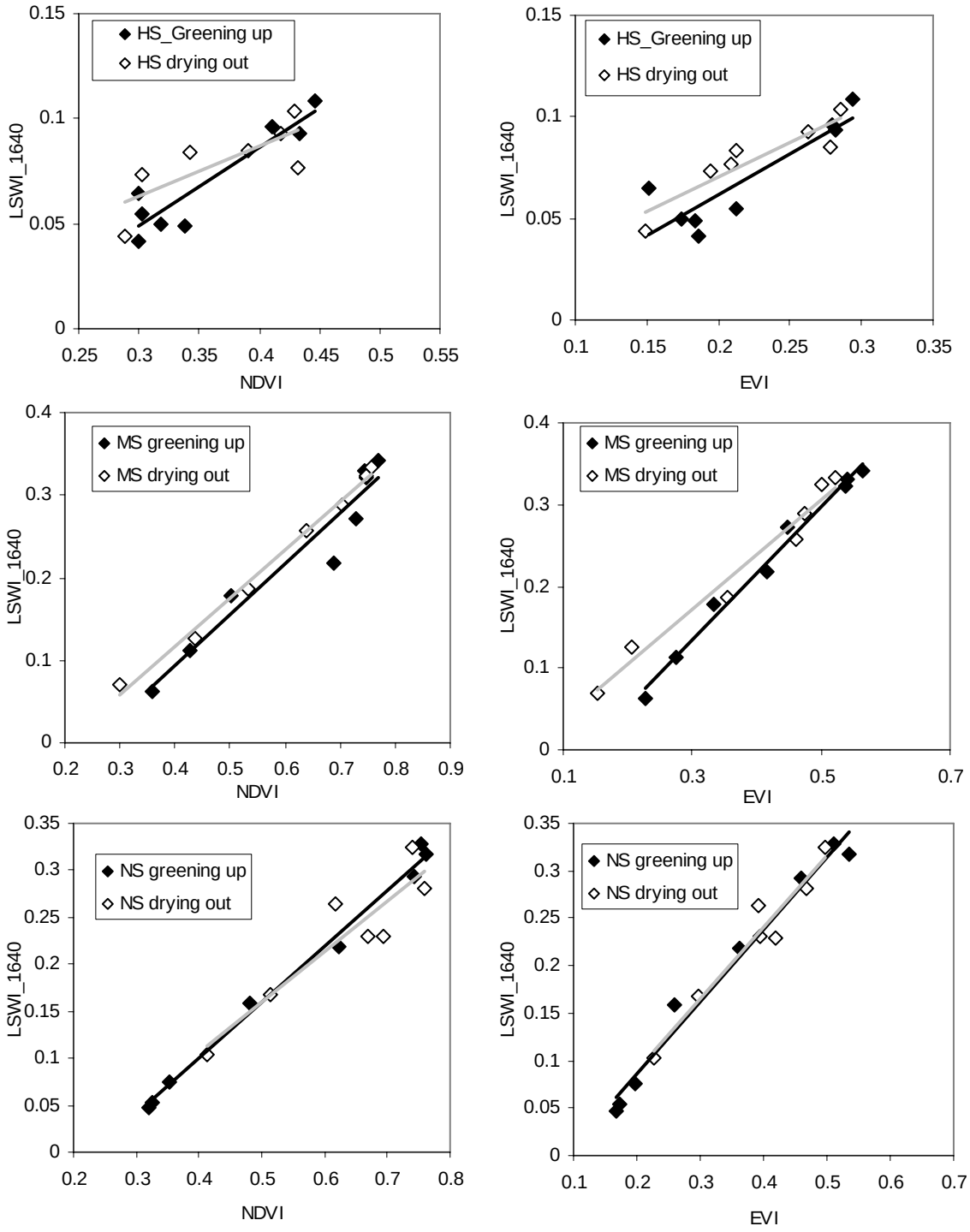

Figure 15: VI-LSWI(1640) scatterplots over 3 different sites that have different salt contents during the greening up and drying out periods in summer season.

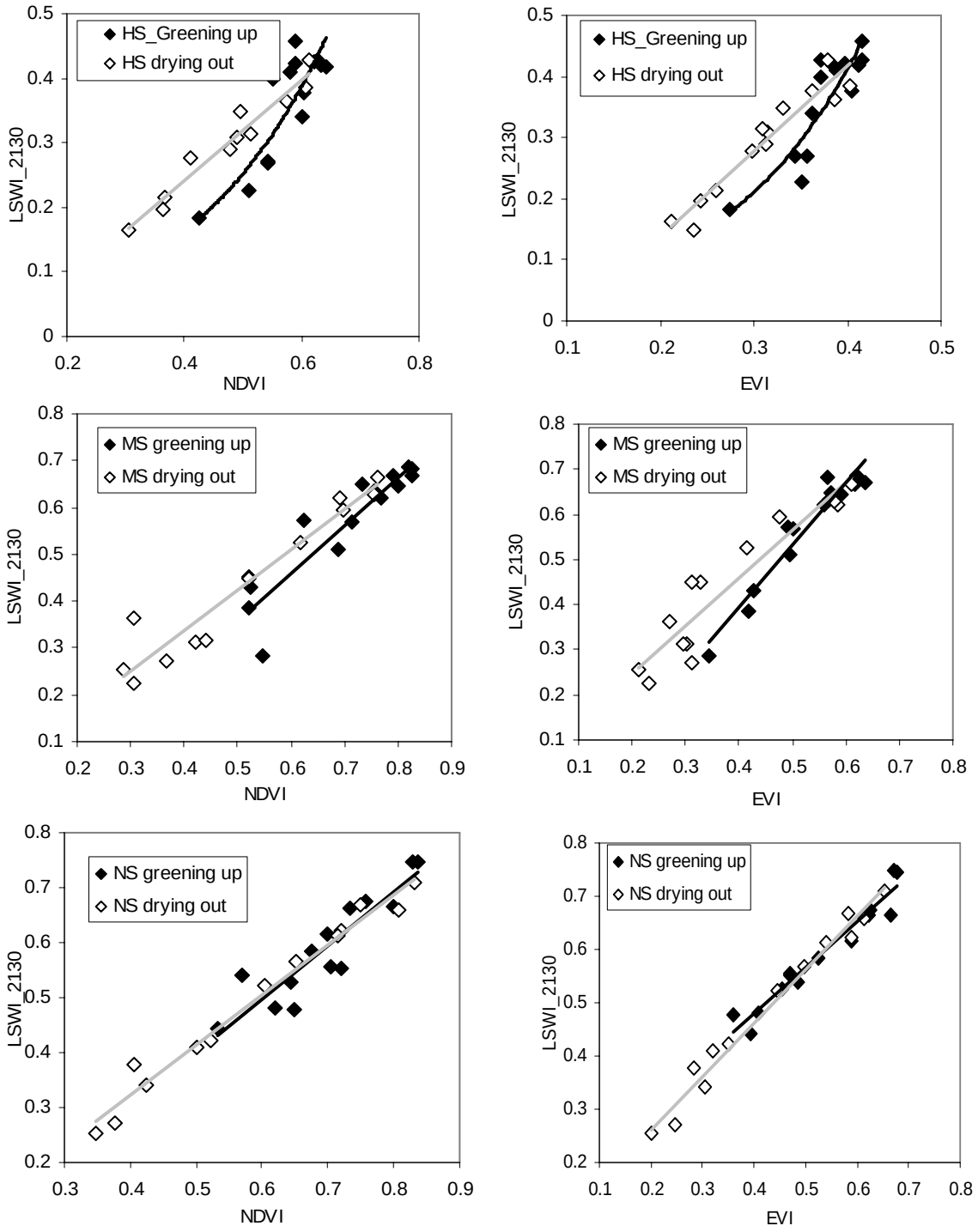

Figure 16: VI-LSWI(2130) scatterplots over 3 different sites that have different salt contents during the greening up and drying out periods in winter season.

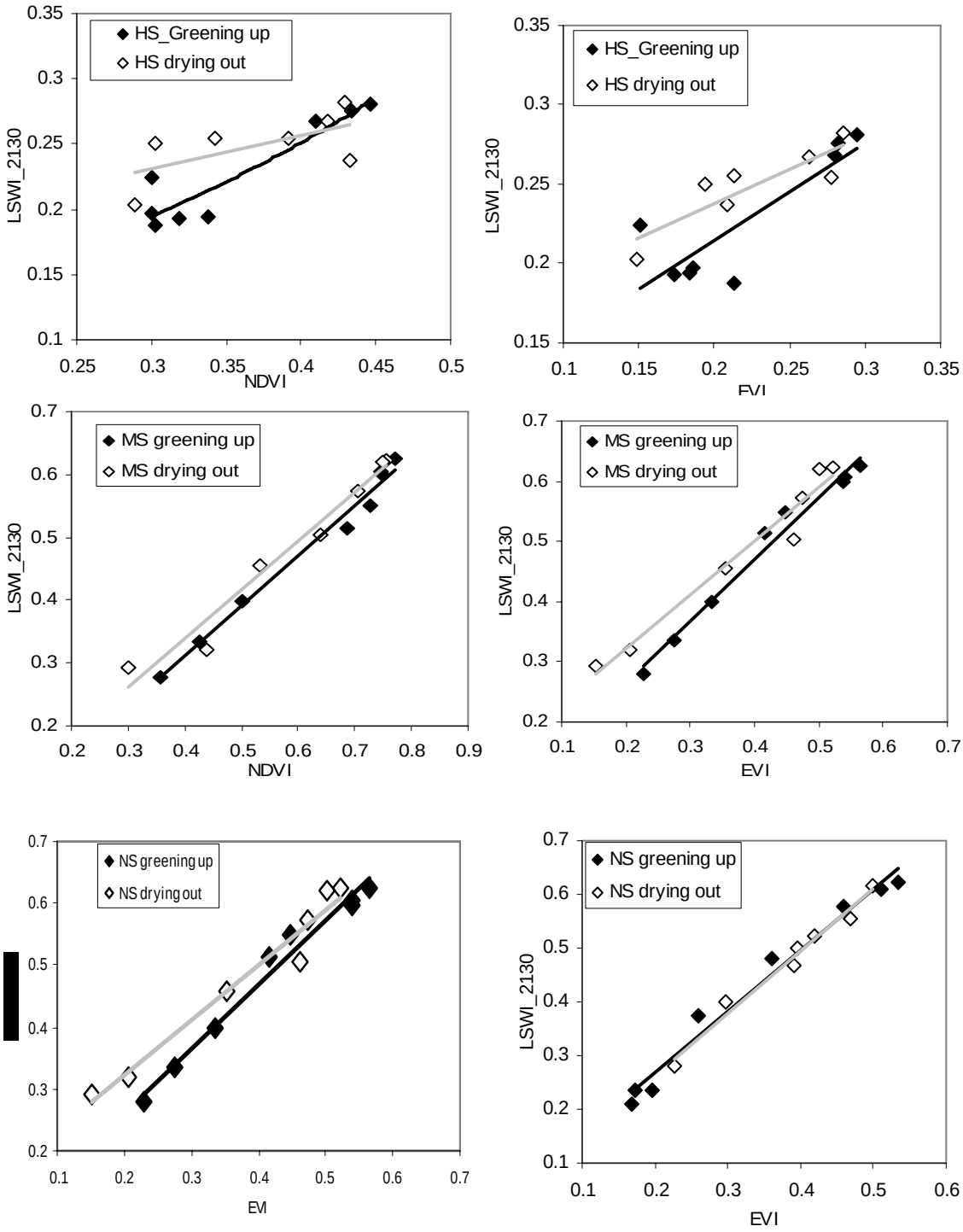

Figure 17: VI-LSWI(2130) scatterplots over 3 different sites that have different salt contents during the greening up and drying out periods in summer season.

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