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REMOTE SENSING FOR ESTIMATING SOIL SALINITY[a]

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INTRODUCTION

Many soils in arid areas of the world are affected by high water tables and resultant soil salinity. Detection of the saline areas and of the degree of salinity in the rooting profile is of considerable interest to agricultural workers involved in reclamation of these soils. Early detection of saline areas may permit preventive measures before significant crop damage is apparent. Furthermore, rapid detection of saline areas, using advanced methods and procedures can greatly accelerate initiation of reclamation processes.

Aerial photography has been used for detailed study of forest vegetations and for many other purposes.[4,5] Recently, Myers, Ussery, and Rippert[6] used black and white infrared aerial photography for detection of drainage and salinity problems.

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[4] American Society of Photogrammetry, "Manual of Photographic Interpretation," George Banta Co., Inc., Menasha, Wis., 1960, 868 pp.

[5] Schulte, D. W., "The Use of Panchromatic, Infrared and Color Aerial Photography in the Study of Plant Distribution," Photogrammetric Engineering, Vol. XVII, No. 5, 1951, pp. 688-712.

[6] Myers, V. I., Ussery, L. R., and Rippert, W. J., "Photogrammetry for Detailed Detection of Drainage and Salinity Problems," Transactions, ASAE, Vol. 6, 1963, pp. 332-334.

This paper describes the application of aerial photo interpretation using Ektachrome infrared aero film for estimating the severity and extent of salt-affected areas at a number of sampling sites in cotton fields on non-irrigated farms in the Lower Rio Grande Valley. The farms lie in an area affected by a seasonally high water table. In addition, leaf temperature measurements of cotton plants affected by various degrees of salinity are shown.

SALINITY IN RELATION TO REFLECTANCE AND LEAF TEMPERATURES

Excessive soluble salt concentrations in the plant root zone affect plant growth in many ways. The most common of these is the restricted water uptake by plant roots resulting from increased osmotic pressure of saline solutions.[7,8] Specific ion toxicity can also affect plant growth and appearance. However, Chang and Dregne[9] suggest that cotton is so tolerant to toxic ions that unfavorable environmental conditions resulting from excess salts generally limit growth and yields before ion toxicity.

Plants are frequently good indicators of conditions that occur below the soil surface. These conditions are manifested in plant appearance and spectral reflectance from leaf surfaces. The root systems of plants explore a rather large soil volume. A plant sample, therefore, is more representative of the site conditions than is a single soil sample.

Cotton growing in saline areas exhibits marked visual symptoms of moisture stress. An examination of salinity effects on plant appearance and of the light reflectance properties of plant leaves was reported in a previous paper.[6] The earlier study related spectral reflectance from cotton leaves, measured by a recording spectrophotometer, to soil salinity from field sites. These studies utilized the near-infrared part of the spectrum to approximately 0.95 micron—the limit of sensitivity of aerial infrared photographic film.

The measurement of plant leaf temperatures offers another possible technique for detecting the occurrence and extent of soil salinity. The specific capacity of the plant surface to absorb radiation, together with a number of other properties regulating the dissipation of incident radiation energy, influence the temperature of the plant.[10] Such properties are the ability of leaves to turn their leaf surfaces toward incoming solar radiation, the anatomical structure of the leaves, plant mechanisms that limit transpiration, transpirational cooling of the leaves, and the capacity for releasing a certain amount of heat in physiological processes, such as respiration. In the case of plants affected by salinity, physiological changes in leaves may influence leaf temperature.

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[7] Bernstein, Leon, and Hayward, H. E., "Physiology of Salt Tolerance," Annual Review of Plant Physiology, Vol. 9, 1958, pp. 25-46.

[8] Gingrich, J. R., and Russell, M. B., "A Comparison of the Effects of Soil Moisture Tension and Osmotic Stress on Root Growth," Soil Science, Vol. 85, 1957, pp. 185-194.

[9] Chang, C. W., and Dregne, H. E., "Effect of Exchangeable Sodium on Soil Properties and on Growth and Cation Content of Alfalfa and Cotton," Proceedings, Soil Science Soc. of Amer., Vol. 19, 1955, pp. 29-35.

[10] Molga, M., "Agricultural Meteorology—Part II: Outline of Agrometeorological Problems, Meterologia Rolnicza," published for the Natl. Science Foundation and the Dept. of Agric. by the Centralny Instytut Informacji Naukowo-Technicznejl Ekonomicznej, Warsaw, Poland, 1962.

Salinity may influence leaf color, physiological structure, leaf thickness, and other properties. It is well known that plant leaves do not absorb the total radiant energy that strikes their surface. The major part of incident radiation is reflected by the leaf surface or passes through the leaf. The amount of energy lost in this way depends on the leaf thickness, the smoothness of leaf surface, the intensity of leaf coloring, etc.[10] Only a small percentage of the energy absorbed by plant leaves is used in the photosynthetic process. Approximately 90% of it is converted into thermal energy and is used for transpiration and for raising the leaf temperature. It is then radiated outward to the environment of the plant in the form of longwave (thermal) radiation.

The specific physiological or anatomical changes that take place in cotton plants affected by various degrees of salinity and their influences on leaf temperatures are not known. Some of the changes that obviously take place, such as intensity of leaf coloring, and probably leaf thickness, have been mentioned as affecting the amount of energy absorbed or lost by leaves. Molga[10] describes an experiment performed by A. Made who obtained temperature records of the fleshy, hard leaf of Bilbergia nutans, the temperature of the thin leaf of Plectranthus fruticosus, and a curve for the temperature of the air surrounding the leaves. During midday, leaf surfaces were 10°C warmer than the air. The fleshy, thicker leaf, having greater thermal inertia, showed delayed reaction to temperature variations and its temperature extremes were slightly lower than those in the thin leaf.

Several investigators have found significant temperature differences among plants subjected to differential moisture stress.[11,12] It is well known that plants having abundant soil moisture in the root zone transpire more rapidly than plants having inadequate moisture for plant growth.

INFRARED THERMOMETRY

According to Tanner,[13] it has been difficult in the past to determine the temperature difference between plants or between plants and air because there has been no satisfactory way of defining and measuring plant temperatures. Developments in infrared thermometry in recent years have provided instruments that accurately measure radiation from plant leaf and other surfaces. Such instrumentation surmounts the sampling problem by integrating into a single measurement the thermal radiation from all plant surfaces in the field of view of the instrument. Then, also, the temperature sample from the radiated upper part of the plant should give emphasis to the parts of the plant participating most actively in transpiration.

An infrared radiometer can be used on the ground to measure temperatures over a wide spectral range. However, measurement of temperatures from aircraft presents a problem because of atmospheric interference. Fortunately, the atmosphere offers several "windows" for energy transmission in the infrared spectrum. One particularly good window occurs between 8 and 14

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[11] Curtis, Otis F., "Wallace and Clum 'Leaf Temperature': A Critical Analysis with Additional Data," American Journal of Botany, Vol. 25, 1938, pp. 761-771.

[12] Strogonov, B. P., Kleshain, A. F., and Ivanitskaya, Ye. F., "On the Temperature of Cotton Leaves with Different Types of Soil Salinity and Varying Water Supply," Doklady Adak. Nauk., SSSR, Vol. 93, No. 1, 1953, pp. 179-182.

[13] Tanner, C. B., "Plant Temperature," Agronomy Journal, Vol. 55, 1963, pp. 210-211.

microns in which energy is transmitted freely.[14] It is in this range that most infrared radiometers and thermometers operate.

PHOTOGRAPHIC FILMS FOR REFLECTANCE STUDIES

A previous salinity study involving photogrammetry[6] utilized black and white infrared film and a camera with an 89-A dark-red filter. However, black and white photographs record reflectance only as tones of gray, rather than true shades of gray and variations of color as seen by the human eye. In black and white photography, the limitation inherent in reproductions of only monochromatic gray tones can be partly overcome by specific film-filter combinations that increase tonal contrasts between salinity conditions. Even with this increased tonal contrast, the final result will be registered in a relatively limited range of black, gray, and white tones of which the human eye can distinguish only about 100 to 300. It is possible to make accurate distinctions between about 200,000 colors on the basis of hue, value, and chroma.[5] Hue means the specific wavelength pattern of the color. Value is the brightness or degree of blackness or whiteness, and chroma is the brilliance or color saturation.

A false-color film has been developed that is sensitive in the near-infrared wavelength range where reflectance differences due to soil salinity are most pronounced. The principles of false-color systems were used during World War II for camouflage detection. This film, now referred to as Ektachrome infrared (IR) aero film, has three layers: one layer is infrared sensitive, another is green sensitive, and the third is red sensitive.[15] The film emphasizes the infrared reflection of healthy green vegetation that appears bright red or pink on the photographs. Cotton plants affected by salinity appear as darker shades of red and, when seriously affected, nearly black.

Ektachrome IR photos permit making a distinction betwen vegetation and soil which is not always possible using black and white photos. It is especially useful where vegetation is sparse because the bright color of vegetation, as it appears on the photos, simplifies the identifications of living plants in contrast to the background. On black and white photos, the background can be of approximately the same shade as that of the plants, making photo interpretation difficult.

METHODS AND MATERIALS

Four dryland cotton farms in an area affected by a seasonally high water table and resultant salinity were selected as reference farms for the study. Soil salinity on any given farm varies widely from unaffected to severely affected soils. Soil sampling sites were located by visual selection on these farms to give a gradation in plant appearance and degree of salinity. Twenty sites were selected on the four farms.

Five farms were selected for prediction tests which were similar to the reference farms in that they each had a wide range of salinity-affected cotton.

[14] Suits, G. H., "The Nature of Infrared Radiation and Ways to Photograph It," Photogrammetric Engineering, Vol. XXVI, No. 5, 1960, pp. 763-772.

[15] Tarkington, Raife G., and Sorem, Allan L., "Color and False-Color Films for Aerial Photography," Photogrammetric Engineering, Vol. XXIX, No. 1, 1963, pp. 88-95.

Twenty-five random prediction sites were located to give a wide variation of soil salinity.

Soil samples were taken from two holes at each reference and prediction site at depth increments of 0-1, 1-2, 2-3, 3-4, and 4-5 ft. The samples from each hole for a given depth increment were combined for each sampling site. Soil samples were analyzed for moisture content and for electrical conductivity of the saturation extract (EC_e).

Aerial photographs were taken simultaneously with the soil sampling so they could be used for prediction of salinity. An 1,800-acre area was included in the photographs. A K-17 aerial camera with a 6-in. lens was used. The plants were photographed from an elevation of 1,500 ft. Ektachrome infrared aero film, which requires a No. 12 yellow filter to eliminate the blues and a special color balancing filter provided with each roll of film, was used. Photos were made in sequence to produce a 60% overlap in successive exposures so that they could be examined stereoscopically.

Previous soil analyses and film transparency examinations were used to establish salinity groupings of the reference sites. On the basis of the reference sample salinity groupings, the salinity levels of prediction sites were estimated. The soil salinity prediction observations were made from the film transparencies. A magnifying glass and a stereoscope were used in examining the sites on the film. A stereoscope is useful for delineating salinity areas; however, examination of the sites for prediction purposes in this study was not necessarily made using a stereoscope. Film transparencies of both reference and prediction sites were examined to estimate salinity of prediction sites.

Plant temperatures were measured using a Stoll Hardy[16] infrared radiometer. (Trade names and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the United States Department of Agriculture.) With this instrument the target temperature is compared against the temperature of a built-in aluminum block with black body cavity. The radiometer's sensing element was held a few inches away from the leaf surface. The leaf temperature is obtained by adding deflection of an ammeter calibrated in degrees centigrade to the reference block temperature, as indicated by a precision thermometer inserted into it. To avoid including the cooler interior part of plants in the field of incidence of the sensing element, it was necessary to measure the temperature of individual leaves. Several such individual measurements were averaged to arrive at the temperature for a particular site. Leaf temperatures were measured at 20 sites on two dates in 1964 and at 21 sites on a single date in 1963. The 1964 sites were the same as some of those used for the photogrammetry studies, and the 1963 sites were in the same general area.

RESULTS

In establishing a correlation between photographic color contrast and the average salinity (EC_e) in the profile, the depth increment of 0 ft to 5 ft was selected, on the basis of statistical studies, as the critical soil zone affecting plant color and height. The sites on the reference farms were arranged into

[16] Gates, D. M., "Energy Exchange in the Biosphere," Harper and Row, Publishers, New York, N. Y., 1962, pp. 86-89.

five salinity ground (numbered 1 to 5) based on visual observation of the photographs. The higher the number, the higher is the degree of salinity (see Table 2). A salinity group includes the range of average salinity values in the 0-ft to 5-ft profile emcompassing the sites included in the group. The 25 prediction

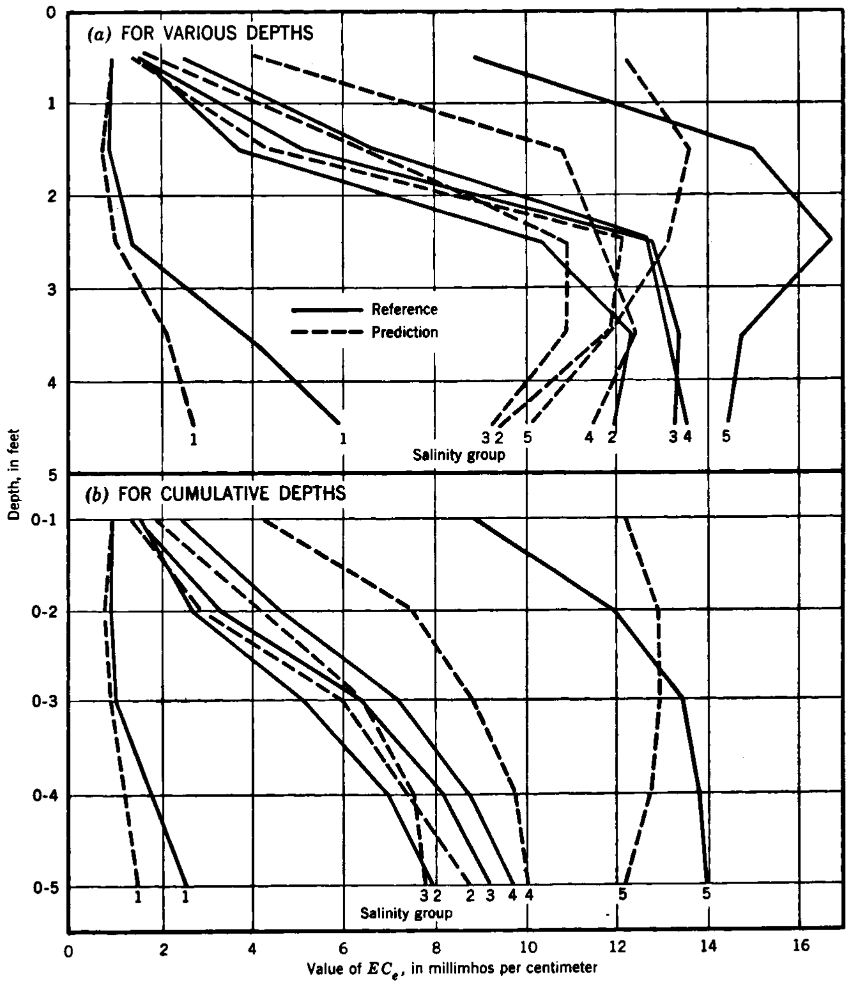

FIG. 1.—AVERAGE SALINITY LEVEL (EC_e)

sites were then classed in the five groups, based on visual comparison of these sites with the reference sites. A sixth group was identified on aerial photos as bare soil, which was higher in salinity than the five groups representing salinity-affected cotton

The salinity level (EC_e) was averaged by 1-ft increments for the reference and for the prediction sites. This average salinity level increased with depth to 3 ft in both reference and prediction soils. In some cases, particularly in prediction soils, the salinity level decreased from 3 ft to 5 ft (Fig. 1).

The salinity level was also averaged for both the reference and prediction sites on a cumulative basis. This was accomplished by averaging the EC_e for the 0 to 1, 0 to 2, 0 to 3, 0 to 4, and 0 to 5-ft depths. On this

TABLE 1.—STATISTICAL COMPARISONS OF EC_e LEVELS

Salinity groups						
Reference	Predicted	*t*	Significance[a]	Salinity groups reference	*t*	Significance
(a) Salinity level averaged at each foot						
1	1	1.713	NS[b]	2 versus 1	3.025	S[c]
2	2	0.413	NS	3 versus 2	3.015	S
3	3	1.334	NS	4 versus 3	1.546	NS
4	4	-0.353	NS	5 versus 4	3.008	S
5	5	1.270	NS			
(b) Salinity level cumulatively averaged over depths						
1	1	1.810	NS	2 versus 1	3.528	S
2	2	-1.051	NS	3 versus 2	3.152	S
3	3	0.299	NS	4 versus 3	2.992	S
4	4	-3.637	S	5 versus 4	11.30	S
5	5	-0.223	NS			

[a] Significance was evaluated at the 5% level.
[b] NS = nonsignificant.
[c] S = significant.

TABLE 2.—MINIMUM AND MAXIMUM EC_e VALUES

Salinity group	Reference		Predicted	
	Minimum	Maximum	Minimum	Maximum
	in millimhos per centimeter			
1	1.03	3.80	0.61	4.45
2	7.39	8.30	5.62	9.72
3	7.71	10.55	5.78	9.35
4	8.82	10.83	9.06	11.11
5	12.69	15.69	10.14	13.67

basis, the salinity level increased with depth except for the prediction sites of salinity group No. 5 where a decrease occurred below 3 ft.

The statistical *t*-test was used to determine significance of differences among salinity groupings of the reference soils and between paired reference and prediction soils within each salinity grouping. The *t*-values and the significance of differences are presented in Table 1.

The only reference soil salinity groups that were not significantly different were salinity groups 3 and 4 in which average salinity levels by each foot of depth were compared. Inspection of the curves in Fig. 1 shows that the lines for salinity groups 3 and 4 of the reference samples followed closely together. All other differences between salinity levels of reference samples for the various salinity groups were significant, indicating that the reference sites were properly selected and classified, and actually represented soils of different degrees of salinity.

Comparing the salinity levels between reference and predicted soils within each salinity group gave only one significant difference. It occurred at salinity group No. 4 for the cumulative average salinity level. This difference is evident in Fig. 1(*b*). It would probably not have occurred if more than two prediction sites had fallen in salinity group 4. With the exception of the one significant difference, the salinity level of the predicted samples is the same as that of the reference samples. Therefore, the salinity level of soil can be

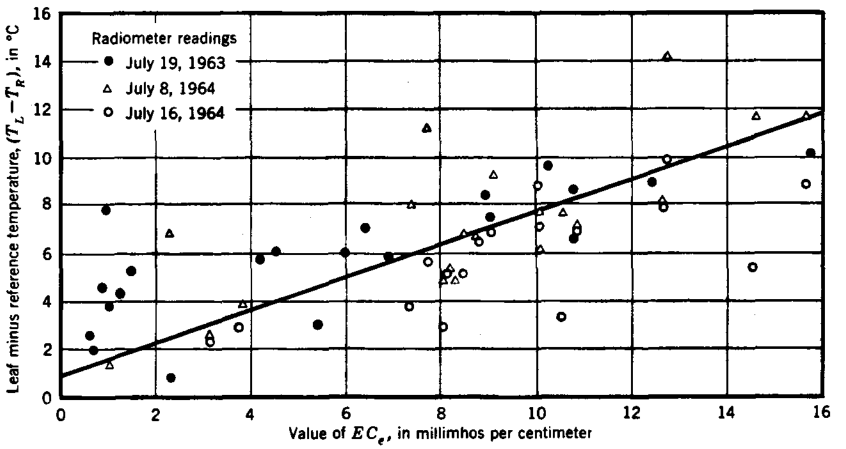

FIG. 2.—RELATION BETWEEN LEAF MINUS AMBIENT TEMPERATURE AND THE AVERAGE SOIL SALINITY (EC_e)

predicted successfully within a certain range by the aerial photography technique.

The minimum and maximum EC_e values of the 5-ft profiles for both reference and prediction sites are given in Table 2. In general, the range in EC_e values for reference and prediction sites is on the same order of magnitude. Furthermore, the ranges for each salinity group differ markedly except for salinity groups 2 and 3 of the prediction sites.

Three different predictors agreed remarkably well in predicting the salinity level on the basis of plant growth as indicated by the colored film transparencies. Only in 4 of 25 sites did the predictors disagree. In every case at least two predictors agreed, and the other only disagreed by one salinity grouping.

The soil salinity level is highly correlated with the cotton leaf temperature at any particular site. A regression relationship between leaf minus reference temperature (T_L - T_R) and the average soil salinity level in the 5-ft profile is illustrated in Fig. 2. The value

$$T_L - T_R = 0.927 - 0.692\ (EC_e)$$

and r = 0.839 in which r is significant at the 1% level. The data include temperature measurements made on a single date in 1963 and on two dates in 1964. Similar relationships were established for the average salinity level of the upper 3-ft profile for all three dates together and separately and for the 5-ft profile at the three dates separately. The regression equations and correlation coefficients are given in Table 3. All of the analyses gave significant regression and correlation coefficients. The data indicate that soil salinity can be predicted from cotton leaf temperature with reasonable accuracy.

TABLE 3.—REGRESSION COEFFICIENTS, INTERCEPTS, AND CORRELATION COEFFICIENTS[a]

Date of Temperature Measurement	Depth[b] in feet	a, in °C	b	r	r^2
			°C per millimho per centimeter		
July 19, 1963	0-3	3.877	0.452	0.829	0.687
July 8, 1964	0-3	3.625	0.550	0.750	0.562
July 16, 1964	0-3	2.982	0.380	0.676	0.457
All dates together	0-3	3.497	0.453	0.782	0.611
July 19, 1963	0-5	3.692	0.419	0.805	0.648
July 8, 1964	0-5	1.855	0.627	0.760	0.578
July 16, 1964	0-5	0.988	0.512	0.756	0.571
All dates together	0-5	0.927	0.692	0.893	0.798

[a] Regression equations are $(T_L - T_R) = a + b\ (EC_e)$,
in which $(T_L - T_R)$ = leaf minus ambient temperature, °C.,
a = intercept on y-axis, °C.,
b = regression coefficient, °C per MMHO per CM,
EC_e = salinity level, MMHO per CM, and
r = correlation coefficient.
[b] Depth over which EC_e was averaged.

Plant height was also measured and statistically analyzed for differences between salinity groups. Average heights in inches were 60.0_a, 47.0_b, 40.5_{bc}, 34.0_c, and 17.0_d for salinity ratings of 1 through 5, respectively. Values followed by the same letter do not differ significantly at the 0.05 probability level.

Some plant temperature measurements were made with the radiometer from a circling aircraft; however, there were not enough of these measurements to permit including them in the statistical studies. In general, however, the aerial measurements agreed well with the ground measurements, except where plant growth was sparse permitting the radiometer to measure soil surface temperatures.

Measuring plant temperatures from the air integrates plant temperatures over a larger area than is possible with ground measurements, and eliminates

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KEY WORDS: aerial photography; color (materials); infrared radiation; irrigation; photogrammetry; salinity; surface temperature

ABSTRACT: Cotton was used as an indicator plant to relate the salinity in the 0 to 5 ft profile at some reference locations to that at a number of prediction sites where the salinity was unknown. Aerial photographs were taken using ektachrome infrared aero film for observing the salinity-affected cotton. On the basis of color tones, it was possible to distinguish five levels of salinity. The levels of salinity significantly affected photographic features, making it possible to estimate with reasonable accuracy the degree of salinity in the soil profile from interpretation of film transparencies. Infrared radiometer measurements of cotton leaf temperatures were made on the ground and from an airplane. The limited aerial measurements compared favorable with ground measurements. Statistical studies of the temperature data taken on the ground indicate that soil salinity can be predicted from cotton leaf temperatures with reasonable accuracy.

REFERENCE: Myers, Victor I., Carter, David L., and Rippert, William J., "Remote Sensing for Estimating Soil Salinity," Journal of the Irrigation and Drainage Division, ASCE, Vol. 92, No. IR4, Proc. Paper 5040, December, 1966, pp. 59-68.