Kenneth R. Piech
J. E. Walker
Calspan Corporation
Buffalo, N.Y. 14221

Interpretation of Soils*

Additional information on site soil characteristics can be extracted from conventional color aerial imagery through careful analysis of image photometric properties.

Introduction

Aerial photographic soil surveys have traditionally been based upon landform analyses and visual evaluation of the tonal properties and spatial patterns of soil elements. Although these techniques have proven quite successful, the interpreter frequently cannot evaluate soil properties to the accuracy or extent desired.

Abstract: *Conventional photointerpretation techniques such as landform analyses can be usefully supplemented by photometric information extracted from color imagery. For example, the interpreter can use a reflectance ratio obtained from the red and blue spectral bands of the color image to delineate relative soil moisture and texture patterns. If the darker soil element has a greater red-to-blue reflectance ratio than the lighter soil element, the tonal variation between the soil elements is caused principally by moisture. If the darker soil element has a smaller red-to-blue reflectance ratio, the soil elements differ principally due to texture. To perform the ratio analyses, the interpreter must relate soil image densities to reflectances by calibrating the color imagery through density variations in shadow images. The photometric calibration and interpretation can be easily accomplished using a photointerpretation console currently being developed for the Reconnaissance Applications Section, Rome Air Development Center, Department of the Air Force. The aerial camera can then be used as an accurate photometer to augment standard engineering interpretation processes.*

For example, it is often difficult to delineate soil boundaries where geometrical pattern and texture confuse the interpreter's evaluation of tonal differences. Tonal variations can also be caused by soil properties which are not of direct interest or, in the case of repetitive cover, tonal variations can be caused by peripheral effects (such as illumination, atmospheric or measurement system variations) which are unrelated to soil properties. More precise aerial survey classification of parameters such as drainage class, void ratio and bearing strength would be highly desirable, and, as suggested by this paper, may be attainable.

One promising technique for augmenting landform analyses is to use the photometric information contained in the color photograph. The camera supplying the image for landform analysis can, at the same time, be utilized as an accurate photometer through which the engineer can extend the conventional analyses. Image density fluctuations can be related to terrain reflectance variations, and then to terrain physical properties.

Reduction of image densities to terrain reflectance and physical properties requires image photometric calibration. Calibration entails use of conventional sensitometric tech-

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niques such as step wedges, and photometric interpretation of standard scene objects such as shadow areas.[1,2] Further, careful analysis of the calibrated image in terms of ratios of reflectances in different spectral bands can provide new spatial patterns which yield information not evident in the interpretation of tonal variations in a single spectral band.[2]

This paper attempts to indicate how more detailed information on relative soil moisture and texture patterns can be extracted from a conventional color photographic image through ratio analysis of image photometric information. Specifically, moisture and texture gradients can be delineated (i.e., discriminated and ordered) through ordering of such ratios. The next section of the paper briefly reviews the calibration process necessary for using the camera as a photometer, and briefly describes a photointerpretation console which will enable the engineer-interpreter to perform photometric analyses quickly and accurately. The third section discusses the application of the photometric soil moisture-texture ratio analysis. The fourth section summarizes the text and relates the work to future analyses.

Reduction of Density Values to Reflectance Values

This section describes the calibration process necessary for utilizing the camera as a photometer. The calibration process entails measurement of soil element densities, and reduction of these density values to reflectances. A more complete description of the calibration process and its physical motivation may be found in References 1 and 2.

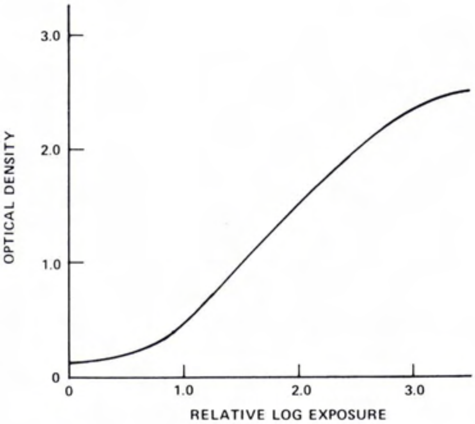

FIG. 1. A typical *D*-log-*E* curve.

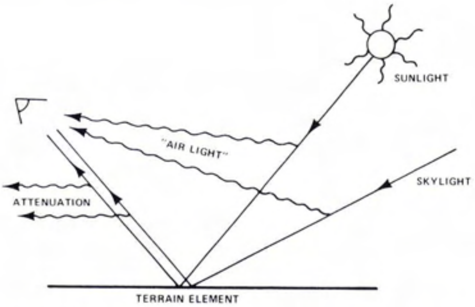

FIG. 2. Atmospheric and illumination effects involved in establishing the exposure of a scene element.

Photographic densities can be accurately measured and recorded by a number of commercially available densitometers. The film densities are, however, a function of both processing conditions and survey parameters. Processing effects can be removed through use of a step wedge which has been processed with the imagery. Densitometry of the wedge yields a density-relative exposure relationship (the *D*-log-*E* curve of Figure 1) which is effectively a film response curve reflecting the effects of film processing. The details of using a wedge and *D*-log-*E* curve are well known (at least for black-and-white imagery) and have been described elsewhere.[3] Such a *D*-log-*E* curve enables film densities to be related to the relative exposures causing the densities.

The resultant exposures, however, must still be related to terrain reflectance values. Such reduction is important because exposure depends on meteorological conditions, altitude of measurement, and illumination conditions such as proportion of sunlight to skylight, and the amount of *air light* (the contribution to exposure by illumination scattered to the camera by the air column beneath the camera). These effects are depicted in Figure 2.

All of these effects can be approximately coupled into three parameters for a given spectral band: α, α', and β.[1] The parameter α is proportional to atmospheric transmittance and total (sunlight + skylight) irradiance; α' is proportional to atmospheric transmittance and skylight irradiance; and β is proportional to the amount of air light in the scene. The exposure E in sunlight of an object with reflectance R is

$$E = \alpha R + \beta, \tag{1}$$

whereas the exposure of the same object in

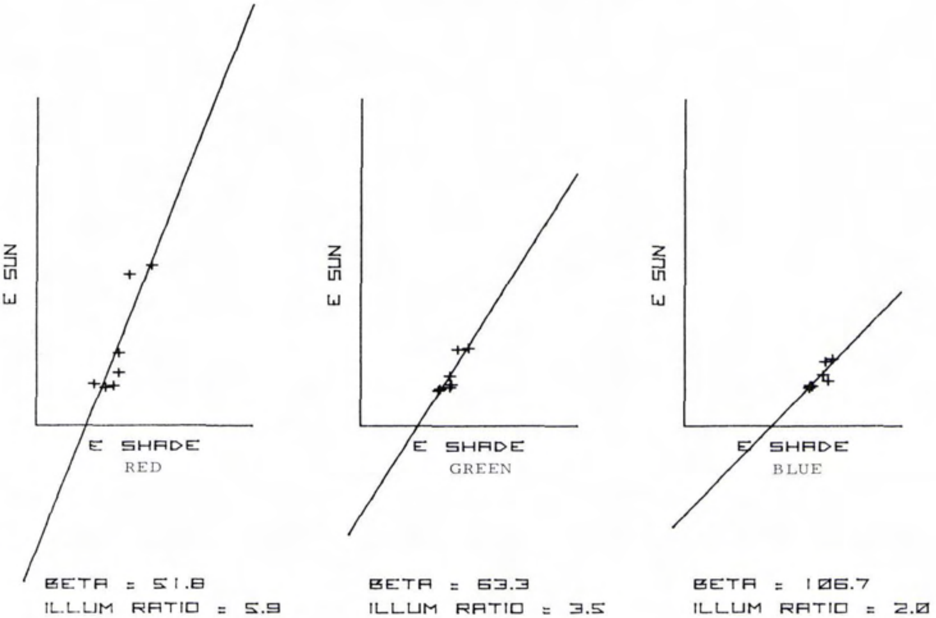

FIG. 3. Typical calibration curves for a color image at a scale of 1:40,000. The parameter "illum ratio" is δ/α' (Cf. text).

shadow, E', is

$$E' = \alpha' R + \beta. \qquad (2)$$

Color-film measurement of terrain reflectance thus requires knowledge of α, α', and β in each of the three color film bands. These parameters can be determined in a straightforward manner using a shadow calibration procedure called the Scene Color Standard (SCS) technique.[1]

Calibration is accomplished by densitometry of the illumination discontinuities at shadow edges. It is convenient to write $\alpha = \delta + \alpha'$, where δ is a term proportional to solar irradiance only. The discontinuity measured at shadow edges on two different terrain elements then determines β and δ/α' as follows.

In the sunlight just outside a shadow the exposure E is

$$E = (\delta + \alpha') R + \beta. \qquad (3)$$

The R is the terrain reflectance. Just inside the shadow the exposure E' is given by Equation 2. Equations 2 and 3 yield

$$E = (1 + \delta/\alpha') E' - \beta\ \delta/\alpha' \qquad (4)$$

Equation 4 is a linear relationship between E and E' with slope $(1 + \delta/\alpha')$ and intercept $-\beta\delta/\alpha'$. Two shadows determine the slope and intercept, and hence β and δ/α'. In practice a number of shadows are analyzed, and a least squares fit is made to the data. Figure 3 shows typical calibration curves for calibration of a color image at a scale of 1:40,000.

The essential measurement and atmospheric conditions have now been determined. One aspect remains: that of establishing an absolute level of reflectance, akin to laboratory use of a MgO standard or its equivalent. A tar or sheet asphalt scene element in sunlight (roadway, roof) is usually used to establish the value of α and complete the calibration. These elements are used as: (1) their reflectances are spectrally flat; (2) their reflectance remains constant to good approximation over the year; and (3) their reflectance can be easily estimated or measured. Other objects more appropriate for a particular survey can, of course, be used.

One minor point needs to be added for completeness. The skylight irradiance inside and outside the shadow is only some portion of the sky dome, k, due to solid angle shielding by the shadowing object. The factor k can be easily determined from metric considerations[1]. In practice at, high altitudes only larger buildings suffice for densitometry, and k is practically constant for all the structures utilized. The factor α' in Equations 1-4 should therefore be replaced by $k\alpha'$ and interpretation of the resulting values of slope and intercept so modified.

At an altitude of 10,000 feet, β can be equivalent to about a 5-10 percent reflector.[1,4] At lower altitudes, β will usually not decrease much below a 2-3 percent equivalent reflector because of camera flare, which is included in the additive light factor represented by β. It must be emphasized that the actual values of β will depend strongly on meteorological conditions, the spectral band (bandwidth, central wavelength) in which the measurement is made, and the flare characteristics of the instrument utilized. Because of the wide variation of β (and also α and α') with atmospheric, illumination and measurement system variables, exposures must be carefully reduced to reflectances for engineering applications of photometric interpretation.

The SCS technique has been successfully used to measure volume reflectances of bodies of water, and reflectances of common terrain objects.[1] The technique enables the interpreter to relate measured density values to scene reflectances. No preplaced ground reflectance panels are required, and hence the calibration procedure can be used for operational aerial surveys. Further, the technique provides a measure of the angular nature of the incident illumination (through evaluation of the ratio of sunlight to skylight irradiance), which is important for interpretation of reflectance values.

A photointerpretation console which will enable the interpreter to calibrate color film quickly and accurately is currently being fabricated for the Reconnaissance Applications Section, Rome Air Development Center. The console will also enable the interpreter to obtain color encoded displays of spectral reflectance ratios from the color imagery. The importance of spectral ratios for soil analyses is described in the next section.

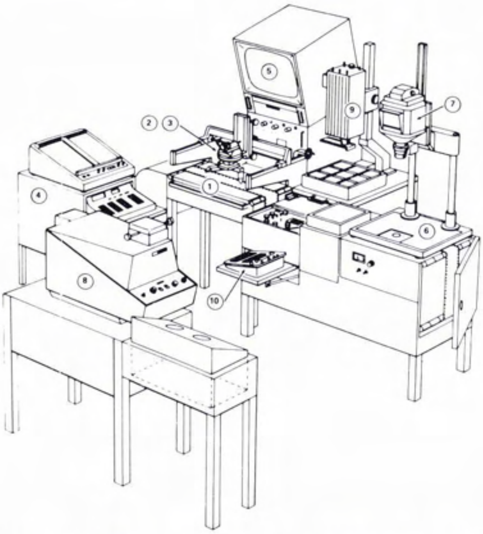

FIG. 4. The experimental photointerpretation console. The concept and development of the console was sponsored by Rome Air Development Center, U.S. Air Force.

Figure 4 contains a schematic of the experimental photointerpretation console. The console provides the image interpreter with all of the capabilities he presently utilizes; i.e., (1) a variable illumination light table and (2) zoom stereo magnification with reticules and scales for mensuration in a convenient location. However, in addition, (3) a micro-macro densitometer capability, (4) a desk calculator and display capability and (5) a CRT color display capability are provided to quantify and present spectral ratio information to the interpreter. To generate this information another light table (6) is required to photographically copy and develop (7, 8) the spectral ratio imagery which is then displayed to the density slicing and color encoding vidicon (9) for display on the color CRT, through a control panel (10).[2]

The additional console equipment enables the image interpreter to easily modify the original color imagery so that (1) new and different image spatial properties are detectable, (2) these new images have an understandable physical significance to the task the interpreter is performing, and (3) sufficient other scene detail is recorded to allow the interpreter to identify the location of the new information on the original imagery.

An example of the generation of spectral ratio displays and their application to mapping of flooded acreage has been previously presented.[2]

RATIO ANALYSIS OF MOISTURE AND TEXTURE PATTERNS

Our purpose is to motivate further use of the photometric properties of aerial color imagery by describing photometric procedures to extract soil moisture and texture patterns within a land-form element. Reflectance investigations of this type have been useful in analyses of the lunar and Martian surfaces.[5-7] Similar terrestial soil analyses have also been conducted,[8] although these investigations have been almost exclusively limited to laboratory studies because of the lack of a convenient measurement system.

It is frequently difficult to establish whether soil tonal variations are due to moisture or texture, as increased moisture content and increased average particle size will both darken the tone of a soil element. Similarly, decreased moisture content and decreased particle size will both result in a lighter tone.[*] Except for cases where moisture variation significantly changes surface structure, surface moisture content and surface structure or particle size can be ordered and discriminated by comparing reflectance ratios between red or infrared regions and the blue spectral band. For purposes of this discussion, only red and blue bands are considered.

The photometric interpretation rule is as follows. The interpreter obtains the red to blue reflectance ratio of the darker (1) and lighter (2) soil elements. Then if

$$R_1/B_1 < R_2/B_2, \qquad (5)$$

texture is the cause of the tonal variation, with the darker element (1) having coarser texture; if

$$R_1/B_1 > R_2/B_2 \qquad (6)$$

moisture is the cause of the tonal variation, with element 1 having greater moisture content. Here R and B denote red and blue reflectance; subscripts 1 and 2 denote darker and lighter soil elements respectively. The red band reflectance is used to define the darker soil element.[9]

Motivation for Equations 5 and 6 may be found in Figures 5-6. Figure 5 shows the variation of total reflectance, as measured on a Beckman spectrometer, for various sieved sizes of a soil sample.[10] The increase in brightness as particle size decreases is well known.[5-10] Reflection occurs at each particle-air interface, with absorption occurring during passage through a particle. Absorption thus increases with particle size. As a result, the smaller the particle size, the more significant multiple scattering or multiple reflections become in establishing reflectance. Multiple scatter in turn emphasizes the spectral region with smallest absorption, i.e., the red band. Computation of red/blue reflectance ratios from Figure 5 yields ratios in accord with Equation 5, with ratios decreasing monotonically with increasing size difference.

Figure 6 depicts the spectral dependence of the ratio between total reflectance of wet and dry soil samples for various soil types. Computation of corresponding red/blue ratios yields results in accord with Equation 6. It should be emphasized that Equation 6 is only valid where moisture variation does not alter surface structure significantly. We have found deviation from Equation 6 upon addition of small amounts (~ 5 percent by weight) of moisture to some silts and clays. In these instances further addition of moisture brought ratios back in accord with the rule and yielded a monotonic variation with further moisture addition.

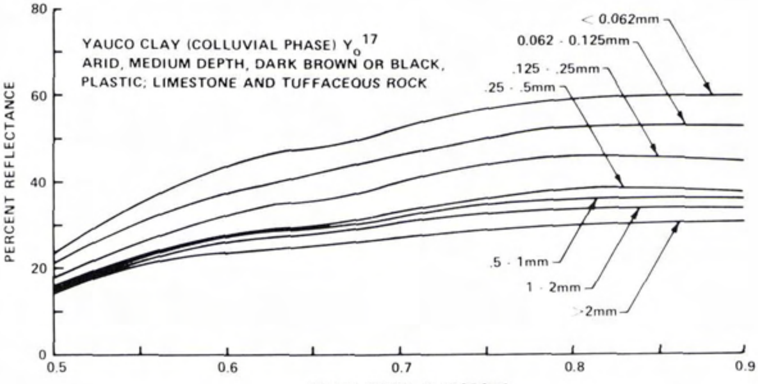

FIG. 5. Variation of total reflectance for various sieve sizings of a Yaucoa clay.

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[*] The only realistic exceptions to this particle size-reflectance change rule of which the authors are aware would be wet bog soils with high iron sulfide contents. Opaque materials such as FeS_2 darken with decreasing particle size. Oxidation normally transforms opaque sulfides to less opaque sulfates which obey the reflectance change rule. Oxidation, however, is inhibited in the wet bog soils, and hence a large iron sulfide content may result in an exception to the general reflectance variation statement. A more detailed discussion may be found in Reference 9.

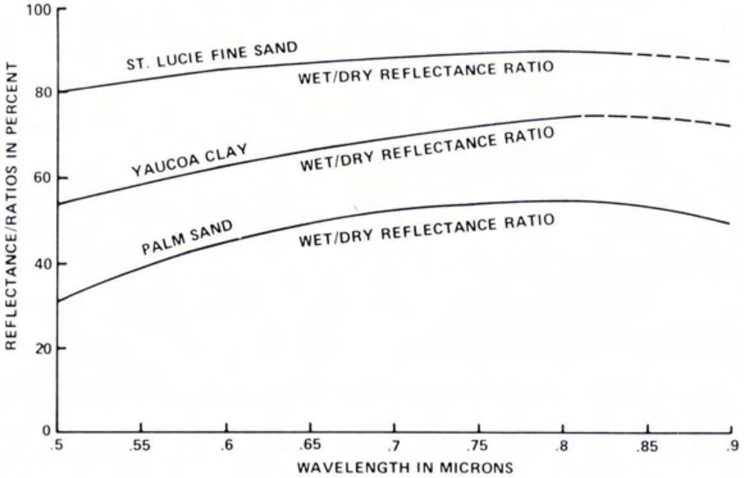

FIG. 6. Wet-to-dry reflectance ratio for various soils as determined from total reflectance measurements.

Data similar to Figures 5 and 6 can be generated photographically. Ground photographs were taken of soil samples in trays. Plus X film was used, with blue and red data points corresponding to reflectances associated with Wratten 39 and 25 filters. Figure 7 depicts ratios between red and blue reflectances of various soil types as a function of moisture content. Figure 8 depicts ratios between the red and blue reflectances of samples of a silt loam soil separated into different size classes through sieving, and the ratios between the red and blue reflectances of the natural size distribution. For the unsieved distribution, 20 percent of the particles by weight are finer than 0.16 mm, 50 percent are finer than 0.6 mm, and 80 percent are finer than 0.9 mm. The results of Figures 7 and 8 are in agreement with the interpretation rule of Equations 5 and 6.

Figures 7 and 8 are, it is believed, the first verification of the moisture-texture reflectance rules obtained through photographic photometry. Previously these rules had been obtained in various forms only through laboratory photometers.[4,10]

Figures 9 and 10 contain a final example from 70-mm MS Ektachrome imagery. The three fields denoted *A*, *B*, and *C* on Figure 9 all have slightly different tonal properties, which the interpreter would expect to be due to moisture content. Figure 9 was calibrated

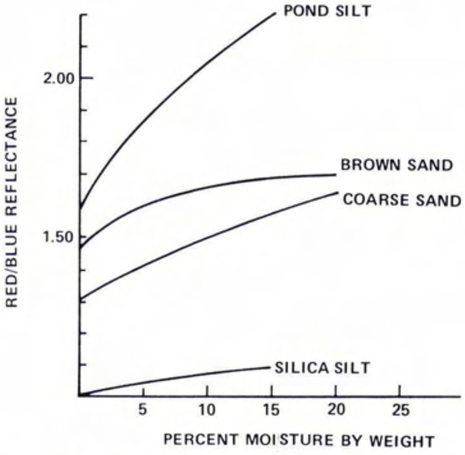

FIG. 7. Ratio of red-to-blue reflectance for various soil types as a function of percent moisture by weight.

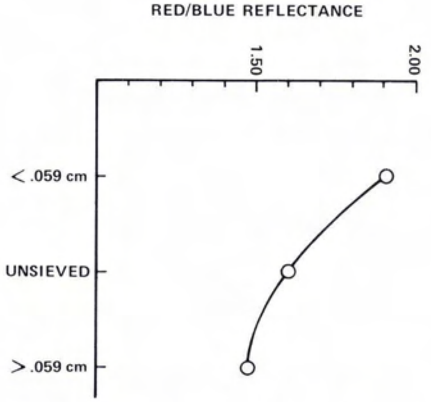

FIG. 8. Ratio of red-to-blue reflectance for various size sievings of a silt loam soil.

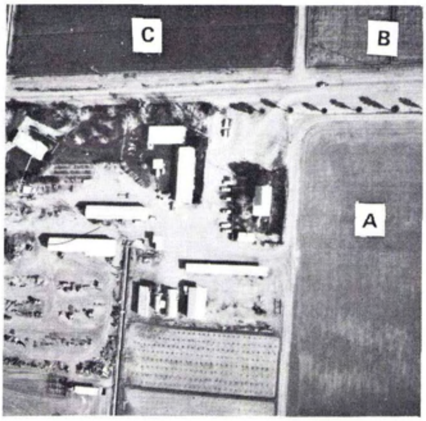

FIG. 9. Black-and-white copy of original aerial color image used for soil moisture analyses.

using the shadows within the scene, and the red/blue ratios and red reflectances of the fields were determined to be *A*:1.39 and 23 percent, *B*:1.13 and 25 percent, and *C*:1.51 and 11 percent. The interpretation rule of Equations 5 and 6 indicates that field *C* contains more moisture than both *A* and *B*, and that *A* contains more moisture than *B*.

The image in Figure 10 was taken near the specular reflection direction to enhance the effects of moisture in the fields. There is a dramatic change in the tone of Field *C*. Examination of Figure 10 shows that indeed Field *C* contains much more moisture, as evidenced by the large amount of specular reflection from interstitial water in the field. Irrigation is by flooding (note the irrigation ditches), and Field *C* has been recently flooded. Field *A* has been recently furrowed and disked. The moisture difference between *A* and *B* is due to the greater moisture content of the recently overturned subsurface soil. The moisture conditions are in accord with the ratio predictions.

SUMMARY

Additional information on soil properties can be extracted from conventional color aerial imagery through careful analysis of image photometric properties. The aerial camera can be used as a photometer, and the resulting photometric data can be related to terrain physical properties. The interpretation process entails precise densitometric measurement and calibration to terrain reflectances through scene objects such as shadow areas. Ratios between the reflectance of a soil element in red and blue spectral bands can be used to discriminate and delinate soil element moisture and texture variations.

It should be emphasized that photometric ratio analyses presented here are intended to supplement conventional interpretation techniques, and not supplant them. In fact, the key reason for using the camera as a photometer is because the image used for the photometric analyses then has the same high degree of spatial resolution and the same format as that used for the conventional interpretation. In addition, no further field equipment is required. The entire process thus involves the extraction of additional information from existing imagery, and becomes an extremely attractive one for the interpreter. An experimental photointerpretation console which will integrate the photometric techniques into conventional photointerpretation procedures is currently being fabricated.

Although the ratio analyses described are helpful in establishing and defining moisture and texture patterns, the relationships of these ratios to moisture content and texture parameters are still highly empirical and necessitate further investigation. For example, it would be very desirable to be able to relate ratio values to the *degree* of moisture and textural change. Additional effort is also required to relate variation of terrain reflectance with illumination and view angle to soil properties such as void ratio and bearing strength.[5]

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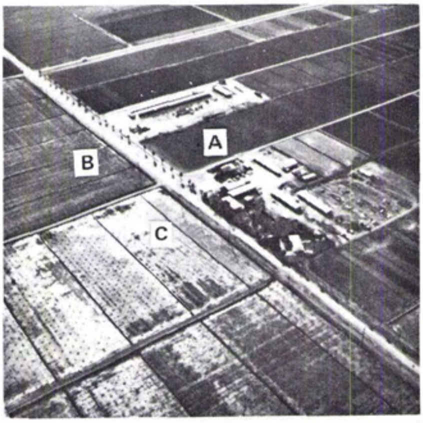

FIG. 10. Image of Fields of Figure 9 taken near specular reflection direction to enhance moisture conditions.

cial thanks are due Prof. Dwight Sangray of Cornell University for supplying some of the soil samples utilized.

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