AERIAL PHOTOGRAPHY FOR SENSING PLANT ANOMALIES

by

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ABSTRACT

Changes in the red tonal response of Kodak Ektachrome Infrared Aero 8443 film (EIR) have been often incorrectly attributed solely to variations in infrared light reflectance of plant leaves, when the primary influence was a difference in visible light reflectance induced by varying chlorophyll contents. Assuming a relatively low cyan positive image density (high infrared light reflectance), a high compared with a low chlorophyll content reduces the reflection of visible light, the yellow and magenta positive images remain highly saturated, and the viewer has an impression of a darker red tone (higher red color saturation).

Comparisons are made among aerial photographic images of high- and low-chlorophyll foliage. New growth, foot rot, and boron and chloride nutrient toxicities produced low-chlorophyll foliage, and EIR transparency images of low-chlorophyll foliage were light red or white compared with dark-red images of high-chlorophyll foliage.

Deposits of the sooty mold fungus that subsists on the "honeydew" produced by brown soft scale insects, obscured the citrus leaves' green color. Infected trees appeared as black images on EIR film transparencies compared with red images of healthy trees.

The detection of brown soft scale infestations of citrus trees with EIR film is practical. Further work is planned to distinguish among photographic images produced by boron and chloride toxicities, iron deficiency, and foot rot of citrus trees. The new Kodak Aerochrome

Infrared 2443 film will be used, and it should give results superior to those of the EIR film.

INTRODUCTION

The interpretation of false color imagery to detect spectral reflectance differences among plant genera and between healthy and abnormal plants is difficult and often requires an empirical procedure. Changes in the red tonal response of Kodak Ektachrome Infrared Aero 8443 film (EIR)[1] have been often incorrectly attributed solely to variations in infrared light reflectances of the subjects. Light- and dark-red tonal appearances on transparencies have been interpreted as indicating high and low infrared reflectances, respectively, when the primary influence may have been variations in visible light reflectances induced by different plant leaf chlorophyll concentrations.

This paper considers aerial photography with EIR film for sensing plant anomalies, and it stresses the importance of considering effects of different leaf chlorophyll concentrations, in addition to internal leaf structure, on the absorptance of visible light in interpreting false-color imagery. Examples are given where the plant foliage either differs widely in chlorophyll contents or the plant leaves' green color is obscured.

REVIEW OF LITERATURE

EIR AND AIR FILMS

EIR film (1) has three image layers individually sensitized to green, 500 to 600 nanometer (nm); red, 600 to 700 nm; and infrared radiation, 700 to 900 nm. A yellow filter is used on the camera to absorb the blue radiation, to which these layers are also sensitive. Upon processing, yellow, magenta, and cyan positive images are formed in the green-, red-, and infrared-light sensitive layers, respectively. The overall impression to an observer viewing the finished print or transparency will depend upon the positive images in the dye layers that predominate with respect to visual appearance. Because the eye sensitivity peaks in the green, the magenta layer generally contributes most to the subjective impression of lightness or darkness in a color

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[1] Use of a company or product name by the Department does not imply approval or recommendation of the product to the exclusion of others that may also be suitable.

print or transparency. For example, healthy leaves, with high infrared compared with low infrared reflectance for unhealthy leaves, record red because a light-toned cyan image (less dense or less saturated) results, allowing the transmittance of more red light in the viewing.

Kodak has replaced the EIR 8443 film with a new emulsion series, Kodak Aerochrome Infrared Film 2443 (AIR). Interpretation of tonal responses of the new AIR film should be essentially alike the interpretation of the EIR film, except that the slower cyan dye layer of the AIR film compared with the EIR film should reduce the red saturation in the photography (2).

Chlorophyll Effects on Red Saturation of EIR Film

Spraying cotton plants (Gossypium hirsutum L.) at the square stage of plant development with Cycocel [(2-chloroethyl) trimethylammonium chloride)] (3), at 100 g/ha (0.545 lb/A) in enough water to produce run-off, increased the chlorophyll content of their leaves compared with leaves of plants sprayed with only the amount of water used for applying the Cycocel treatment (4). The Cycocel treatment increased absorptance 13% at the chlorophyll absorption band, 550 nm; and only 2 to 3% over the 750- to 1350-nm wavelength interval (WLI). Near-infrared light reflectance of upper surfaces of single leaves, measured with a spectrophotometer, was inversely related and visible light reflectance was directly related to the reflectivity of field plots of cotton recorded on EIR aerial photographs. The tonal response on EIR transparencies was darker red for Cycocel-treated plots than for untreated plots. This was caused by increased chlorophyll contents in leaves of Cycocel-treated plants.

High salt levels in the soil increased the chlorophyll contents of cotton leaves and produced a high red color saturation and appearance on EIR transparencies (5), compared with a light red appearance of cotton leaves from plants grown on a low salt soil. Also, young leaves near the top of a representative cotton plant photographed to give a darker green and deeper red appearance for conventional color (CC) and EIR films, respectively, than did lower mature leaves (5). Young leaves had more chlorophyll than the older leaves. High compared with low chlorophyll leaves absorbed more light within the visible spectrum (4,5), correspondingly reducing red light reflectance over the approximate 600- to 700-nm WLI. When less red light impinged on the EIR film, a magenta positive image was produced with high saturation. Transmission of the dark red-toned color of the magenta image contributed most to the viewer's impression of darkness in the EIR transparency or color print.

PRESENTATION OF RESULTS

First, brief consideration will be given to the influence of internal leaf structure on light reflectance, transmittance, and absorptance. Next, physiological and environmental factors that affect citrus leaf light reflectance will be reviewed briefly and illustrated. Examples of plant anomalies that will be presented are: boron (B) and chloride (Cl^-) nutrient toxicities, citrus species differences, sooty mold (fungus) deposits resulting from brown soft scale infestations, and foot rot (fungus) of citrus trees.

To facilitate ensuing discussions, the 500- to 2500-nm spectral range has been arbitrarily divided into: the 500- to 750-nm visible region dominated by pigment absorption (chlorophylls and carotenoids); the 750- to 1350-nm near-infrared WLI, a region of high reflectance and low absorptance that is affected primarily by internal leaf structure; and the 1350- to 2500-nm WLI, a region of high absorption by water--the strongest water absorption bands occurring at 1450 and 1950 nm.

SPECTRA OF MATURE CITRUS LEAVES

The diffuse reflectance, transmittance, and absorptance of mature citrus leaves (orange, Citrus sinensis (L.) Osbeck) are portrayed in Fig. 1. The reflectance and transmittance spectra are each averages of measurements made on upper surfaces of 10 leaves. Measurements were made with a Model DK-2A spectrophotometer and its reflectance attachment. Data were corrected for the reflectance of the MgO standard to obtain absolute radiometric values (6). Absorptance was calculated as: [100 - (% reflectance + % transmittance)].

Figure 1 shows that reflectance, transmittance, and absorptance were 10, 2, and 90%, respectively, at the 550-nm green peak within the 500- to 750-nm visible WLI. Absorption in this region was primarily caused by pigments. Within the 750- to 1350-nm near-infrared range, there was approximately 55% reflectance, 40% transmittance, and 5% absorptance. Above 1350 nm, absorptance greatly increased because of water absorption of light energy.
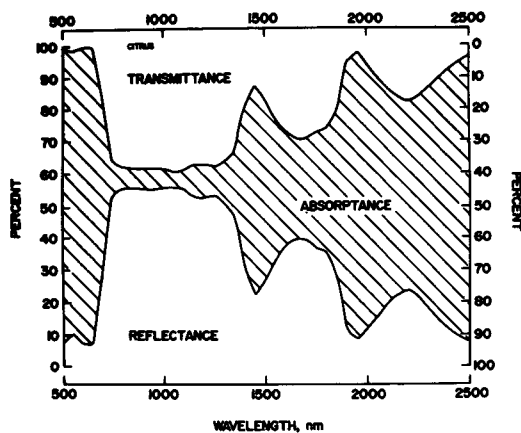
Figure 1.- Diffuse reflectance, transmittance, and absorptance
[100 - (% transmittance + % reflectance)] of the upper (adaxial)
surface of a mature orange leaf (Citrus sinensis (L.) Osbeck).

FACTORS AFFECTING CITRUS LEAF LIGHT REFLECTANCE

Citrus leaf light reflectance is affected by diseases, hormones,
insects, leaf ages (maturation), phyllotaxis (leaf ontogeny relations),
tissue water contents, nutrient deficiencies and toxicities, and spray
residues. Of these factors, the influence of leaf ages, diseases,
insects, and toxic nutrient levels will be considered below following a
general review of leaf structure.

Internal Leaf Structure

A three-dimensional drawing (7) representing a leaf structure that
is similar to a citrus leaf's structure is shown in Figure 2. The top
layer of cells is the upper (adaxial) epidermis. The epidermal cells
have a cuticular layer on their upper surfaces that diffuses but reflects
very little light. The long narrow cells in the leaf mesophyll below
the upper epidermis are palisade parenchyma cells. They house many
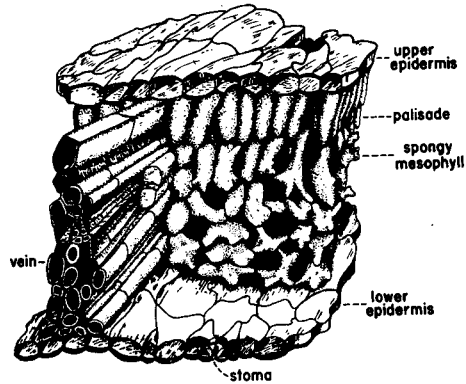
Figure 2.- Three-dimensional drawing of a leaf structure that is similar to the structure of a citrus leaf (redrawn from Van Nostrand's Scientific Encyclopedia, 1947).

chloroplasts with chlorophyll pigments that absorb some of the visible light, particularly at the 430-nm (blue) and 680-nm (red) wavelengths. The cells below the palisade cells are spongy parenchyma cells. The palisade and spongy parenchyma cells have many air spaces among them (intercellular air spaces). It is here that oxygen and carbon dioxide exchange takes place for photosynthesis and respiration. The lower (abaxial) epidermis is like the upper epidermis, except a stoma or port is present where gases enter and leave a leaf.

The air spaces in leaf mesophylls are important in remote sensing because hydrated cell wall - air faces scatter near-infrared light (8).

Leaf Age (Maturation)

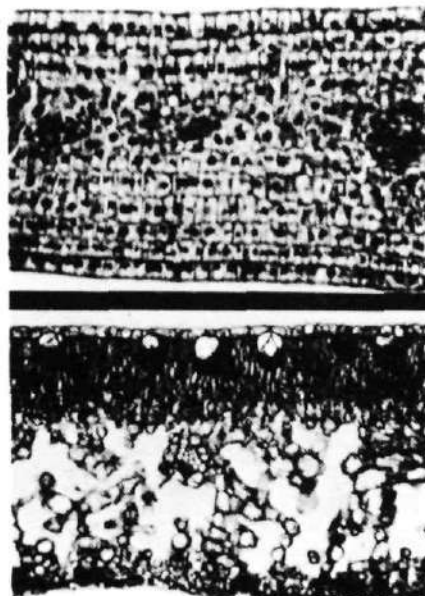The effect of leaf age on internal leaf structure is shown in Figure 3.

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Figure 3.- Microphotographs of leaf transections of young (top,
125 X) and mature (bottom, 64 X) citrus leaves.

The top citrus leaf transection represents a very young citrus leaf
(fifth leaf from apex of new growth flush, 125 X), and the transection
at the bottom of the screen represents a mature citrus leaf (eighth leaf
from apex of previous growth flush, 64 X). The young leaf is compact
with few air spaces in its mesophyll, while the old leaf is "spongy" or
has many air spaces. The young compact leaf has lower light reflectance
than the mature leaf, Figure 4. The spongy mature leaf represented by
the solid black line, compared with the compact young leaf represented
by the dotted line, had about 5% and 15% more reflectance in the visible
(500 to 750 nm) and near-infrared wavelength (750 to 1350 nm) ranges,
respectively. The "spongy" effect in the mature leaf increases reflec-
tance because there are more intercellular air spaces (8). Scattering
of light within leaves occurs at cell wall (hydrated cellulose) - air
cavity interfaces that have refractive indices of 1.4 and 1.0, respec-
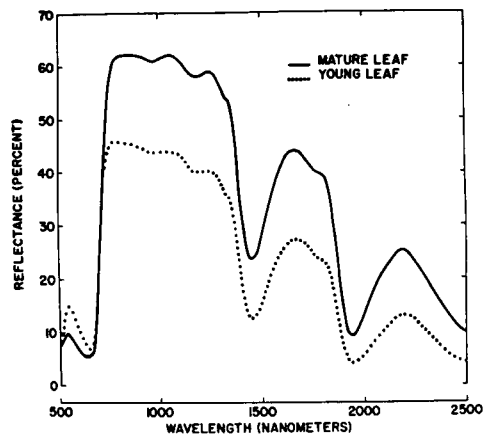tively.

Figure 4. Diffuse reflectance of the upper (adaxial) surfaces of young (bottom dotted line spectrum) and mature (upper solid line spectrum) orange leaves (Citrus sinensis (L.) Osbeck).

Toxic Nutrient Levels

Too much salt in the soil or irrigation water affects physiological functions of plants and subsequently plants become stunted and toxicity symptoms become apparent in their foliage. Too much boron (B) produces citrus leaves with yellowish areas on their leaf surfaces, and too much chloride (Cl⁻) gives a brownish tip burn (9).

An experiment with toxic levels of B and Cl⁻ is being conducted on citrus trees by A. Peynado, Research Chemist, Crops Research Division, Weslaco, Texas, using an experimental design with four blocks (10). There are 16 Red Blush grapefruit (Citrus paradisi, Macf.) and 16 Valencia orange (Citrus sinensis (L.) Osbeck) trees within each block. The grapefruit and orange trees are each on 16 different root-stocks. Two treatments, that began in 1963, have been applied to the grapefruit and the orange trees within each block. Eight orange and eight grapefruit trees in each block have been irrigated with canal

water (control treatment); and eight orange and eight grapefruit trees in each block have been irrigated with irrigation water with 4,000 ppm sodium chloride (NaCl) and calcium chloride ($CaCl_2$) and 6 ppm of boron (B) added (salt treatment).

Figure 5 shows that healthy compared with B- and Cl^--affected leaves had about 3% less reflectance over the 750- to 1350-nm near infrared WLI.
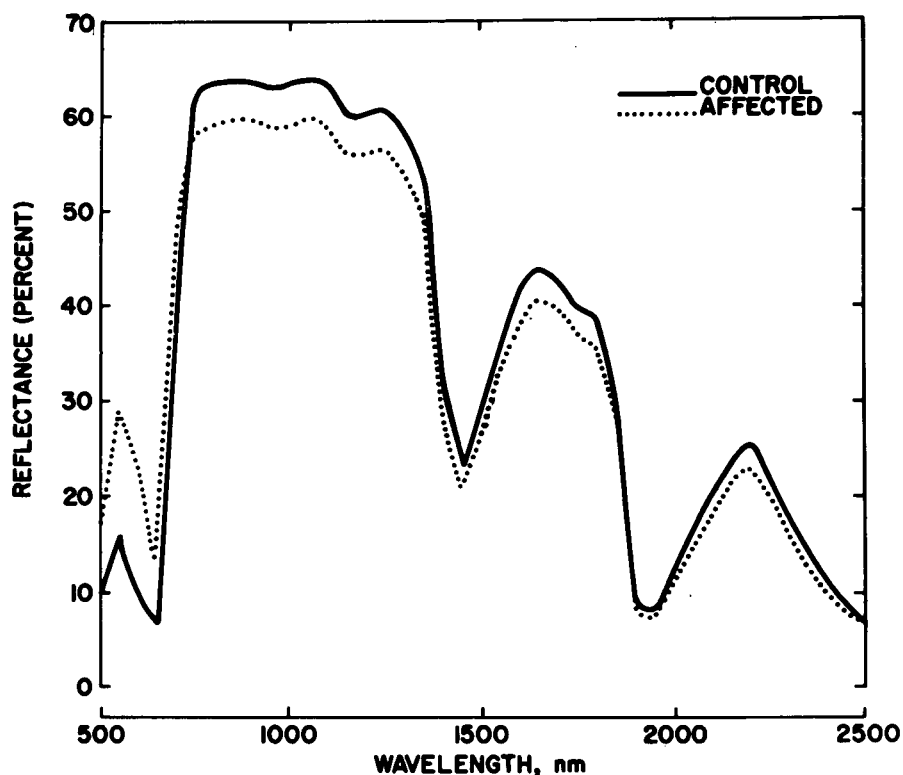

Figure 5.- Diffuse reflectance of upper (adaxial) leaf surfaces of healthy (control, solid line) and salt-affected (dotted line) citrus leaves.

This variation in reflectance was primarily caused by differences in leaf structure. Microscopic examinations of leaf transections indicated that healthy leaves had a more spongy mesophyll than affected leaves. However, the largest difference in reflectance between healthy and affected leaves was in the 500- to 750-nm WLI. Affected leaves were much lower in chlorophyll than healthy and had approximately 12% higher reflectance at the visible green reflectance peak of 550 nm.

Aerial photographs with EIR film (Figure 6 A) were taken of the experimental plots at an altitude of 3,000 ft with a 50-mm lens. Sixteen orange trees with no visual toxic salt symptoms and 12 grapefruit trees with rootstocks that were insensitive to the salt treatment photographed dark red; whereas grapefruit trees with the salt-sensitive Troyer citrange rootstock gave whitish-tree images on the EIR transparency. Thus it seems feasible that remote sensing with aerial photography can be used to detect the presence of salinity-stressed citrus trees.

Species Differences

Aerial photographs were taken of an orchard of Red Blush grapefruit, Valencia and navel oranges, and Cleopatra tangerine trees at an altitude of 2,000 ft with a 50-mm lens (Figure 6 B). All trees had a new flush of growth except for the tangerine trees. The tangerine trees gave dark red images on the EIR transparency in contrast to lighter red colored images for the grapefruit and orange trees; because new foliage on citrus trees is lighter green in color (less chlorophyll) than the foliage of the previous flushes of growth. One of the main problems in the photographic remote sensing of citrus maladies is to distinguish them from new foliage growth that usually occurs five times per year.

Citrus Foot Rot

Citrus foot rot is a fungal disease caused by Phytophthora citrophthora (Sm. & Sm.) and Phytophthora parasitica Dast. These fungi produce a gummy exudate at or near the graft union on citrus trees; wood rots underneath, leaves lose color, decline sets in, and eventually foot rot girdles the tree trunk and the tree dies. The foliage of foot rot-affected citrus trees lose their chlorophyll and become chlorotic (yellowish-white) in contrast to the dark-green foliage of healthy trees.

An overflight of a grapefruit citrus orchard, Citrus paradisi Macf., Nucellar - CES-3 selection of Red Blush on Citrus aurantium Linn. Sour Orange rootstock, near Monte Alto, Texas was made at an altitude of 2,000 ft (under cloudless skies with moderate haze), at 11:29 a.m., central standard time, December 5, 1968, in an easterly direction (10). Photographs were taken with a Zeiss, 6-in. focal length camera (scale 1:4,000), using 9-in. Kodak Ektachrome Infrared Aero 8443 film and a Zeiss D light-orange filter, approximate 100% absorption edge at 500 nm.

On EIR transparencies, healthy trees produced red images in contrast to white images for trees severely infected with foot rot (Figure 6 C).

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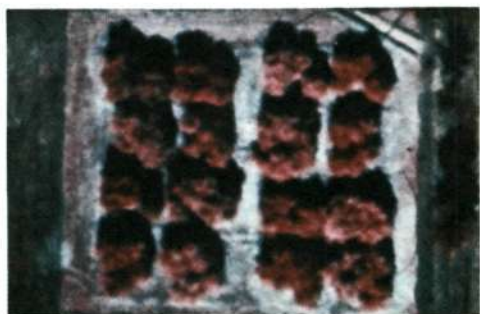
A. Salt toxicity, photography
scale 1/18,000, enlarged 20 X.

B. Kinds of citrus trees,
photography scale 1/12,000,
enlarged 2 X.

C. Foot rot, photography scale
1/4,000, enlarged 5 X.

D. Sooty mold, photography
scale 1/10,000, reduced 0.5 X

Figure 6.- Aerial photographs of plant anomalies with EIR film.
  A. Salt toxicity. Dark red trees are orange trees with no signs of
being affected with boron and chloride salt additions, and grapefruit
trees with salt insensitive rootstocks. (The trees in each block have
grown together and cannot be individually identified in the photo-
graph.) White images in each block are grapefruit trees with a salt
sensitive rootstock.
  B. Kinds of citrus trees. The two dark red trees on the bottom of the
photograph, four rows in from the right, are tangerine trees with no
new foliage (leaves dark green color, high chlorophyll). The remaining
lighter colored trees are Red Blush grapefruit and orange trees with a
new flush of foliage (leaves light green color, low chlorophyll).

Figure 6.- Continued
   C. Foot rot. The white tree in the center of the photograph has an
   advanced infection of foot rot, and the tree below it and to its left
   has an early case of foot rot. Healthy trees are red.
   D. Sooty mold. Black trees are infested with brown soft scale, non-
   infested trees are red.

   Figure 6 C is an EIR color photograph of foot rot-infected trees,
and red images of healthy trees. Various degrees of white-appearing
trees were detected among the red-appearing trees on the EIR color film.
The white tree in the center of the photograph has an advanced infection
of foot rot, and the tree below it and to its left has an early case of
foot rot.

Sooty Mold

   Brown soft scale insects (Coccus hesperidum L.) start excreting
large quantities of a sugary solution known as "honeydew" soon after
establishment on the citrus leaf. The black sooty mold fungus,
Capnodium citri, Berk. and Desm., develops rapidly on the leaf surface
when the honeydew is abundant, and forms a dense black coating of inter-
woven filaments (hyphae). If the coating is heavy, it impairs plant
growth and production. Light reflectance in the visible and near-
infrared is considerably reduced (11). Figure 7 shows spectrophotometric
measurements of diffuse reflectance of upper citrus leaf surfaces having
varying amounts of sooty mold (11). Mature citrus leaves (spectrum 1)
with no trace of sooty mold had reflectance values of 58 and 53% at 770
and 1300 nm, respectively. Leaves heavily coated with sooty mold
(spectrum 4) had reflectance values of 9 and 23% at 770 and 1300 nm,
respectively. A light sooty mold coating (spectrum 2) reduced reflec-
tance 14 and 2 percentage points at the 770- and 1300-nm wavelengths,
respectively.

   Citrus trees coated with deposits of sooty mold photographed black
with EIR film compared with red images of noninfested trees (Figure 6 D).

   The detection of brown soft scale infestations of citrus trees with
EIR film has been demonstrated (11). A commercial service to the grow-
ers is feasible at the present time. It could function as entomological
ground surveys now function; that is, a commercial service would photo-
graph the trees, ground check suspicious areas in groves, and make
recommendations for spraying of the orchards. It is estimated that the
cost of surveys could be reduced up to 50% with this technique (12).
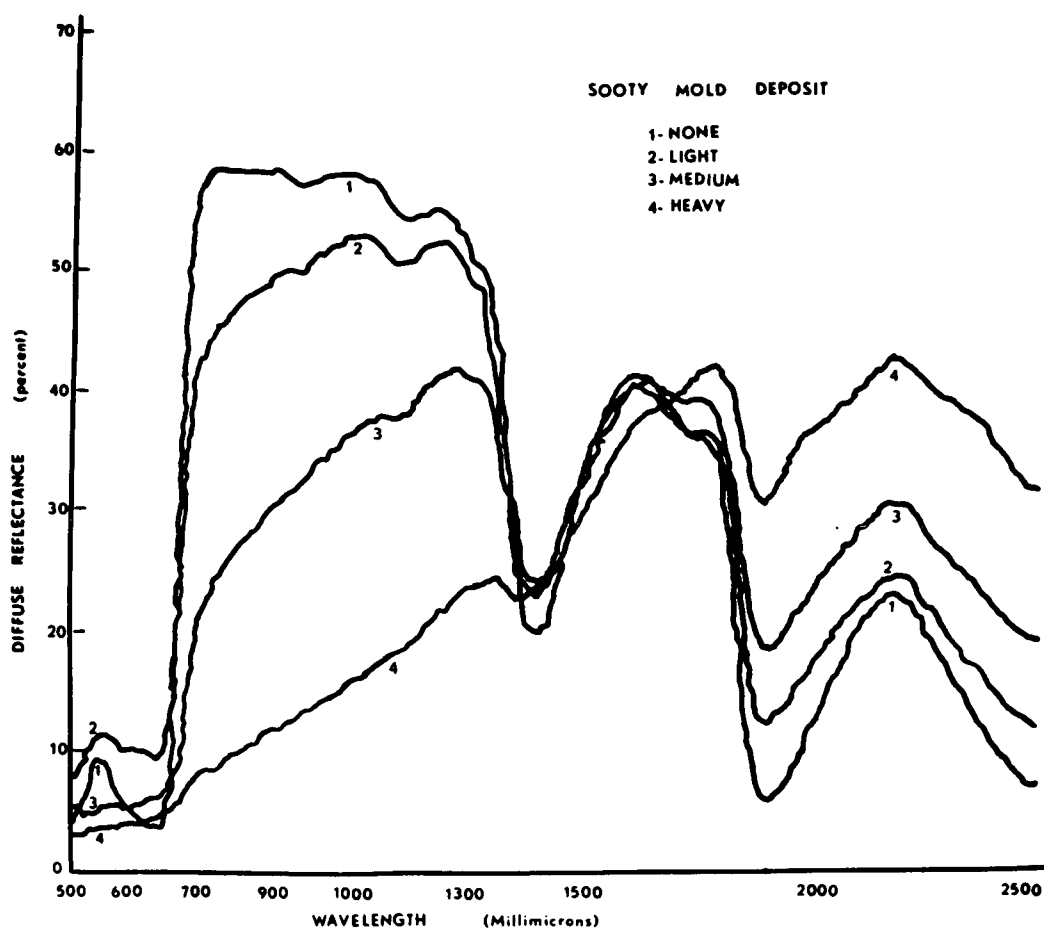
Figure 7.- Effect of sooty mold on reflectance (percent) of leaves coated with varying amounts of the fungus (reproduced from Hart and Myers, 1968).

FUTURE PLANS

Further work is planned for comparing film images of boron and chloride toxicities, iron deficiency, and foot rot of citrus trees. The new Kodak Aerochrome Infrared 2443 (AIR) film will be used, and it should give results superior to those of the EIR film. If visual interpretation among foot rot and the nutritional maladies is impractical, computer discrimination procedures (13) will be applied to densitometer readings on AIR film transparencies.

The detection of brown soft scale infestations of citrus trees with EIR film is practical. A commercial service to the growers is a possibility in the near future.

Research is in progress to detect insect damage on citrus trees with EIR films to assess the effectiveness of biological and chemical insect control applications.

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