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Kenneth R. Summy
The University of Texas Rio Grande Valley

Christopher R. Little

Ruben A. Mazariegos
The University of Texas Rio Grande Valley

James H. Everitt
The University of Texas Rio Grande Valley

M. R. Davis

See next page for additional authors

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Authors

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Detecting Stress in Glasshouse Plants Using Color Infrared Imagery: A Potential New Application for Remote Sensing

**K. R. Summy[1], C. R. Little[1], R. A. Mazariegos[1], J. H. Everitt[2],
M. R. Davis[2], J. V. French[3], and A. W. Scott, Jr.[4]**

[1]*University of Texas - Pan American, 1201 West University Drive, Edinburg, TX 78541*
[2]*U. S. Department of Agriculture, Agricultural Research Service, Weslaco, TX 78596*
[3]*Texas A&M University - Kingsville Citrus Center, Weslaco, TX 78596*
[4]*Rio Farms, Inc., Monte Alto, TX 78538*

ABSTRACT

Studies were conducted to evaluate the effectiveness of color infrared (CIR) film for detecting physiological stress in plants located within glasshouse structures. Spectroradiometer measurements obtained within and outside of a structure constructed of polycarbonate plastic indicated no significant attenuation or disruption of visible and near-infrared radiation entering the structure. CIR photographs of cucumber seedlings (*Cucumis sativus*) obtained within the greenhouse were comparable in quality to those obtained outside the structure, and clearly distinguished between foliage of healthy plants and those subjected to a moderate level of nitrogen stress. In CIR imagery of a trifoliate orange tree (*Poncirus trifoliata* (L.) Raf.) obtained within a greenhouse constructed of yellow fiberglass panels, leaves damaged by citrus red mites (*Panonychus citri* [McGregor]) were distinguishable from healthy foliage, and the distribution of damaged leaves on the tree itself was clearly evident. These results suggest that remote sensing techniques which have been used successfully to monitor conventional field crops are readily extendable to the commercial glasshouse environment with certain modifications.

RESUMEN

Se condujeron estudios para evaluar la eficacia de la película infrarroja de color (CIR) para detectar el estrés fisiológico en las plantas situadas dentro de un invernadero. Las mediciones del spectroradiómetro obtenidas dentro y fuera de un invernadero construido con plástico de policarbonato no indicaron ninguna atenuación o interrupción significativa de la radiación visible y del cercano infrarrojo que penetraba al invernadero. Las fotografías con CIR de las plantas de semillero de pepino (*Cucumis sativus*) obtenidas dentro del invernadero fueron comparables en calidad a aquellas obtenidas fuera de este, y distinguieron claramente entre el follaje de plantas sanas y de aquellas sometidas a un nivel moderado de estrés de nitrógeno. En imágenes de CIR de un naranjo trifoliado (*Poncirus trifoliata* (L.) Raf.) obtenidas dentro de un invernadero construido de paneles amarillos de fibra de vidrio, las hojas dañadas por el ácaro rojo de los cítricos (*Panonychus citri* [McGregor]) se distinguieron del follaje sano, y la distribución de hojas dañadas en el árbol mismo fueron claramente evidentes. Estos resultados sugieren que las técnicas de detección a distancia que se han utilizado con éxito para supervisar campos de cultivo convencionales, también pueden usarse fácilmente, con algunas modificaciones, en cultivos comerciales en invernadero.

Additional Index Key Words: Remote Sensing, Glasshouse, Horticulture, Pest Management

The development of color infrared (CIR) film during World War II is generally recognized as one of the landmark achievements in the field of remote sensing (Avery and Berlin 1992). Although originally developed by Eastman Kodak as a means to detect military camouflage, its potential for monitoring vegetation and other land surface features was quickly realized and exploited (Colwell 1956). During the past sixty years, CIR film and other types of "multispectral" imagery (i.e., imagery involving use of two or more regions of the electromagnetic spectrum) have been used extensively to detect and monitor phenomena occurring on both land and water surfaces and have found numerous applications in agriculture (see reviews in Avery and Berlin 1992, Campbell 1996, Jensen 2000, Lillesand and Kiefer 2000, Ryerson and Curran 1997, Wilke and Finn 1996).

Successful use of remote sensing in agriculture has been predicated on knowledge regarding the nature of electromagnetic radiation (EMR) and its interactions with vegetation and other ground surface features. EMR is characterized by both electrical and magnetic properties and has properties of both particles and waves, which are most commonly measured in billionths of a meter, or nanometers (nm). The totality of EMR emitted by the sun forms a continuum (i.e., the electromagnetic spectrum) which extends from short-wavelength high-energy radiation (e.g., gamma- and x-rays) to long-wavelength low-energy forms of energy, e.g. radio waves (Fig. 1). EMR wavebands which have proved to be of greatest value in the remote sensing of vegetation include the blue, green and red wavebands of the visible spectrum (400 - 500 nm, 500 - 600 nm and 600 - 700 nm, respectively) and several wavebands of radiation that are not detectable by the human visual system, i.e., the near-infrared (700 - 1,300 nm) and mid-infrared (1,300 - 3,000 nm) regions of the spectrum (Fig. 1). Conventional CIR film includes separate emulsions sensitive to green, red and near-infrared wavelengths (blue is normally removed by use of yellow filters), and is specifically designed to produce “false color” images, i.e., features in the landscape that reflect significant amounts of green, red and near-infrared radiation appear to be blue, green and red, respectively, in the resulting image. The purpose of this design was to ensure that camouflaged military vehicles (which are generally painted green and reflect relatively little near-infrared radiation) would be clearly distinguishable from live vegetation which is also green, but reflects a significant amount of near-infrared radiation. Extensive reviews of the theory and use of CIR imagery are provided in Avery and Berlin (1992), Campbell (1996), Jensen (1996, 2000), Lillesand and Kiefer (2000), Wilke and Finn (1996).

The degree to which incident EMR is absorbed, transmitted or reflected by vegetation is largely governed by the presence (or absence) of photosynthetic pigments and the structure of cells within the spongy mesophyll layer of leaves (Gates et al. 1965, Gausman et al. 1969, Myers 1970). A typical “spectral profile” of healthy foliage usually indicates relatively low reflectance of blue and red wavelengths, a somewhat higher reflectance of green wavelengths, and a pronounced increase in reflectance of near- and mid-infrared radiation (Fig. 1). The relatively low reflectance of blue and red radiation results from the fact that these wavelengths are absorbed by chlorophyll a and other photosynthetic pigments during the process of photosynthesis. Reflectance of green wavelengths, which are relatively unimportant in photosynthesis, typically occurs at higher levels and confers the greenish coloration that is characteristic of most healthy plant foliage. In contrast, plant stress is typically accompanied by a reduction or shutdown in photosynthesis, the effect of which is a reduction in the absorption (and

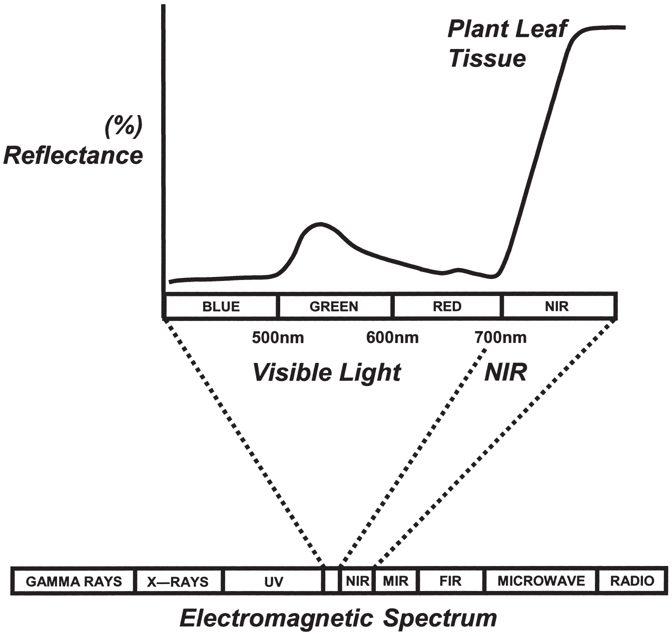

Fig. 1. The electromagnetic spectrum and a typical spectral reflectance curve for healthy plant tissue (diagram courtesy of C. R. Little).

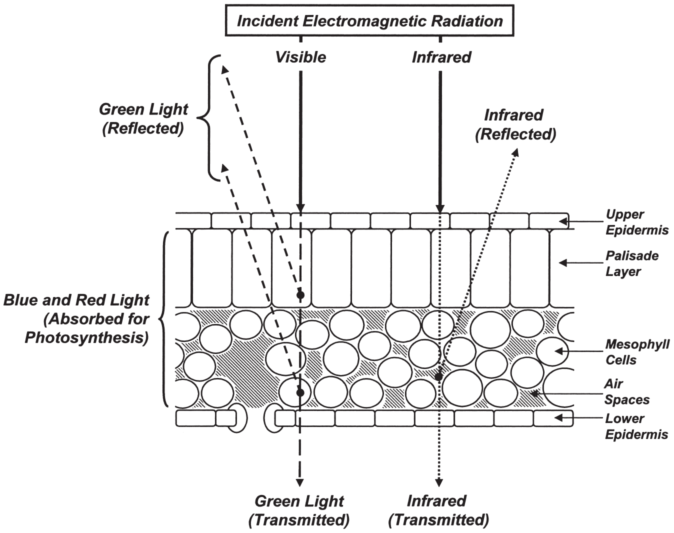

Fig. 2. Structure of a typical plant leaf, showing patterns of transmission, absorption and reflectance of incident electromagnetic radiation in various regions of the spectrum (diagram courtesy of C. R. Little).

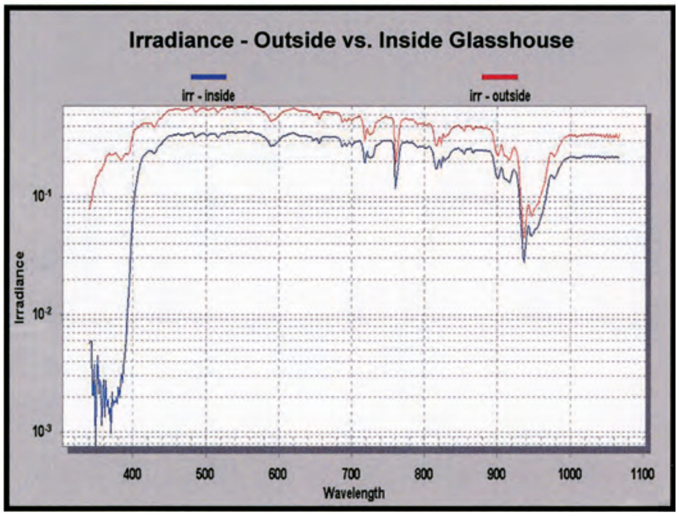

Fig. 3. Comparison of irradiance curves measured inside a glasshouse structure constructed of polycarbonate plastic (blue line) and outside under clear and sunny conditions (red line).

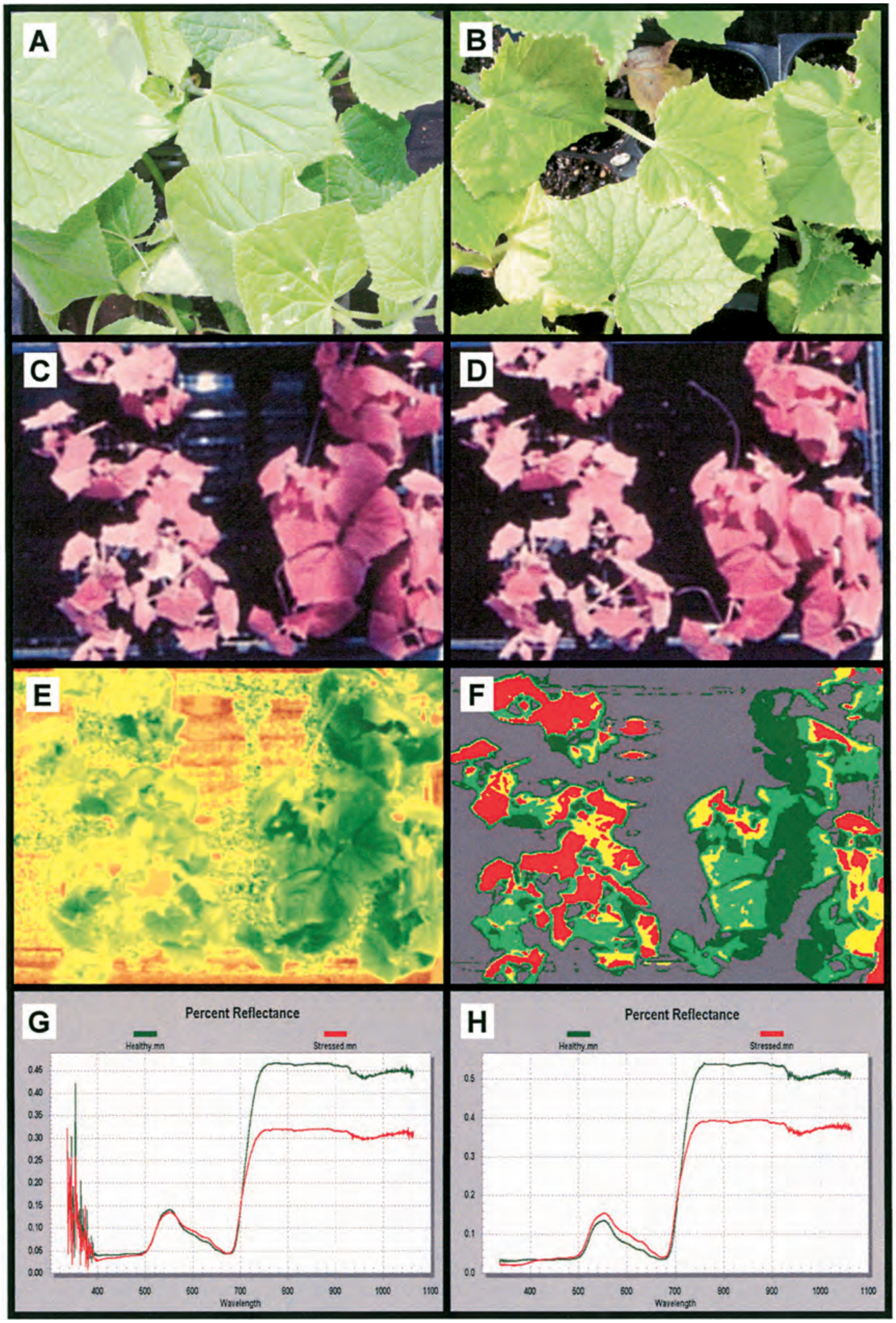

Fig. 4. Conventional color (RGB) photographs of cucumber (*Cucumis sativus*) seedlings, showing foliage of healthy plants (A) in relation to counterparts subjected to mild nitrogen deficiency (B). Color infrared (CIR) photographs of healthy (right) and stressed (left) cucumber foliage acquired within a polycarbonate plastic glasshouse (C) and outside under clear sunny conditions (D). Normalized Difference Vegetation Index (E) and an unsupervised image classification (F) developed from CIR imagery acquired under glasshouse conditions. Spectral reflectance curves for foliage of healthy plants (green line) and stressed counterparts (red line) measured within the polycarbonate plastic glasshouse (G) and outside under natural lighting conditions (H). Photographs in A-D from Summy et al. (2004).

hence, a higher reflectance) of blue and red wavelength EMR. Thus, the chlorotic appearance of plants subjected to certain nutrient deficiencies is a result of increased reflectance of red wavelengths which, when combined with reflected green wavelengths, is perceived by the human eye as yellow.

In contrast to visible light, reflectance of near-infrared radiation (which is not utilized by plants) is governed primarily by the structure and configuration of air spaces within the spongy mesophyll layers of leaves (Fig. 2). Senescence, physiological stress and other factors that change the configuration of these cells are commonly manifested as a significant reduction in near-infrared reflectance by the affected foliage (Wiegand et al. 1972, Murtha 1978). Herein lies one of the principal advantages of CIR imagery that has made it so useful in monitoring agricultural crops, i.e., it provides the means to detect the effects of certain physiological changes that are not detectable by the human visual system. This capability has been used to effectively detect and monitor a variety of stress factors in agricultural crops, including damage caused by salinity and moisture stress (Myers et al. 1963, Everitt et al. 1981), nutrient deficiencies (Thomas and Oerther 1977) and a variety of agricultural pests and plant diseases (Colwell 1956, Brenchley 1964, Norman and Fritz 1965, Hart and Myers 1968, Hart et al. 1973, Blazquez et al. 1979, Blazquez and Horn 1980, Blazquez et al. 1988, Payne et al. 1971, Toler et al. 1981, Everitt et al. 1994, 1996).

Despite the demonstrated effectiveness of CIR film and other types of multispectral imagery in monitoring conditions in conventional field crops, surprisingly little effort has been made to develop remote sensing techniques suitable for use in commercial glasshouse operations, which collectively represent one of the largest agricultural industries in the United States (Summy et al. 2004). One of the major distinctions between conventional field crops and crops grown within glasshouses is that the latter occur within an enclosure that may include construction materials that either attenuate or otherwise interfere with one or more of the EMR wavebands of importance in multispectral imagery. Thus, determination of such effects (if they exist) represents a critical first step in the development of remote sensing techniques suitable for use in the glasshouse environment. Our objectives in this study were 1) to evaluate the effect(s) of a common construction material on incident EMR entering a glasshouse structure, 2) to compare the quality of CIR photographs of plant foliage acquired inside and outside the structure, and 3) to evaluate a variety of image-enhancement techniques that might be used to accentuate differences between healthy and stressed plant foliage in CIR imagery acquired in this manner. Using examples provided by Summy et al. (2004) and additional data collected during these studies, we assess the potential of CIR imagery as a means to monitor the condition of glasshouse crops and discuss certain modifications in image acquisition and processing procedures that will probably be requisite to adoption of remote sensing technology by the commercial glasshouse industry.

MATERIALS AND METHODS

Studies were conducted in a greenhouse constructed of polycarbonate plastic panels which was located at Rio Farms, Inc., in Monte Alto, TX, and in a greenhouse constructed of yellow fiberglass panels at the Texas A&M-Kingsville Citrus Center in Weslaco, TX. In the first study (Monte Alto), a group of healthy cucumber seedlings (*Cucumis sativus* L.) and a similar-aged group of seedlings that had been subjected to a moderate level of nitrogen deficiency were photographed both inside and outside the glasshouse structure on 9 September 2003 under clear sunny conditions (see Summy et al. 2004). Vertical photographs of the two plant cohorts were acquired at a distance of ~1.5 m using a 35mm camera loaded with Kodak Ektachrome CIR® film and equipped with a focal plane shutter and Wratten 15 (yellow) filter mounted on a 50 mm lens. In order to assess the effects of the glasshouse materials used in this particular structure on the quality of EMR entering the greenhouse, irradiance (i.e., incoming radiant flux, in terms of watts/m^2 per wavelength interval λ) was measured both inside and outside the structure using a FieldSpec® VNIR spectroradiometer equipped with a Remote Cosine Receptor (Analytical Spectral Devices, Boulder, CO). Spectroradiometer measurements collected inside and outside the structure using an 18º IFOV adapter and a white Spectralon® reference panel (ASD, Boulder, CO) were used to evaluate reflectance by foliage of the two plant cohorts. Similar procedures were used to acquire CIR photographs and spectroradiometer measurements of a trifoliate orange tree (*Poncirus trifoliata* [L.] Raf.) in the Weslaco greenhouse on 23 September 2003. The latter exhibited both healthy foliage and leaves damaged by feeding activities of citrus red mite, *Panonychus citri* [McGregor] (Acari: Tetranychidae).

In both studies, CIR photographs were separated into separate green, red and near-infrared channels using Adobe Photoshop 6 (Adobe Systems, Inc., San Jose, CA). These separate channels were used to develop a derivative image, the Normalized Difference Vegetation Index (NDVI), which is defined as NDVI = (NIR – Red) / (NIR + Red) (Rouse et al. 1974, Deering et al. 1975, Jensen 1996, 2000). One of the underlying assumptions of the NDVI is that significant changes in the physiology or biomass of plant foliage will produce ratios of near-infrared to red reflectance that are distinguishable in a derivative image of the two wavebands, e.g., an increase in reflectance of red wavelengths due to reduced photosynthetic activity would tend to lower the ratio of these two wavelengths in stressed plants relative to that occurring among healthy counterparts.

Separate green, red and near-infrared channels were also used to develop an unsupervised image classification, using the CLUSTER Procedure of IDRISI32 v. 2 (Clark University, Worcester, MA). This procedure and other statistical clustering algorithms are designed to identify "natural spectral classes" in CIR imagery and are commonly used to develop thematic maps of vegetation and other ground surface features (Jensen 1996, Lillesand and Kiefer 2000). Our purpose in conducting these analyses was to evaluate the potential role of these procedures to more effectively distinguish healthy from stressed foliage in CIR imagery acquired within the glasshouse environment.

RESULTS AND DISCUSSION

A comparison of irradiance measurements collected inside and outside the greenhouse indicated an overall reduction in the intensity of illumination, but no significant changes in spectral properties of visible and near-infrared wavebands entering the greenhouse (Fig. 3). However, a significant disruption of ultraviolet radiation (350-400 nm) was evident in the measurement taken inside the greenhouse, which was presumably an effect of the built-in "UV protection" of the polycarbonate panels. In this particular case, interference with UV radiation was inconsequential as UV and blue wavebands are normally blocked by use of yellow (Wratten 12 or 15) filters when using CIR film. However, the magnitude of the UV interference exemplifies the importance of determining effects of glasshouse materials prior to using CIR imagery under natural lighting conditions. For example, if such interference involved any or all of the green, red or near-infrared wavebands, acquisition of acceptable CIR imagery within this particular type of structure would be difficult, if not impossible, under natural lighting conditions.

Although foliage of healthy and stressed cucumber plants exhibited a similar coloration in conventional color (RGB) photographs (Figs. 4a and 4b), CIR imagery obtained both inside and outside the glasshouse revealed significant differences in coloration of the two foliage types, i.e., the former were considerably darker and more magenta in coloration than the latter (Figs. 4c and 4d). These differences became more pronounced in an NDVI image, which suggested a considerably higher ratio of near-infrared to red reflectance (coded as green) in the foliage of healthy plants (Fig. 4e). Moreover, an unsupervised image classification identified four natural spectral classes in the two foliage types, one of which (coded as red) occurred primarily in foliage of stressed plants (Fig. 4f). An explanation for these observations was provided by spectral curves which indicated similar reflectance of visible (blue, green and red) wavebands by foliage of both types, but substantially lower reflectance of near-infrared radiation by stressed plants (Figs. 4g and 4h). A reduction in near-infrared reflectance is a typical symptom of plant stress and generally occurs as a result of subtle changes in the cell structure of the spongy mesophyll layer of leaves (Campbell 1996).

Two important observations in these studies are particularly relevant to the proposed use of CIR imagery as a means to detect physiological stress in glasshouse crops. First, CIR imagery obtained within the greenhouse was comparable in quality and provided an interpretation similar to imagery acquired outside the structure under natural lighting conditions (Fig. 4c-d). Thus, the materials of this particular structure (polycarbonate plastic) did not significantly attenuate or degrade any of the wavebands (green, red and near-infrared) useful in multispectral imagery. More important, CIR imagery detected a subtle form of plant stress which was distinguishable with near-infrared reflectance before it became evident in the visible region of the spectrum (Fig. 4g-h). This capability potentially provides the means to identify (and ameliorate) various forms of plant stress at an early stage, thus preventing the physiological degradation that is commonly manifested as visible symptoms, e.g., a reduction or shutdown in photosynthesis, which results in the chlorotic appearance characteristic of nutrient deprivation.

Another recurrent problem in greenhouse horticulture involves the development of pest infestations (insects, mites and pathogens) that commonly cause damage equivalent to (or greater than) that encountered in conventional field crops. Among the most destructive of these pests are spider mites (Acari: Tetranychidae) which damage or destroy both epidermal and mesophyll cells of leaves as a result of feeding activities, thus producing a mottled appearance that is evident visually (Figs. 5a and 5b). CIR imagery of a trifoliate orange tree obtained within a greenhouse under natural lighting conditions (on September 23, 2003) clearly distinguished between the deep red coloration of healthy foliage (Fig. 5c) and the pinkish mottling exhibited by leaves damaged by citrus red mite (*P. citri*) (Fig. 5d). CIR imagery also revealed the distribution of damaged leaves on the tree itself (Fig. 5e), which became even more evident in an unsupervised image classification (Fig. 5f). Spectral curves revealed a substantial reduction in reflectance of all wave bands (including the visible region) by damaged leaves, which was presumably an effect of the extensive destruction of both epidermal and mesophyll cells (Fig. 6).

The capability of high-resolution imagery to distinguish between healthy and damaged foliage within a single tree is significant in the sense that it suggests a potential of CIR imagery to detect small aggregations of spider mites in glasshouse plantings during an early stage of development, i.e., before they exhibit their typical rapid population increases and become general infestations. Providing greenhouse managers with the technology to detect (and control) such incipient infestations at an early stage of development would be analogous to providing forest managers the technology to detect (and extinguish) smoldering camp fires before they become raging forest fires.

In summary, these preliminary studies suggest that many of the remote sensing techniques that have been used so successfully in conventional field crops for the past six decades may, with certain modifications, be readily extendable to the commercial glasshouse environment. This transition, however, will be predicated on the development of remote sensing techniques that are reliable, relatively inexpensive, and usable under all weather (lighting) conditions. Thus, additional research is needed to define the spectral properties of the major glasshouse crops and to determine when and in what wavebands damage caused by a variety of production factors (nutrient deficiencies, arthropod pests and pathogens) first becomes detectable. Research designed to assess the effects of additional glasshouse materials and weather conditions on the quality of incident EMR is critical if acquisition of CIR imagery is based on natural lighting conditions, although artificial lighting configurations designed to provide optimal lighting under all circumstances could conceivably be developed and would thus mitigate this requirement. Given the

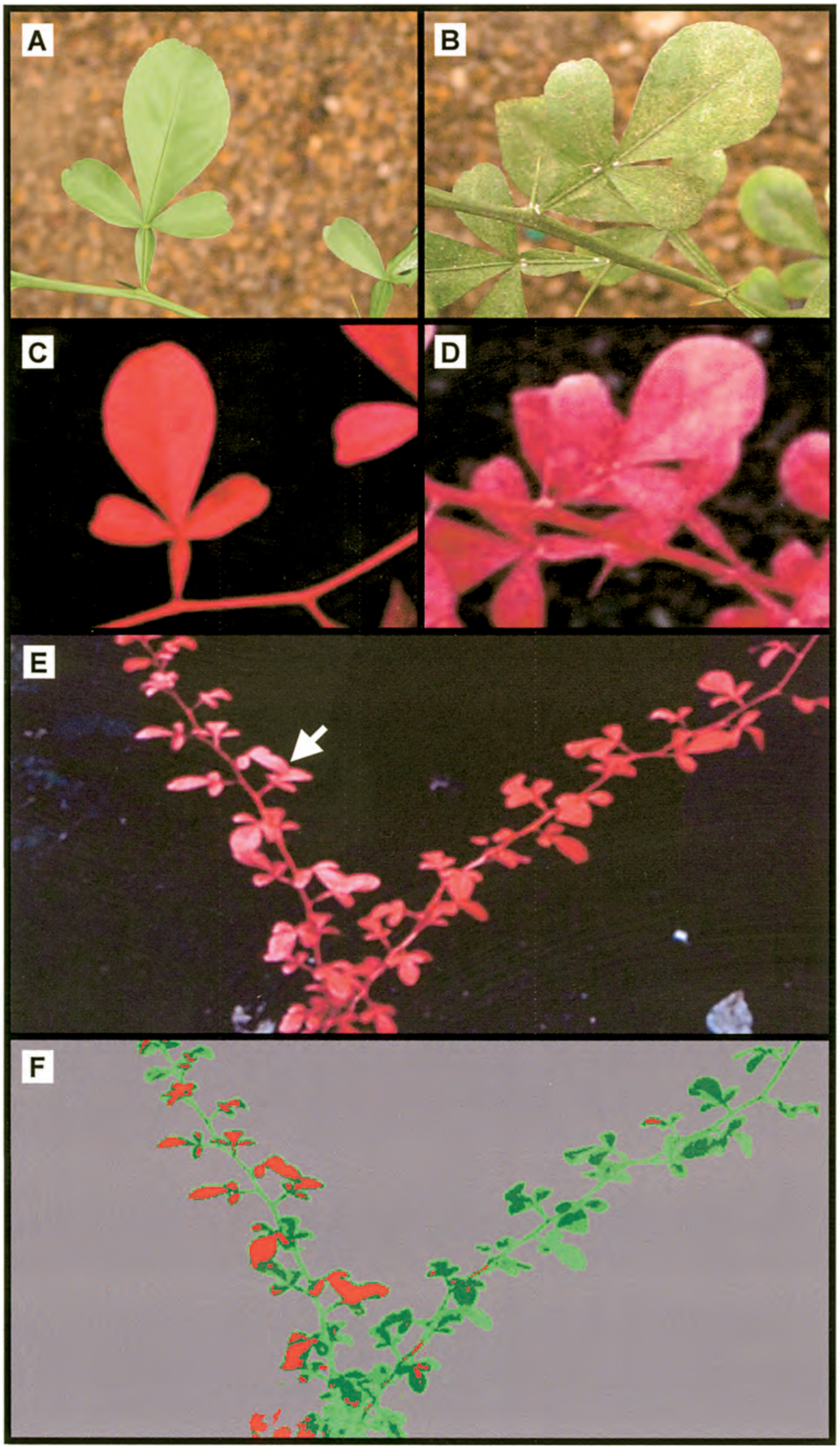

Fig. 5. Conventional color (RGB) photographs of trifoliate orange (*Poncirus trifoliate*), showing healthy foliage (A) and effects of damage caused by citrus red mite (*Panonychus citri*) (B). Color infrared (CIR) photographs showing healthy (C) and mite-damaged foliage (D). CIR photograph showing effects of mite damage (light areas indicated by arrow) on branch (E) and results of an unsupervised image classification (F).

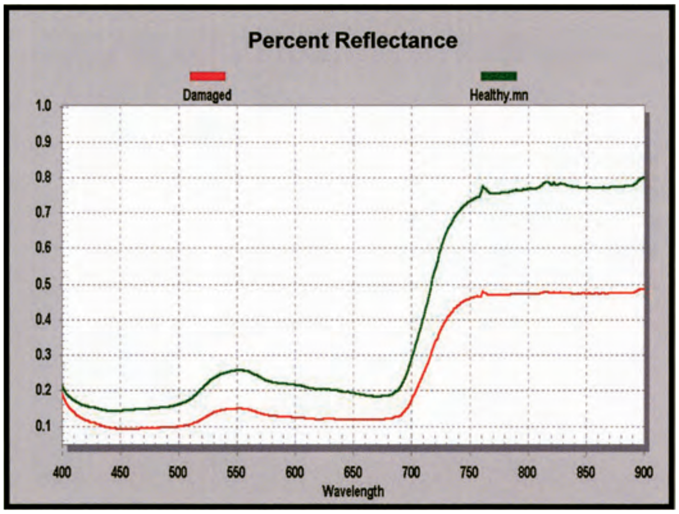

Fig. 6. Comparison of spectral reflectance curves for healthy foliage of trifoliate orange (green line) and the effects of damage caused by citrus red mite (red line).

current cost of CIR film (in this case, $39 per 36-frame roll) and the need for film-processing facilities, use of high-resolution digital CIR cameras capable of acquiring a voluminous amount of imagery and storing such data on relatively inexpensive computer disks would appear to be a requisite for adoption of this technology. Although current CIR camera systems are used primarily for research and are relatively expensive, the development of inexpensive CIR camera systems and "user-friendly" software for processing imagery by personnel who are not trained remote sensing specialists is not beyond the realm of current technology, provided that a suitable demand exists. The magnitude of the demand for this technology will be largely dependent on future demonstrations of efficacy by researchers and the attitude adopted by commercial glasshouse operators, i.e., whether they are willing to invest in new technology designed to detect plant stress at an early stage, or whether they decide to continue with the conventional approach of allowing plant stress to progress to the point where it produces the visible symptoms recognized by trained glasshouse workers.

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