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Kenneth R. Summy
The University of Texas Rio Grande Valley

Christopher R. Little

James H. Everitt
The University of Texas Rio Grande Valley

Ruben A. Mazariegos
The University of Texas Rio Grande Valley

J. V. French

See next page for additional authors

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Kenneth R. Summy,[1] Christopher R. Little,[2] James H. Everitt,[3]
Ruben A. Mazariegos,[1] J. Victor French, [4] Mamoudou Setamou,[4] and Jesus Mata[4]

[1]The University of Texas – Pan American, Edinburg, Texas
[2]Kansas State University, Manhattan, Kansas
[3] USDA Agricultural Research Service, Weslaco, Texas
[4] Texas A&M University – Kingsville Citrus Center, Weslaco, Texas

ABSTRACT

Research was conducted to evaluate the effectiveness of multispectral (conventional color and color infrared) imagery and a common vegetation index (simple ratio) for detecting incipient infestations of spider mites (*Tetranychus* spp.; Acari: Tetranychidae) and false spider mites (*Brevipalpus* spp.; Acari: Tenupalpidae) on selected crops under glasshouse conditions. Although damaging infestations of both mite species were associated with intense feeding injury which was readily detectable by visual inspection, subtle levels of foliar damage caused by the two mite species were difficult to detect by visual inspection and were not readily distinguishable from undamaged (healthy) foliage in conventional color (CC) or color infrared (CIR) imagery. In contrast, foliage exhibiting subtle levels of mite feeding injury was readily distinguished from healthy foliage in derivative imagery based on the *Simple Ratio* (SR), a vegetation index defined as the ratio of near-infrared to red reflectance (700-1100 nm and 600-700 nm, respectively) for each pixel in the imagery. CIR and SR images were shown to be considerably more effective than CC imagery in the initial detection and subsequent monitoring of a spider mite infestation on glasshouse cucumbers which increased from incipient to annihilative levels within a period of approximately six weeks. The rationale for and potential uses of CC, CIR, and derivative imagery based on SR and other vegetative indices for monitoring pest infestations on glasshouse crops are discussed.

Additional Index Words: remote sensing, spider mites, greenhouse, vegetation indices.

Various types of remotely sensed imagery have been used for many years to monitor the condition of various agricultural crops (see reviews in Avery and Berlin 1992; Campbell 2007; Jensen 2007; Lillesand et al. 2004; Ryerson et al. 1997; Everitt et al. 2003). Color infrared (CIR) imagery has proven to be particularly useful in this respect as many forms of plant stress are associated with changes in near-infrared (NIR) reflectance, which is influenced by the internal structure of leaves (Campbell 2007) and involves wavelengths which are not detectable by the human visual system (Colwell 1956, Jensen 2007). In an effort to facilitate conventional visual interpretation of CIR imagery, various image-enhancement procedures have been developed, including techniques for contrast manipulation, spatial feature manipulation, and multi-image manipulation (Lillesand et al. 2004; Jensen 2005). Among the most useful of these techniques are various vegetation indices which are based on ratios of two or more waveband regions, particularly the red (600-700 nm) and near-infrared regions (700-1,100 nm) for each pixel in the imagery (Lillesand et al. 2004).

Our objectives in this study were to evaluate the effectiveness of two types of digital multispectral imagery (conventional color and CIR) and imagery based on a common vegetation index (the *Simple Ratio,* defined as the numerical ratio of NIR/Red) for detection of incipient infestations of spider mites (*Tetranychus* spp.; Acari: Tetranychidae) and false spider mites (*Brevipalpus* spp.; Acari: Tenupalpidae) on selected crops in the glasshouse environment. The former is one of the most destructive pests of glasshouse crops in the United States and other areas of the world (Gill and Sanderson 1998), while the latter is a major concern to citrus nurseries in southern Texas and other subtropical and tropical areas because of its role as an efficient vector of leprosis virus (Anciso 2002). In both cases, the availability of remote sensing technology suitable for use within the glasshouse environment and capable of detecting incipient (low-level) infestations of such pests would greatly facilitate efforts to develop effective pest management programs and increase the profitability of glasshouse crop production (Summy et al. 2003; Little and Summy 2008).

MATERIALS AND METHODS

Foliage of cucumber (*Cucumis sativus*) plants exhibiting variable levels of damage caused by spider mites (*Tetranychus* spp.) were excised and photographed using a 35mm Nikon SLR camera equipped with 50 mm lens and Wratten 15 (yellow) filter. The camera was loaded with Kodak Ektachrome Professional Infrared EIR® film, and exposures were obtained using an artificial (quartz halogen) lighting source (Summy et al. 2004). CIR imagery was scanned at 300 dpi using an Epson Expression® 1600 desktop scanner, and individual waveband images (green, red and NIR) were imported into Idrisi Kilamanjaro® (Clark University, Worcester, MA) for development of CIR composites and vegetation indices based on NIR/R ratios. A conventional color (CC) image was also acquired from the same vantage point and under the same lighting conditions using a Sony Mavica® CD400 digital camera with 5 Mp resolution. Similar procedures were used to acquire and process imagery of damage caused by false spider mites (*Brevipalpus* sp.; Acari: Tenupalpidae) on potted citrus plants.

Spectral reflectance of healthy and damaged foliage of each type were measured using a FieldSpec® VNIR spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO) which is sensitive to wavelengths extending from the ultraviolet (300-350 nm) through the NIR region (700-1,100 nm) in 10-nm intervals. Spectral measurements were collected at a distance of 0.5-1.0-m above plants using a target probe with 18-degree field of view and a Remote Cosine Receptor to measure irradiance or incident radiation. Prior to the first spectral measurement and at frequent intervals thereafter, a reference measurement was acquired using a Spectralon® reference panel to facilitate real-time conversion of radiance measurements to percent reflectance using Dual RS^3 software (Analytical Spectral Devices, Inc. Boulder, CO). Reflectance measurements were processed using ViewSpec Pro® software (Analytical Spectral Devices, Boulder, CO) and mean reflectance values at selected wavelengths in the blue (450 nm), green (550 nm), red (650 nm) and NIR region (850 nm) were compared using one-way analysis of variance and Tukey's pairwise comparison test (SPSS 2000).

An experimental evaluation of this technology was conducted in glasshouse facilities of the Texas A&M University – Kingsville Citrus Center in Weslaco, Texas during August – October, 2005. Twenty-five pots containing cucumber seedings were arranged in a 5 x 5 –pot configuration, and the center pot was inoculated with four female mites (*T. utricae*) on 10 August. Plants were photographed at this time and on two additional occasions (30 September, and 10 October) using both CC and CIR imagery (cameras described previously) from a vertical perspective at an altitude of ~ 2.0 m under quartz-halogen lighting conditions. This experiment provided a means to compare the effectiveness of CC, CIR and ratio imagery for monitoring the increase of a spider mite infestation under actual glasshouse production conditions.

RESULTS AND DISCUSSION

Feeding injury to cucumber foliage caused by spider mites (*Tetranychus* spp.) was accompanied by a progressive increase in reflectance of all visible wavelengths (blue, green and red) as the intensity of damage increased (Table 1). Although moderate and heavy levels of damage were readily detectable by visual inspection of foliage, differences in reflectance by undamaged and slightly-damaged foliage were subtle and difficult to distinguish by visual inspection or use of conventional color imagery (Table 1; Fig. 1). Similarly, reflectance of NIR wavelengths by undamaged and slightly-damaged foliage occurred at similar levels (38.4 and 36.5%, respectively; $P>0.05$) and the two categories were essentially indistinguishable in conventional CIR imagery (Table 1; Fig. 1). However, the ratio near-infrared to red reflectance decreased progressively as levels of mite damage increased ($F=903.2$; $df=3,16$; $P<0.001$) (Table 1), and the transformation of CIR imagery to ratio imagery (NIR/R) facilitated the discrimination of mite damage at all levels including the subtle differences between undamaged and slightly-damaged foliage which were essentially indistinguishable with other types of imagery (Fig. 1).

Feeding injury to citrus caused by false spider mites (*Brevipalpus* spp.) is commonly associated with chlorosis or discoloration which tends to be most pronounced along leaf edges (Fig. 2). No significant differences in spectral reflectance of visible wavelengths were detected among plants exhibiting three levels of mite feeding damage ($P>0.05$), whereas NIR reflectance was greatest among plants exhibiting 'light' and 'medium' damage (36.4 and 38.6%, respectively) and lowest among counterparts exhibiting 'heavy' damage (28.7%; $P<0.05$) (Table 2). Ratios of near-infrared to red reflectance

Fig. 1. Foliage of cucumber (*Cucumis sativus*) exhibiting various levels of foliar damage caused by spider mites (*Tetranychus* spp.), photographed in conventional color (left), color infrared (middle), and transformed to simple ratios of near-infrared to red reflectance (right). Damage levels within each frame ranged from zero (upper left), to slight damage (upper right), to moderate damage (lower left) to heavy damage (lower right). (Modified from

decreased progressively as mite damage increased (F=17.2; df=2,9; $P<0.001$; Table 2), and imagery based on the simple ratio (SR) clearly indicated relatively high NIR/R ratios among plants exhibiting 'light' damage and relatively low ratios among counterparts exhibiting 'heavy' damage (Fig. 2).

In both cases, the use of derivative imagery based on the simple ratio (SR) greatly facilitated the detection and interpretation of feeding damage caused by the two foliar-feeding mite species. By providing both a quantitative measure of damage (i.e., the NIR/R ratios *per se*) and a visual interpretation of damage levels (i.e., imagery based on NIR/R ratios), imagery based on SR facilitated the detection of subtle levels of damage that were difficult or impossible to detect using conventional CC or CIR imagery alone. The biological rationale for the use of ratio imagery is based on the premise that the numerator of the ratio (NIR reflectance) tends to be relatively high in healthy plant foliage and commonly decreases as a result of stress and/or senescence, whereas the denominator (red reflectance) tends to be relatively low in healthy

Table 1. Comparison of spectral reflectance measurements for cucumber (*Cucumis sativus*) foliage exhibiting selected levels of damage caused by spider mites (*Tetranychus* spp.).

Damage level[b]	Wavelength Interval[a]				
	450nm	550nm	650nm	850nm	NIR/R
Control	8.1a	16.1a	7.1a	38.4a	5.4a
Light	9.0b	19.6b	8.8b	36.5a	4.2b
Medium	13.3c	28.6c	16.0c	44.0b	2.8c
Heavy	27.9d	38.4d	35.9d	35.7a	1.0d

[a] Means within columns followed by same letter not significantly different at 5% probability level (Tukey's pairwise comparison test).
[b] Control = uninfested healthy leaves; Light = mite feeding injury (stippling) localized on leaf and damage minimal; Medium = stippling extensive, but greenish coloration in most areas of leaf indicative of functional chloroplasts; Heavy = stippling extensive with bleached coloration in most areas of leaf indicative of wholesale destruction of chloroplasts..

Table 2. Comparison of spectral reflectance measurements for citrus foliage exhibiting selected levels of damage caused by false spider mites (*Brevipalpus* spp.).

Damage Level[b]	Wavelength Interval[a]				
	450nm	550nm	650nm	850nm	NIR/R
Light	6.2a	11.5a	6.3a	36.4a	5.8a
Medium	5.1a	12.7ab	7.9a	38.6a	5.0b
Heavy	6.6a	13.5b	8.6a	28.7b	3.3c

[a]Means within columns followed by same letter not significantly different at 5% probability level (Tukey's pair-wise comparison test).
[b] Light = feeding injury localized with minimal damage to leaf; Medium = feeding injury evident throughout leaf but damage minimal and leaf margins normal; Heavy = feeding injury extensive and leaf margins discolored.

(photosynthesizing) plant foliage and commonly increases as a result of stress factors that impede or halt photosynthesis (Campbell 2007). Thus, relatively small decreases in the magnitude of NIR reflectance (which is primarily a function of the structure and condition of air cells in the spongy mesophyll layer of leaves) and/or increases in the magnitude of red reflectance (which is primarily an effect of photosynthetic efficiency and/or changes in the composition of photosynthetic pigments) result in relatively large decreases in the magnitude of the NIR/R ratio. Such sensitivity is very advantageous in the glasshouse crop environment where effective control of spider mites and other pests is largely predicated on the detection of pest infestations while the latter are still in the incipient stage of development, i.e., before they have become widespread and abundant.

The potential effectiveness of remotely sensed imagery and vegetation indices in the management of glasshouse crop pests was exemplified by trends documented in the TAMU-K glasshouse experiment during 2005 (Figs. 3-5). Foliar damage caused by spider mites (*T. urticae*) increased substantially from the time of inoculation on 10 August (Fig. 3a-c) to 30 September, when foliar feeding damage was distinguishable in CC imagery (Fig. 3a). A somewhat greater extent of damage was evident in both CIR imagery (Fig. 4b) and imagery based on the SR vegetation index acquired on this same date (Fig. 4c). By 10 October, extensive damage throughout the planting was evident in all types of imagery (Fig. 5a-c). Thus, an initial inoculation involving four spider mites to a single plant located near the center of the planting generated an incipient infestation which expanded rapidly and essentially destroyed the entire planting within a period of approximately six weeks. The rapidity of this expansion is typical of those occurring in spider mite infestations in the glasshouse environment, and exemplifies the need for monitoring procedures that are efficient, inexpensive and capable of detecting incipient pest infestations. The latter typically occur at relatively low levels in a highly aggregated distribution that may be very difficult, if not impossible, to detect using conventional visual inspection (Summy et al. 2003).

Many of the traditional criticisms of conventional remote sensing of outdoor field crops do not appear to represent major constraints to the use of this technology in the glasshouse crop environment. In particular, the requirement for clear sunny conditions for acquisition of CIR imagery is irrelevant if a suitable artificial lighting source is utilized. Quartz-halogen bulbs have been shown to emit all of the wavelengths required for the acquisition of both CC and CIR imagery (Summy et al. 2004; Jensen 2007), and CC and CIR imagery acquired using artificial lighting sources tends to be comparable in quality to imagery acquired under natural lighting conditions (Summy et al. 2004). Use of artificial lighting thus facilitates the acquisition of both CC and CIR imagery under all weather and ambient lighting conditions (a requisite for use of this technology for monitoring glasshouse crops), and use of CIR and ratio imagery provides a means to detect subtle forms of plant damage caused by pest infestations which have not yet increased to damaging levels and which may not exhibit conventional (visible) symptoms of damage.

Fig. 2. Foliage of citrus plants exhibiting various levels of foliar damage caused by false spider mites (*Brevipalpus* spp.), photographed in conventional color (upper), color infrared (middle), and transformed to simple ratios of near-infrared to red reflectance (lower). Damage levels within each frame ranged from slight (left), to moderate (middle) and heavy (right). (Modified from Summy et al. 2005).

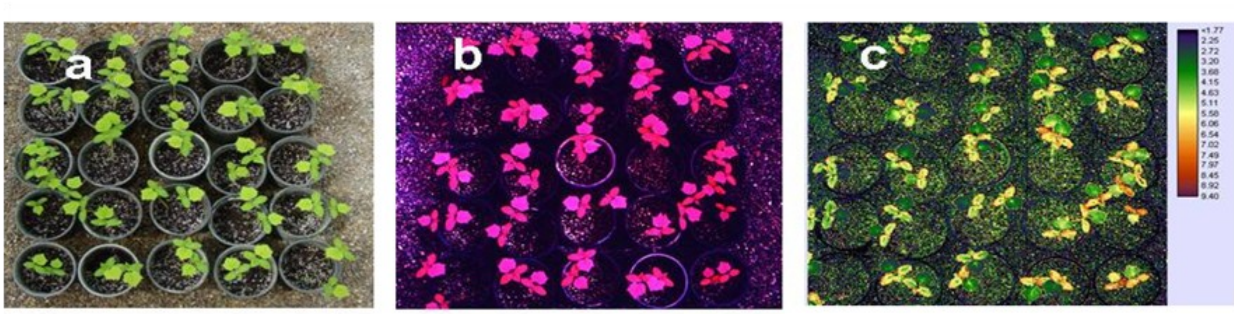

Fig. 3. Uninfested cucumber seedlings photographed in conventional color (a), color infrared (b) and transformed to ratios of near-infrared to red reflectance (c) prior to inoculation with four spider mites (*Tetranychus urticae*) on 10 August 2005. (Modified from Summy et al. 2005).

Fig. 4. Spider mite feeding damage was evident in all types of imagery acquired on 30 September 2005. CC imagery (a) suggested that mite feeding damage (characterized by light green or white foliage) was largely concentrated within the central portion of the planting, whereas CIR imagery (b) suggested a much greater extent of foliar damage (characterized by whitish and pinkish coloration). A similar interpretation was provided by ratio imagery (c), which indicated relatively low NIR/R ratios (characterized by bluish and greenish coloration) within the central portion of the planting and relatively high ratios (characterized by orange and purple) in the remainder of the planting.

Fig. 5. Extensive mite feeding damage within the central portion of the planting was evident in CC imagery acquired on 10 October 2005 (a). A much greater extent of damage was evident in CIR imagery (b) and ratio imagery (c), both of which indicated extensive damage throughout the planting.

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