Subtropical Plant Science, 56: 44-51.2004

Evaluation of Artificial Lighting Sources for the Acquisition of Color Infrared Imagery Under Glasshouse Conditions

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ABSTRACT

Research was conducted to evaluate the spectral properties, illumination intensities and lighting patterns of four basic categories of bulbs and lamps which could conceivably serve as sole lighting sources for the acquisition of color infrared (CIR) imagery under glasshouse conditions. Bulbs and lamps in two major categories (fluorescent tubes and sodium- and mercury-vapor glasshouse lamps) were deemed unsuitable for this purpose either because they emitted little or no near-infrared (NIR) radiation or because they imparted an overall bluish cast that seriously degraded the quality of CIR imagery. All of the incandescent and quartz halogen lamps evaluated in these studies exhibited spectral properties suitable for CIR image acquisition, i.e., they emitted relatively high levels of both visible and NIR radiation. However, most bulbs and lamps in these categories were characterized by either inadequate levels of illumination or reflectors that produced a circular lighting pattern in which luminosity varied substantially from the center portion of the image to the edges. The most suitable bulb evaluated was a heavy-duty (500W) quartz halogen lamp with a rectangular reflector which, when modified by the addition of crumpled aluminum foil to the reflector housing, produced adequate levels of illumination that was distributed in a near-uniform pattern across the target area. Color infrared imagery of plant foliage acquired using this lamp as a sole lighting source was comparable in quality to imagery of the same plant material acquired under natural lighting conditions. The performance of this particular lamp is used to exemplify the stringent requirements of any lamp under consideration as a sole lighting source for CIR image acquisition within the glasshouse environment.

RESUMEN

Se investigaron las propiedades espectrales, las intensidades de iluminación y los patrones de luz de cuatro tipos básicos de bulbos y lámparas que podrían servir como fuentes únicas de luz para la adquisición de imágenes infrarrojas (CIR) bajo condiciones de invernadero. No se consideraron adecuados para este propósito los bulbos y las lámparas en dos categorías importantes (tubos de fluorescencia y lámparas de invernadero de vapor de mercurio y sodio ya que o emitieron muy poca o ninguna radiación infrarroja cercana (NIR) o porque impartieron un tono azul que degradó seriamente la calidad de las imágenes CIR. Todas las lámparas incandescentes y de halógeno de cuarzo evaluadas en estos estudios exhibieron propiedades espectrales adecuadas para la adquisición de imágenes infrarrojas, por ejemplo, emitieron niveles relativamente altos de radiación visible y de radiación cercana al infrarrojo. Sin embargo, las mayoría de los bulbos y lámparas en esta categoría se caracterizaron por producir niveles inadecuados de iluminación o por producir un patrón de luz circular en el cual la luminosidad varió substancialmente de la porción central de la imagen a las orillas. El bulbo probado que resultó mas adecuado fue la lámpara de halógeno-cuarzo con un reflector rectangular el cual, cuando se modificó por la adición de papel aluminio arrugado al nicho del reflector, produjo niveles adecuados de iluminación que se distribuyeron en un patrón casi uniforme a lo largo de la área expuesta. Las imágenes infrarrojas del follaje vegetal tomadas usando esta lámpara como única fuente de luz fueron comparables en calidad a las imágenes del mismo follaje tomadas bajo condiciones de luz natural. El desempeño de esta lámpara en particular es usado para ejemplificar los estrictos requerimientos para cualquier lámpara que sea usada como única fuente de luz para la adquisición de imágenes de color infrarrojo en ambiente de invernadero.

Color infrared (CIR) film and other types of multispectral imagery have been used for many years to monitor the physiological condition of agricultural crops (Avery and Berlin 1992, Campbell 1996, Wilke and Finn 1996, Ryerson and Curran 1997, Jensen 2000, Lillesand and Kiefer 2000). Color infrared film consists of three emulsions with sensitivities to electromagnetic radiation (EMR) in the green (500-600 nm), red (600-700 nm) and near-infrared (700-900 nm) regions of the spectrum (Lillesand and Kiefer 2000). As all three emulsions are sensitive to EMR in the blue region

Table 1. Luminosity (in footcandles) of selected incandescent and quartz halogen bulbs at a distance of 2.0 m from the lighting source.

Category	Bulb Type	Luminosity +/- SD[1]
		foot-candles
Incandescent	GE 75W Standard Bulb	24.0 +/- 0.0
Incandescent	GE 120W Flood-lamp	127.7 +/- 0.5
Quartz Halogen	GE 45W Flood-lamp	28.0 +/- 0.0
Quartz Halogen	TCP Heavy Duty Lamp	114.0 +/- 0.8

[1]Mean based on average of 3 measurements.

(400-500 nm), this waveband is normally filtered out by using yellow (minus-blue) filters attached to the lens. Modern digital CIR cameras are sensitive to these same wavebands which are recorded electronically as separate images (one each for the green, red and near-infrared wavebands) using either charge-coupled devices (CCDs) or complementary metal oxide semiconductor (CMOS) technology (Fig. 1). When separate images for green, red and near-infrared wavebands are projected as blue, green and red, respectively, a composite image is produced in which green objects appear blue, red objects appear green, and those with high near-infrared (NIR) reflectance appear red (Lillesand and Kiefer 2000). Although such "false color" imagery was originally designed for camouflage detection (i.e., to distinguish between healthy green foliage and green military vehicles), its capability for discriminating between healthy and stressed vegetation was quickly recognized and exploited (Colwell 1956, Gausman *et al.* 1969, Gausman 1985). Since the end of World War II, CIR imagery has been used extensively to detect many types of stress in agricultural crops, including salinity and moisture problems (Myers *et al.* 1963, Everitt et al. 1981), nutrient deficiencies (Thomas and Oerther 1977), and damage caused by various pests (Colwell 1956, Brenchley 1964, Norman and Fritz 1965, Hart and Myers 1968, Payne *et al.* 1971, Hart et al. 1973, Blazquez *et al.* 1979, Blazquez and Horn 1980, Toler *et al.* 1981, Blazquez *et al.* 1988, Everitt *et al.* 1994, 1996).

Thusfar, the majority of remote sensing applications in agriculture have involved monitoring the condition of conventional (outdoor) crops such as cotton, corn and citrus (Jensen 2000). Recent studies have demonstrated the feasibility of using CIR imagery for detecting certain types of physiological stress in glasshouse crops such as cucumber, *Cucumis sativus*, under natural lighting conditions and discussed many of the problems that must be addressed if remote sensing technology is to be used effectively within the artificial glasshouse environment (Summy *et al.* 2004a, 2004b). Although most of the common glasshouse materials do not appear to seriously degrade the quality of EMR transmitted to the interior of the glasshouse, shadowing caused by overhead obstructions may complicate interpretation of CIR imagery and automated image classifications developed from such imagery. One of the major problems that must be addressed relates to poor lighting conditions caused by inclement weather conditions, which have long represented one of the major constraints to acquisition of CIR imagery in conventional crop systems. As many glasshouse crops are produced on a continuous basis, i.e., during all seasonal periods, and are subject to various pest infestations that may cause damage equivalent to or greater than that occurring in conventional outdoor crops, it is imperative that any remote sensing techniques designed to monitor crops within the glasshouse environment be usable under all weather conditions. Use of an artificial lighting source could conceivably facilitate the acquisition of CIR imagery under all ambient lighting conditions provided that the particular lighting source emits the proper wavebands of EMR and produces adequate illumination that is distributed in a relatively uniform pattern across the target area.

In an attempt to develop an artificial lighting source designed to facilitate CIR image acquisition under all weather conditions, we conducted a survey of four major categories of bulbs and lamps commonly used in glasshouses: 1) standard "cool white" and "plant growth" fluorescent tubes, 2) mercury- and sodium-vapor glasshouse lamps, 3) incandescent bulbs and floodlamps, and 4) quartz halogen lamps (Fig. 2). For selected bulbs within each category, we evaluated 1) spectral emittance properties, 2) illumination intensities at a distance (approximately 2.0 m) comparable to that at which the CIR camera would normally be positioned with respect to the target, and 3) lighting patterns produced by particular bulb designs.

MATERIALS AND METHODS

Spectral emittance properties of each bulb type were evaluated using a FieldSpec VNIR spectroradiometer (Analytical Spectral Devices, Boulder, CO) equipped with a remote cosine receptor (RCR) designed to measure irradiance (watts/m^2/per wavelength interval, l) across a spectrum extending from 300-1100 nm. In each case, irradiance was measured by positioning the RCR at a distance of 0.5 m from the emitting bulb which served as the sole lighting source. Illumination intensities of bulb types deemed to have suitable spectral properties (i.e., adequate levels of both visible and near-infrared EMR) were measured at a distance of 2.0 m from the emitting bulb using a Lux / FC light meter (Sper Scientific, Ltd., Scottsdale, AZ). Lighting patterns of candidate bulbs exhibiting both suitable spectral properties and adequate illumination intensities were evaluated by positioning the lighting source at a distance of 2.0 m from a white wall and measuring illumination intensities at intervals of 0.0, 0.5 and 1.0 m from the center of a "cross-hair" pattern in both horizontal and vertical directions.

Digital CIR images of cucumber (*Cucumis sativus*) foliage

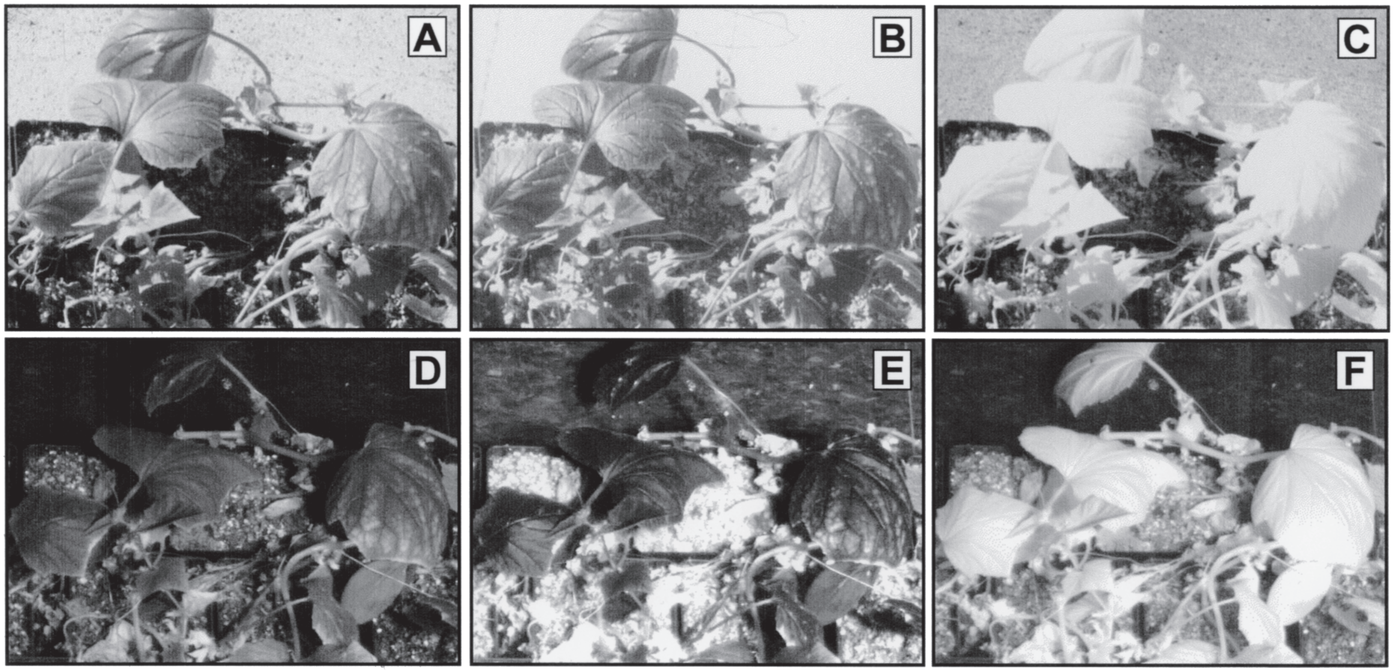

Fig. 1. Color-infrared (CIR) imagery of *Cucumis sativus* plants taken under natural (sunlight) and artificial lighting conditions (500W quartz-halogen lamp) using a digital CCD CIR camera. Under sunlight, separate (A) green (visualized as blue), (B) red (visualized as green), and (C) near-infrared (visualized as red) wavebands were used to construct a composite CIR image. Using a quartz-halogen lamp, separate (D) green (visualized as blue), (E) red (visualized as green), and (F) near-infrared (visualized as red) wavebands are used to construct a composite CIR image. Composite CIR images are not shown.

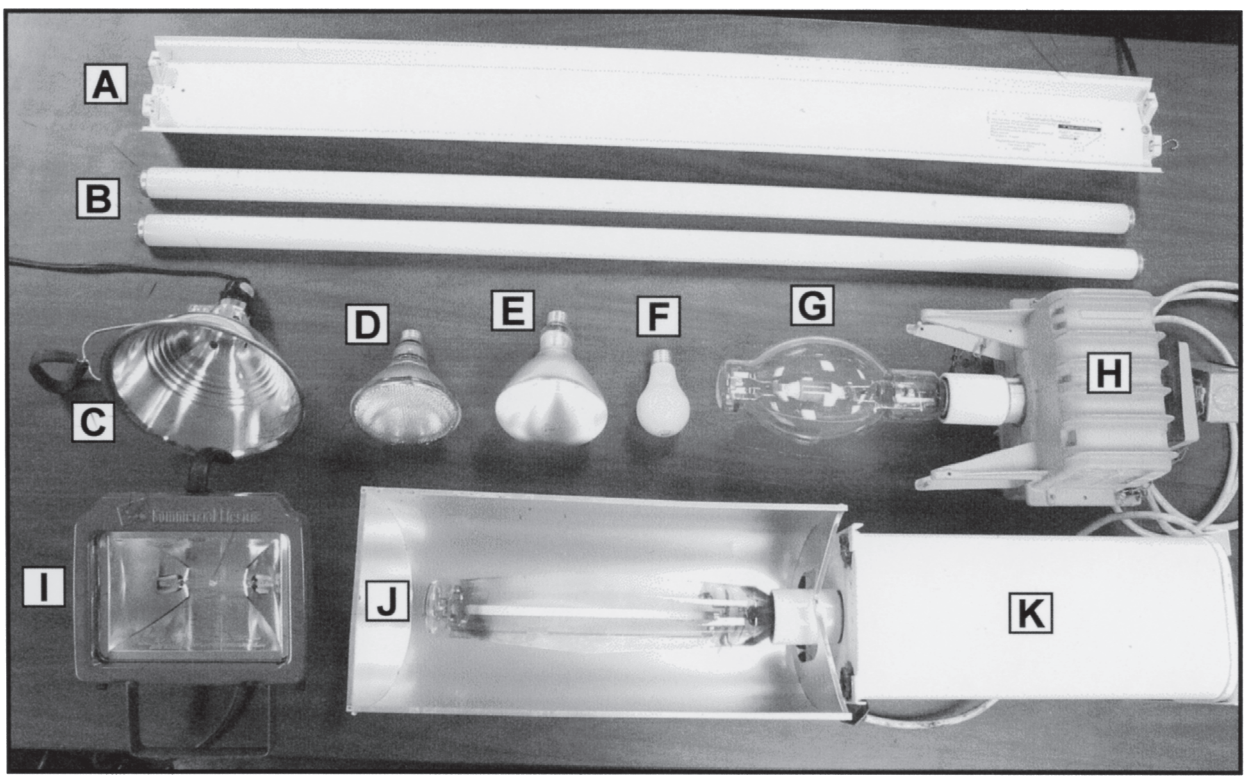

Fig. 2. Lighting sources (and equipment) evaluated in this study. (A) Receptacle for fluorescent tubes, (B) "cool-white" (top) and "plant-growth" (bottom) fluorescent tubes, (C) receptacle-conical reflector for thread-mounted bulbs, (D) 45 W quartz-halogen flood-lamp, (E) 120 W incandescent flood-lamp, (F) 75 W incandescent bulb, (G) mercury-vapor glasshouse lamp, (H) mercury-vapor lamp receptacle, (I) 500 W quartz-halogen lamp, (J) sodium-vapor glasshouse lamp, and (K) sodium-vapor lamp receptacle.

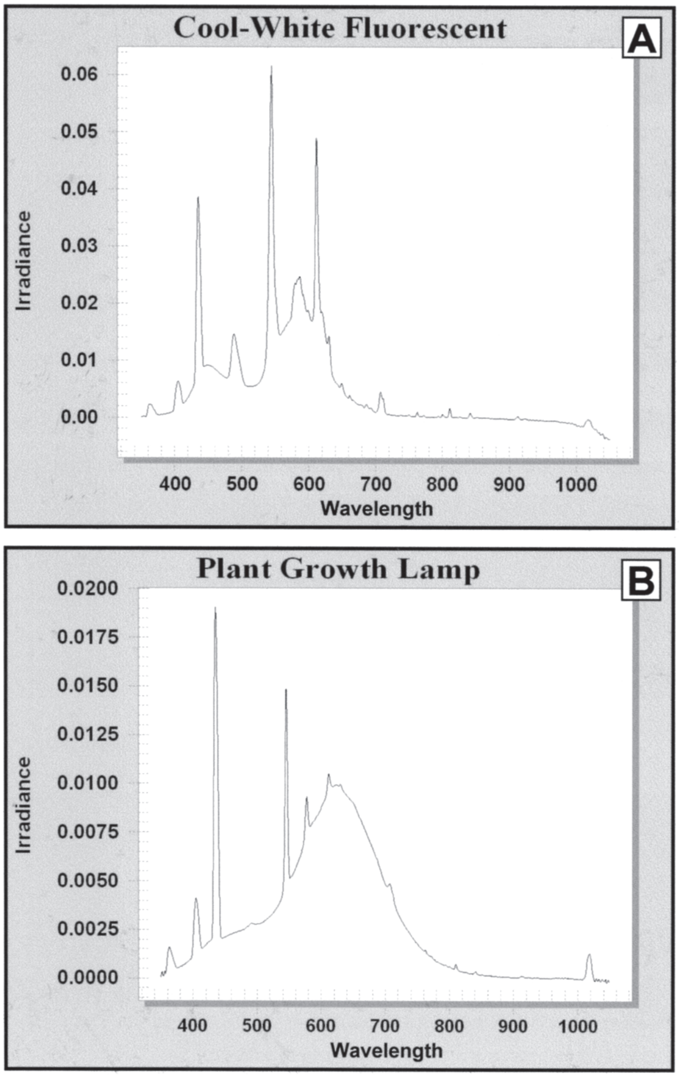

Fig. 3. Spectral profiles (irradiance) of (A) "cool-white" and (B) "plant-growth" fluorescent ballasts as measured in the visible and near-infrared wavelengths.

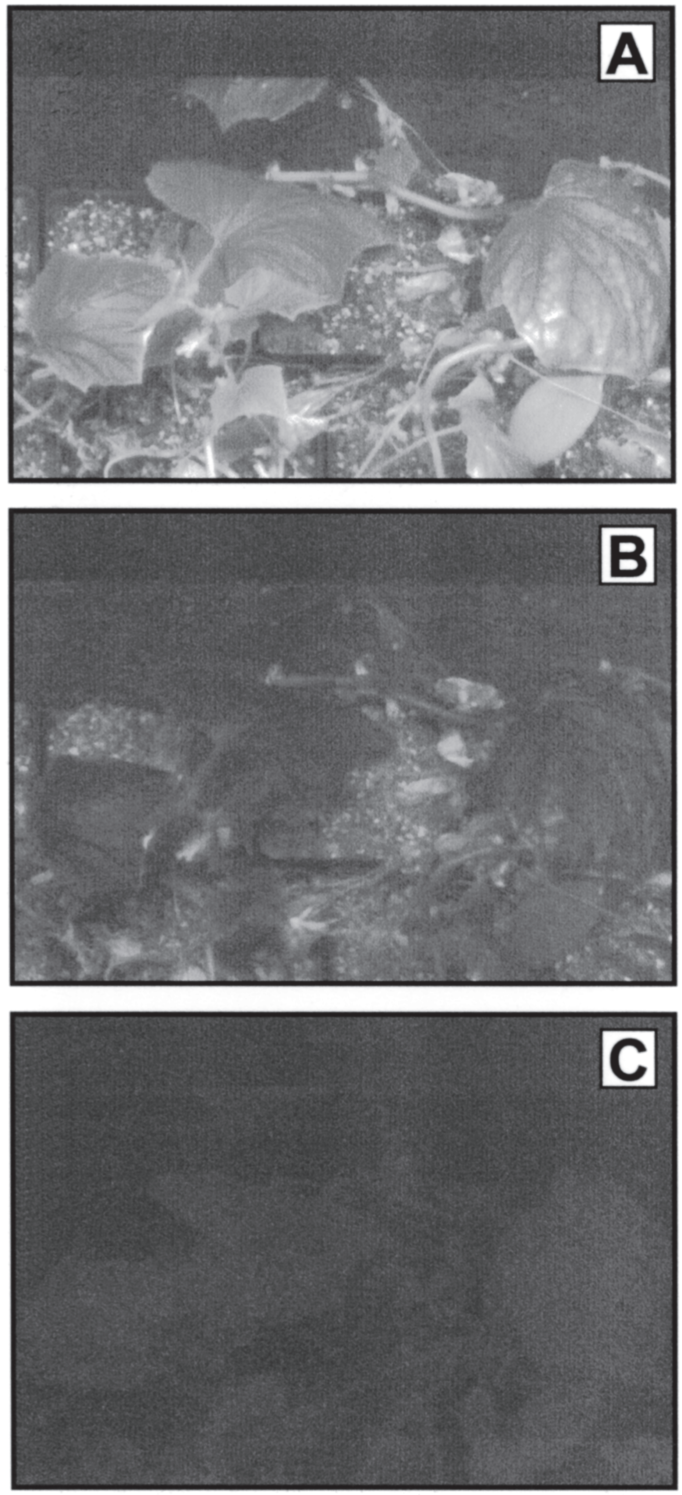

Fig. 4. Color-infrared (CIR) imagery of *Cucumis sativus* plants taken under artificial lighting conditions produced by a "plant-growth" fluorescent source. Images were acquired using a digital CCD CIR camera. Separate (A) green (visualized as blue), (B) red (visualized as green), and (C) near-infrared (visualized as red) wavebands are used to construct a composite CIR image (not shown).

were acquired under various lighting sources using a DuncanTech MS-3100 CIR camera system (DuncanTech, Auburn, CA) equipped with a NI 1424 frame-grabber (National Instruments, Austin, TX). Images acquired in this manner were separated into green, red and NIR waveband images using Adobe Photoshop 6 (Adobe Systems, Inc., San Jose, CA), which were then imported as TIFF files into IDRISI32 v. 2 (Clark University, Worcester, MA) for processing. The quality of green, red and NIR waveband images of cucumber plants acquired using artificial lighting sources was compared to imagery of these same plants acquired under natural (clear sunny) lighting conditions.

RESULTS AND DISCUSSION

Two of the lamp categories evaluated in these studies exhibited one or more major limitations that precluded their use as sole lighting sources for CIR image acquisition. Dominant wavelengths emitted by "cool white" fluorescent tubes occurred in the blue and green regions of the spectrum (400-500 and 500-600 nm, respectively) while peak emittance

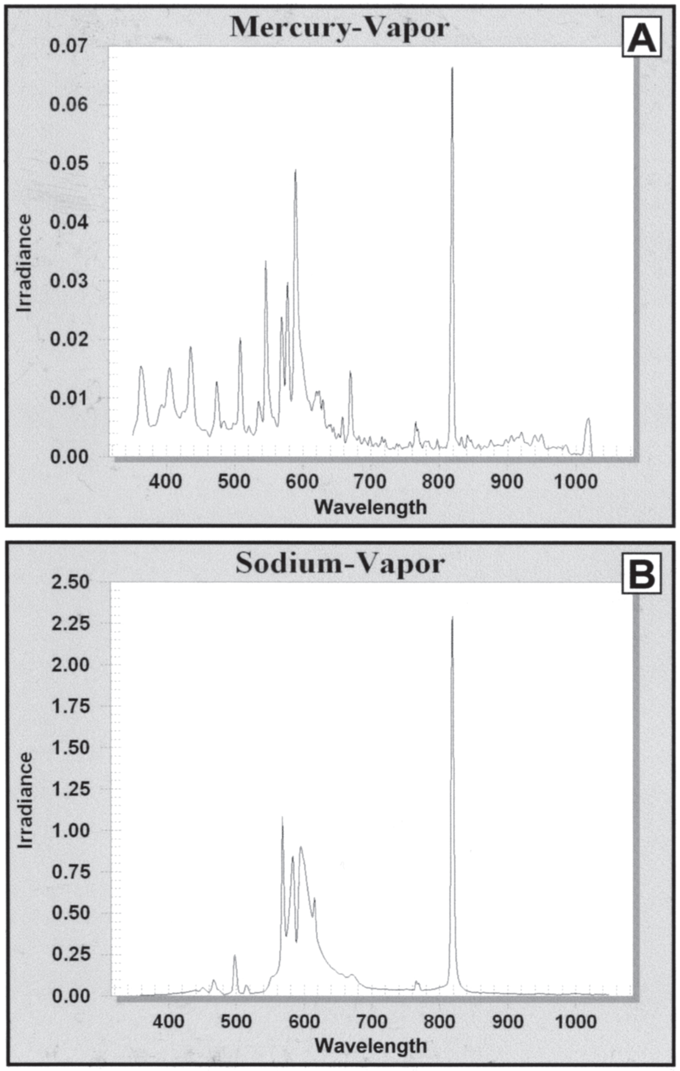

Fig. 5. Spectral profiles (irradiance) of standard glasshouse (A) mercury-vapor and (B) sodium-vapor lamps as measured in the visible and near-infrared wavelengths.

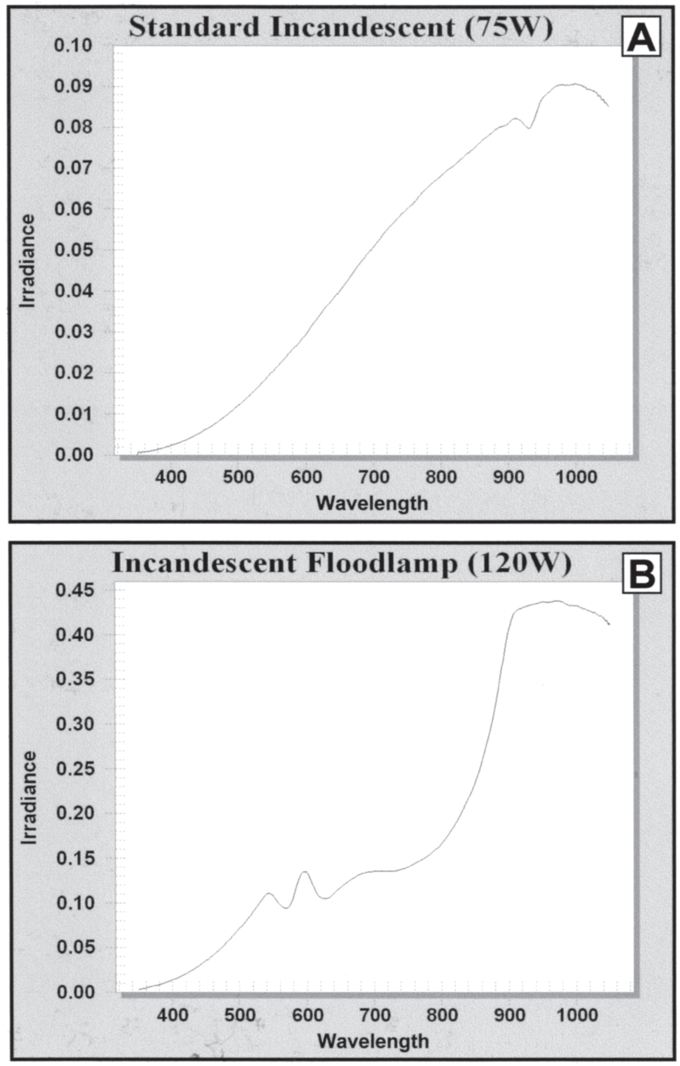

Fig. 6. Spectral profiles (irradiance) of standard (A) incandescent bulb (75 W) and (B) incandescent flood-lamp (120 W) as measured in the visible and near-infrared wavelengths.

of fluorescent "plant growth" lamps occurred in the green and red (600-700 nm) regions (Fig 3). Both lamp types emitted little or no EMR in the NIR region (700-900 nm), and CIR imagery acquired using such lamps as the sole lighting source contained no usable spectral information in the NIR waveband, i.e., the image for the NIR waveband was entirely black due to the lack of NIR reflectance (Fig. 4). Standard sodium- and mercury-vapor glasshouse lamps emitted EMR primarily in the visible (blue and green) regions, with NIR emittance restricted to a distinct "spike" that occurred within a narrow waveband interval centered at 820 nm (Fig. 5). In addition to the relatively low levels of NIR radiation, the preponderance of green wavelengths emitted by sodium- and mercury-vapor lamps imparted an overall bluish cast that seriously altered the spectral quality of CIR imagery obtained using these lamps as sole lighting sources (a similar effect was produced by both types of fluorescent tubes). Thus, bulbs and lamps in both of these categories appear to be entirely unsuitable for CIR image acquisition, and their operation in glasshouses at the time of image acquisition would very probably degrade the quality of any other type of lighting source used (see also Summy *et al.* 2004a). All of the incandescent and quartz halogen bulbs and lamps evaluated in these studies exhibited spectral properties suitable for CIR image acquisition, i.e., irradiance curves indicated emittance of relatively high levels of both visible and NIR radiation (Figs. 6 and 7). However, illumination intensities at a distance of 2.0 m from the lighting source varied considerably, ranging from a minimum of 24 footcandles (FC) for standard 75 W incandescent bulbs to a maximum of 128 FC for 120W incandescent floodlamps (Table 1). Moreover, the conical reflector design of most sealed incandescent and quartz halogen bulbs produced a circular lighting pattern characterized by relatively high levels of illumination within the central portion of the image and a substantial decrease in illumination intensities toward the edges (Fig. 8a). Placement of a clear translucent plastic diffuser over the bulb lens ameliorated this "central hotspot" problem only slightly (Fig. 8b), and resulted in a 70% reduction in illumination intensities within the central portion of the image (Fig. 9).

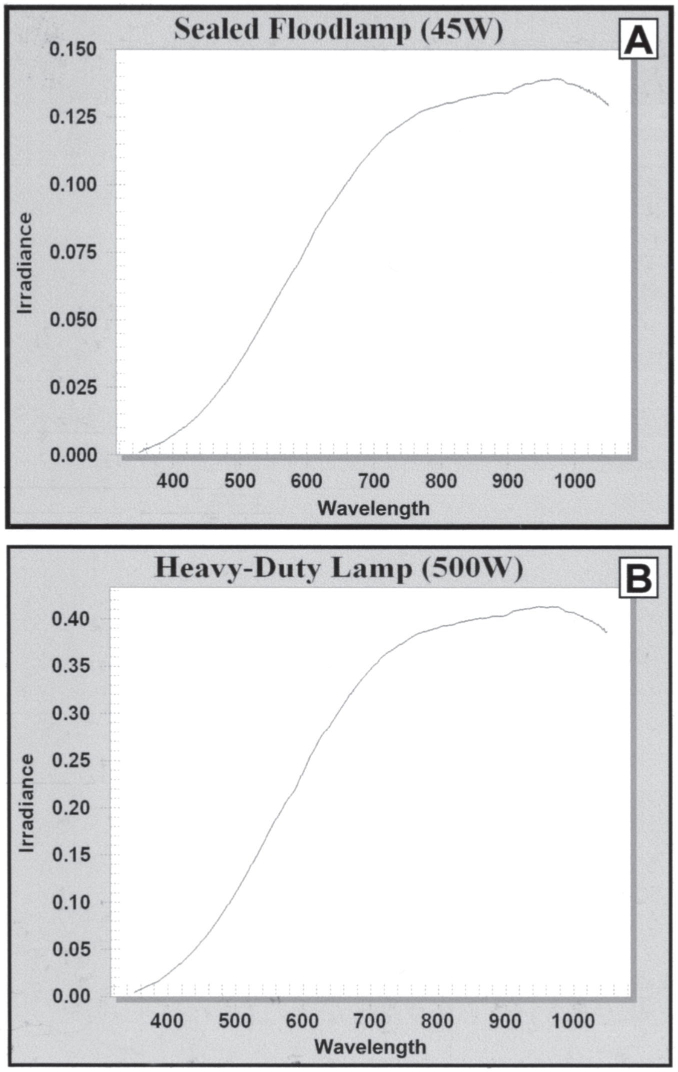

Fig. 7. Spectral profiles (irradiance) of (A) quartz-halogen sealed flood-lamp (45 W) and (B) quartz-halogen heavy-duty rectangular lamp (500 W) as measured in the visible and near-infrared wavelengths.

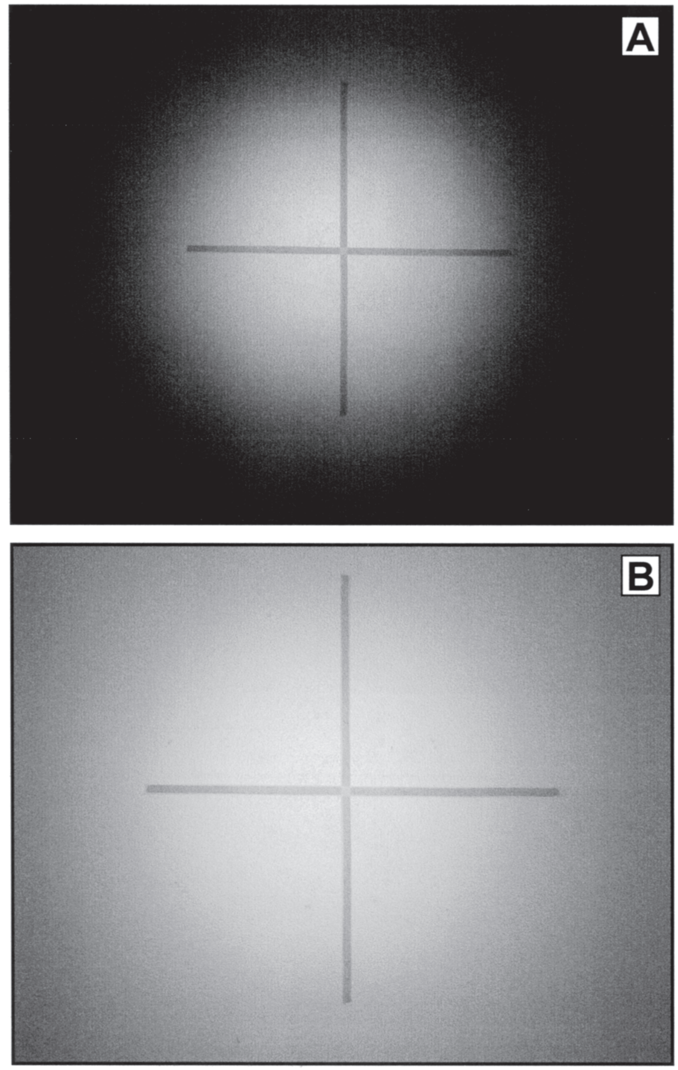

Fig. 8. Illumination pattern emitted from an incandescent flood-lamp (120 W) (A) without a diffuser and (B) with a diffuser. The incandescent diffuser used in this study was composed of opaque plastic.

The most suitable lighting source evaluated in these studies was a 500W ‘Commercial Electric’ quartz halogen lamp with a rectangular reflector housing (Technical Consumer Products, Inc., Aurora, OH). This particular lamp (Fig. 10a) emitted relatively high levels of both visible and NIR radiation (Fig. 7b) and produced a rectangular lighting pattern in which luminosity ranged from 114.2 +/- 0.12 FC in the central portion of the image to 49.9 +/- 0.25 FC at a distance of 1.0 m from the center (Figs. 9 and 11a). Variation in luminosity within the image was reduced substantially (from 50.0 +/- 1.25 FC in the center of the image to 32.1 +/- 0.26 FC at a distance of 1.0 m from the center) by placement of crumpled aluminum foil within the reflector housing (Fig. 10b). Although this modification reduced luminosity within the central portion of the image by ~50% (Fig. 9), the result was a nearly uniform lighting pattern across the target area (Fig. 11b). Multispectral CIR imagery of cucumber plants obtained using this lamp as a sole lighting source (Fig. 1d-f) was acceptable and comparable in quality to imagery of these same plants acquired under natural (clear sunny) lighting conditions (Fig. 1a-c).

CONCLUSIONS

The performance and properties of the ‘Commercial Electric’ quartz halogen bulb exemplify the stringent requirements of any bulb used as a sole lighting source for CIR image acquisition. Bulbs used for this purpose must emit EMR in the green, red and NIR regions of the spectrum at levels sufficient to provide adequate illumination in a relatively uniform pattern across the target area. Provided these conditions are met, CIR imagery of plant foliage acquired under artificial lighting sources may be comparable in quality to imagery obtained under optimal natural lighting conditions. An important ramification of this statement is that use of a suitable artificial lighting source provides a means to facilitate CIR image acquisition on a continuous basis (regardless of local weather conditions), which is requisite for the adoption of this technology by the commercial glasshouse industry.

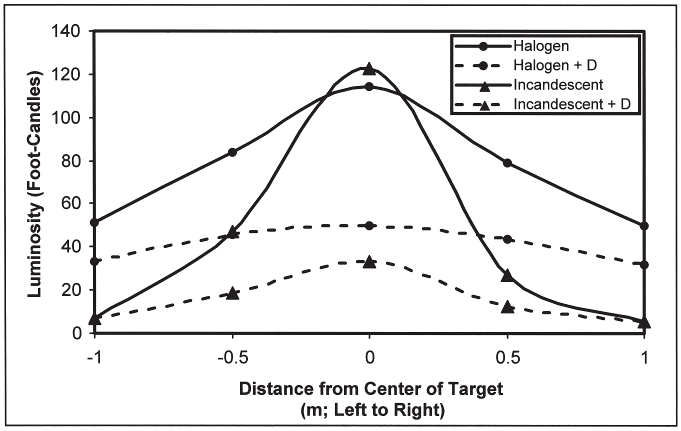

Fig. 9. Luminosity (foot-candles) as measured at the center, 0.5 m, and 1.0 m from the center of illumination patterns cast by halogen, halogen + D (diffused by aluminum foil) incandescent, and incandescent + D (diffused using opaque plastic) lighting sources.

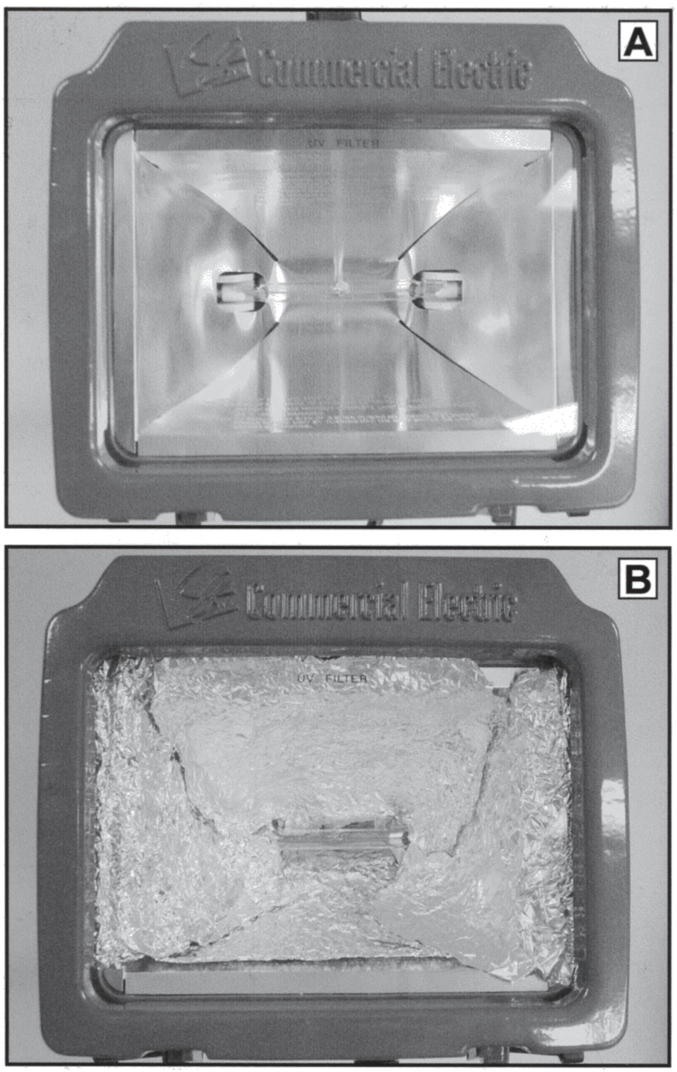

Fig. 10. Rectangular quartz-halogen light sources (500 W) evaluated in this study. (A) Non-diffused and (B) diffused (using aluminum foil).

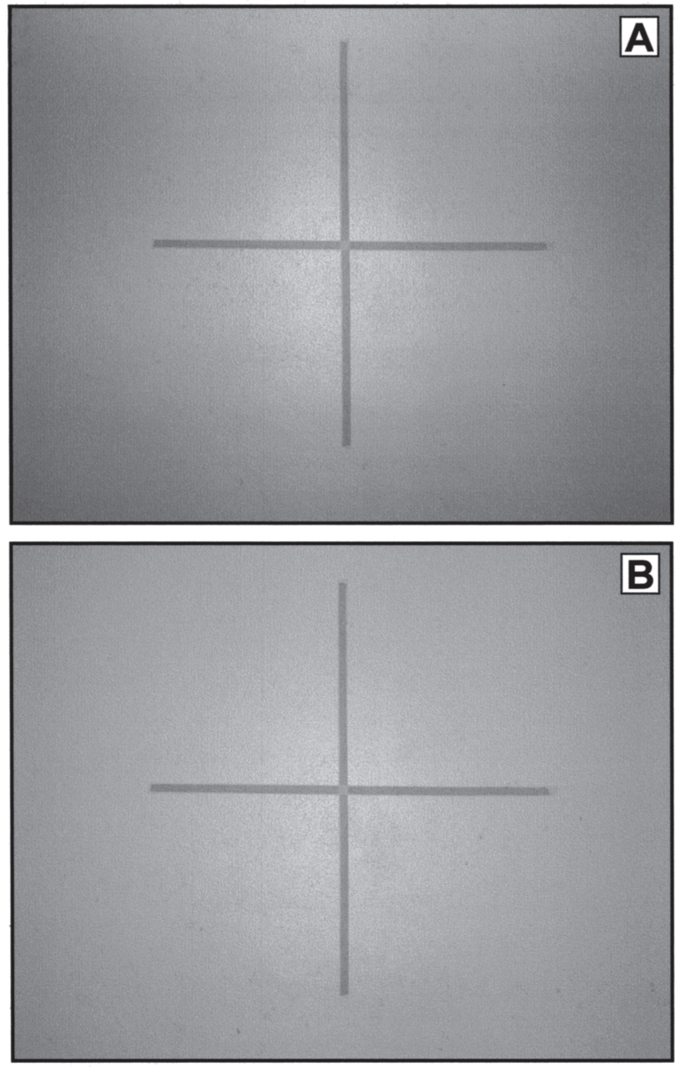

Fig. 11. Illumination patterns emitted from a quartz-halogen heavy-duty rectangular lamp (500 W) lighting source (A) without a diffuser and (B) with a diffuser. The quartz-halogen diffuser used in this study was composed of aluminum foil.

ACKNOWLEDGMENTS

Digital camera equipment and image-processing software used in these studies was procured through a grant provided by the Office of Naval Research and the Air Force Office of Scientific Research (Grant No. F49620-02-1-0016).

LITERATURE CITED

Avery, T. E. and G. L. Berlin. 1992. Fundamentals of Remote Sensing and Airphoto Interpretation. Prentice Hall, Upper Saddle River, N. J.

Blazquez, C. H., and F. W. Horn. 1980. Aerial Color Infrared Photography Applications in Agriculture. National Aeronautics and Space Administration, Reference Pub. 1067, Washington, D. C.

Blazquez, C. H., G. J. Edwards, and F. W. Horn. 1979. Aerial color infrared photography A management tool. Florida

State Hort. Soc. Proc. 92:13-15.

Blazquez, C. H., O. Lowe, J. R. Sisk, and M. D. Bilbrey. 1988. Use of aerial color infrared photography, dual color video, and a computer system for property appraisal of citrus groves. Photogram. Eng. & Remote Sensing 51:233-236.

Brenchley, G. H. 1964. Aerial photography for the study of potato blight. World Rev. of Pest Control 3:68-84.

Campbell, J. B. 1996. Introduction to Remote Sensing. Guilford Press, New York.

Colwell, R. N. 1956. Determining the prevalence of certain cereal diseases by means of aerial photography. Hilgardia 26:223-286.

Everitt, J. H., A. H. Gerbermann and M. A. Alaniz. 1981. Microdensitometry to identify saline rangelands on 70 mm color infrared film. Photogram. Eng. & Remote Sensing 47:1357-1362.

Everitt, J. H., D. E. Escobar, K. R. Summy, and M. R. Davis. 1994. Using airborne video, global positioning system, and geographic information system technologies for detecting and mapping citrus blackfly. Southwestern Entomol. 19:129-138.

Everitt, J. H., D. E. Escobar, K. R. Summy, M. A. Alaniz, and M. R. Davis. 1996. Using spatial information technologies for detecting and mapping whitefly and harvester ant infestations in south Texas. Southwestern Entomol. 21:421-432.

Gausman, H. W. 1985. Plant leaf optical parameters in visable and near-infrared light. Graduate Studies - Texas Tech University, No. 29. Texas Tech University Press, Lubbock, TX.

Gausman, H. W., W. A. Allen and R. Cardenas. 1969. Reflectance of cotton leaves and their structure. Remote Sensing of Environ. 1:110-122.

Hart, W. G., and V. I. Myers. 1968. Infrared aerial color photography for the detection of populations of brown soft scale in citrus groves. J. Econ. Entomol. 61:617-624.

Hart, W. G., S. J. Ingle, M. R. Davis, and C. Magnum. 1973. Aerial photography with infrared color film as a method of surveying for citrus blackfly. J. Econ. Entomol. 66:190-194.

Jensen, J. R. 2000. Remote Sensing of the Environment: An Earth Resource Perspective. Prentice Hall, Upper Saddle River, N.J.

Lillesand, T. M. and R. W. Kiefer. 2000. Remote Sensing and Image Interpretation. John Wiley and Sons, Inc., New York.

Myers, V. I., L. R. Ussery and W. J. Rippert. 1963. Photogrammetry for detailed detection of drainage and salinity problems. American Soc. of Agric. Engineers 6:332-334.

Norman, G. G. and N. L. Fritz. 1965. Infrared photography as an indicator of disease and decline in citrus. Florida State Hort. Soc. Proc. 75:59-63.

Payne, J. A., W. G. Hart, M. R. Davis, L. S. Jones, D. J. Weaver, and B. D. Horton. 1971. Detection of peach and pecan pests and diseases with color infrared aerial photography. Proc. 3rd Biennial Workshop on Color Aerial Photography in the Plant Sciences, Church Falls, VA. Am. Soc. Photogramm.

Ryerson, R. A. and P. J. Curran. 1997. Agriculture, pp. 365-397 In Manual of Photographic Interpretation (W. R. Philipson, ed). American Society of Photogrammetry and Remote Sensing, Bethesda, MD.

Summy, K. R., C. R. Little, R. A. Mazariegos, J. H. Everitt, and M. R. Davis. 2004a. Technical feasibility of color infrared imagery for monitoring physiological stress in glasshouse crops. In Proceedings, 19th Biennial Workshop on Color Photography & Videography and Airborne Imaging for Resource Assessment, American Society of Photogrammetry and Remote Sensing, Logan, UT, 6-8 October 2003 (CDROM).

Summy, K. R., C. R. Little, R. A. Mazariegos, J. H. Everitt, M. R. Davis, J. V. French,and A. W. Scott, Jr. 2004b. Detecting stress in glasshouse plants using color infrared imagery: A potential new application for remote sensing. Subtropical Plant Science 55:51-58.

Toler, R. W., D. B. Smith, and J. C. Harlan. 1981. Use of aerial color infrared photography to evaluate crop disease. Plant Disease 75:24-31.

Thomas, J. R. and G. F. Oerther. 1977. Estimation of crop conditions and sugar cane yields using photography. American Society of Sugar Cane Technology Proceedings 6:93-99.

Wilke, D. S. and J. T. Finn. 1996. Remote Sensing Imagery for Natural Resource Monitoring. Columbia University Press, New York.