Field Spectra and Airborne Digital Imagery for Detecting *Phytophthora* Foot Rot Infections in Citrus Trees

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Abstract. *Phytophthora* foot rot, caused by *Phytophthora parasitica* (Dast), can result in economic losses for the citrus industry in the Lower Rio Grande Valley of Texas. Therefore, locating foot rot-infected trees in citrus groves is important to citrus growers. Symptoms of the infection include leaf yellowing, canopy defoliation, twig dieback, and short growth flushes. This study evaluated the use of the latest remote sensing technology, that of airborne digital imagery, for the detection of citrus trees exhibiting mild symptoms of foot rot infection. Airborne color-infrared (CIR) digital imagery of two citrus orchards having problems with foot rot infection was acquired. In addition to the aerial digital imagery, ground spectroradiometric measurements were conducted to determine the visible and near-infrared (NIR) spectral reflectance differences between healthy and infected trees. These measurements were also used to help interpret the color tonal renditions between the trees. The CIR digital imagery distinguished infected from noninfected trees. The noninfected trees had a bright red-magenta color rendition, while the infected trees had a dull grayish red tonal response. The NIR spectroradiometric and digital readings were significantly lower for infected trees than for healthy ones ($P \leq 0.05$), whereas the visible reflectance and digital data revealed no significant differences between the trees. The infected trees' dull tonal response in the CIR image was attributed to their lower NIR light intensity. These results indicated that digital imagery has potential for detecting foot rot-infected trees in citrus groves based upon NIR spectral differences. The advantage of airborne digital imagery is its real-time survey for quick field assessment.

Foot and root rot, two well-recognized infectious disease problems in citrus, are caused by soilborne fungi of *Phytophthora* sp. (Grimm

and Timmer, 1981; Klotz, 1978). Foot rot infection occurs when the bark of the scion near the ground surface is infected by the fungi. Symptoms of foot rot infection include: development of large cankers that frequently exude amber gum; formation of a yellow gummy zone at the cambium beyond the dead invaded area; subsequent drying and vertical cracking of the bark; dead areas of bark that remain firm; and canopy defoliation, leaf yellowing, twig dieback, and short growth flushes (Graham and Timmer, 1994; Klotz, 1978). When the *Phytophthora* infection occurs below ground, it is customarily called root rot. The root rot phase of the disease causes the decay of small fibrous roots that eventually result in the decline and dieback of the leaf canopy, as well as reductions in fruit size and production (Klotz, 1978). Both rots generally affect tree vigor and eventually cause plant death.

About 12,150 ha of citrus currently exist in the Lower Rio Grande Valley of Texas. *Phytophthora parasitica* is the cause of foot

and root rot infections in this region (Gausman et al., 1970; Timmer, 1973); however, foot rot is more predominant than root rot. Various management practices are presently used to prevent foot rot infections, but citrus orchard infestations occur each year, resulting in economic losses (Skaria and Miller, 1989; Timmer, 1973). Early detection of foot rot infections allows orchard managers to take action to control the problem. Ground surveys are presently conducted to determine the presence of foot rot. This work is tedious and time-consuming, and in these surveys infected trees can be missed.

Gausman et al. (1970) used aerial photography to detect foot rot infection in a grapefruit (*Citrus paradisi* Macf.) orchard in southern Texas. In addition, they used a laboratory spectrophotometer to study the spectral properties of single infected and noninfected leaves. However, no research has been conducted to study the spectral properties of foot rot-infected and noninfected trees in field situations.

Within the last 10 years, aerial videographic and digital imaging systems have gained popularity as remote sensing tools. Such systems can obtain information in narrow spectral bands in different portions of the electromagnetic spectrum, which can enhance the detection, distinction, and/or assessment of ground parameters (Everitt et al., 1999; Nixon et al., 1985). The imagery can be visually assessed the same day it is acquired, permitting managers to make quick decisions concerning their operations (Everitt et al., 1991). Also, video and digital data are compatible with computer image processing systems, thus allowing the classification and quantification of ground parameters (Everitt et al., 1999; Lulla et al., 1987; Richardson et al., 1985). These systems also can generate imagery that simulate CIR photography (Everitt et al., 1995; Nixon et al., 1985).

Applications of aerial videography in citrus include distinguishing trees infested with blackfly (*Aleurocanthus woglumi* Ashby) from noninfested trees (Everitt et al., 1994), detecting freeze-damaged trees and leaves (Edwards, 1982; Escobar et al., 1983), discriminating between orange and grapefruit trees (Nixon et al., 1985), detecting sooty mold (*Capnodium citri* Berk. and Desm.) deposits on leaves (Hart et al., 1988), and distinguishing between irrigated and nonirrigated orchards (Escobar et al., 1988). Digital imaging systems have been used to monitor other problems related to agriculture and natural resources (Everitt et al., 1999; Yang et al., 1999), but to our knowledge these systems have not been used for citrus grove assessment. Thus, the objectives of this study were: 1) to evaluate the use of airborne digital CIR imagery for the detection in citrus orchards of trees with mild symptoms (early infection) of foot rot; and 2) to determine the in-field visible and NIR spectral reflectance differences between noninfected and infected trees.

Materials and Methods

Two citrus groves, both on sour orange (*Citrus aurantium* Linn.) rootstock, were se-

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lected for this study, one located in La Feria and the other in Alamo, Texas. The La Feria orchard (1.8 ha) had 10-year-old orange [*Citrus sinensis* L. (Osbeck)] trees while the Alamo orchard (11.4 ha) consisted of a mixture of 12- and 16-year-old orange trees and 16-year-old grapefruit trees. For the Alamo orchard, only the 12-year-old orange trees were used for the study.

Prior to field measurements and aerial image acquisition, both orchards were scouted to confirm the presence of foot rot infection. Trees exhibiting mild symptoms of the infection were used for this study. These mildly foot rot-infected trees appeared to be healthy overall but had $\approx 10\%$ to 30% less foliage than did the noninfected trees (Fig. 1A–D).

Field radiometric measurements were acquired on 23 and 26 July 1999 for the Alamo and La Feria orchards, respectively. Measurements were obtained from 14 randomly selected healthy and mildly infected trees each at Alamo, while 10 of each were taken at the La Feria site. The measurements were acquired between 1100 and 1500 HR at the Alamo site, those at the La Feria site between 1200 and 1500 HR. Spectral measurements were acquired with a Barnes multispectral field radiometer (Barnes Engineering Co., Stamford, Conn.) having a sensor with a 15° field of view

(Robinson et al., 1979). A 3.7-m stepladder was used to obtain nadir measurements 2 m above the apical area of the tree canopies (an area representative of what an airborne sensor would acquire), resulting in a viewing area of 0.22 m^2 . The radiometer was standardized every 30 min. The field radiometric measurements were corrected to reflectance using a barium sulfate standard (Richardson, 1981). The radiometric measurements were obtained in the NIR ($0.76\text{--}0.90 \mu\text{m}$), visible red (R, $0.63\text{--}0.69 \mu\text{m}$), and visible green (G, $0.52\text{--}0.60 \mu\text{m}$) portions of the spectrum. These spectral band measurements were used because the wavebands encompassed the filter's narrowband widths used to acquire the CIR digital imagery. The spectral data were used to help interpret the aerial digital imagery.

A true digital video imaging system was used to acquire the imagery in both orchards. This system consists of a computer and a frame mount with three black-and-white (B&W) Kodak Megaplus 1.4i digital cameras (Eastman Kodak Co., San Diego, Calif.) (Escobar et al., 1997). The system cameras are noninterlaced, charge-coupled, device sensors ($1320 \text{ horizontal} \times 1035 \text{ vertical pixels}$) with visible to NIR light sensitivity ($0.4 \text{ to } 1.0 \mu\text{m}$) and a built-in analog-digital video converter

that readily produces a digital video output signal containing 256 gray levels. The cameras had fixed 12.0-mm focal length lenses and each was equipped with a respective narrowband interference filter; one camera had a NIR ($0.845\text{--}0.857 \mu\text{m}$) filter, the second a visible R ($0.623\text{--}0.635 \mu\text{m}$) filter, and the third a visible yellow-green (YG, $0.555\text{--}0.565 \mu\text{m}$) filter. The system's computer is a Gateway 200 Pentium (100 MHZ; Gateway 2000, North Sioux City, S.D.) interfaced with a versa module europa (VME) enclosure containing three image grabbing boards [1024×1024 pixels (one for each camera)]. The configuration of this system permits the acquisition of digital CIR imagery similar in color rendition to that of CIR film. Image acquisition occurred on 26 July 1999 between 1100 and 1200 HR under sunny conditions at an altitude above ground level of $\approx 460 \text{ m}$, providing a ground pixel resolution of $\approx 0.32 \text{ m}$.

Immediately after the image acquisition, the raw digital imagery was downloaded from the system computer to a magneto-optical disk. In the laboratory, each image was transferred to the Adobe Photoshop software (version 5.0, Adobe Systems, San Jose, Calif.) and then converted into Tagged Image File Format (TIFF) files. The images were properly aligned using the ERDAS Imagine software (version

Fig. 1. Ground-level photos showing a (A) healthy and a (B) foot rot-infected citrus tree, and photos depicting the apical center of a (C) healthy and (D) foot rot-infected tree, having a scale of 1:20.

8.3.1, Erdas, Atlanta, Ga.). For the alignment process, the CIR digital composite images were separated into their respective B&W image components. The NIR and YG images were registered to the R image. The B&W images for each respective orchard were composited to form the CIR digital composite image. Each composite file was transferred back to the Adobe Photoshop software to extract digital counts of the infected and noninfected trees for each of the digital bands, which were calculated using the Histogram function of the software. A 3×3 pixel matrix was used for obtaining the mean digital counts from the center apical canopy of selected trees. This software also was used to separate the CIR composite digital images into their B&W component images for visual assessment. For illustrative purposes, images presented in this paper were enhanced using the Sharpen and Sharpen edges functions of the Adobe Photoshop software.

The unpaired Student's *t* test was used to determine the significance of the differences between means of the healthy and infected trees for each of the three wavelengths of the spectroradiometer and the digital data. The Statistical Analysis Software (version 6.12, SAS Institute, Cary, N.C.) was used to perform the analysis.

Results and Discussion

Overall spectral reflectance and the digital count data for infected vs. healthy trees were in agreement for the two sites (Table 1). The visible light reflectance and digital data did not differ statistically, but their respective NIR data were significantly different. Thus, the field spectroradiometric data supported the digital count data and vice versa.

The G and R visible light reflectances for the foot rot-infected and noninfected trees were low for both sites (Table 1). The trees' low R reflectances were caused by the strong R light absorption of the foliage, which was primarily due to leaf pigments (Gates et al., 1965). This low R light reflectance reduced the G light reflectance. The low G and R visible light reflectance was attributed to some in-canopy shadowing (Richardson, 1975). Figure 1 C and D depicts the apical canopy photos of a healthy and an infected tree, respectively, that display a portion of their canopy foliar cover and the in-canopy shadowing. Although the photos depict in-canopy shadowing differences between the trees, the visible data were not significantly different. The in-canopy shadowing of infected trees apparently compensated for the missing leaves in the absorption of light. The digital count data agreed with the spectral reflectance data in that both tree conditions had low digital counts (Table 1).

The NIR reflectance values for the healthy trees were 19.6% and 13.3% higher ($P \leq 0.05$) than those for the infected trees in the Alamo and La Feria orchards, respectively (Table 1); this was attributed to the higher foliar density of their canopies and confirmed by overhead apical photographs of an infected and a healthy tree (Fig. 1 C and D). A higher foliar density

leads to a greater NIR reflectance (Myers et al., 1983; Thomas et al., 1967). The total NIR reflectance of a canopy tends to be reduced more than the visible reflectance when foliage losses occur because of fewer multiple leaf layers (Knippling, 1970). The NIR digital count data also showed that the noninfected trees had significantly higher digital values than did the infected trees (Table 1), which supported the NIR spectral reflectance data.

Since the digital imagery results depicted the same color tonal differences between the foot rot-infected and noninfected trees for both citrus groves, only the imagery for the La

Feria grove is discussed. Figure 2A shows the aerial CIR digital image of the La Feria citrus grove, while Fig. 2B–E depicts an enlarged image of the delineated rectangular area within the orchard showing the CIR composite (B), and its respective B&W NIR (C), YG (D), and R (E) image band components. In the enlarged CIR image (Fig. 2B) the mildly infected tree had a dull grayish-red image tonal response (arrow 2), while the noninfected tree appeared in a bright red-magenta rendition (arrow 1). Although this study was primarily focused on the detection of trees that displayed mild symptoms of the foot rot disease, the CIR image also

Table 1. Mean canopy light reflectance and digital count measurements of foot rot-infected and noninfected trees for the Alamo and La Feria, Texas, citrus groves.

Site	Tree condition	Canopy reflectance for three wavelengths (%)			Digital counts for the three wavelengths		
		Green	Red	Near-infrared	Yellow-green	Red	Near-infrared
Alamo	Infected	3.7 a ²	1.8 a	27.8 a	79 a	76 a	146 a
	Noninfected	3.5 a	1.6 a	34.6 b	78 a	72 a	200 b
La Feria	Infected	4.1 a	2.0 a	36.4 a	63 a	63 a	174 a
	Noninfected	4.0 a	1.9 a	42.0 b	58 a	58 a	195 b

²Means separation within columns by Student's unpaired *t* test, $P \leq 0.05$.

Fig. 2. Color-infrared, digital, composite image of the La Feria, Texas, citrus orchard (A), and close-ups of the rectangular area enclosed in dashed lines within (A), including its color-infrared (B), near-infrared (C), yellow-green (D), and red black-and-white (E) components. The arrows on images (B), (C), (D), and (E) point to the following: arrow 1, healthy tree; arrow 2, a tree displaying mild symptoms of the foot rot infection; arrows 3, 4, and 5, trees that display more advanced symptoms of the foot rot infection.

shows other trees with more advanced symptoms of the infection [Fig. 2B: arrows 3, 4, and 5 (tree 5 was completely defoliated)]. Thus, the CIR digital imagery can detect different levels of foot rot conditions.

The CIR composite's B&W image band components literally coincided with the tree canopy spectral reflectance measurement data. For example, subtle gray-scale differences occurred between the healthy (arrow 1) and mildly infected (arrow 2) trees on the B&W YG and R images (Fig. 2D–E), making differentiation between them difficult. The dull, dark appearance of both noninfected and infected trees in the R image band was attributed to the low light intensity of their foliage as a result of their red visible light absorption. This light absorption, in turn, also caused the trees' YG light intensity to be low, producing a dull gray tonal response in this image band. These R and YG image bands substantiated the results of the *t* test of the digital counts in that noninfected and foot rot-infected trees were not significantly different (Table 1).

Apparent differences between the noninfected (Fig. 2C: arrow 1) and foot rot-infected (Fig. 2C: arrow 2) trees were observed on the NIR image. The healthy tree had a whitish-gray tone in comparison with the dull gray response of the foot rot-infected tree. Based on the NIR field spectra (Table 1), the dull light intensity of the infected tree was a result of low NIR reflectivity; conversely, the whitish gray response of the noninfected tree was attributed to greater NIR light reflectance. Differences between the trees were caused by differences in their foliar canopy cover, as previously stated in the NIR spectral reflectance results. This NIR image band clearly illustrated the concept of how foliar cover affects the NIR response.

The red color of the healthy and diseased trees in the CIR composite image was attributed to the combination of the three CIR B&W image components. The dull red tonal rendition difference of the foot rot trees in comparison with the bright red response of the noninfected trees resulted from their low NIR light intensity. Therefore, these results revealed that the differences between mildly foot rot-infected and noninfected trees were not in the visible region, but in the NIR portion of the electromagnetic spectrum.

Our results indicate that CIR airborne digital imagery can be a useful tool for detecting mild foot rot infected-trees in citrus orchards. The color of mildly infected trees was a dull grayish-red color on the CIR image in comparison with a bright red rendition for the healthy trees. The advantage of airborne digital imagery over photography is its potential as a real-time survey for quick assessment of the

field of interest. The citrus orchard digital image (Fig. 2A), for example, was obtained in the morning and by midafternoon it was visually assessed and ready for image analysis. Also, aerial image acquisition provides more coverage of the field(s) than can be accomplished by ground surveys. These findings should be useful to citrus growers, extension officers, pathologists, and surveyors who are interested in using airborne digital imagery for detecting *Phytophthora* foot rot infections in citrus orchards known to have the problem.

Literature Cited

- Edwards, G.J. 1982. Near-infrared aerial video evaluation for freeze damage. *Proc. Florida State Hort. Soc.* 95:1–3.
- Escobar, D.E., R.L. Bowen, H.W. Gausman, and G.R. Cooper. 1983. Use of a near-infrared video recording system for the detection of freeze-damaged citrus leaves. *J. Rio Grande Valley Hort. Soc.* 36:61–66.
- Escobar, D.E., J.H. Everitt, and M.R. Davis. 1988. Potential of mid-infrared video imagery for use in irrigation management studies, p. 248–255. In: P. Mausel (ed.). *Proc. 1st Wkshp. on Videography*. Amer. Soc. Photogramm. Remote Sensing, Terre Haute, Ind.
- Escobar, D.E., J.H. Everitt, J.R. Noriega, M.R. Davis, and I. Cavazos. 1997. A true digital imaging system for remote sensing applications, p. 470–484. In: J.H. Everitt (ed.). *Proc. 16th Biennial Wkshp. on Videography and Color Photography in Resource Assessment*, Amer. Soc. Photogramm. Remote Sensing, Weslaco, Texas.
- Everitt, J.H., D.E. Escobar, D.N. Appel, W.N. Riggs, and M.R. Davis. 1999. Using airborne digital imagery for detecting oak wilt disease. *Plant Dis.* 83:502–505.
- Everitt, J.H., D.E. Escobar, I. Cavazos, J.R. Noriega, and M.R. Davis. 1995. A three-camera multispectral digital video imaging system. *Remote Sens. Environ.* 54:333–337.
- Everitt, J.H., D.E. Escobar, and F.W. Judd. 1991. Evaluation of video imagery for distinguishing black mangrove (*Avicennia germinans*) on the lower Texas gulf coast. *J. Coastal Res.* 7:1169–1173.
- Everitt, J.H., D.E. Escobar, K.R. Summy, and M.R. Davis. 1994. Using airborne video, global positioning system, and geographical information system technologies for detecting and mapping citrus blackfly infestations. *Southwestern Entomologist* 19(2):129–138.
- Gates, D.M., H.J. Keegan, J.C. Schleter, and V.R. Weidner. 1965. Spectral properties of plants. *Appl. Optics* 4:11–20.
- Gausman, H.W., W.A. Allen, R. Cardenas, and R.L. Bowen. 1970. Detection of foot rot disease of grapefruit trees with infrared color film. *J. Rio Grande Valley Hort. Soc.* 24:36–41.
- Graham, J.H. and L.W. Timmer. 1994. *Phytophthora* diseases of citrus. On-line, publication/1994/DOCUMENT_CH087.
- Grimm, G.R. and L.W. Timmer. 1981. Control of *Phytophthora* foot rot and root rot. *Citrus Ind.* 62(10):34–39.
- Hart, W.G., J.H. Everitt, D.E. Escobar, M.R. Davis, and M.G. Garza. 1988. Comparing imaging systems for assessment of diverse conditions of agricultural resources, p. 160–165, 269–270. In: P. Mausel (ed.). *Proc. 1st Wkshp. on Videography*. Amer. Soc. Photogramm. Remote Sensing, Terre Haute, Ind.
- Klotz, L.J. 1978. Fungal, bacterial, and nonparasitic diseases and injuries originating in the seedbed, nursery, and orchard, p. 1–66. In: W. Reuther, E.C. Calavan, and G.E. Carman (eds.). *The citrus industry. Vol. 4. Crop protection*. Agr. Sci. Publ., Univ. of California, Berkeley.
- Knipling, E.B. 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. *Remote Sens. Environ.* 1:155–159.
- Lulla, K., P. Mausel, D. Skelton, and W. Kramber. 1987. An evaluation of video-band based vegetation indices, p. 270–279. In: J.H. Everitt and P.R. Nixon (eds.). *Proc. 11th Biennial Wkshp. on Color Aerial Photography and Videography in the Plant Sci. and Related Fields*. Amer. Soc. Photogramm. Remote Sens., Weslaco, Texas.
- Myers, V.I., M.E. Bauer, H.W. Gausman, W.G. Hart, J.L. Heilman, R.B. McDonald, A.B. Park, R.A. Ryerson, T.J. Schmutge, F.C. Westin. 1983. Remote sensing in agriculture, p. 2111–2228. In: R.N. Colwell (ed.). *Manual of remote sensing*, 2nd ed. Amer. Soc. Photogramm. Remote Sens., Bethesda, Md.
- Nixon, P.R., D.E. Escobar, and R.M. Menges. 1985. Use of multi-band video system for quick assessment of vegetal condition and discrimination of plant species. *Remote Sens. Environ.* 17:203–208.
- Richardson, A.J. 1981. Measurement of reflectance factor under daily and intermittent irradiance variations. *Appl. Opt.* 20:1336–1340.
- Richardson, A.J., R.M. Menges, and P.R. Nixon. 1985. Distinguishing weed from crop plants using video remote sensing. *Photogramm. Eng. Remote Sens.* 52:1785–1790.
- Richardson, A.J., C.L. Wiegand, H.W. Gausman, J.A. Cuellar, and A.H. Gerberman. 1975. Plant, soil, and shadow reflectance components of row crops. *Photogramm. Eng. Remote Sens.* 41:1401–1407.
- Robinson, B.F., M.E. Bauer, D.P. DeWitt, L.F. Silva, and V.C. Vanderbilt. 1979. Multiband radiometer for field use, p. 8–15. In: H.P. Field, E.F. Zalewski, and F.M. Zweibaum (eds.). *Measurements of optical radiations*. Intl. Soc. Optical Eng., Bellingham, Wash.
- Skaria, M., and S.A. Miller. 1989. A rapid test for detecting *Phytophthora* sp. in citrus. *J. Rio Grande Valley Hort. Soc.* 42:63–65.
- Thomas, J.R., C.L. Wiegand, and V.I. Myers. 1967. Reflectance of cotton leaves and its relation to yield. *Agron. J.* 59:551–554.
- Timmer, L.W. 1973. Characteristics of *Phytophthora* isolates from Texas citrus orchards. *J. Rio Grande Valley Hort. Soc.* 27:44–48.
- Yang, C., J.H. Everitt, and J.M. Bradford. 1999. Airborne digital imagery and yield monitor data for identifying spatial plant growth and yield patterns. Paper No. 991134. Amer. Soc. Agr. Eng., St. Joseph, Mich.