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

Reginald S. Fletcher
U.S. Department of Agriculture, Agricultural Research Service, Integrated Farming and Natural Resources Research Unit, 2413 E. Highway 83, Weslaco, TX 78596

Mani Skaria
Texas A&M University Kingsville Citrus Center, 312 N. International Boulevard, Weslaco, TX 78596

David E. Escobar and James H. Everitt
U.S. Department of Agriculture, Agricultural Research Service, Integrated Farming and Natural Resources Research Unit, 2413 E. Highway 83, Weslaco, TX 78596

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 1978). When the fungi infect trees, they may cause leaf yellowing, twig dieback, and short growth flushes. These symptoms are particularly noticeable when the bark 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 gummous zone at the cambium beyond the dead invaded area; subsequent drying and vertical cracking of the bark; 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.

Materials and Methods

Two citrus groves, both on sour orange (Citrus aurantium Linn.) rootstock, were se-
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 ≈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 m². 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 (0.76–0.90 µm), visible red (R, 0.63–0.69 µm), and visible green (G, 0.52–0.60 µm) portions of the spectrum. These spectral band measurements were used because the wavebands encompassed the filter’s narrowband band 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 horizontal × 1024 vertical pixels) with visible to NIR light sensitivity (0.4 to 1.0 µm) 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 (0.845–0.857 µm) filter, the second a visible R (0.623–0.635 µm) filter, and the third a visible yellow-green (YG, 0.555–0.565 µm) 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 ≈460 m, providing a ground pixel resolution of ≈0.32 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 $3 \times 3$ 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 foliage 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. 1C 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>
<thead>
<tr>
<th>Site</th>
<th>Tree condition</th>
<th>Canopy reflectance for three wavelengths (%)</th>
<th>Digital counts for the three wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Green</td>
<td>Red</td>
</tr>
<tr>
<td>Alamo</td>
<td>Infected</td>
<td>3.7 a</td>
<td>1.8 a</td>
</tr>
<tr>
<td></td>
<td>Noninfected</td>
<td>3.5 a</td>
<td>1.6 a</td>
</tr>
<tr>
<td>La Feria</td>
<td>Infected</td>
<td>4.1 a</td>
<td>2.0 a</td>
</tr>
<tr>
<td></td>
<td>Noninfected</td>
<td>4.0 a</td>
<td>1.9 a</td>
</tr>
</tbody>
</table>

Means 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


