Change detection of cotton root rot infection over 10-year intervals using airborne multispectral imagery

Chenghai Yang ^{a,*}, Gary N. Odvody ^b, J. Alex Thomasson ^c, Thomas Isakeit ^d, Robert L. Nichols ^e

^a *USDA-ARS Southern Plains Agricultural Research Center, Aerial Application Technology Research Unit, 3103 F and B Road, College Station, TX 77845, USA*

^b *Texas AgriLife Research and Extension Center, 10345 State HWY 44, Corpus Christi, TX 78406, USA*

^c *Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843, USA*

^d *Department of Plant Pathology and Microbiology, Texas A&M University, College Station, TX 77843, USA*

^e *Cotton Incorporated, 6399 Weston Parkway, Cary, NC 27513, USA*

* Corresponding author. Tel: 1-979-260-9530

E-mail address: chenghai.yang@ars.usda.gov (C. Yang).

ABSTRACT

Cotton root rot is a very serious and destructive disease of cotton grown in the southwestern United States. Accurate information regarding its spatial and temporal distribution within fields is important for effective management of the disease. The objectives of this study were to examine the consistency and variation of cotton root rot infections within cotton fields over 10-year intervals using airborne multispectral imagery and to assess the feasibility to use historical imagery to create prescription maps for site-specific management of the disease. Airborne

multispectral images collected from a 102-ha cotton field in 2001 and 2011 and from a 97-ha field in 2002 and 2012 in south Texas were used in this study. The images were rectified and resampled to the same pixel size between the two years for each field. The normalized difference vegetation index (NDVI) images were generated and unsupervised classification was then used to classify the NDVI images into root rot-infected and non-infected zones. Change detection analysis was performed to detect the consistency and change in root rot infection between the two growing seasons for each field. Results indicate that the spatial patterns of the disease were similar between the two seasons, though variations existed for each field. To account for the potential expansion and temporal variation of the disease, buffer zones around the infected areas were created. The buffered maps between the two years agreed well. The results from this study demonstrate that classification maps derived from historical images in conjunction with appropriate buffer zones can be used as prescription maps for site-specific fungicide application to control cotton root rot.

Keywords. Airborne multispectral imagery, buffer zone, change detection, cotton root rot, image classification, NDVI.

1. Introduction

Cotton root rot, caused by the fungus *Phymatotrichopsis omnivora*, is a destructive cotton disease occurring throughout the southwestern United States and northern Mexico (Percy, 1983). Cotton (*Gossypium hirsutum* L.) is an economically important crop that is highly susceptible to this disease. The symptoms usually begin during extensive vegetative growth, are more visible during flowering and fruit development, and continue through the growing season (Smith et al., 1962). Infected plants wilt and quickly die with the leaves attached to the plants. The fungus usually spreads more during rainy years as moisture favors all aspects of the

disease cycle. Plants infected earlier in the growing season will die before bearing fruit, whereas infection occurring at later growth stages will reduce cotton yield and lower lint quality (Ezekiel and Taubenhaus, 1934; Yang et al., 2005).

Cotton root rot has plagued the cotton industry for more than 100 years (Pammel, 1988; Uppalapati et al., 2010). Cultural practices such as deep plowing, organic amendments, late planting, and rotation with monocotyledonous crops have been used to reduce the occurrence and severity of the disease (Smith et al., 1962; Rush and Lyda, 1984). Some fumigants and fungicides applied to root rot-infected areas reduced the incidence of the disease, but they were not consistently effective and economical for long-term control (Lyda and Burnett, 1970; Whitson and Hine, 1986). Despite decades of research efforts, effective practices for control of this disease were lacking until TOPGUARD® Fungicide, a commercial formulation of flutriafol from Cheminova, Inc. (Wayne, NJ), showed considerable promise for suppressing this disease in field studies (Isakeit et al., 2009, 2012).

TOPGUARD (flutriafol) was used effectively in Texas from 2012 to 2014 to control cotton root rot under Section 18 emergency exemptions granted by the U.S. Environmental Protection Agency (EPA). As a result, growers achieved lower cotton root rot incidence, higher yields, and better fiber quality (Drake et al., 2013). In early 2015, TOPGUARD® TERRA Fungicide, a new and more concentrated formulation of flutriafol developed specifically for this market, was registered by the EPA. It provides the same level of cotton root rot control as TOPGUARD. Growers generally treat their fields uniformly even though they are aware that only portions of their fields are infected. There are probably two main reasons for the uniform treatment. One is that growers want to make sure all existing and potential new infections are treated since they are not sure if the infection patterns will expand from year to year. The other reason is that site-specific application equipment and the capacity to create prescription maps are not readily available for their use. Since only portions of the field are infected, it may not be appropriate to treat the whole field. Therefore, it is necessary to define the infected areas within the field so

that variable rate technology can be used to apply the fungicide only to the infected areas for more effective and economical control.

Remote sensing has long been used as a useful tool for mapping cotton root rot in cotton fields (Taubenhaus et al., 1929; Nixon et al., 1975, 1987). Remote sensing is perhaps the only practical means for accurately and effectively mapping this disease because of large numbers of infected areas and their irregular shapes within cotton fields. In our previous studies, airborne imagery has been successfully used to map the extent of cotton root rot infections near the end of the growing season when cotton root rot is fully pronounced for the season (Yang et al., 2005) and to monitor the progression of the infections within cotton fields during a growing season (Yang et al., 2014). In these studies, ISODATA (Iterative Self-Organizing Data Analysis) unsupervised classification applied to multispectral imagery has been used to identify root rot-infected areas. With this method, the optimal number of spectral classes is determined based on the average transformed divergence for each classification map. The spectral classes are then grouped into root rot-infected and non-infected zones.

More recently, Yang et al. (2015) evaluated and compared two unsupervised classification techniques (ISODATA applied to multispectral imagery and to NDVI) and six supervised classification techniques (minimum distance, Mahalanobis distance, maximum likelihood, spectral angle mapper (SAM), neural net, and support vector machine (SVM)) for mapping and detecting cotton root rot from airborne multispectral imagery. Although all eight methods appear to be equally effective and accurate for detection of cotton root rot, the NDVI-based classification can be easily implemented without the need for complex image processing capability. Therefore, it has been recommended as one of the simple and accurate classification methods to map cotton root rot and develop prescription maps for effective and economical control of this disease.

The objectives of this study were to: (1) examine the consistency and variation of cotton root rot infection within two cotton fields based on airborne multispectral imagery taken over 10-year

intervals; and (2) assess the feasibility to use historical imagery to create prescription maps for site-specific management of the disease. This information is important not only for a better understanding of the progression of the disease over a relatively long period of time, but also for the formulation of site-specific strategies for effective control of the disease.

2. Materials and methods

2.1 Study area

This study was conducted in two center-pivot irrigated fields near Edroy, Texas over 10-year intervals. Field 1 was a 102-ha circular field with center coordinates of (27°58'19"N, 97°42'29"W) and Field 2 was a 97-ha semicircular field with center coordinates of (28°1'10.86"N, 97°42'49.22"W). Both fields had a history of cotton root rot. Cotton and grain sorghum had been cropped alternately in the fields. Cotton was planted to Field 1 in 2001 and 2011 and to Field 2 in 2002 and 2012.

2.2 Image acquisition

Three different imaging systems were used to acquire images from the two fields in four different years shortly before harvest when root rot was fully expressed for the respective season. A three-camera imaging system described by Escobar et al. (1997) was used to acquire images from Field 1 on 9 July 2001 and from Field 2 on 19 July 2002. The imaging system consisted of three digital charge coupled device (CCD) cameras and a computer equipped with three image digitizing boards that had the capability of obtaining 8-bit images with 1024 × 1024 pixels. The three cameras were filtered for spectral observations in the green

(555–565 nm), red (625–635 nm), and near-infrared (NIR, 845–857 nm) wavelength intervals, respectively.

A four-camera imaging system described by Yang (2012) was used to acquire images from Field 1 on 7 July 2011. The system consisted of four high-resolution CCD digital cameras and a ruggedized PC equipped with frame grabbers and image acquisition software. The four cameras were filtered to capture 12-bit images with 2048×2048 pixels in four spectral bands: blue (430–470 nm), green (530–570 nm), red (630–670 nm), and NIR (810–850 nm), respectively. A two-camera imaging system described by Yang et al. (2014) was used to take images from Field 2 on 25 July 2012. The system consisted of two consumer-grade digital cameras with a 5616×3744 pixel array. One camera captured normal RGB color images, while the other camera was equipped with a 720-nm long-pass filter to obtain NIR images.

A Cessna 206 single-engine aircraft was used to acquire imagery from the two fields in each of the four years at an altitude of 3050 m (10,000 ft) above ground level between 1130h and 1530h local time under sunny conditions. Images from the three-camera and four-camera systems were saved to the respective on-board computers as three-band and four-band Tiff files, respectively, while images from the two-camera system were stored in two separate CompactFlash (CF) cards in both 14-bit RAW and 8-bit JPEG files. The ground pixel size achieved was 1.3 m in 2001 and 2002 and 1.0 m in 2011 and 2012.

2.3 Image processing and classification

An image-to-image registration procedure based on the first-order polynomial transformation model was used to align the individual band images in the three-band and four-band composite images as well as the RGB and NIR images from the two-camera system. The aligned images were then georeferenced or rectified to the Universal Transverse Mercator (UTM), World Geodetic System 1984 (WGS-84), Zone 14, coordinate system based on a set of ground control

points around each field located with a Trimble GPS Pathfinder ProXRS receiver (Trimble Navigation Limited, Sunnyvale, California). The root mean square errors for rectifying the images using first-order transformation were within 2 m. All images were resampled to 1 m resolution using the nearest neighborhood technique. All procedures for image alignment and rectification were performed using ERDAS Imagine (Intergraph Corporation, Madison, Alabama).

The rectified images for the two dates were stacked as one image for each field. A field boundary or an area of interest (AOI) was defined for each field. Normalized difference vegetation index (NDVI) images were created for each field and year combination using the following formula:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where NIR and RED stand for the reflectance values for the NIR and red bands, respectively. NDVI values range from -1 to 1 with low positive and even negative values for infected plants and high positive values for healthy plants.

The NDVI images were classified into root rot-infected and non-infected zones using ISODATA unsupervised classification (Intergraph Corporation, 2013). The ISODATA method began with two classes and arbitrary class means from the NDVI image statistics. Each pixel was assigned to the class that had a smaller NDVI difference to the pixel. Each time the clustering repeated, the means of the two classes were recalculated and used for the next iteration. The process continued until the number of iterations reached 100 or the percentage of unchanged pixels reached 99.99% between two iterations. Pixels with lower NDVI values correspond to the root rot-infected zone, while pixels with higher NDVI values belong to the non-infected zone.

2.4. Change detection and buffer creation

Change detection analysis was performed on the classification maps to determine the class changes between the two years for each field. Change detection statistics, including common root rot areas in both years and root rot areas only in one of the two years, were calculated.

To simulate the potential expansion and temporal variation of the disease, buffer zones around the infected areas were created using ArcInfo GIS (ESRI, Inc., Redlands, California). The classification maps generated in ERDAS Imagine were converted into ArcInfo grids. Then the GRID EXPAND function in ArcInfo was used to create buffer zones of 1–20 m with an increment of 1 m around the infected areas in each grid. The total area of the original root rot areas and the buffered areas for each of the 20 buffer distances were derived from the buffered grids.

To further examine the consistency and change of root rot infection over the 10-year intervals, the original classification map for one year was compared with each of the buffered classification maps for the other year to determine the overlapped areas between the original map and each buffered map.

3. Results and discussion

3.1. Image classification

Fig. 1 shows the color-infrared (CIR) images acquired in 2001 and 2011 and the corresponding two-zone classification maps for Field 1. On the CIR images, non-infected plants showed a reddish-magenta tone, while infected plants had a greenish or cyanish color. The root rot-infected areas can be easily distinguished from the non-infected areas on the CIR images.

A visual comparison of the classification maps and their respective CIR images indicates that the two-zone classification maps effectively identify apparent root rot areas within the fields.

The estimated percent root rot areas for the field were 13.6% in 2001 and 17.8% in 2011. The overall spatial patterns of infections between the two years were similar, but the infected area increased in 2011 and there were changes in infection locations.

Fig. 2 shows the CIR images acquired in 2002 and 2012 and the corresponding two-zone classification maps for Field 2. Similarly, the two-zone classification maps accurately identify apparent root rot areas within the field. The estimated percent root rot areas for the field were 11.7% in 2002 and 8.7% in 2012. The overall spatial patterns of infections between the two years were similar, but the infected area decreased in 2012 because some of the infected areas in 2002 were not fully pronounced in 2012. Nevertheless, cotton root rot occurred in the same general areas within the field and there were a few newly-infected areas in 2012. This recurrent pattern of the disease was also found in many other fields (Yang et al., 2012).

Fig. 1. Airborne color-infrared images (top) and two-zone classification maps (bottom) derived from NDVI images for a 102-ha cotton root rot-infected field (Field 1) near Edroy, Texas in 2001 and 2011.

Fig. 2. Airborne color-infrared images (top) and two-zone classification maps (bottom) derived from NDVI images for a 97-ha cotton root rot-infected field (Field 2) near Edroy, Texas in 2002 and 2012.

3.2. Change detection

Fig. 3 shows the overlaid map (left) of the two classification maps in 2001 and 2011 for Field 1. The red shows the infected areas in both years, the blue shows the infected areas only in 2001, and the yellow depicts the infected areas only in 2011. Change detection analysis showed that 7.8% of the field was infected in both years, while 5.8% of the field was infected only in 2001 and 10.0% only in 2011 (Table 1). Thus, the total infected area in either 2001 or 2011 was 23.6% ($7.8\% + 5.8\% + 10.0\%$) as shown by the merged two-zone map in Fig. 3 (right).

Fig. 3. Overlaid four-zone classification map between 2001 and 2011 (left) and merged two-zone classification map for Field 1.

Table 1

Change detection statistics in terms of percent area (%) between two classification maps from airborne imagery acquired in 2001 and 2011 for Field 1.

		Initial state (2001)		
	Class	Infected	Non-infected	Row total
Final state (2011)	Infected	7.8	10.0	17.8
	Non-infected	5.8	76.4	82.2
	Column total	13.6	86.4	
	Class change	4.2	-4.2	

Fig. 4 shows the overlaid map (left) of the two classification maps in 2002 and 2012 for Field 2. Change detection analysis showed that 5.3% of the field was infected in both years, while 6.4% of the field was infected only in 2002 and 2.8% only in 2012 (Table 2). Thus, the total infected area in either 2002 or 2012 was 14.5% (5.3% + 6.4% + 2.8%) as shown by the merged two-zone map in Fig. 4 (right). The merged two-zone infection maps for both fields can be used as base maps for site-specific fungicide treatment.

Fig. 4. Overlaid four-zone classification map between 2002 and 2012 (left) and merged two-zone classification map for Field 2.

Table 2

Change detection statistics in terms of percent area (%) between two classification maps from airborne imagery acquired in 2002 and 2012 for Field 2.

		Initial state (2002)		
	Class	Infected	Non-infected	Row total
Final state (2012)	Infected	5.3	2.8	8.1
	Non-infected	6.4	85.5	91.9
	Column total	11.7	88.3	
	Class change	-3.6	3.6	

3.3. Effect of buffer distance on root rot maps

Fig. 5 presents the percent root rot areas with buffers of 0–20 m for the separate years and the two years combined for Fields 1 and 2. It can be seen clearly that percent area increased with buffer distance, but the increase rate decreased with buffer distance. At smaller buffer distance, percent area increased faster with buffer distance. At larger buffer distance, percent area increased at a slower rate. For example, percent area would have increased to anywhere between 2.2 and 3.8 times if the fungus had expanded by 20 m for the two fields, compared with the 1.8 to 2.9 times for the first 10 m buffer. For the second 10 m, the net increase was only 0.4 to 0.9 times of the original areas, much smaller than for the first 10 m. The reason for this difference is partly due to the fact that the original classification maps contained many small polygons and these polygons expanded in all directions and quickly filled the gaps between polygons at smaller buffer distances. As buffer distance increased further, the increase rate tended to reduce. Nevertheless, as buffer distance continues to increase, all the curves in Fig. 5 will eventually reach the 100% maximum.

Fig. 5. Percent root rot area with buffers of 0–20 m for two separate years and the two years combined for Fields 1 and 2.

Tables 3 and 4 summarize the percent root rot area with buffer zones of 0–10 m around the infected areas for the separate years and the two years combined for Fields 1 and 2, respectively. For Field 1, the percent root rot area increased from 13.6% for the 0-m buffer (original infection) to 39.6% (almost tripled) for the 10-m buffer in 2001, and from 17.8% for the 0-m buffer to 47.6% (2.7 times the original) for the 10-m buffer in 2011 for Field 1. For Field 2, the percent root rot area increased from 11.7% for the 0-m buffer to 20.6% (1.8 times) for the 10-m buffer in 2002, and from 8.1% for the 0-m buffer to 22.6% (2.8 times) for the 10-m buffer in 2012. When the classification maps for the two years were merged, the percent root rot area increased from 23.6% for the 0-m buffer to 50.6% (more than doubled) for the 10-m buffer for Field 1, and from 14.5% for the 0-m buffer to 26.4% (1.8 times) for the 10-m buffer for Field 2. Clearly, root rot areas could have increased to anywhere between 1.8 to 2.9 times the original areas if the fungus had expanded by 10 m for the two fields.

Table 3

Root rot area with buffer in percent area (%) at 11 buffer distances for 2001, 2011 and the two years combined for Field 1.

Year	Buffer distance (m)										
	0	1	2	3	4	5	6	7	8	9	10
2001	13.6	18.3	21.9	25.0	27.6	30.0	32.2	34.3	36.2	38.0	39.6
2011	17.8	24.4	28.8	32.3	35.3	37.9	40.2	42.3	44.2	46.0	47.6
2001 & 2011	23.6	29.7	33.7	36.9	39.6	41.9	44.0	45.9	47.6	49.2	50.6

Table 4

Root rot area with buffer in percentage (%) at 11 buffer distances for 2002, 2012 and the two years combined for Field 2.

Year	Buffer distance (m)										
	0	1	2	3	4	5	6	7	8	9	10
2002	11.7	13.1	14.4	15.4	16.4	17.2	18.0	18.7	19.4	20.0	20.6
2012	8.1	10.5	12.4	14.2	15.7	17.1	18.4	19.6	20.6	21.6	22.6
2002 & 2012	14.5	16.6	18.3	19.8	21.1	22.2	23.1	24.0	24.9	25.6	26.4

The expansion rate with buffer distance depends on the spatial distribution and extent of the original root rot infection. It can be seen from Fig. 5 and Tables 3 and 4 that Field 1 had more root rot than Field 2 and that the expansion rate with buffer distance were generally faster for Field 1 than for Field 2. Moreover, the expansion rate with buffer differed for different years for the same field. For example, the expansion rate looked similar for the two years for Field 1, but differed for the two years for Field 2. The expansion rate was much faster for 2012 than for 2002 for Field 2. Although original infection was smaller for 2012 than for 2002, the percent root rot area with a 5-m buffer for 2012 reached that for 2002.

Figs. 6 and 7 show the two-zone classification maps with a 5-m buffer around infected areas for the two separate years and the two years combined for Fields 1 and 2, respectively. The percent root rot areas with the buffer were 30.0%, 37.9% and 41.9% (or 2.2, 2.1 and 1.8 times the original infection) for 2001, 2011, and the two years combined for Field 1. For Field 2, the percent root rot areas with the buffer were 17.2%, 17.1% and 22.2% (or 1.5, 2.1 and 1.5 times the original infection) for 2002, 2012, and the two years combined for Field 2. These maps along with other maps created with different buffer distances can be used for estimation of root rot areas and for site-specific fungicide treatment of cotton root rot.

Fig. 6. Classification maps with a 5-m buffer around infected areas for 2001, 2011 and the two years combined for Field 1.

Fig. 7. Classification maps with a 5-m buffer around infected areas for 2002, 2012 and the two years combined for Field 2.

3.4. Overlapped root rot area between years with buffer distance

Based on the change detection analysis results, only 7.8% of the infection out of the 13.6% in 2001 and the 17.8% in 2011 occurred simultaneously in both years for Field 1 (Table 1). Similarly, only 5.3% of the infection out of the 11.7% in 2002 and the 8.1% in 2012 occurred in both years for Field 2 (Table 2). In other words, only 57% (7.8/13.6) of the infection in 2001 and 44% (7.8/17.8) of the infection in 2011 overlapped for Field 1, and only 45% (5.3/11.7) of the infection in 2002 and 65% (5.3/8.1) of the infection in 2011 overlapped for Field 2. From the analysis in Section 3.3, by creating a buffer zone around the infected areas, the root rot area with the buffer could increase significantly. It will be interesting to see how much the overlapped root rot area will be between the two years for each field if the root rot area for one year is expanded by a buffer distance.

Fig. 8 presents overlapped percent root rot areas between two years when buffer zones of 0–20 m were created for one year for Fields 1 and 2. The overlapped percent area increased

with buffer distance asymptotically, approaching the 100% maximum. For example, overlapped percent areas with a 9-m buffer exceeded 90% for either year for Field 1, whereas overlapped percent areas with a 12-m buffer exceeded 90% for either year for Field 2. By increasing the buffer distance further, overlapped percent areas will continue to increase but at a much lower rate. Although larger buffer distance will ensure more potential root rot areas are covered in the prescription map, but the treatment areas will also increase significantly. The optimal buffer distance depends on the particular infection in each field. If images are available only for one season, larger buffer distance can be used; otherwise, merged root rot maps for multiple seasons should be used with smaller buffer distance.

Fig. 8. Overlapped percent root rot area between two years if buffer zones of 0–20 m are created for one year for Fields 1 and 2.

Tables 5 and 6 summarize the overlapped root rot areas between two years when buffer zones of 0–10 m were created for one year at a time for Fields 1 and 2, respectively. When the root rot areas with buffers of 0–10 m for 2001 were overlaid with the original root rot map for

2011 for Field 1, the overlapped area over the original infection for 2011 increased from 44.1% for the 0-m buffer to 92.5% for the 10-m buffer. When the root rot areas with buffers of 0–10 m for 2011 were overlaid with the original root rot map for 2001 for Field 1, the overlapped area over the original infection for 2001 increased from 57.7% for the 0-m buffer to 97.0% for the 10-m buffer. Similarly, the overlapped area over the original infection for 2012 increased from 65.1% to 90.9% with buffers of 0–10 m applied to the original root rot maps for 2002, and the overlapped area over the original infection for 2002 increased from 45.3% to 88.3% with buffers of 0–10 m applied to the original root rot maps for 2012 for Field 2. Obviously, by applying a buffer distance to the original root rot map in one year, the buffered map will cover most of the original infection in the other year. This result is important if only one year's imagery is available for generating prescription maps.

Table 5

Overlapped root rot area in ha and percentage (%) between two years if buffer zones are created for one year for Field 1.

Year with buffer	Overlapped area	Buffer distance (m)											
		0	1	2	3	4	5	6	7	8	9	10	
2001	(ha)	8.0	10.3	12.0	13.1	14.0	14.7	15.3	15.8	16.2	16.5	16.8	
	(%)	44.1	56.9	65.9	72.2	77.1	81.1	84.3	87.0	89.3	91.1	92.5	
2011	(ha)	8.0	10.2	11.3	12.0	12.4	12.7	13.0	13.1	13.3	13.4	13.5	
	(%)	57.7	73.1	81.2	86.2	89.3	91.6	93.3	94.6	95.6	96.3	97.0	

Table 6

Overlapped root rot area in ha and percentage (%) between two years if buffer zones are created for one year for Field 2.

Year with buffer	Overlapped area	Buffer distance (m)										
		0	1	2	3	4	5	6	7	8	9	10
2002	(ha)	5.1	5.5	5.8	6.1	6.3	6.5	6.7	6.8	6.9	7.0	7.1
	(%)	65.1	70.5	74.5	77.7	80.5	82.9	85.0	86.8	88.3	89.6	90.9
2012	(ha)	5.1	6.2	7.0	7.7	8.2	8.6	8.9	9.2	9.5	9.8	10.0
	(%)	45.3	55.1	62.4	68.1	72.5	76.2	79.3	82.0	84.4	86.5	88.3

4. Conclusions

Results from this study demonstrate that cotton root rot tends to occur in the same general areas within fields in recurring years, even though variations in infection patterns exist over the years. The relative stability of cotton root rot-infected areas indicates that historical remote sensing imagery can be used for the site-specific management of the disease in the future years. Numerous unsupervised and supervised image classification methods can be applied to multispectral imagery for accurately differentiating infected areas from non-infected areas, but the NDVI-based ISODATA classification appears to be a simple and effective method for generating root rot infection maps.

To account for the potential expansion and temporal variation of the disease, buffer zones can be added around the infected areas in the original classification maps for generating prescription maps. The selection of the optimal buffer distance depends on multiple factors such as infection extent and pattern, availability of imagery for single season or multiple seasons, and the producer's risk tolerance. For the two fields in this study, when the images from both years were used to create merged classification maps, a buffer distance of 5 m would be appropriate. When the image from one single year was used, a buffer distance of 10 m could be necessary. Although arbitrary, a buffer distance of 3–12 m should be sufficient to accommodate the

expansion and temporal variation of the disease. The procedures and results presented in this paper provide general guidelines for the creation of prescription maps and have practical implications for site-specific management of cotton root rot.

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