Post-hurricane Analysis of Citrus Canker Spread and Progress towards the Development of a Predictive Model to Estimate Disease Spread Due to Catastrophic Weather Events

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Abstract

Many factors have been involved in the spread of citrus canker (Xanthomonas axonopodis pv. citri); however, the 2004 hurricane season appears to have been one of the major factors leading to the widespread and numerous citrus canker infections discovered in late 2004 and 2005. Geospatially referenced citrus canker infection data from infections that were discovered after the 2004 hurricanes were examined in relation to wind and rain conditions experienced during the hurricanes and used to develop a predictive model to explain storm-related spread of citrus canker. The model incorporates a "threshold" concept for wind and rains that, in-effect, incorporates only biologically significant weather parameters in the calculations. When applied to three distinct areas of the state, the predictive model accounted for approximately 80% of the hurricane related and subsequent secondary spread of citrus canker over the next 14 months. Therefore, the use of the predictive model shows great promise a tool to predict disease spread as a result of extreme weather events and as a means of targeting resources for citrus canker survey and detection activities.

Introduction

The bacterium, Xanthomonas axonopodis pv. citri (Xac), that causes Asiatic citrus canker (ACC) can be dispersed in gentle rain, rain with wind, rain storms, tropical storms, and hurricanes. These meteorological events are progressively more effective at dispersing inoculum over greater distances. Apart from dispersal during meteorological events, inoculum can be dispersed mechanically from within-trees to very long distance dispersal through human activities, including the movement of infected plant material over short distances (local) to long range dispersal (global = among countries and continents). From an epidemiological point of view, epidemics of ACC are composed of a series of discontinuous pulses of inoculum that first introduce Xac to the host population, with a combination of multiple meteorological and mechanical events that further disperse inoculum and exacerbate the epidemic. However, dispersal events vary greatly in distance and quantity of inoculum dispersed.

Historically, numerous storm and mechanical transmission events have contributed to the spatial distribution and patterns of spread of citrus canker in Florida (6). In particular, three hurricanes (Charley, Frances, and Jeanne) that crossed the Florida peninsula during 2004 exacerbated preexisting ACC infections and dispersed the pathogen extremely widely and resulted in the establishment of numerous new infections at substantial distances from the pre-existing infections.
History of Multiple Citrus Canker Epidemics in Florida

ACC has a long history in Florida. The disease was first found around 1912 spread throughout the southeastern U.S. on imported seedlings from Japan, and was declared eradicated from Florida and the adjacent states by 1933 (5,12). ACC was rediscovered in Manatee Co., Florida south of Tampa Bay in 1986, and was declared eradicated by 1994 (20). Three years later, the disease re-emerged in the same general area on the west coast of Florida where the 1980s outbreak had occurred. In the meantime, a new and separate infection of ACC was discovered in urban Miami in 1995, with an estimated introduction some time in 1992 or 1993 (7,16,17,18).

When detected in Miami in 1995, the disease was contained in an area of approximately 36.3 km$^2$ (14 mile$^2$) of mostly residential properties southwest of the Miami International Airport. To deal with this epidemic, a cooperative state/federal citrus canker eradication program (CCEP) was established between the Florida Department of Agriculture and Consumer Services (FDACS), Division of Plant Industry (DPI), and the United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS).

Concurrently, ACC was rediscovered in commercial citrus in Manatee Co. on the west coast of Florida in June 1997. Subsequent outbreaks of ACC have occurred in both residential and commercial citrus in most counties in the southern half of Florida. The origins of inoculum for this nearly state-wide epidemic are believed to be related predominantly to the inoculum reservoir in residential Dade and Broward counties (4). Extensive eradication efforts from 1995 to the present have resulted in the removal or destruction of 6,993,651 commercial trees, 4,224,175 commercial nursery trees, and 844,327 infected and exposed dooryard citrus trees statewide. Following the 2004 hurricane season, over 25,779 ha (63,701 acres) of commercial citrus trees have been removed or are scheduled to be removed in an effort to eradicate the disease from commercial plantings.

The situation in Florida was exacerbated by the introduction of the Asian citrus leafminer (Phyllocnistis citrella Stainton) in 1993. ACC has increased significantly as a consequence of the insect’s feeding activities which create wounds that expose susceptible leaf mesophyll tissues to splashed inoculum, thus increasing the probability of infection by Xac (10). Whereas foliar wounds on citrus leaves normally callus within 1 to 2 days, leafminer induced wounds resist callus formation for about 14 days, allowing the highly susceptible mesophyll tissues to be exposed for a much longer time (1,2).

ACC is characterized by erumpent lesions on fruit, foliage, and young stems of susceptible cultivars of citrus (8,18). Unfortunately, most commercial citrus varieties grown in Florida are moderately to highly susceptible to the disease, especially grapefruit (Citrus paradisi) and early and mid-season maturing cultivars of sweet orange (C. sinensis). When the disease is severe, defoliation, dieback, and fruit drop (reducing yield quantity) can occur and infected fruit that remain are often scarred with lesions (reducing yield quality) and therefore less valuable or entirely unmarketable (8,11). In addition, strict international trade regulations in some regions prohibit export of fruit from canker-endemic areas, further restricting potential markets (7,9). This results in even greater financial impact as many of these markets pay a premium price for fresh citrus. If Xac should become endemic in Florida, it will result in a severe curtailment of commerce in fresh citrus fruit, which comprises approximately 20% of the State’s $9 billion commercial citrus industry (13,14). Furthermore, highly susceptible cultivars, including grapefruit, will be difficult to impossible to grow profitably due to the cost of canker management, including the need for expensive bactericidal sprays that would be required to maintain yields and quality.

During seasons when spring and summer rains are combined with wind speeds in excess of 8 m/s (17.9 mph), damage from the disease can range from nominal to significant (19). Recently, it was demonstrated that inoculum begins to exude from wetted lesions within 1 to 5 minutes and is immediately available for dispersal. During a simulated 54-h continuous rainstorm with continual inoculum removal, the maximum concentration of bacteria was exuded within the first one to two hour period following the beginning of the rain, although
inoculum was produced continuously at a lower concentration for the duration of the experiment (3).

The dramatic increase in disease incidence subsequent to the hurricanes of 2004 instigated the current research in an attempt to understand the patterns of disease spread resulting from extreme storm events. The purpose of this study was to firstly develop a model to assess spread of ACC during catastrophic wind/rain events and secondly to attempt to validate the model based on post-storm ACC infections identified by the CCEP.

**Estimation of Citrus Canker Spread via Hurricanes and Development of Wind/Rain Index Vectors**

**2004 hurricane season.** During the 2004 hurricane season, three hurricanes significantly affected the citrus production areas of Florida (Fig. 1). On August 13, hurricane Charley made landfall on the lower west coast of Florida and crossed the state on a northeasterly track (Fig. 2a), taking the hurricane over the southern, western, central, and northern citrus production areas. On September 5, hurricane Frances made landfall in the Treasure Coast area on the east coast of Florida and crossed the state on a northwesterly track (Fig. 2b), taking the hurricane primarily over the Indian River, central, western, and northern citrus production regions. On September 25, hurricane Jeanne made landfall in essentially the same area as hurricane Frances and again crossed the state on a northwesterly track over the same production areas (Fig. 2c). At the time of all three hurricanes, *Xac* infections, either known at the time of the hurricane or discovered after the hurricane but with estimated ages of infection that pre-dated the storms, were present in some of the production areas.

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Fig. 1. Citrus production areas in Florida.
Citrus canker eradication program surveys. Disease detection surveys conducted as part of the ACC eradication program were conducted jointly by FDACS, which was responsible for general surveys in commercial groves and residential properties, and by USDA-APHIS, which was responsible for sentinel surveys in both residential and commercial citrus groves. General surveys were conducted at yearly intervals with the intent that a portion of every commercial grove and all trees on residential properties (in target areas) would be surveyed at least once a year. Sentinel surveys were conducted more frequently; however, not all groves or residential properties were visited. Instead, the intent was to target geographic areas by preferentially selecting susceptible cultivars in plantings (both residential and commercial) that were stratified across the survey area. When infected plants were found in either survey (general or sentinel), the intensity and the frequency of the survey were increased until the extent of the infected area was delimited. As infected trees were found, their positions were recorded by GPS equipment. When the number of infected trees was small or when the infected trees were on residential properties, GPS coordinates were collected for all infected trees. However, if the number of infected trees was large (in commercial groves), GPS coordinates were collected only from trees that defined the outer edges of the area infected within the property. The GPS data points from both residential and commercial finds were entered into a geographic information system (GIS) database and these data were used for subsequent vector analyses.

Citrus canker study areas. Based on post-storm surveys over a 14-month period, three areas with canker infection were studied to determine the impact of hurricanes on the subsequent spread of ACC as a result of the storm events. The first area of study consisted of a three-county area comprised by Indian River, St. Lucie, and Martin counties, collectively known as the Treasure Coast (Fig. 3). The second and third areas of study were in Lee/Charlotte and Orange counties, respectively (Fig. 3). These three areas were selected for study based on two criteria. The first criterion was the detection of numerous new \( Xac \) infections within the area during the 14-month period of time following the 2004 hurricanes. The second, and probably the most important criterion, was the identification, sometimes after the fact, of trees with infections that predated the 2004 storms. Infection aging was based on an estimate of the age of the branches on which lesions were found in relation to the known flush and growth patterns of citrus trees in the area (\( Xac \) only tends to infect fresh flush or injured tissue). Trees with lesions that pre-dated the 2004 hurricanes were assumed to be the initial foci of infection for subsequent spread as a result of the storms.
In the Treasure Coast area, two trees in close proximity to each other were identified as pre-dating hurricanes Frances and Jeanne and all subsequent infections that were detected in the three-county area were assumed to have originated due to direct spread from these two trees as a result of the storm(s) and from subsequent secondary spread that occurred over the ensuing 14-month period as a result of secondary weather events, mechanical spread, and other unidentified mechanisms of spread. This assumption is based on the observation that all infections identified in the area of study other than the two trees identified as the foci of infection were infections that post-dated the hurricane spread events (i.e., infections were found on flushes that were contemporaneous with or occurred after the hurricane events). In the second area of study, approximately 17 trees were identified in Lee Co. that pre-dated hurricane Charley. All the infection that was detected in the two-county area was assumed to have originated due to direct spread from these 17 trees as a result of the storm and other post-storm secondary spread over a 14-month period. In the third study area, several discrete areas of infection were found that were traced back to single trees in each of the areas that pre-dated hurricane Charley. Data from the two largest areas of infection in Orange Co. (identified as areas 4 and 6 by the USDA-APHIS survey teams) were studied.

**Weather data.** Weather data were collected from weather stations located in close proximity to the three study areas where ACC was detected during the post storm surveys. Data were collected by automated weather stations operated by the Florida Automated Weather Network (FAWN, fawn.ifas.ufl.edu) or from weather stations operated as part of the Citizen Weather Observer Program (CWOP, www.wxqa.com). The FAWN network consists of 34 weather stations located primarily at University of Florida research stations and is geared towards agricultural users and are therefore largely located in agricultural areas. CWOP weather stations are privately operated weather stations operated by amateur radio operators whose data are made available to the National Oceanic and Atmospheric Administration (NOAA). CWOP stations are primarily located in urban areas and their data are checked for quality by NOAA and then redistributed to users. The weather data used were collected at hourly intervals over the time period of the hurricanes and consisted of rainfall per hour plus wind speed and wind direction both collected at a 9.14-m (30-ft) elevation.

**Calculation of vectors and indices.** Wind-rain index vectors (WRIV) were calculated based on the concept of a "wind rose" analysis (Fig. 4) commonly used for presenting wind speed, wind direction, and wind duration data all incorporated into a single graph. However, instead of using wind speed
in the calculations, a wind-rain index ($I_{wr}$) using predetermined thresholds was calculated and substituted for the wind speed value normally used in a wind rose analysis. The assumption behind the use of $I_{wr}$ was that both wind ($w$) and rain ($r$) must occur at the same time in order for $Xac$ to be dispersed further than a few meters. Therefore $I_{wr}$ would account for both meteorological conditions that must be present in order for long-distance spread to occur.

To determine the WRIV that occurred during a storm event, individual $I_{wr}$ values were calculated for each hour of weather data using the formula:

$$I_{wr} = 100 \times \left(\frac{w}{w_{max}}\right)^a \times \left(\frac{r}{r_{max}}\right)^b$$

where, $w_{max} = 33.5$ m/s (75 mph), $r_{max} = 5.08$ cm/h (2.0 inches/h). To obtain values for $w$ and $r$, the windspeed and rainfall amounts were compared to predetermined threshold wind and rainfall values. If $w \geq$ threshold then $w =$ windspeed and if $r \geq$ threshold then $r =$ rainfall. However, if $w <$ threshold or if $r <$ threshold, then $w = 0$ or $r = 0$, respectively.

The $I_{wr}$ and the wind direction data associated with the $I_{wr}$ were plotted using commercially available wind rose software (WRPlot View, Lakes Environmental Software, Ontario, Canada) in 15° wind direction increments in a "blowing to" orientation. Since a threshold concept was used in the calculations, for any time period for which either $w$ or $r$ values did not meet or exceed the thresholds, the $I_{wr}$ would reduce to zero and thus would drop out of the calculation leaving only those WRIV in the wind rose that could potentially spread $Xac$. Therefore the wind rose calculated using $I_{wr}$ results in a diagram that only presents biologically significant meteorological events (Fig. 5).

Fig. 4. A wind rose diagram depicting the distribution of wind direction and speed in the Treasure Coast area during hurricanes Frances (4-5 August 2004) and Jeanne (24-25 August 2004). The wind vectors are in 15 degree increments and are expressed in a "blowing to" orientation.
Determination of \( w \) and \( r \) thresholds. To determine the thresholds for \( w \) (wind speed) and \( r \) (accumulated rainfall volume for a 1.0-h period) variables for use in the calculation, the distribution of infection data for the Treasure Coast area from the citrus canker surveys were plotted (Fig. 6) using commercially available GIS software (ArcMap 9.0, ESRI, Redlands, CA). \( \text{WRIV} \) were computed with \( I_{wr} \) using all possible combinations of \( w = 4, 6, 8, 10, \) and 12 m/s (8.9, 13.4, 17.9, 22.4, and 26.8 mph) and \( r = 0.16, 0.318, 0.477, 0.635, 0.795, \) and 0.953 cm/h (0.063, 0.125, 0.188, 0.250, 0.313, and 0.375 inch/h) as thresholds. FAWN weather data from the Fort Pierce station were used for all calculations at the Treasure Coast study site. This station was located approximately 14.16 km (8.8 miles) from the pre-storm foci of infection. Due to the propinquity of the hurricane tracks and the fact that hurricane Jeanne occurred within a few weeks of hurricane Frances the weather data from both storms were combined in these analyses.

Fig. 5. A wind rose diagram depicting WRIV in the Treasure Coast area during hurricanes Frances (4-5 August 2004) and Jeanne (24-25 August 2004) using \( w = 8 \) m/s (17.9 mph) and \( r = 0.318 \) (0.125 inch/h). The wind vectors are in 15 degree increments and are expressed in a "blowing to" orientation.
For all WRIV computed, the length of the vectors was set at 56.3 km (35 miles). This assumption was based on an observation from the Lee/Charlotte Co. area of study that indicated that distances of spread could be up to 56.3 km as result of hurricane induced wind and rain (Irey and Gottwald, unpublished). The WRIV for individual \( w \) and \( r \) threshold combinations in the wind rose plots were overlaid on the infection data in the GIS plots using the foci of infection in each study area as the origin for the WRIV (Fig. 7). The percentage of GPS data points (representing infected trees) overlaid by the WRIV compared to the total number of GPS data points in the Treasure Coast area of study was used as the measure of the "goodness of fit" of the model for each combination of \( w \) and \( r \) thresholds (Fig. 8). Thresholds of \( w = 8 \) m/s (17.9 mph) and \( r = 0.318 \) cm/h (0.125 inch/h) were selected as the thresholds for use in subsequent analyses. This combination of thresholds resulted in the smallest set of WRIV that captured the largest percentage of infected trees (82.8%). Due to the methodology used in the commercial grove surveys (i.e., in some instances, only the perimeter of the infected area was delimited by GPS points), it is likely that the estimates of percent capture are an underestimation of the actual number of trees captured by the WRIV.
Calculated citrus canker spread vectors using thresholds for the treasure coast area applied to the Lee/Charlotte and Orange County study areas. The WRIVs, using $I_{wr}$ calculated with $w = 8$ m/s (17.9 mph) and $r = 0.318$ cm/h (0.125 inch/h) as thresholds estimated from the Treasure Coast data, were applied to weather data from hurricane Charley for the Lee/Charlotte and Orange County study areas. Both of these areas were residential areas and CWOP weather data were used in the analyses. Numerous power failures associated with hurricane Charley made it difficult to find complete weather data.
data sources in the area of study for the desired time period. For the Lee/Charlotte County area, a CWOP station located in Naples, FL, approximately 50 km (31 mi) south of the foci of infection and 34 km (21 mi) east of the track of the storm was used for the WRIV computations. Although it would have been desirable to have weather data from a source closer to the foci of infection, this was the only station that could be located with complete data for August 13, 2004 (hurricane Charley). Similarly, it was difficult obtain data for the Orange County area. The closest station to the areas of study in Orange County had incomplete data so data from the two closest stations (approximately 24 and 34 km [15 and 21 mi] away) were combined to calculate the WRIV.

WRIV calculated using $I_{wr}$ with $w = 8$ m/s (17.9 mph) and $r = 0.318$ cm/h (0.125 inch/h) as thresholds for the Lee/Charlotte County study area (Fig. 9) captured 86.3% of the infected trees identified in the residential ACC surveys. Similarly, WRIV calculated using the same thresholds for Orange County (Fig. 10) captured 79.5% and 81.8% of the infected trees in the two residential sub areas studied. Unlike the commercial grove surveys, the residential citrus canker surveys identified all infected trees found with GPS points therefore the ~ 80% combined capture calculations accurately represents the extent of the known infected trees overlaid by the WRIV estimates. Although this method explained a relatively high percentage of the subsequent infections that developed and were discovered, some of the subsequent infection fell outside of the predicted vectors. This could be due to the intent to make the vector predictions conservative (i.e., the smallest set of WRIV that captured the largest percentage of infected trees was used) and not over predict the affected area. However, the data include not only infections representing spread due to the hurricanes themselves but also takes into account infections resulting from secondary spread that occurred post-hurricane(s) during the following 14 months. Thus some of the secondary spread events could have taken inoculum beyond the bounds of the vectors predicted by meteorological conditions associated with only the main meteorological event, i.e., the hurricane(s).

![Fig. 9. WRIV for the Lee/Charlotte County area using $w = 8$ m/s (17.9 mph) and $r = 0.318$ cm/h (0.125 inch/h) as thresholds to calculate $I_{wr}$. Individual WRIV were extended 50 km (35 mi) in each "blowing to" direction. Percent capture of infected trees by WRIV = 86.3%.](image)
Discussion and Application of WRIV Calculations to Direct Survey Efforts and Search for Pre-Hurricane Citrus Canker Foci

The fact that hurricanes and other severe weather events have had a significant impact on the incidence of citrus canker in Florida is apparent. However, predicting the magnitude and the direction of spread due to these extreme weather events has been difficult due to the complexity of the wind and rain patterns associated with each storm. For example, in a "typical" hurricane, wind directions can be in exact opposite directions depending on which side of the hurricane track is being monitored. This is due to the counter-clockwise rotation of storms in the northern hemisphere. Similarly, if the measurement site is directly on the track of the storm, high winds and rains will be experienced in one direction, followed by a lull (as the eye of the storm passes over), and then again followed by high winds and rain from the opposite direction. Therefore, depending on the location of an individual site in relation to the storm track, it is possible that high winds and rains may be experienced from a range of directions (Fig. 11). Further complicating the issue is the fact that sufficient wind and rain to cause dispersal may not occur together, so measurement of wind alone cannot accurately predict spread. However, the use of the WRIVs calculated using $I_{wr}$, which incorporates both wind and rain in the calculation, appears to show promise as a tool to predict the spread of citrus canker.

**Fig. 10.** WRIV for the Orange County area using $w = 8$ m/s (17.9 mph) and $r = 0.318$ cm/h (0.125 inch/h) as thresholds to calculate $I_{wr}$. Individual WRIV were extended 50 km (35 mi) in each "blowing to" direction. Percent capture of infected trees by WRIV for Area 4 = 79.5%. Percent capture of infected trees by WRIV for Area 6 = 81.8%.
Multiple new infections of ACC were discovered in commercial citrus plantations and residential areas over the 14 months following the three hurricanes in 2004. New infections occurred in areas previously believed to be free of ACC and at considerable distance from any known sources of infection. Determining the location of the unknown sources of inoculum that gave rise to these newly infected trees and the removal of these sources is a necessity for effective eradication of the disease. The WRIV calculation method was employed to delimit suspect survey areas and direct CCEP survey crew efforts. This was achieved by using the GPS location of new post-hurricane citrus canker infections [infections determined to have occurred subsequent to the passing of the hurricane(s)] as a focal point, and generating the $I_{wr}$ and wind rose to determine the associated vectors(s) for the storm(s) that impacted that area. However, the vectors were reversed toward the "blowing from" direction, i.e., toward a suspected source of infection. These vectors were then transferred to a GIS map of the area and overlayed on commercial and residential citrus plantings. Thus the vectors were intended to backtrack over a potential dispersal gradient, toward the pre-hurricane inoculum source. This methodology was applied on several occasions to identify pre-hurricane foci of infection that could subsequently be used to further delimit the areas that must be surveyed.

An example of how this method was applied is in Polk County (Fig. 12A). Numerous post-storm, infections were found following the 2004 hurricanes, however, there was no apparent link or pattern between them. Using WRIVs calculated for hurricane Charley for several weather sites surrounding the infections in Polk County (Fig. 12B) it was possible to identify the direction that potential inoculum would have originated from. Using this information, the infections that were found post-storm were re-evaluated and it was possible to determine which of the infections was likely to predate the storm (Fig. 12C). In the case of Polk County, it was determined that much of the infection in Polk County originated from a pre-storm infection located at the southern edge of the county.

Fig. 11. Radar loop of hurricane Wilma as it passed over south Florida on August 24, 2005.
Fig. 12. Example of the application of WRIVs to post-storm discoveries of citrus canker in Polk County.

(A) Post-storm citrus canker infections relative to the track of hurricane Charley.

(B) At the time of the initial discovery of the infections, there was no indication of the original foci of inoculum. Using weather data from weather data sites near the known infections, midpoint rays of the WRIV were plotted.

(C) These rays when considered in a “blowing from” indicate the direction of potential initial inoculum sources. Consensus WRIV were calculated and applied to known infections. The infection sites were re-evaluated to determine the age of infections and likely pre-storm infection sites were identified.

When pre-hurricane foci were detected, the method was deployed yet again. This time vectors were calculated using the GPS location of the pre-hurricane point of disease, calculating the $I_{wr}$ and windrose and giving the vector a "blowing to” orientation. In this way, a new search area was delimited for CCEP survey crews to attempt to find additional new post-hurricane infections that could also have arisen from the newly discovered pre-hurricane focus. An example of how this process was used occurred in Hardee County. WRIVs were calculated for all three 2004 storms and examined in relation to known pre-storm infections (Fig. 13a). Using existing grove data to locate groves planted to susceptible cultivars located within the predominant WRIV, CCEP personnel were directed to search groves within the WRIV and they were immediately able to locate new ACC infections (Fig. 13b).
Such ‘targeting’ of CCEP survey efforts is of considerable benefit because it greatly reduces the survey effort to the most critical survey search area, providing a higher probability of finding both new and older but previously unknown infections, making more efficient use of CCEP personnel and fiscal resources. The targeted survey augments the other surveying methodologies for more rapid and complete detection of citrus canker in an area.

The application of this calculated $I_{wr}$ method to track the spread of ACC (and possibly other diseases or pests) will undoubtedly be useful in the future, since NOAA has determined that the annual occurrence of hurricanes and tropical storms has been escalating since 1995 and that the U.S. is experiencing an anticipated 30-year period of increased Atlantic and Gulf hurricane activity (15). This long-term forecast makes it quite realistic to assume that extreme storm activity will continue to be a major factor affecting the spread of ACC in Florida.

Fig. 13. Example of the application of WRIVs to post-storm discoveries of citrus canker in Hardee County. (A) WRIVs were calculated for hurricanes Charley, Frances, and Jeanne in a “blowing from” orientation. (B) The predominant vector indicated that canker infection was likely in a NNW direction. CCEP personnel then inspected a grove planted with a susceptible cultivar in line with the predominant WRIV and were able to identify a new citrus canker infection.
Literature Cited