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REVIEW

Panorama of citrus canker in the United States

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Abstract
This review summarizes the current status of citrus canker in the United States. The disease is present in Florida, Louisiana, and Texas. In Florida, the eradication program ended in 2006 and now citrus canker is endemic to many citrus-growing areas, although it is still possible to find canker-free groves. In endemic areas, the disease is controlled using windbreaks, applying copper-based bactericides, controlling the citrus leafminer, and applying systemic plant activators. In Louisiana, citrus canker was identified in 2013, the first time since the 1940s, and has since been identified in 10 of the parishes where plant material and fruit are not allowed to leave the quarantine areas. There are no eradication efforts in Louisiana and removal of trees is voluntary. Finally, citrus canker resurfaced in Texas in 2015 and has been detected in several locations. Currently only the type A^W strain is present in Texas and quarantine efforts are being taken to mitigate the risk of introduction of the type A strain into the state.

Keywords *Xanthomonas citri* · Outbreak · Pustules · Leafminer · State regulations

Introduction

Although citrus canker was reported for the first time in 1914 in the USA (Berger 1914), the disease was actually a serious problem in Florida several years earlier following its official detection around 1910 (Berger 1914; Stall and Civerolo 1991). It is believed that it was firstly found in Texas in 1911, in the Upper Gulf Coast area (Alvin & Port Arthur) (Berger 1914). Berger (1914) also identified citrus canker in Louisiana on a budded tree from Texas. It was believed to have been eradicated by 1947 based on extensive surveys conducted between 1947 and 1952 in which no positive citrus canker samples were found (Dopson 1964). The disease in Florida was traced back to Satsuma (*Citrus unshiu*) and *Poncirus trifoliata* seedlings that originated in Japan, with the latter being used as rootstocks (Berger 1914). In 1915, Hasse (1915) isolated for the first time the causal agent of citrus canker and fulfilled Koch's postulates by infiltrating a suspension of the bacteria previously isolated into young grapefruit (*C. paradisi*) leaves to reproduce symptoms and reisolating the bacterial pathogen. Although citrus canker was considered a new disease (Berger 1914), later Fawcett and Jenkins (1933) found citrus canker symptoms in herbarium samples collected in 1827–1831 on *C. medica* in India and 1842–1844 on *C. aurantifolia* in Indonesia. Skaria and Da Graça (2012) provided several lines of evidence based on typical citrus canker symptoms associated with citrus leaves in herbarium collections indicating that the bacterial pathogen is probably native to Asia.

Following the appearance of citrus canker in Florida in 1910 (Berger 1914), citrus growers became alarmed by the severity of the disease and began eradication efforts (Stall and Civerolo 1991). In the same year, the US began a federal-state cooperative eradication program to eliminate any citrus plant with symptoms of the disease. By 1915, the State Plant Board of Florida (present-day Division of Plant Industry) was formed and began the official eradication program. The program included restrictions on importing new citrus plant material from foreign countries, chemical defoliation of citrus trees, and

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cutting or burning of symptomatic trees in the field. This program was later implemented preventively in Alabama, Georgia, Louisiana, Mississippi, South Carolina, and Texas also during 1915 (Dopson 1964). The disease was declared officially eradicated in Florida around 1933 (Schubert et al. 2001) although Dopson (1964) did not definitively support the statement. However, according to Dopson (1964) intensive surveys were made in Louisiana and Texas in the late 1940s in which no citrus canker was detected over a 3-year period leading to the conclusion that both states were free of the disease in the early 1950s.

Several decades later, in 1986, a new outbreak occurred in west central Florida in which several residential areas were identified as containing trees that were affected by the disease (Schubert et al. 2001). Although more than 600 trees were removed, the pattern of spread and age of the lesions indicated that the disease was present for several years (Stall and Civerolo 1991). Along with the residential trees, commercial trees were removed in an area of 240 ha (Schubert et al. 2001). After eradication efforts were implemented, the disease was declared officially eradicated in 1994. According to Gottwald et al. (2002), the disease reappeared in 1997 in commercial groves located in the same area where the eradication program had occurred.

Currently, citrus canker is present in Florida, Texas and Louisiana (Table 1). The pathogen has not been reported in other southeastern states where citrus is grown. In states where citrus canker is at low incidence and has not spread much, as in Texas and Louisiana, eradication of symptomatic and suspect citrus trees in regulated areas is the main strategy to control the disease. In Florida, where eradication is no longer an option, management strategies are required for disease control. We discuss the current status of citrus canker in these three regions.

Post eradication situation in Florida

In 1995, multiple residential citrus trees near the Miami International Airport in Miami (Dade County), Florida, were identified as being infected with the disease; furthermore, the citrus leafminer pest (*Phyllocnistis citrella*) was shown to be associated with disease and to enhance spread through the East Coast and Central areas in Florida (Schubert et al. 2001; Skaria and Da Graça 2012; Stall and Civerolo 1991). After several attempts to eradicate citrus canker disease in Florida, the local climate (characterized by seasonal hurricanes and storms), the difficult conditions of the citrus industry, and the economy of the region at that moment (middle 2000's) made it impossible to continue the eradication program (Canteros 2005; Gottwald et al. 2005; Irey et al. 2006; Muraro et al. 2000). Following analyses of the impact of the hurricanes in 2004 and 2005 the USDA assessed that eradication of citrus canker in Florida was not feasible (Gottwald et al. 2005), and therefore, in January 2006, the Animal and Plant Health Inspection Service of the US Department of Agriculture (APHIS-USDA) cut the funds for eradication efforts (Centner and Ferreira 2012), and soon after, the State of Florida officially halted the eradication program and repealed the eradication statute.

Following the end of the eradication program in Florida in 2006, the disease has been found in all citrus producing areas of the state based on samples received by the Florida Department of Agriculture and Consumer Service's Division of Plant Industry (FDACS-DPI) (Fig. 1). Most of the samples came from the southern and central part of the state, while very few positive samples have come from North Florida where citrus production is minor (Fig. 1a, b). As of 2019, the disease has been identified in 30 counties in Central and

Table 1 States in the US with occurrence or detection of citrus canker outbreaks and strategy of control

State	Location	Strategy of control
Florida	1910 (Dopson 1964)	Quarantine and eradication
	1986 (Stall and Civerolo 1991)	Quarantine and eradication
	1995 (Miami Dade County)	Quarantine and eradication until 2006; management since then
Texas	1911 (Alvin & Port Arthur)	Quarantine and eradication
	2015 (Rancho Viejo, Cameron County)	Quarantine and eradication
	2016 (Houston, Harris County)	Quarantine and eradication
	2018 (Perland City)	Quarantine and eradication
Louisiana	1914 (Lake Pontchartrain)	Quarantine and eradication
	2013 (Orleans, Jefferson, Plaquemines and St. Charles Parishes)	Voluntary removal of affected trees
	2014 (St. Bernard Parish)	Voluntary removal of affected trees
	2016 (Lafourche, St. John The Baptist, and St. James)	Voluntary removal of affected trees
	2019 (East Baton Rouge and Livingston Parishes)	Voluntary removal of affected trees

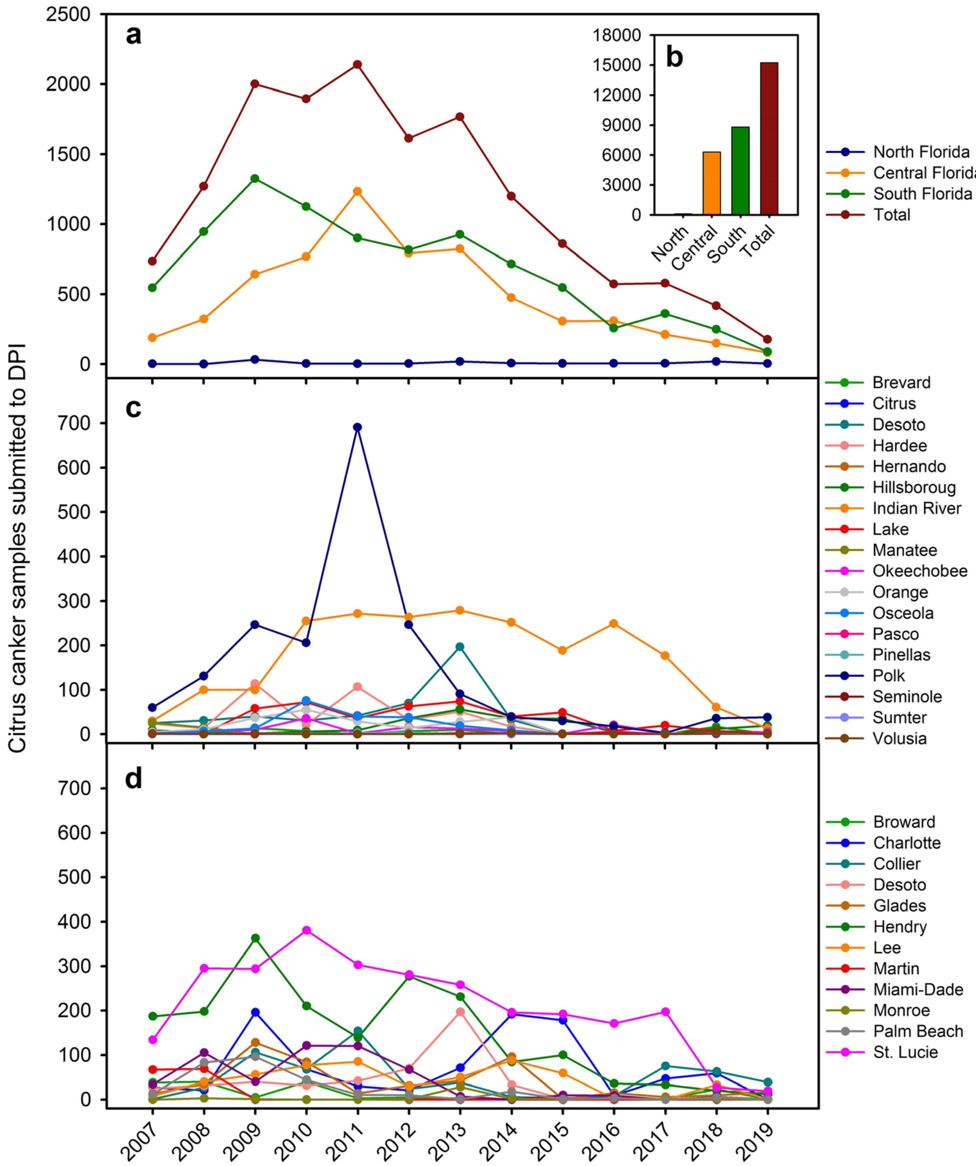

Fig. 1 Citrus Canker samples submitted to Florida Division of Plant Industry (DPI) from 2007 to 2019. Total samples of citrus canker submitted by year and region (**a, b**). Total samples submitted from Central (**c**) and South (**d**) Florida counties. The counties that are not listed have not submitted samples with citrus canker

South Florida (Fig. 1c and d). According the 2020 electronic Code of Federal Regulations (e-CFR 2020), only the state of Florida is listed as a quarantined area (Department of Agriculture 2020). Regulated nursery stock may not be moved interstate from a quarantined area except in accordance with protocols outlined in the 2020 e-CFR 2020 (see below).

Recent introduction and quarantine efforts in Texas

The Texas citrus production area is located in three counties in the Southern region of the state (Cameron, Willacy and Hidalgo). After the 1911 outbreak, citrus canker reappeared in late 2015 in Texas with detections on lime and lemon trees in Rancho Viejo, TX (Cameron County) (da Graça et al. 2017). It was determined later that the isolates from this incidence were the Wellington (A^W) strain, previously described by Sun et al. (2004) in Florida. The new outbreak probably originated from the illegal entry of infected plant material from Asia. This very specific type of *X. citri* subsp. *citri*, which was also found in Florida in 2000, is believed to have originated in India (Li et al. 2005; Schubert et al. 2001), where strains with similar genetic characteristics and host specificity also had been found (Ah-You et al. 2009).

In May 2016, citrus canker was confirmed in two sour orange trees (*C. aurantium*) at a city park in Houston, TX. This resulted in a delimiting survey by USDA to assess the spread and distribution of the disease in the Harris County area. Unlike the isolate from South Texas, the isolates from the Harris County detection were determined to be likely the more aggressive typical A strain.

Shortly after, in July 2016, citrus canker was detected on several hundred trees from a retail nursery in Richmond, TX, (Fort Bend County, located adjacent to Harris County) which were subsequently destroyed. These trees originated from several production nurseries that were inspected and found to be free of citrus canker, suggesting that infection occurred post arrival at the retail nursery. A subsequent survey by the Texas Department of Agriculture resulted in additional finds of citrus canker on dooryard (homeowner/personal) plantings. Infected trees were destroyed and sanitarily removed.

Approximately nine months after Hurricane Harvey hit the Upper Gulf Coast, citrus canker was reported in the Pearland area (Brazoria County, TX) on a residential citrus plant that resulted from a diagnostic support request by the homeowner. A subsequent delimiting survey from this detection resulted in finding 22 additional infected trees. Survey work is continuing in these urbanized areas (the greater Houston area) to monitor additional incidences of citrus canker.

As a result of these detections, there are four state regulated zones enacted in Texas. Three are located in the Upper Gulf Coast: parts of Harris County, parts of Fort Bend County, and parts of Brazoria County, and one zone are located in South Texas (parts of Cameron County). (For more information on legal description of quarantined area and associated maps visit https://www.texasagriculture.gov/RegulatoryPrograms/PlantQuality/PestandDiseaseAlerts/CitrusCanker.aspx). It is believed that all detections in the Upper Gulf Coast are caused by the more aggressive A strain of *X. citri*, while isolates from South Texas are the A^W strain that has a more limited host range. The Texas Department of Agriculture and Texas A&M AgriLife Extension Service are aggressively promoting education and awareness outreach of this disease to enhance success of the quarantine currently in place and to prevent the encroachment of the A strain into Texas citrus production areas. The latest amendment to the Federal Order on citrus canker in Texas occurred in September 20, 2019, which incorporated into the regulated area parts of Harris, Fort Bend, and Brazoria counties.

Recent introduction and quarantine efforts in Louisiana

In Louisiana, citrus canker was detected on sweet orange (*C. sinensis*) in 2013, the first time since 1940 (Dopson 1964). It was initially observed in New Orleans (the Parish of Orleans) and later in Jefferson, Plaquemines and St. Charles Parishes. In 2014, it was found in St. Bernard Parish. In 2016, Lafourche, St. John The Baptist, and St. James Parishes were added to the quarantine zone in Louisiana. In 2019, it was found in East Baton Rouge and Livingston Parishes. Currently, citrus canker is present in ten Parishes in Louisiana (Fig. 2). The Louisiana Department of Agricultural and Forestry does not have any eradication program, and citrus canker positive tree removal are voluntary by the owner. No plant material including fruit are allowed to leave the quarantine areas. Only potted nursery trees produced under APHIS approved structures and inspected regularly are allowed to be shipped from the affected areas.

Citrus canker management in Florida post eradication era

In Florida, after citrus canker became endemic and the eradication program ended in 2006 (Centner and Ferreira 2012), the disease has spread over much of the citrus-growing areas of the state, but it is still possible to find canker-free groves. In these areas, preventive measures are undertaken to exclude the disease. The decontamination of equipment and machinery is useful for preventing grove-to-grove dissemination. The removal of symptomatic and suspect trees is encouraged only when the number of affected trees in low and the nearest focus of the disease is more than a mile away. Defoliation and pruning may also be performed in areas surrounding foci of infected trees that have been removed to reduce disease inoculum. It is recommended that these measures are associated with regular surveys and copper sprays on the young flush (Dewdney et al. 2019).

Several measures contribute to the management of citrus canker in endemic areas, such as use of less susceptible cultivars or species, planting of arboreal windbreaks, spray of copper-based bactericides, control of the citrus leafminer, and application of systemic resistance inducers (Ference et al. 2018). However, after more than a decade since the eradication program ended in Florida, not all measures are adopted and some are only partially adopted. After 2006, by state and federal rule, all citrus nursery stock production had to be moved indoors. Presently, citrus nursery stock can only be produced in certified citrus greenhouses that have been built to very specific standards to exclude citrus pests and diseases and are inspected every 30 days by state inspectors. As of 2019, due to the expense of building and difficulty of maintaining certified citrus greenhouses, only 56 certified citrus nurseries exist in the state. As has been the case for over 50 years, Florida's citrus nurseries can only receive budwood for propagation from DPI's Citrus Budwood Registration program. This program cleans citrus germplasm of all diseases and pathogens before releasing the variety for propagation. Clean budwood combined with certified greenhouses ensures that growers receive disease-free citrus trees for planting in the field (Trevor Smith, Personal Communication).

The citrus industry in Florida is comprised mostly of Valencia and Hamlin sweet oranges and grapefruit. While Valencia is considered moderately susceptible, the other two are highly susceptible to citrus canker (Gottwald et al. 2002).

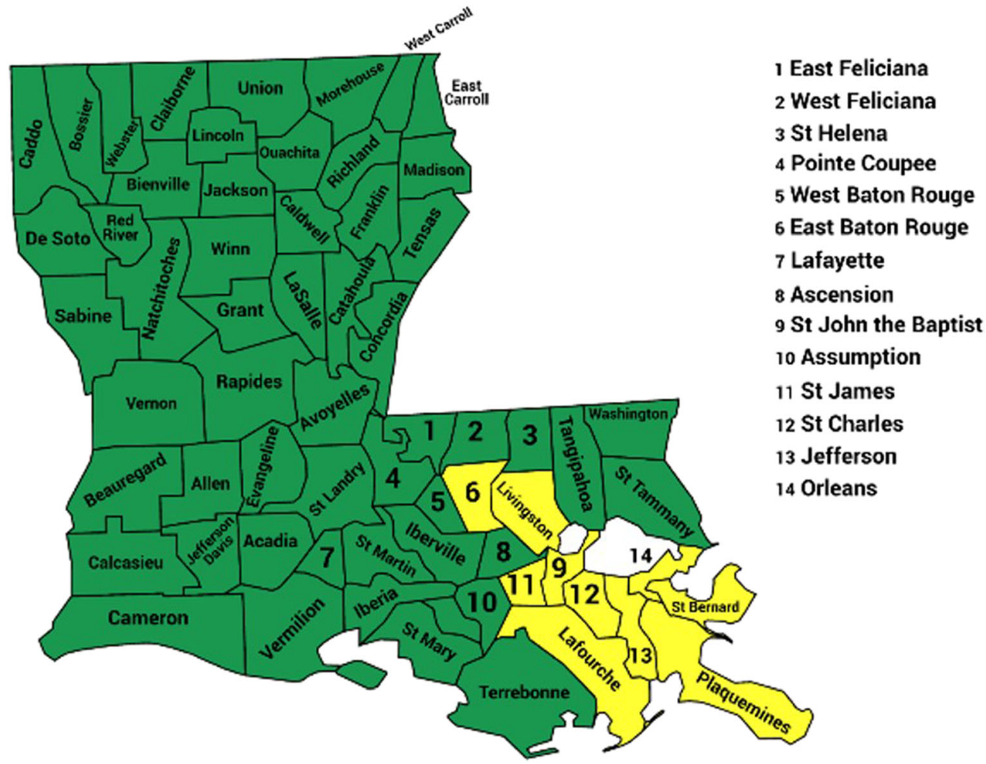

Fig. 2 Current distribution of citrus canker in Louisiana. Areas in yellow indicate parishes where citrus canker was present as of 2019

Thus, growers need to adopt other measures of control in order to avoid losses due to the disease. Arboreal windbreaks are recommended around 5- to 10-acre blocks or along fence lines, ditches, and wetlands. The main purpose of this measure is to reduce speed of gusty winds, which contribute to the formation of wounds that serve as entrances for the canker-causing bacteria into the host (Canteros et al. 2017; Graham et al. 2016). *Corymbia torelliana* is the most suitable species because the tree retains its leaves and branches all the way to the ground (Fig. 3). As the establishment of windbreak barriers requires labor for planting and maintenance and displaces a significant area of groves, this measure is not widely used in Florida. Windbreaks have been used in the perimeter of most grapefruit and some Hamlin sweet orange groves. Valencia orange blocks in Florida usually are not protected by windbreaks as this cultivar is less susceptible to citrus canker under field conditions.

Copper sprays are the main measure adopted by citrus growers in Florida. Applications of copper bactericides are necessary when the tree has young expanding leaves and fruit, and when climatic conditions are favorable to the pathogen in spring and summer. The number of applications depends on the cultivar, age of the grove, weather conditions, and association with other management techniques (Dewdney et al. 2019). The spray interval is an important factor in the management of citrus canker in citrus groves. Shorter intervals replace the protective layer more often and leave the tissues unprotected for less time. Because young groves have more frequent and uneven vegetative flush, the trees are more predisposed to the occurrence of citrus canker and, therefore, require shorter application intervals than mature groves (Behlau et al. 2010). In Florida, no more than five copper sprays at 21-day intervals are usually necessary from April to July for early processing oranges to protect susceptible fruit with up to 40 to 50 mm diameter (Graham et al. 1992; Lanza et al. 2019). Because grapefruit remains moderately susceptible until late September to mid-October, additional sprays are necessary (Dewdney et al. 2019). The rates of copper products per spray may vary from 0.5 to 1.0 kg metallic copper/ha depending on the application interval, the weather, and the age of the groves (Behlau et al. 2017; Graham et al. 2010).

The control of the citrus leafminer is another important component of citrus canker management in Florida. Despite not acting as a vector of *X. citri* (Belasque et al. 2005), the leafminer exacerbates both the incidence and severity of citrus canker (Hall et al. 2010). Wounds caused by the feeding of the larvae on young leaf and stem tissues are more easily infected by *X. citri* and remain prone to infection for longer periods than do mechanical wounds (Christiano et al. 2007). In Florida, leafminer control is recommended on the main summer flushes to reduce disease pressure. Sprays on the spring flush are usually not necessary (Dewdney et al. 2019).

Finally, the use of systemic acquired resistance (SAR) inducers is recommended to aid with the management of citrus canker where disease pressure is high. Resistance inducers have no direct effect on the pathogen. These products act by

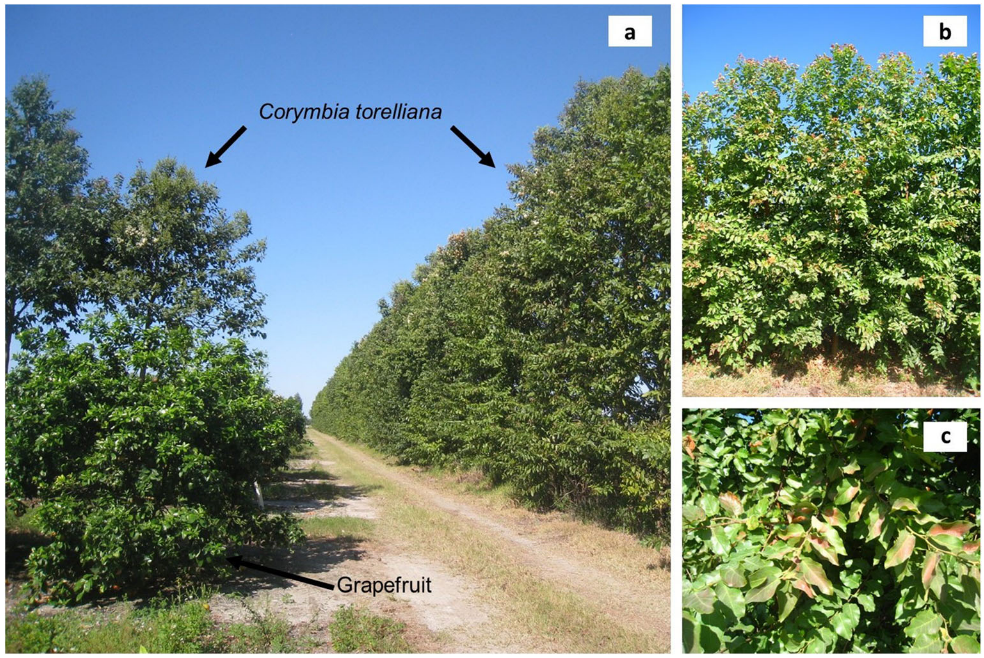

Fig. 3 *Corymbia torelliana* windbreaks in Florida. General view of windbreak barriers in a grapefruit grove (**a**), front view of a young windbreak (**b**), and (**c**) close up of the leaves

triggering natural defenses in the host before the onset of disease (Graham et al. 2016; Graham and Myers 2013). SAR is signaled by salicylic acid, which leads to the accumulation of pathogenesis-related (PR) proteins, possibly involved with host resistance (Zhang et al. 2010). Acibenzolar-S-methyl (ASM), a functional homologue of salicylic acid, is the most widely known commercially produced inducer of SAR (Tally et al. 1999). Drench applications of SAR inducers are recommended at the beginning of each season before weather becomes favorable for infection and the citrus trees start to flush. Applications should continue throughout the spring, summer, and fall at 60-day intervals in young non-bearing groves and at 45–60 day intervals in young bearing groves. In mature groves, applications in the fall are not necessary (Dewdney et al. 2019). Soil-applied neonicotinoid insecticides used in young groves up to three years for the control of the Asian citrus psyllid (*Diaphorina citri*), the vector of Huanglongbing (*Candidatus* Liberibacter asiaticus), are also able to induce SAR and aid with the control of citrus canker (Graham et al. 2016; Graham and Myers 2013).

Impact on the citrus industry

The main consequences of citrus canker are the defoliation of trees, the depreciation of production to the fresh market, and the premature fruit drop. Although apparently less impactful, defoliation due to the high severity of citrus canker can compromise the development of the citrus trees, especially in the first years after planting (Behlau et al. 2014; Ference et al. 2018; Gottwald et al. 2002). Leaf drop compromises the photosynthetic area of the plant and may affect the future crops. Citrus canker also affects the quality of production for the fresh fruit market. Fruit with lesions are non marketable. Moreover, citrus-producing areas where canker is present also face quarantine restrictions and eventual loss of access to important fresh fruit markets. The greatest impact of the disease, however, is related to fruit drop before harvest. When disease control measures are not implemented, crop losses may reach up to 80% in more severe cases, depending on the cultivar, age of the tree, and weather conditions (Behlau and Belasque 2014). Conversely, the integrated management of citrus canker, using the control measures described above, is capable of reducing fruit drop or even preventing any impact of the disease on production (Dewdney et al. 2019). Fruit drop due to canker can be observed from the early developmental stages until harvest (Lanza et al. 2019). Citrus canker is harmless to humans and other animals.

The impact of canker on fruit loss in Florida where it is endemic can be severe because of the favorable weather conditions and the high susceptibility of grapefruit and the early-season orange varieties to the disease. Moreover, there has been an increase in the costs with the regular copper sprays needed to minimize fruit drop and blemishes on fruit for the fresh fruit markets (Muraro 2012; Muraro et al. 2000; Singerman and Burani-Arouca 2017). The direct cost related to canker management in Florida is estimated at US$214.00/ha, which represents 3.84% of the total production costs (Singerman and Burani-Arouca 2017).

Citrus canker also has a significant impact on the regulations for the commercialization of fresh fruit from endemic areas. Over the years since the eradication ended in Florida in 2006 the rules became less strict as the knowledge about the potential risk of infection to healthy plants from discarded, cankered fruit evolved. Initially, the Animal and Plant Health Inspection Service (APHIS) of the US only allowed the movement of fruit from inspected, canker-free groves to non-citrus producing states. Later, in 2007, fruit were no longer required to be produced in groves where canker was absent. Instead, the fruit was supposed to be free of canker in the packinghouse as attested by an APHIS inspector. Upon demonstration that decontaminated packed fruit do not serve as an efficient vehicle for dissemination of the disease (Gottwald et al. 2009), since 2009, APHIS has not restricted the market of fruit with canker lesions in the country (e-CFR-2020. Title 7; Subtitle B; Chapter III; Part 301; Subpart M; Sect. 301.75-7). With this decision, the inspections were halted, and the shipment of any commercially packed and disinfected citrus are now permitted to all states and territories in the US (Tim Riley, Personal communication). The interstate movement of plants or buds remains prohibited with exceptions for certified materials used for propagation (Brannigan 2020).

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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