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Case Study

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Control of Pierce's Disease Through Areawide Management of Glassy-Winged Sharpshooter (Hemiptera: Cicadellidae) and Roguing of Infected Grapevines

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Abstract

The General Beale Pilot Project serves as a case study for the use of areawide monitoring and treatment programs for glassy-winged sharpshooter (GWSS), *Homalodisca vitripennis* (Germar), and monitoring and roguing programs for grapevines infected with *Xylella fastidiosa,* to achieve regional management of Pierce's disease. The Project is located in southeast Kern County, CA, and contains ~2,800 ha of citrus and grapevines grown within approximately 50 km^2. For nearly 20 yr, an average of 470 traps have been used to monitor GWSS populations regionally by the California Department of Food and Agriculture, and to inform coordinated, areawide treatments by the USDA-APHIS Areawide Treatment Program to overwintering GWSS in citrus. Grape growers were responsible for treating their own vineyards, and for the roguing of infected grapevines based on surveys provided by the University of California. Herein, we provide a history of the General Beale Pilot Project, broken down into six eras based on levels of Project success, which incorporate data on GWSS captures, pesticide use, and disease incidence. We describe patterns of success related to the regional coordination of effective treatment and roguing programs that can be used by grape and neighboring citrus growers for areawide management of Pierce's disease. We conclude by describing current and future challenges for Pierce's disease management, including pesticide availability and resistance, GWSS refuges, the inability to detect and rogue infected vines in the year they become infected, and the sustainability of voluntary programs that rely on public funding.

Key words: General Beale Pilot Project, IPM, areawide management, roguing, *Xylella*

The management of insect-vectored plant diseases often requires a combination of cultural, biological, and chemical controls. In cases where the vector is highly mobile and feeds on a wide range of host plants, successful management often requires intervention that is coordinated on a regional scale (Chandler and Faust 1998, Faust 2008). For nearly two decades the General Beale Pilot Project has served as a case study for the use of areawide management programs for the control of Pierce's disease in grapevines. This includes areawide, coordinated chemical control programs for glassy-winged sharpshooter, *Homalodisca vitripennis* (Germar), in combination with roguing programs for grapevines infected with the bacteria *Xylella fastidiosa* (*Xf*) (Sisterson and Stenger 2013). The Project also documents the value of public-private partnerships and willingness on the part of individual farmers to make sacrifices that benefit the entire farming community.

The Vector: Glassy-Winged Sharpshooter

Glassy-winged sharpshooters (GWSS) are polyphagous insects that feed on more than 100 species of agricultural and ornamental plants, as well as weeds (Hoddle et al. 2003). They are indigenous to the southeastern United States and northeastern Mexico (Triapitsyn and Phillips 2000), and were first detected in California in 1990 (Sorensen and Gill 1996). While feeding, GWSS are capable of acquiring and vectoring various strains of *Xf* (Blua et al. 1999, Hopkins and Purcell 2002).

In this case study, GWSS overwinter primarily as adults in citrus and typically have two generations per year (Castle et al. 2005, Park et al. 2006). Overwintering GWSS lay egg masses in citrus in spring that hatch and pass through five nymphal instars before reaching adulthood in summer. The adults then move out of citrus to feed on deciduous plants, including grapevines, where they can acquire

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and transmit *Xf*. Nymphs that hatch from egg masses laid during the summer develop into adults in the fall that migrate back into citrus. Adults that have acquired *Xf* do not pass the bacteria to their offspring (no transovarial transmission) and nymphs that acquire the bacteria lose it each time they molt (Almeida and Purcell 2003).

GWSS is an excellent vector of diseases caused by *Xf*. Compared with native sharpshooters, GWSS are larger, have greater dispersal capabilities, and spread disease farther into vineyards (Blackmer et al. 2004, 2006). Native species, such as the blue-green sharpshooter, *Graphocephala atropunctata* (Signoret) (Hemiptera: Cicadellidae), in the north coast region of California, primarily spread *Xf* to vines in close proximity to riparian areas where they overwinter (Varela et al. 2001). GWSS are much larger and more robust than blue-green sharpshooters, which makes them capable of feeding on more woody parts of the vine where the introduction of *Xf* is more likely to cause a persistent infection that is not removed in the winter during pruning (Varela et al. 2001).

GWSS are attacked by multiple species of egg parasitoids in the genus *Cosmocomoidea* (Hymenoptera: Mymaridae) (=*Gonatocerus*) (Triapitsyn and Phillips 2000, Triapitsyn and Bernal 2009). The most common species, *C. ashmeadi* (Giralt), is rarely found in California's Central Valley during the winter when GWSS are almost exclusively in the adult stage. However, it can be found at low levels inside GWSS eggs in citrus in the spring and becomes prevalent wherever GWSS egg masses are found during summer. This is especially true in locations with minimal to scarce use of pesticides, such as urban landscapes or organic citrus orchards, where conservation biological control is practiced (Varela et al. 2019, Grafton-Cardwell et al. 2020). These locations have also been the primary targets for augmentative release programs by the California Department of Food and Agriculture (CDFA) since 2001 (Pilkington et al. 2005). Due to limited budgets and a focus on establishing biological control in areas where chemical-based control programs are not practical, parasitoid releases into the General Beale Pilot Project were rare.

Pierce's Disease: *Xylella fastidiosa*

Xylella fastidiosa is a xylem-limited bacterial plant pathogen (Sicard et al. 2018) that causes a variety of diseases in agricultural and landscape plants (Rapicavoli et al. 2018, Hopkins and Purcell 2002). It is transmitted by insects that feed on xylem sap, including spittlebugs (Aphrophoridae) and several species of sharpshooters in the leafhopper family (Cicadellidae) (Hewitt et al. 1942, Frazier and Freitag 1946, Houston et al. 1947, Severin 1949). After inoculation, bacteria multiply in the parenchyma cells of the xylem vessels to form tyloses that plug the vessels. Once blocked, water flow throughout the plant is restricted and disease occurs (Fry and Milholland 1990).

In grapevines, infection by *Xf* causes Pierce's Disease (PD) (Hopkins and Purcell 2002). This disease is endemic to California and was first described in 1892 in southern California by plant pathologist Newton Pierce (Pinney 1989). In California's inland valleys, PD was relatively unknown and not of commercial concern during the 20th century. This changed after the introduction of GWSS, with the first widespread PD epidemic reported in the Temecula Valley in the late 1990s (Perring et al. 2001). In the early 2000s, there were fears that similar epidemics could occur in the >370,000 ha of grape production in California (NASS 2019).

There is currently no known cure for PD. Newly planted vines that become infected often die within a few months to a year, whereas newly infected mature vines may die within 1–2 yr, or become unproductive and live for many years (Varela et al. 2001). Time to death varies according to varietal susceptibility, with table grape cultivars such as Red Globe and Scarlet Royal known to be among the most susceptible (Burbank 2018). Symptoms of PD include scorched leaves, persistent petioles, interveinal greening on the canes, and shriveled fruit clusters (Varela et al. 2001).

In the San Joaquin Valley, *Xf* is typically acquired by GWSS and inoculated into grapevines during the summer months of July through September. Prior to those dates, the titer of *Xf* during periods of rapid shoot growth are relatively low, even in chronically infected vines (Sisterson et al. 2020). Additionally, until July most GWSS are located in citrus, which is not a host for the strain of *Xf* that causes PD (Chang et al. 1993). After September, inoculation of *Xf* into canes, especially if the inoculation occurs toward the cane tip, has a decreased risk of leading to a chronic development of PD (Sisterson et al. 2020). This is due to the likelihood that canes will be pruned prior to the movement of *Xf* into permanent tissues, or due to natural winter curing (Feil et al. 2003, Daugherty and Almeida 2018, Sisterson et al. 2020).

Methods and Approach: The General Beale Pilot Project

Location

The case study was located in the General Beale region of Kern County, CA (Fig. 1). This region is ~5 km from east to west and ~10 km from north to south (50 km^2). It is flanked by State Route 58 to the north,

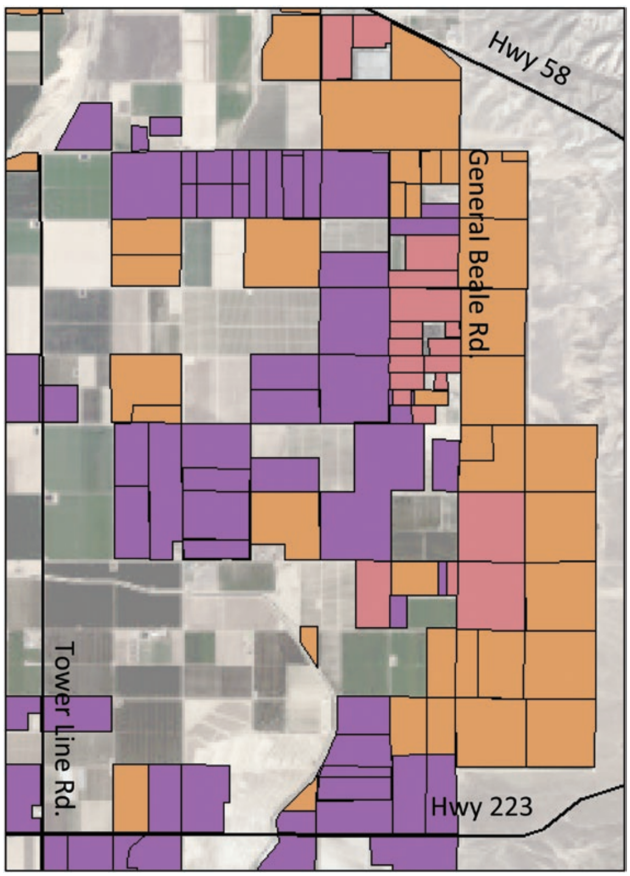

Fig. 1. The General Beale Pilot Project was located in a region approximately 5 km wide and 10-km long against the southeast foothills of Kern County, east of Tower Line Road and between State Routes 58 and 223. Primary crops in the Project include citrus (orange), grapes (purple), and cherries (pink). Source: Kern County Agricultural Commissioner, Permitted Crop Boundaries, 2001.

State Route 223 to the south, Tower Line Road to the west, and the Sierra Nevada foothills on the east. Queries for data on acreage and pesticide use within the project were done using the geographical boundaries of Township 30S Range 30E Sections 19–36 and Township 31S Range 30E Sections 1–30. Since the Project began in 2001, the region has contained ~1,600 ha of citrus and ~1,250 ha of grapevines (KCDA 1998–2018) that are grown at proximities to each other that are well within the dispersal range of GWSS (Blackmer et al. 2006). Imbedded within the citrus are ~30 km of primarily *Eucalyptus* sp. trees that are planted in strips to protect citrus trees and fruit from strong winds. These windbreaks can act as refuges for GWSS.

USDA-APHIS Areawide Treatment Program

This case study was started with the inception of the USDA-APHIS Areawide Treatment Program for GWSS in 2001 (USDA-APHIS 2002). During that time, there were significant outbreaks of GWSS within the region, biological control was at a minimum as foreign exploration for classical biological control agents were still in their infancy, and vineyards were becoming infected with PD. Grape growers in central California were fearful that they would see a repeat of the devastation that the invasion of GWSS and associated epidemics of PD had recently caused near Temecula, CA (Perring et al. 2001).

The primary goal of the USDA Areawide Treatment Program was to kill GWSS, while they were concentrated in citrus during the winter and spring before they could migrate to grapes in the summer. This was done by using annual public funds from the Federal Farm Bill to reimburse citrus growers for the cost of insecticide treatments chosen from an approved list of GWSS-effective products and applied at the Program's prescribed treatment timing. The need to treat, locations to be treated, and treatment timing were determined by a team of public and private task force members representing the USDA, CDFA, Kern County Agricultural Commissioner's office, The University of California (UC) Cooperative Extension, and agricultural industry. Local treatment coordinators were hired to communicate treatment needs to citrus growers and assist them with paperwork for reimbursements. Treatment coordinators also provided advice to grape growers who were making insecticide applications to vineyards at their own expense.

CDFA Pierce's Disease Control Program

The mission of the Pierce's Disease Control Program is to minimize the statewide impact of Pierce's disease and its vectors in California (CDFA 2018). As part of its efforts to suppress GWSS populations and prevent its spread, the Pierce's Disease Control Program provided a systematic deployment of GWSS traps within the General Beale Pilot Project. Staff of the CDFA GWSS Trapping Program installed yellow panel traps (Seabright Laboratories, Emeryville, CA) at a height of approximately two meters on bamboo poles at the outside corners of fields containing host crops. This produced an average of 470 ± 17 (SD) traps annually on a 400 m (quarter mile) grid that were georeferenced and serviced every one to two weeks since March 2001. GWSS captures were plotted onto regional heat maps that were posted online by the CDFA Pierce's Disease Control Program (CDFA PDCP 2001–2019) to show weekly and cumulative GWSS captures (Fig. 2). Maps were used for a variety of purposes, including decisions about regional insecticide use and to identify vineyards at greatest risk of Pierce's disease.

Pierce's Disease Surveys

From 2001 to 2019 (except 2016) approximately 50–60 vineyards were inspected annually for vines symptomatic of PD by staff from UC Cooperative Extension, Kern Co. Initial inspections were done

Fig. 2. The California Department of Food and Agriculture Pierce's Disease Control Program monitored for glassy-winged sharpshooters by deploying a grid of over 450 traps monitored every one to two weeks since 2001. Captures were georeferenced and converted into heat maps that were posted online to assist growers and public agencies with management decisions. The representative map shown is from 4 to 10 March 2001. Comparison to Fig. 1 reveals a typical springtime pattern of primarily dark blue (zero) captures per week in vineyards and green (>10) to orange (>100) captures per week in citrus.

by looking for PD symptoms in peripheral vines that could be seen when looking into the vineyard from the edges during August and September. This is the period when visual symptoms are at their peak but is prior to when leaves begin to senesce (Fig. 3).

Vineyards with at least one symptomatic vine on the periphery were targeted for systematic PD surveys. Also surveyed were vineyards that had high GWSS capture rates on heat maps generated by the CDFA GWSS Trapping Program (Fig. 2, CDFA PDCP 2001–2019), were located next to citrus, had a history of PD, or were planted with highly susceptible grape varieties like Red Globe or Scarlet Royal. Each vine in all or part (minimum 2.5 ha) of each vineyard was surveyed by inspectors looking for visual symptoms of PD while riding slowly on all-terrain vehicles. Vines that appeared symptomatic were marked and petiole samples were sent to the CDFA Plant Health and Pest Prevention Services Plant Pest Diagnostic Lab for confirmation of *Xf* by ELISA (2007–2018) or qPCR (2019). Following laboratory confirmation, the number of diseased vines per vineyard was tallied, either through direct counts (if the entire vineyard was surveyed) or through extrapolation (if only a portion was surveyed).

From 2001 through 2008, 36.8 ha (~47,000 vines) were surveyed annually, with an additional 450,000 vines (343.6 ha) surveyed annually in 2002 and 2003 as part of a supplemental survey program on 41 vineyards. From 2009 to 2019, surveys were conducted in an average of 23 vineyards with an average of 183 ha of vines. Surveys were primarily funded by local table grape growers through the Consolidated Central Valley Table Grape Pest and Disease Control District. This organization was created by growers to generate industry funds that could be used to control, eradicate, remove, or prevent the spread of the glassy-winged sharpshooter or PD (FAC 2005).

Roguing and Inoculum-Reduction Programs

Each winter, grape growers were expected to remove all vines that were confirmed to be positive for *Xf* during fall surveys. This

Fig. 3. Pierce's disease surveys were conducted by the University of California every August and September when visual symptoms were at their peak, including scorched leaves and persistent petioles. Vines positive for Pierce's disease were marked and removed during the fall or winter.

included infected vines in portions of each vineyard that were surveyed by UC, as well as in the remainder of each vineyard where surveys were done internally by vineyard employees. Removal was defined as the complete unearthing of the vine, including the trunk and roots, to ensure that infected regrowth did not occur (Fig. 3, Daugherty et al. 2018). Growers were also encouraged to have good weed management programs to ensure that weeds did not serve as an additional source of *Xf* inoculum (Wistrom and Purcell 2005). For vineyards with high rates of infection, growers were encouraged to remove the entire vineyard, and typically did so due to a decline in productivity. In the rare event that infection rates exceeded 20% without voluntary mitigation, legal action was threatened by the County Agricultural Commissioner, working in conjunction with the Consolidated Central Valley Table Grape Pest and Disease Control District, to use the Commissioner's abatement authority to make mitigation mandatory.

Project Activities and Outcomes

2001: Areawide Management Begins

Yellow panel traps were installed by the CDFA GWSS Trapping Program by late February 2001 and caught a total of 16,927 GWSS by the end of the year (Fig. 4a). Over a period of two weeks from late February to early March, approximately one-half of all citrus was treated with a foliar knock-down insecticide, after which nearly all citrus was treated systemically (applied to the soil through the irrigation system) with imidacloprid after petal fall as part of the USDA Areawide Treatment Program (Supp Table 1 [online only]). These treatments were in addition to insecticides for other pests that may have impacted GWSS (Supp Table 2 [online only]). Grape growers treated their vineyards with approximately one neonicotinoid and one organophosphate or carbamate (Supp Table 2 [online only]). These treatments provided excellent GWSS control regionally.

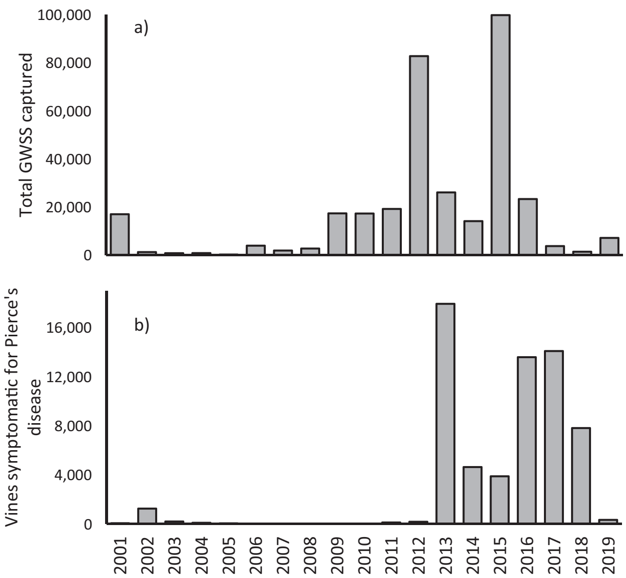

Fig. 4. Long-term trends in a) the total number of glassy-winged sharpshooters captured annually on yellow panel traps in the General Beale Pilot Project, and b) the number of vines infected by *Xylella fastidiosa*. Source: Glassy-winged sharpshooter Trapping Program using 470 ± 17 (SD) traps annually, Pierce's Disease Control Program, California Department of Food and Agriculture, 2001–2019, and University of California Pierce's Disease Surveys.

Surveys for PD in two vineyards found 48 infected vines (1.8 positives per 1,000 vines; Fig. 4b).

2002–2005: Excellent GWSS Control, PD Removal Ongoing

From 2002 until 2005 the USDA-APHIS Areawide Treatment Program recommended spot treatments as needed in the General Beale Pilot Project while the bulk of the program budget was dedicated to reducing GWSS in other regions of Kern and Tulare Counties. Treatments of foliar insecticides were applied to approximately 20% of citrus acreage in March 2002 and 50% of the citrus acreage in August 2003 (Supp Table 1 [online only]). In 2004 and 2005, the program switched to the use of systemic applications of imidacloprid and made applications to approximately 50% of all citrus in early fall 2004, and 25% of all citrus in June 2005 (Supp Table 1 [online only]). Due to a recognition that windbreaks were serving as refuges for GWSS in prior treatments, aerial applications of acetamiprid were made to 5.5 and 13.7 km of windbreaks during August in 2003 and 2004, respectively (Supp Table 3 [online only]). Windbreaks were not treated in 2005. On average from 2002 to 2005, grapes were treated one to two times annually with GWSS-effective products (Supp Table 2 [online only]).

Aggressive treatment programs in 2001 followed by 4 yr of spot treatments led to a significant reduction in GWSS and PD (Fig. 4). From 2002 until 2005, a total of 2,840 GWSS were captured (Fig. 4a). This was an average of 710/yr, or 1.5/trap/yr. Pierce's disease surveys from three vineyards (36 ha) over a 4-yr period found 650, 78, 82, and 38 infected vines, respectively, from 2002 to 2005 (Fig. 4b). The intense survey of 41 vineyards in 2002 found 1,124 infected vines in one 46-ha vineyard, with another 14 vines in the remaining 298 ha (Hashim and Hill 2003). In 2003, surveys across these same locations found 188 infected vines (1 per 2,500), of which 182 were in the same vineyard with high infection rates during the previous year.

2006–2008: Return of GWSS, PD Almost Absent

From 2006 to 2008, there was an increase in annual GWSS captures ranging from 1,827 to 3,852 per year compared to an average of 710/yr during the previous 4 yr (Fig. 4a). In response to these captures, the USDA-APHIS Areawide Treatment Program returned to the use of coordinated areawide treatments to citrus annually (Supp Table 1 [online only]). Systemic applications of imidacloprid were made to approximately one half of all citrus prior to bloom or after petal-fall in 2006, with the same treatment applied to all citrus in the spring of 2007. In 2008, all citrus was treated with a foliar application of acetamiprid. Throughout this period aggressive approaches were taken to control GWSS in windbreaks, including aerial applications of acetamiprid during spring–summer 2006, January 2007, August 2007, March 2008, August 2008, and November 2008 (Supp Table 3 [online only]). From 2006 to 2008 grape growers averaged approximately three applications of GWSS-effective products annually (Supp Table 2 [online only]).

During 2007 and 2008, surveys in the same 36 ha previously sampled in 2004 to 2005 found a total of two and three infected vines, respectively, for annual average infection rates of <1 per 10,000 vines (Fig. 4b).

2009–2011: Reduced GWSS Control, PD Reappears

From 2009 to 2011, there was a resurgence of GWSS throughout the region (Fig. 4a). Annual captures ranged from 17,217 to 19,121 per year: an approximate 32-fold increase compared with the average of the previous 3 yr (Fig. 4b.) This occurred despite efforts to increase the number of insecticide applications and decrease application intervals (Supp Table 1 [online only]). In 2009, all citrus was treated systemically during a 2-wk period from 27 June to 9 July. Due to reduced efficacy compared to previous years, the program began using two insecticide applications per year. This included a foliar insecticide in the early spring followed by systemic application of imidacloprid around May during 2010 and 2011. Windbreaks were treated by air in approximately July 2009, March 2010, August 2010, February 2011, and June 2011 (Supp Table 3 [online only]), and grapes were treated an average of more than twice annually (Supp Table 2 [online only]).

Surveys from 2009 through 2011 found totals of 0, 9, and 108 infected vines, respectively (Fig. 4b). Though still relatively low (<8 per 10,000), there were concerns that the number of infected vines increased annually during these 3 yr to a level in 2011 that was 36-fold higher than in 2008 despite two straight years of multiple insecticide applications to citrus and windbreaks.

2012–2015: Vector Outbreaks Lead to PD Epidemic

Efforts to control GWSS from 2012 to 2015 were not successful as annual GWSS captures averaged 55,610 per year with peaks of >80,000 in 2012 and 2015 (Fig. 4a). This was despite foliar and systemic insecticide applications to all citrus in the spring of each year (Supp Table 1 [online only]), one to two treatments to windbreaks annually (Supp Table 3 [online only]), and approximately two annual applications of GWSS-effective treatments to grapes (Supp Table 2 [online only]).

As efforts to control GWSS failed, an epidemic of PD ensued. Increases of 19,121 to 82,672 GWSS per year from 2011 to 2012 (Fig. 4a) led to increases in PD from 165 to 17,924 vines from 2012 to 2013, respectively (Fig. 4b). The increases in PD were due to the combined effects of an increase in the number of vineyards with PD presence as well as an increase in the percentage of vines infected per vineyard (Fig. 5). Despite the efforts of most table grape growers to identify and remove infected vines annually, in some cases by the removal of complete vineyards, the number of infected vines remained between 3,872 and 13,576 from 2014 through 2016 (Fig. 4b).

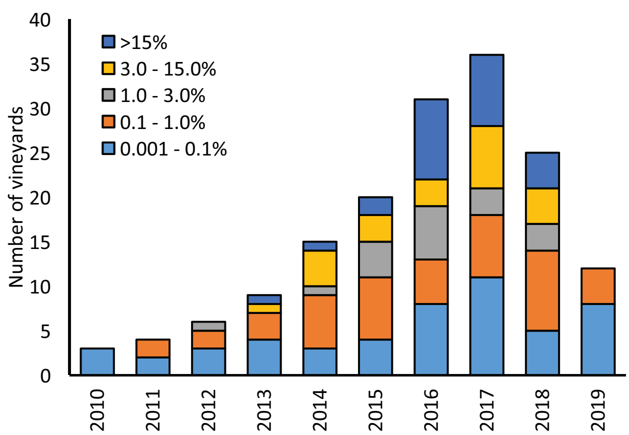

Fig. 5. Number of vineyards with at least one vine infected by *Xylella fastidiosa* in University of California surveys in the General Beale Pilot Project, categorized by five levels of disease incidence (% vines infected). Data are based on systematic surveys conducted in all vineyards for which at least one symptomatic vine was found during initial screenings of >50 vineyards annually.

2016–2019: Aggressive GWSS Control, PD Epidemic Reversed

Aggressive approaches to GWSS control and PD removal reversed trends of a disease epidemic from 2016 through 2019 (Fig. 4). Facilitating this effort was evidence suggesting that insecticides classified as neonicotinoids (IRAC 2020) were no longer highly effective against GWSS in the region (Redak et al. 2017, Andreason et al. 2018), and a determination that pyrethroid insecticides were more effective when weather was cool.

For these reasons, and new observations during late 2014 that GWSS were mating and laying eggs during the winter, the USDA Areawide Treatment Program switched to annual winter applications of pyrethroids or butenolides beginning in 2015, and made its last treatments of foliar and systemic neonicotinoids during 2016 (Supp Table 1 [online only]). Between 2016 and 2019, there were also increased pressures on citrus growers to apply pyrethroids, neonicotinoids, organophosphates, or carbamates at their own expense to satisfy export requirements related to Fuller rose beetle, *Naupactus godmanni* (Crotch) (Coleoptera: Circulionidae) for fruit destined for Korea, and to help prevent the establishment of Asian citrus psyllid (CDFA 2014), *Diaphorina citri* (Kuwayama) (Hemiptera: Psyllidae). As a result, subsidized treatments from the USDA Areawide Treatment Program decreased to <1,000 ha annually from 2017 to 2019 (Supp Table 1 [online only]), but overall acreage treated with GWSS-effective materials ranged from 3,362 to 5,595 ha annually (Supp Table 2 (online only)). This assisted in overall suppression of GWSS such that the USDA Areawide Treatment Program was able to reduce the percentage of orchards receiving government-subsidized treatments annually, avoid the need for windbreak treatments from 2017 through 2019 (Supp Tables 1 and 3), and divert those budgets to regions of Kern County that were experiencing outbreaks of GWSS outside of the General Beale Pilot Project. Throughout this time period, grape growers maintained an average of greater than two GWSS-effective materials applied annually (Supp Table 2 [online only]).

As a combined result of these efforts, the peak annual GWSS capture rate of 99,721 in 2015 was reduced by 77% to 23,236 in 2016, and by 96% to an average of 4,027 from 2017 to 2019 (Fig. 4a). Associated with reductions in GWSS captures were aggressive roguing efforts, including the removal of 235 ha of vineyards following surveys in the fall of 2018, in addition to spot-removal of infected vines elsewhere. Infected vines peaked at 13,576 in 2016, 1 yr after peak GWSS captures in 2015. Subsequently, the number of infected vines reduced annually from 14,076 in 2017, to 7,801 in 2018, and to 319 in 2019 (Fig. 4b). There were also reductions in the number of vineyards with more than 1% infection from a peak of 18 in 2016 and 2017 to zero in 2019 (Fig. 5).

Major Findings

The General Beale Pilot Project showed that areawide treatment programs for GWSS, in combination with survey and roguing programs for vines infected with *Xf*, have the potential to be a highly successful integrated approach for PD management. Two keys to success at the beginning (2001–2005) and end (2017–2019) of the case study were excellent vector and disease control over a period of two consecutive seasons. This time frame was required due to the disease latency period whereby mature vines infected with *Xf* commonly did not show symptoms until the following season (Fig. 6). As a result, vines that became infected during any given year went unnoticed during an initial fall survey. By the time infected vines became symptomatic and marked for removal the next fall, they had

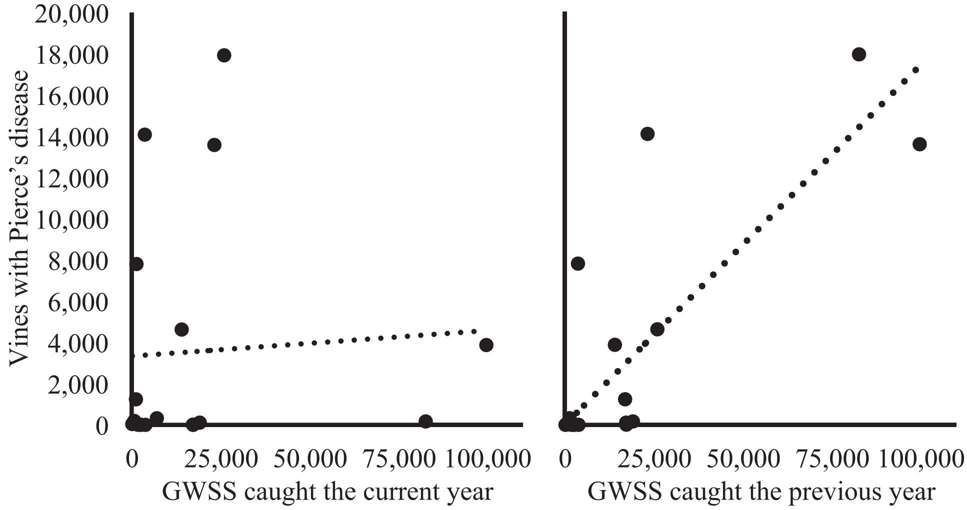

Fig. 6. The relationship between annual GWSS captures and the appearance of PD symptoms a) during fall surveys during the same year and b) during fall surveys the following year. Each dot represents one year. These charts display that GWSS captures are a) not indicative of PD that will be found during the same season (NS; $R^2 = 0.002$), but are b) strongly correlated to symptomatic vines the following fall ($y = 0.169X$; $P < 0.0001$; $R^2 = 0.60$). The inability to detect and remove vines with *Xf* in the year they are inoculated is a primary challenge for PD management programs.

already served as inoculum sources for a new round of vine-to-vine spread to newly infected, but asymptomatic vines. Growers with a desire to break the disease cycle should be particularly diligent with PD survey and vine roguing programs 1 yr following years with elevated GWSS captures.

Despite the successful management of PD at the start and end of this case study, the interim years from 2012 to 2018 documented the impact of PD when vector and disease management programs functioned at levels below their potential. This includes a rapid increase in vector populations associated with a slow onset of disease epidemic due to the time it takes for inoculum to build up, and also the slow decline in disease after vectors have been controlled due to the time it takes for inoculum to dissipate (Fig. 4).

For heavily infected vineyards the best way to break the disease cycle was through vineyard removal. Though rather draconian, removing the entire vineyard ensures complete and immediate disease removal, and allows for a new, uniformly planted vineyard to replace it. Replanting a vineyard may also have secondary benefits, such as to replace an outdated variety with a new one that fits a particular niche in the fresh market. Since 2011, 16 entire vineyards were removed due to PD within the General Beale Pilot Project, including all but one vineyard that was planted to the more susceptible cultivars Red Globe and Scarlet Royal. Between 2001 and 2019, a total of 802 ha of vineyards were removed from the General Beale Pilot Project at least once due to PD (56% of the 1,435 ha in 2001), of which ~340 ha were permanently replanted to other commodities (KCDA 1998–2018). Based on an average value of $50,000/ha (KCDA 2019), this is an approximately $17 million reduction in the value of table grape production in the project due to PD. If GWSS were left unchecked, and similar losses of 25% occurred to the 25,373 ha of table grapes county-wide (KCDA 2019), losses in table grape production would be approximately $320 million annually.

Until a cure for PD can be achieved, grape growers in regions with a history of PD and presence of GWSS as a vector are encouraged to follow the successful formula implemented in the General Beale Pilot Project:

- *August to September*—Survey for and remove grapevines that are symptomatic for PD. If vines cannot be removed immediately, mark symptomatic vines for removal during the winter. Assume the presence of asymptomatic, yet PD-positive, vines that escape detection and survive to the next season.
- *November to February*—Control adult GWSS in their overwintering habitat. Take action to ensure that no refuges exist, such as windbreaks. Coordinate treatments regionally to a short application window, ideally less than 10–14 d.
- *March to June*—Monitor the overwintering host for egg masses and nymphs from GWSS that may have survived winter treatment. If needed, retreat the overwintering host to control the first in-season generation of GWSS before they become adults that migrate to grapes in summer months.
- *April to July*—Treat grape vineyards with a systemic insecticide to ensure that immigrating GWSS that acquire the *Xf* bacteria from any chronically infected vine (infected but still asymptomatic during surveys the previous fall) are unable to move to and infect new vines.
- Repeat this process annually to account for inefficiencies in efforts to control GWSS and rogue infected vines.

Current and Future Challenges

Reliance on Insecticides

During the past two decades, the General Beale Pilot Project has faced challenges and obstacles that will continue to persist in the future. The greatest of these is the long-term sustainability of an areawide management program based primarily on the use of insecticides. Each year there are added restrictions on the use of insecticides that are effective on GWSS. Currently, the greatest threats come from proposed restrictions on the use of neonicotinoids by the California Department of Pesticide Regulation. If approved, these restrictions would limit the use of neonicotinoids to one application of one active ingredient in this chemical class per year to individual orchards or vineyards. This would likely make this chemical class unavailable for GWSS control as growers prioritize its use for other pests, such as vine mealybug or Fuller's rose beetle, at spray timings that are not ideal for control of GWSS. Additional challenges include the cancelation of the use of broad-spectrum insecticides, such as chlorpyrifos, at a time that new registrations of insecticides that are effective against GWSS are rare.

Resistance and Pesticide Rate Increases

Overreliance on one or a few pesticide chemistries has the potential to lead to pesticide resistance, as occurred within the General Beale Pilot Project. In hindsight, we know that a major factor in the lack of GWSS control from 2009 until 2016 was the development of resistance to imidacloprid (Andreason et al. 2018, Redak et al. 2017) with cross resistance to acetamiprid (Redak et al. 2017). Since 2001 we estimate that the average citrus grove in the General Beale Pilot Project was treated with neonicotinoids ~15 times during a 12-yr period from 2004 to 2016 as part of the USDA-APHIS Areawide Treatment Program (Supp Table 1 [online only]), with ~16 applications to windbreaks during the same time period (Supp Table 2 [online only]). This is in addition to applications of neonicotinoids applied by citrus growers for other pests, such as Fuller rose beetle and Asian citrus psyllid (Supp Table 4 [online only]).

Grape growers within the General Beale Pilot Project also applied imidacloprid to the majority of table grape acreage annually for control of GWSS and vine mealybug (*Planococcus ficus* Signoret, Hemiptera: Pseudococcidae), with supplemental applications of acetamiprid, thiamethoxam, clothianidin, or dinotefuran for additional vine mealybug control (Supp Tables 2 and 4). There have also been increases in per-hectare use rates, especially for imidacloprid (Supp Table 5 [online only]). During the early 2000s, growers typically applied imidacloprid at low rates to the foliage for leafhoppers and GWSS (<0.2 kg a.i./ha). As time progressed, simultaneous increases in GWSS and vine mealybug, coupled with decreased product costs as generics entered the market, resulted in increased application rates averaging 0.35 kg a.i./ha from 2011 until 2017. When considering that some growers treat individual vineyards more than once (two injections of half rates instead of one injection of a full rate), it is likely that most treated vineyards received close to the maximum allowable amount of imidacloprid per season (0.56 kg a.i./ha, Bayer 2013). Opportunities to increase rates as a way to improve efficacy have been exhausted.

Continued Grower Cooperation in Voluntary Programs

Management of areawide programs that are voluntary have unique challenges, especially when growers of one commodity are being asked to make chemical treatments to their orchards for the benefit of their neighbors. Within the Project, success required constant communication to growers regarding treatment options, the coordination of treatment timing, and of the benefits of treatments. These were accomplished through numerous extension meetings sponsored by the USDA, CDFA, and UC, and included input from growers about their concerns and recommendations regarding the best approaches for implementation. This allowed for buy-in from industry that was required to make a voluntary program successful.

In the case of grape growers, compliance with recommendations was naturally high due to the risks of direct losses associated with PD, and because most insecticides that are effective against GWSS also help control mealybugs and leafhoppers. However, insecticide treatments in citrus were more difficult to justify voluntarily because direct feeding by GWSS at densities being found were not known to cause economic losses to navel oranges (Grafton-Cardwell et al. 2020), and strains of *Xf* that cause citrus variegated chlorosis (Chang et al. 1993) are not present in California. For that reason, voluntary treatments were incentivized through direct reimbursement by the USDA Areawide Treatment Program for products chosen by the grower from a list of effective options. Future success will require continued inclusion of growers in the decision-making process regarding voluntary treatment programs, and continued education and extension efforts on the value of areawide coordination of treatments.

Refuges

Refuges that allow GWSS to escape insecticide treatments have been a constant concern for the duration of the General Beale Pilot Project. In the case of windbreaks, treating with insecticides will continue to be problematic due to the need to use products labeled for ornamentals instead of agricultural crops, tree height, and because ~11 km of windbreaks (41%) in the Project cannot be treated by air due to their proximity to major highways or to avoid drift onto agricultural crops registered for organic production. Over the past two decades, these issues were addressed, in part, by making applications by helicopter, or by reducing the height of trees in the windbreaks to facilitate treatment by ground. Also serving as refuges were a small but increasing percentage of the total citrus and grape acreages that were being produced organically. To date, all insecticides that are approved for use on organically produced crops have lacked sufficient residual to provide effective control without a prohibitive number of applications. Addressing this issue in the future will require new and more effective insecticides for organic use, or more effective use of biological control.

Weather

Changes in weather patterns may continue to provide challenges regarding GWSS management. During the winter, ambient temperatures during extended periods of dense fog typically remain below the minimum required for GWSS feeding (10°C, Son et al. 2009), leading to overwintering mortality through desiccation. However, during the past decade, improved air quality has led to a significant reduction in the number of winter days with dense fog (Gray et al. 2019, NWS 2020). This has made it easier for GWSS to survive the winter, and during the past few years, there have been observations of oviposition and presence of nymphs in the late winter and early spring at earlier dates than the previous decade. This has led to concerns that additional climatic changes could lead to a third GWSS generation each year that complicates management programs.

Public Funding

For nearly two decades, the General Beale Pilot Project has relied on the use of public funds to subsidize the costs of the USDA Areawide Treatment Program and to maintain regional GWSS monitoring and biological control programs through CDFA. To date, the use of these funds has been invaluable in efforts to keep GWSS at bay and to curb PD epidemics. Continued efforts to educate legislators regarding the value of public funding in efforts to battle GWSS and PD will be critical to future success.

Supplementary Data

Supplementary data are available at *Journal of Integrated Pest Management* online.

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