Distribution and Management of Citrus in California: Implications for Management of Glassy-Winged Sharpshooter

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ABSTRACT The epidemiology of Pierce's disease of grape (*Vitis* spp.) in California has changed over the past 10 yr due to the introduction of an exotic vector, *Homalodisca vitripennis* (Germar), the glassy-winged sharpshooter. Although this insect is highly polyphagous, citrus (*Citrus* spp.) is considered a preferred host and proximity to citrus has been implicated as a significant risk factor in recent epidemics of Pierce's disease in southern California. Consequently, a detailed knowledge of the distribution and management of citrus in relation to grape is needed to improve insect and disease management. Analysis of data on the area planted to these two commodities indicates that only five counties in California concomitantly grow >1,000 ha of grape and >1,000 ha of citrus: Riverside, Kern, Tulare, Fresno, and Madera counties. Comparison of the distribution of grape and citrus within each of these counties indicates that the percentage of grape that is in proximity to citrus is greatest for Riverside County, but the total area of grape that is in proximity to citrus is greater for Fresno, Kern, and Tulare counties. The use of carbamates, neonicotinoids, organophosphates, and pyrethroids as part of the citrus pest management program for control of key insect pests was compared among the same five counties plus Ventura County from 1995 to 2006. Ventura County was included in this analysis as this county grows >10,000 ha of citrus and has established glassy-winged sharpshooter populations. The use of these broad-spectrum insecticides was lowest in Riverside and Ventura counties compared with the other four counties. Analysis of historical trapping data at the county scale indicates a negative association of broad-spectrum insecticide use with glassy-winged sharpshooter abundance. These results are used to retrospectively analyze the Pierce's disease outbreaks in Kern and Riverside counties.

KEY WORDS *Homalodisca vitripennis*, Pierce's disease, *Xylella fastidiosa*, epidemiology

Pierce's disease has been a chronic problem in California's grape (*Vitis* spp.) growing regions for over a century (Hewitt 1958). This disease is caused by the bacterium *Xylella fastidiosa,* various strains of which cause several other economically important crop diseases, including oleander leaf scorch and almond leaf scorch (Hopkins and Purcell 2002). Pierce's disease is incurable and susceptible varieties of grape often die within a few years of infection (Goodwin and Purcell 1992). The pathogen is vectored by xylem-feeding insects, including sharpshooters and spittlebugs (Redak et al. 2004). In California, there are several native insects capable of vectoring *X. fastidiosa,* and key vector species vary by region (Hopkins and Purcell 2002). However, the epidemiology of Pierce's disease in California has changed over the past 10 yr due to the arrival of an exotic vector, the glassy-winged sharpshooter, *Homalodisca vitripennis* (Germar) (Blua et al. 1999, Purcell and Saunders 1999).

Before the arrival of *H. vitripennis* to California, incidence of Pierce's disease was typically limited to the margins of vineyards that bordered habitats known to support insect vectors. For example, in vineyards along the north coastal regions of California, disease incidence was highest on vineyard edges that bordered riparian areas, a known habitat of the blue-green sharpshooter, *Graphocephala atropunctata* (Signoret) (Purcell 1975). Likewise, in vineyards in the San Joaquin Valley of California, diseased vines were often associated with vineyard edges that bordered permanent irrigated pastures, known habitats for the sharpshooters *Draeculacephala Minerva* Ball and *Xyphon fulgida* Nottingham (Purcell and Frazier 1985). In both cases, new infections were thought to occur due to incidental movement of inoculative vectors

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into vineyards from surrounding habitats with limited vine-to-vine spread of the pathogen.

Spread of *X. fastidiosa* by *H. vitripennis* differs from that of native sharpshooters. Recent epidemics of Pierce's disease due to large infestations of *H. vitripennis* have occurred at two locations in California: the Temecula Valley in Riverside County and the General Beale Area in Kern County (10 km northeast of Arvin, CA). Surveys of eight vineyards in the Temecula Valley during 2000 found that 51–80% of vines within a vineyard possessed characteristic symptoms of Pierce's disease (Perring et al. 2001). It has been estimated that 30% of vineyards were lost in the Temecula Valley during this epidemic (Toscano et al. 2004). Likewise, a survey of 11 vineyards in the General Beale Area in 2002 resulted in a wide range of incidence (1–71%) among the affected vineyards (Tubajika et al. 2004). In Kern County, incidence of Pierce's disease remained low in grape production areas outside of the General Beale Area (Hashim and Hill 2003). In both cases, disease incidence was not limited to field margins and vine-to-vine spread of the pathogen was thought to have occurred as a result of infestation by large populations of *H. vitripennis* (Perring et al. 2001, Tubajika et al. 2004).

H. vitripennis is highly polyphagous and has been collected from at least 37 plant families in its native range in the southeastern United States (Hoddle et al. 2003). In California, its range is currently limited to southern California (San Diego, Riverside, Orange, Los Angeles, San Bernardino, and Ventura counties), southern portions of the San Joaquin Valley (Tulare and Kern counties), and isolated urban infestations in the cities of Sacramento, Fresno, San Jose/Santa Clara, and Vacaville (CDFA 2007a). Outside of infested urban areas, *H. vitripennis* has exploited citrus (*Citrus* spp.) as a preferred host, especially during the winter (Blua et al. 2001). Consequently, vineyards that are near citrus are likely to have larger populations of *H. vitripennis* than vineyards that are distant from citrus (Park et al. 2006a, b). Indeed, proximity of vineyards to citrus was implicated as an explanatory factor for the Pierce's disease epidemic in the Temecula Valley (Perring et al. 2001). In 2000, an areawide program was initiated to reduce populations of *H. vitripennis* by treating citrus with a combination of a knockdown insecticide application followed by a systemic insecticide (Hix et al. 2003, Toscano et al. 2004, Stone-Smith et al. 2005). The apparent success of this program further emphasizes the importance of citrus as an integral host in the seasonal population dynamics of *H. vitripennis* in California.

Citrus management practices vary across California. Historically, citrus management in southern California required little use of broad-spectrum insecticides due to a pest management program that relied heavily on biological control (Morse et al. 2007). In contrast, citrus management in the San Joaquin Valley of California has been reliant on the use of broad spectrum insecticides due to poor performance of natural enemies for some key pests (Grafton-Cardwell 2000, Grafton-Cardwell and O'Connell 2006, Morse et al. 2007). In fact, use of broad-spectrum insecticides such as organophosphates and carbamates peaked in the San Joaquin Valley during the 1990s primarily due to resistance problems with California red scale, *Aonidiella aurantii* (Maskell), and citrus thrips, *Scirtothrips citri* (Moulton) (Grafton-Cardwell and Vehrs 1995, Khan and Morse 1998, Grafton-Cardwell 2000). Regional differences in the use of broad-spectrum insecticides in citrus is likely to have had important effects on glassy-winged sharpshooter population growth in citrus, which in turn is likely to have influenced the regional population dynamics of *H. vitripennis* in California.

Because citrus is an important host of glassy-winged sharpshooter, an understanding of regional differences in citrus distribution and management will aid in assessing the risk of future outbreaks of Pierce's disease in different portions of California. Thus, a primary goal of this article is to provide researchers easily accessible information on regional differences in the distribution and management of citrus in California, with emphasis on counties that concurrently grow grapes. A secondary goal, is to evaluate previous outbreaks of Pierce's disease in Riverside and Kern counties in light of this information to determine whether there were unique features of the distribution and management of citrus in those areas that may have contributed to Pierce's disease epidemics. Such a retrospective analysis will aid in assessing the likelihood of a repeat of the events in Riverside and Kern counties.

Materials and Methods

Grape and Citrus Distribution among Counties. The area planted with grape and citrus was compared for all counties in California by using estimates from the National Agriculture Statistics Service for 1998–2005 (NASS 2008a,b). The mean area planted with grape and citrus for each county over these years was determined and mapped at the county scale. To determine which counties planted appreciable areas of both commodities, we plotted the hectares planted with grape against the hectares planted with citrus for each county.

Grape and Citrus Distribution within Selected Counties. The distribution of grape and citrus was compared for the five counties with the highest abundance of citrus and grape (Fresno, Kern, Madera, Riverside, and Tulare). To accomplish this, we used geographic information systems (GIS) maps generated using data from the State of California Pesticide Use Reports from 2003 (CDPR 2003). These reports indicate the crop treated, pounds of active ingredient applied, and the location of the treated field as identified by 1.6-km^2 sections based on the Public Land Survey System (CDFA 2007b). GIS maps were then generated based on the commodities reported to be grown in each section. Importantly, more than one crop may be planted within a section.

Two aspects of the distribution of grape and citrus within each county were evaluated: the percentage of grape that was in proximity to citrus and the area of grape that was in proximity to citrus. Each of these measures was evaluated at two spatial scales. The first spatial scale was at the section level. Thus, the percentage and number of sections with grape plantings that also had citrus plantings were determined. The second spatial scale was greater than the section level analysis. For this analysis, the percentage and number of sections with grape plantings that were within 1.6 km of a section with a citrus planting was determined.

Insecticide Use by County. Insecticide use in citrus from 1995 to 2006 was compared using reports submitted to the California Department of Pesticide Regulation for the five counties with the greatest abundance of grape and citrus (Fresno, Kern, Madera, Riverside, and Tulare; CDPR 1995–2006). In addition, we examined insecticide use in Ventura County because this county has significant citrus production (≈14,000 ha) and established glassy-winged sharpshooter populations (CDFA 2007a). We focused on the following classes of broad-spectrum insecticides: pyrethroids, carbamates, organophosphates, and neonicotinoids. These insecticide classes were chosen because each is known to kill *H. vitripennis* (Grafton-Cardwell et al. 2003b; Prabhaker et al. 2006a,b). The kilograms of active ingredient applied per hectare of citrus was determined by summing the kilograms of active ingredient applied for each insecticide class in each county and then dividing by the hectares planted to citrus in that county during that year. As in previous analyses, the area planted to citrus in each county was estimated from data obtained from the National Agriculture Statistics Service (NASS 2008b). Estimates of the area planted to citrus were available for all years except 2006. Because there was little change between years in the area planted to citrus from 1995 to 2005, we assumed the area planted to citrus in 2006 was the same as in 2005.

Effects of Spray Regime on Abundance. The association of regional spray regime on glassy-winged sharpshooter abundance was assessed for Kern, Riverside, Tulare, and Ventura counties. These counties were chosen for analysis due to the availability of glassy-winged sharpshooter trapping data (CDFA 2007a). Specifically, the California Department of Food and Agriculture maintains a network of yellow sticky panel traps (14 by 23 cm; Seabright Laboratories, Emeryville, CA) in these counties which are monitored year-round. Trapping data for Kern and Ventura counties was available for 2002–2006, data for Tulare County was available for 2003–2006, and data for Riverside County was available for 2005–2006. Over these time periods, an average of 2,222, 533, 3,081, and 826 traps were monitored in citrus groves in Kern, Riverside, Tulare, and Ventura counties, respectively. For Kern, Tulare, and Ventura counties, traps were distributed throughout citrus growing areas in each county. Traps in Riverside County were limited to areas where citrus and grape was grown together. Thus, the analysis for Riverside County was limited to Temecula and Coachella valleys. This required estimating insecticide use and area planted to citrus within these two discrete locations in Riverside County.

For each county and year, we estimated the mean number of adults caught per trap per day for traps located in citrus groves between the beginning of May and the end of August. Then, to assess the combined effects of carbamates, neonicotinoids, organophosphates, and pyrethroids on glassy-winged sharpshooter abundance, we calculated a composite parameter, "spray intensity," for each year in each county and tested for an association between spray intensity and mean catch per trap per day (SAS Institute 2001). Spray intensity was calculated as follows:

$$(C_i/C_{\max}) \times A_{C,i} + (N_i/N_{\max}) \times A_{N,i} + (O_i/O_{\max}) \times A_{O,i} + (P_i/P_{\max}) \times A_{P,i}$$

where C_i, N_i, O_i, and P_i are the kilograms of active ingredient applied per hectare of citrus between the beginning of September in year $i - 1$ and the end of Aug in year i for carbamates, neonicotinoids, organophosphates, and pyrethroids, respectively. These values were standardized by dividing by the highest kilograms of active ingredient applied per hectare for each compound across all years and counties examined (i.e., C_{max}, N_{max}, O_{max}, and P_{max}). The standardized kilograms of active ingredient applied per hectare was then weighted by multiplying by the proportion of citrus treated with each compound in that county between the beginning of September in year $i - 1$ and the end of Aug in year i (i.e., $A_{C,i}$, $A_{N,i}$, $A_{O,i}$, and $A_{P,i}$). The proportion of citrus in each county treated with each compound was estimated by summing the area treated in the insecticide data and dividing by the total area planted to citrus.

The above-mentioned analysis assumes that each compound could have an equal impact on glassy-winged sharpshooter abundance. Although compounds in each insecticide class have been shown to cause high levels of glassy-winged sharpshooter mortality, the residual times of neonicotinoids and pyrethroids are generally longer than those of carbamates and organophosphates (Hix 2002; Grafton-Cardwell et al. 2003b; Bethke et al. 2004a,b). Thus, to better understand which insecticide classes are contributing to the effects observed in the previous analysis, we also determined the number of insecticide classes with above average use in each county in each year and tested for an association with insect abundance. This was accomplished by determining the mean kilograms of active ingredient applied per hectare of citrus for each insecticide class across all counties and years and then comparing the kilograms of active ingredient applied for each county and year to the mean.

Results

Grape and Citrus Distribution among Counties. Of California's 58 counties, 48 reported commercial production of grape, whereas only 18 reported commercial citrus production (Fig. 1). A lack of a report does not mean that grape or citrus were not planted in those

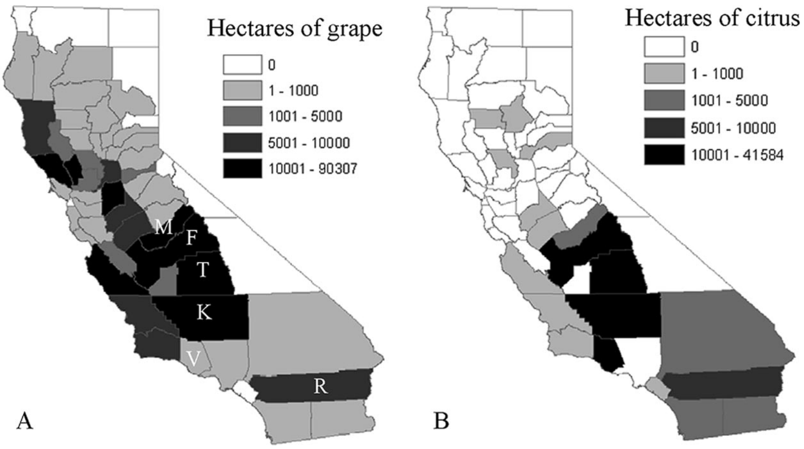

Fig. 1. Mean area planted to grape (A) or citrus (B) in each county in California for the years 1998–2005 (M, Madera; F, Fresno; T, Tulare; K, Kern; R, Riverside; V, Ventura).

counties, but that the area was sufficiently small that it was not tabulated. Moreover, urban plantings of these two crops were not included in the analysis. Of the 48 counties reporting commercial grape production, only 20 counties had >1,000 ha (Fig. 1A). Of the 18 counties reporting citrus production, only nine planted >1,000 ha (Fig. 1B).

There were only five counties that grew >1,000 ha of both grape and citrus: Fresno, Kern, Madera, Riverside, and Tulare counties (Fig. 2A). Among these five counties, Tulare and Riverside had 1.6 times more area planted to citrus than grape (Fig. 2B). In contrast, the area planted to grape was far greater than the area planted to citrus in Fresno, Kern, and Madera counties (Fig. 2B).

Grape and Citrus Distribution within Counties. The proximity of grape to citrus was greatest for Riverside County, with 61% of sections with grape plantings also containing a citrus planting and 90% of sections with grape plantings within 1.6 km of a section with a citrus planting (Figs. 3A and 4E). Despite this, the total area of grape that was in proximity to citrus in Riverside County was lower than that for Fresno, Kern, and Tulare counties (Figs. 3B and 4). This occurred because the total area planted to grape was greater in Fresno, Kern, and Tulare counties than it was in Riverside County (Fig. 2A). Within counties,

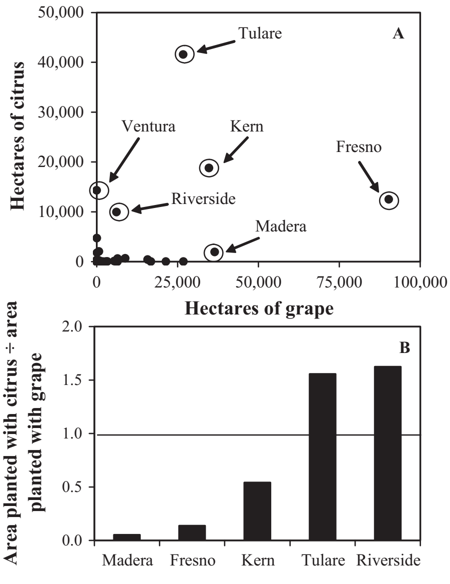

Fig. 2. (A) Scatterplot of the area planted to grape against the area planted to citrus for each county. Means for the years 1998–2005 are shown. (B) Ratio of the area planted with citrus to the area planted with grapes for the five counties with highest abundance of both crops.

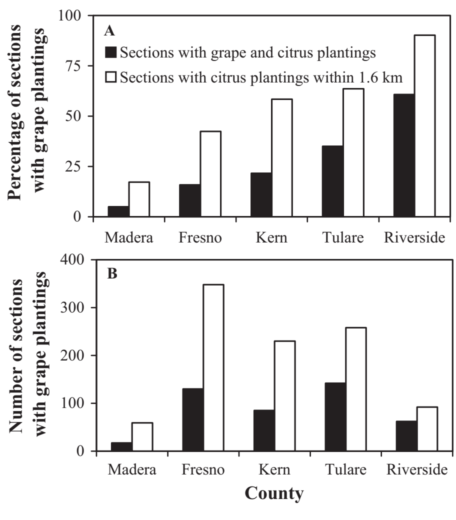

Fig. 3. (A) Percentage of sections with grape plantings that also had a citrus planting and the percentage of sections with grape plantings that were within 1.6 km of a section with a citrus planting. (B) Number of sections with grape plantings that also had a citrus plantings and the number of sections with grape plantings that were within 1.6 km of a section with a citrus planting.

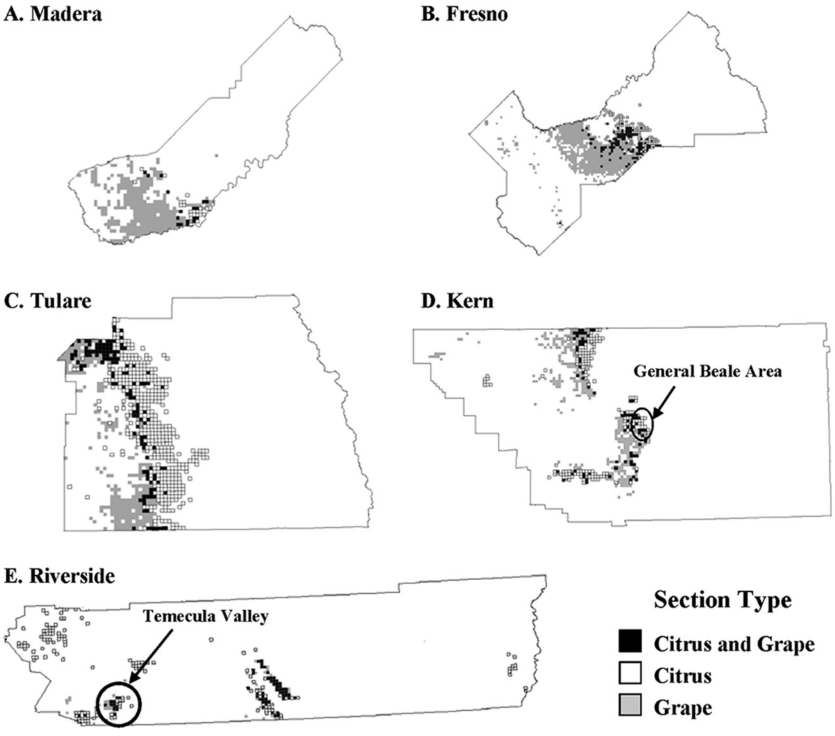

Fig. 4. Distribution of grape and citrus in Madera (A), Fresno (B), Tulare (C), Kern (D), and Riverside (E) counties. The maps indicate whether 1.6-km^2 sections had citrus plantings, grape plantings, or plantings of both in 2003.

the percentage of sections with grape plantings that were in proximity to citrus decreased moving northward through the San Joaquin Valley, with the lowest percentage of grape plantings in contact with citrus in Madera County (Figs. 3 and 4). This occurred because citrus is typically grown on the eastern edge of the San Joaquin Valley (Madera, Fresno, Tulare, and Kern counties) where winter temperatures are warmer, which is favorable for growing citrus (Fig. 4).

Insecticide Use by County. Comparison of kilograms of active ingredient applied per hectare of citrus between counties in the San Joaquin Valley of California (Fresno, Kern, Madera, and Tulare counties) and counties in Southern California (Riverside and Ventura counties) indicates that fewer total kilograms of carbamates, organophosphates, and pyrethroids were applied per hectare of citrus in Southern California than in the San Joaquin Valley of California (Fig. 5). The use of carbamates and organophosphates was lowest in Riverside and Ventura counties because biological control effectively suppresses most key citrus pests in those counties (Grafton-Cardwell and O'Connell 2006). Within Riverside and Ventura counties, the use of organophosphates was higher in Ventura County than in Riverside County (Fig. 5D) due to sprays aimed at controlling citrus bud mite, *Eriophyes sheldoni* (Ewing), a pest of lemons, *Citrus limon* L., which are primarily grown in the coastal areas of California. In contrast to southern California, biological control is less effective at controlling citrus pests in the San Joaquin Valley (Kern, Madera, Fresno, and Tulare counties), which resulted in a reliance on the use of broad-spectrum insecticides (Fig. 5).

Reliance on carbamates and organophosphates to control California red scale and citrus thrips in the San Joaquin Valley through the 1980s and 1990s led to resistance problems with these pests (Grafton-Cardwell and Vehrs 1995, Khan and Morse 1998). Consequently, the use of organophosphate and carbamate insecticides in the San Joaquin Valley was greatest in the mid-1990s (Fig. 5), because growers were applying multiple treatments to control resistant pests (Grafton-Cardwell 2000). Use of broad-spectrum insecticides declined in the San Joaquin Valley after 1997 due to the availability of new insecticide chemistries for control of the aforementioned resistant pests, namely, insect growth regulators (IGRs) and spinosad (Grafton-Cardwell 2000, Grafton-Cardwell and O'Connell 2006). IGRs and spinosad are reported to kill fewer *H. vitripennis* than carbamates, organophosphates, and pyrethroids (Grafton-Cardwell et al. 2003a). This change in insecticide regime resulted in a resurgence of secondary pests, most notably forktailed bush katydids, *Scudderia furcata* (Brunner von Wattenwyl), and citricola scale, *Coccus pseudomagnoliarum* (Kuwana), which resulted in a rise in the use of organophosphate and pyrethroid insecticides during 2000–2006 in the San Joaquin Valley (Fig. 5; Grafton-Cardwell 2000, Grafton-Cardwell and O'Connell 2006).

The use of neonicotinoids was highest in Kern and Riverside counties, and these recent increases were

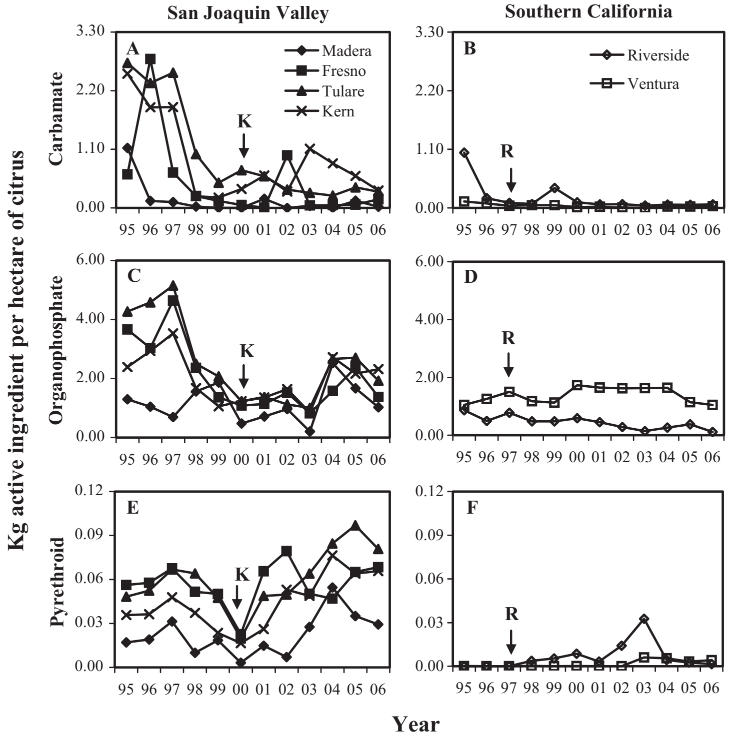

Fig. 5. Kilograms of active ingredient applied per hectare of citrus for three insecticide classes, carbamates (A and B), organophosphates (C and D), and pyrethroids (E and F). Arrows denote the years that increased incidence of Pierce's disease began to be observed in Kern (K) and Riverside (R) counties.

related to the initiation of area-wide control programs targeting persistent populations of *H. vitripennis* in those counties (Fig. 6). The response of the areawide program to observations of increased Pierce's disease was more rapid in Kern County than in Riverside County (compare the years epidemics were first observed in Fig. 5 to years when areawide programs were initiated in Fig. 6). Response in Riverside County was slow because this was the first county impacted and control methods needed to be developed. In contrast, response in Kern County was rapid, due to experience gained from the earlier outbreak in Riverside County.

Effects of Spray Regime on Abundance. Examination of the combined effects of carbamates, neonicotinoids, organophosphates, and pyrethroids via the composite parameter "spray intensity" indicates a negative relationship between spray intensity and mean catch per trap per day (Fig. 7A). Despite the apparent curvilinear relationship of spray intensity with mean catch per trap per day, the relationship was best described by a straight line (F = 13.6, df = 1, 14; $P <$ 0.0025; r^2 = 0.49) (Fig. 7A). Similarly, there was a negative linear relationship between the number of insecticide classes with above average use and mean catch per trap per day (F = 39.7; df = 1, 14; $P <$ 0.0001; r^2 = 0.74) (Fig. 7B). The average kilograms of active ingredient applied per hectare of citrus across counties and years for carbamates, neonicotinoids, organo-

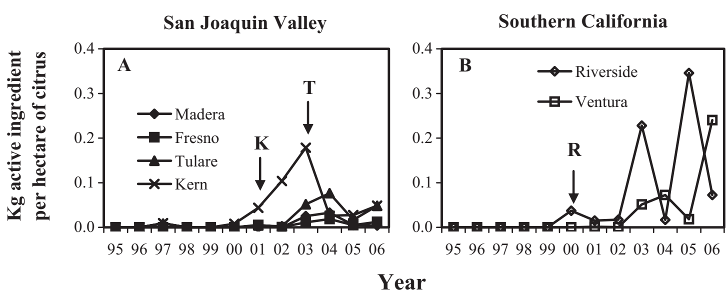

Fig. 6. Kilograms of active ingredient applied per hectare of citrus for neonicotinoids for counties in the San Joaquin Valley (A) and Southern California (B). Arrows denote the year areawide programs were initiated in Riverside (R), Kern (K), and Tulare (T) counties.

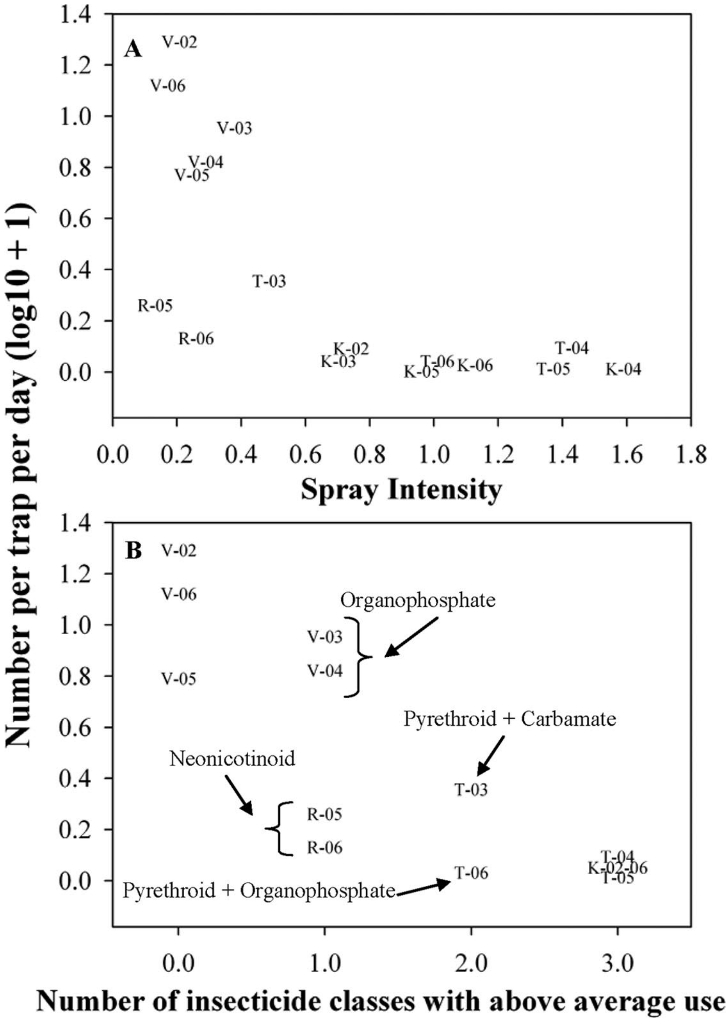

Fig. 7. Effects of insecticide use on glassy-winged sharpshooter abundance. (A) Association of combined spray regime with glassy-winged sharpshooter abundance. See Materials and Methods for calculation of spray intensity. (B) Association of the number of insecticide classes with above average use and glassy-winged sharpshooter abundance. In cases where one or two insecticide classes had above-average use, the class with above-average use is indicated. The county and year that each point represents is indicated by the first letter of each county (K, Kern; R, Riverside; T, Tulare; V, Ventura) and the last two digits of the year. (B) All five observations for Kern County fall approximately on the same point and are indicated by the symbol K-02-06.

phosphates, and pyrethroids was 0.28, 0.09, 1.59, and 0.04, respectively.

Estimates of spray intensity were similar for Ventura and Riverside counties, although trap catch was higher in Ventura County than in Riverside County (Fig. 7A). Examination of the compounds used in these counties and their targets explain this difference. In Ventura County, sprays mainly consisted of organophosphates which targeted citrus bud mite, whereas sprays in Riverside County targeted glassy-winged sharpshooter and consisted of applications of the neonicotinoid Admire which provides effective control for a much longer period (Grafton-Cardwell et al. 2003a) (Fig. 7B). This indicates that glassy-winged sharpshooter control can be achieved by judicious use of appropriate compounds.

Above-average use of three out of the four insecticide classes investigated in this study was always associated with low glassy-winged sharpshooter abundance (Fig. 7B). Of seven county-by-year combinations with above-average use of three insecticide classes, only three observations included above average use of neonicotinoids (Kern County 2002 and 2003, Tulare County 2004). This suggests that simultaneous above-average use of carbamates, organophosphates, and pyrethroids may be suppressing glassy-winged sharpshooter populations in some areas.

Discussion

Among the 20 counties in California that grow >1,000 ha of grape, only five counties concomitantly grew >1,000 ha of citrus (Figs. 1 and 2A). Within counties, the percentage of grape plantings that were in proximity to citrus was greatest for Riverside County and declined moving northward through the San Joaquin Valley (Figs. 3A and 4). However, the area planted to grape that was in proximity to citrus was greater for Fresno, Tulare, and Kern counties (Figs. 3B and 4). Citrus management programs in Southern California (Riverside and Ventura counties) and the San Joaquin Valley of California (Fresno, Madera, Tulare, and Kern counties) differ greatly (Fig. 5). Most notably, counties in the San Joaquin Valley have historically relied on the use of broad-spectrum insecticides, which have negative effects on glassy-winged sharpshooter abundance (Fig. 7). Differences in citrus pest management programs among counties were likely to have had important effects on regional abundances of glassy-winged sharpshooter in California.

In addition to providing accessible information on the abundance, distribution, and management of citrus in California, our secondary goal was to determine whether knowledge of distribution and management of citrus in relation to grape would provide insight into previous outbreaks of Pierce's disease in the Temecula Valley (Riverside County) and the General Beale Area (Kern County). In light of the data summarized here, the glassy-winged sharpshooter transmitted epidemic of Pierce's disease in Temecula Valley is not surprising. The proximity of citrus to grape in Riverside County was greater than anywhere else examined (Figs. 3A and 4E), and the use of broad-spectrum insecticides in citrus was lower in Riverside County than anywhere else examined (Fig. 5). Thus, provided that the areawide control program is maintained, the likelihood that an outbreak due to a citrus-grape interface as seen in Temecula will occur elsewhere seems low.

Increased incidence of Pierce's disease, due to *H. vitripennis*, also was observed in the General Beale Area of Kern County (Fig. 4D). Glassy-winged sharpshooter was first observed in the General Beale Area in 1997, but the Pierce's disease outbreak in this location did not begin until the early 2000s (Hashim and Hill 2003). Because the period between 1997 and 2000 was associated with a decline in the use of organophosphate and carbamate insecticides in citrus in Kern County (Fig. 5A and C), it is reasonable to hypothesize that this change in insecticide regime contributed to the outbreak. If this were the sole factor, however, a more wide-spread Pierce's disease problem throughout Kern County would have been expected. Thus, additional unidentified factors likely played a role in the Pierce's disease outbreak in the General Beale Area. One factor which may have limited the outbreak to the General Beale Area was the rapid response of the areawide program.

Glassy-winged sharpshooter is not currently found in the citrus growing areas of Fresno and Madera counties, although urban populations are found in the city of Fresno (CDFA 2007a). Winter temperature has been hypothesized to play an important role in limiting the distribution of glassy-winged sharpshooter in California (e.g., Johnson et al. 2007a,b). Consequently, winter temperatures in much of Fresno and Madera counties may be to cold for glassy-winged sharpshooter to survive, although citrus production areas within these counties may be suitable for glassy-winged sharpshooter overwintering survival. This is possible as citrus is highly susceptible to frost damage and can only be produced on the east side of the San Joaquin Valley (Fig. 4A and B) where minimum winter temperatures are higher than elsewhere in these counties. Due to these production constraints, the overlap of citrus and grape in Fresno and Madera counties is limited to discrete locations on the eastern side of the valley (Fig. 4A and B). Within these areas, use of broad-spectrum insecticides is higher in Fresno County than in Madera County (Fig. 5). Thus, if glassy-winged sharpshooter were introduced into the citrus producing areas of either of these counties, population growth rates would likely be higher in Madera County than in Fresno County.

We focused on assessment of the distribution and management of citrus due to the importance of this crop in the current population dynamics of the glassy-winged sharpshooter in California. However, glassy-winged sharpshooter is polyphagous (Hoddle et al. 2003), and citrus is not required for survival. Thus, the importance of other host plants and habitats should be considered. One factor not investigated here is the role that urban environments play on regional glassy-winged sharpshooter population dynamics. Some urban areas, such as Bakersfield (Kern County, CA) harbor established populations and the contribution of these populations to outlying agriculture areas is largely unknown. Another key factor in the epidemiology of Pierce's disease not considered here is the location and abundance of potential sources of *X. fastidiosa* inoculum.

In conclusion, the number of counties in California that produce grapes greatly exceeds those that produce citrus (Fig. 1), and the current range of the glassy-winged sharpshooter is largely limited to grape and citrus-producing counties. Consequently, movement of the glassy-winged sharpshooter into a region where grapes are produced but citrus is not, would require the development of new control strategies that do not rely on treating citrus. Thus, researchers are faced with two major challenges. The first is using our current state of knowledge to determine how to best manage glassy-winged sharpshooter in grape–citrus areas where it is already established. The second is predicting which uninfested regions of California are at greatest risk for infestation by the glassy-winged sharpshooter, and if citrus is absent, determining which alternate host plants will play a key role in glassy-winged sharpshooter population dynamics in those areas.

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