Seasonal flight activity by the Asian citrus psyllid in east central Florida

D. G. Hall* & M. G. Hentz
United States Department of Agriculture, Agricultural Research Service, US Horticultural Research Laboratory, 2001 South Rock Road, Fort Pierce, FL 34945, USA

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Abstract
The Asian citrus psyllid, Diaphorina citri Kuwayama (Hemiptera: Psyllidae), is an important invasive citrus pest in the USA because it vectors a bacterium responsible for huanglongbing, a devastating disease of citrus. Information was lacking on seasonal aspects of flight activity by D. citri, which could have ramifications on psyllid management as well as our understanding of epidemiology of the disease. Of interest from a pest management standpoint would be whether D. citri regularly disperses to or away from citrus on a predictable schedule. In research presented here, seasonal flight activity by D. citri was investigated using yellow sticky traps deployed in citrus trees and in fallow areas adjacent to citrus. Results indicated that flight activity by both male and female D. citri away from citrus can occur at any time of the year with consistent dispersal activity during the spring. The research further indicated citrus is continually subject to infestation by immigrating adults and that there is no time during the year that a citrus grower could be assured immigration would not occur. Growers should be aware that adult dispersal occurs regularly during spring and they should time management tactics accordingly. Adult flight activity 2 m from a citrus tree was more pronounced at 1 m above ground than at 2 or 3 m high. At distances of 8–60 m from trees, numbers of adults on traps were similar among the three heights. Males and females were similar with respect to seasonal flight activity. Numbers of adults captured on traps distant from citrus were not correlated with wind speed, sunlight, or air temperature, but there was some evidence that relative humidity influenced flight activity. Although the D. citri life cycle is dependent on flush, data from these studies did not confirm that psyllid dispersal from citrus consistently increases as citrus flush abundance decreases.

Introduction
The Asian citrus psyllid, Diaphorina citri Kuwayama (Hemiptera: Psyllidae), is an important pest of citrus in the USA primarily because it is a vector of ‘Candidatus Liberibacter asiaticus’, one of three bacterial agents of huanglongbing (also known as citrus greening disease; Bové, 2006; Gottwald et al., 2007). Huanglongbing is considered the most devastating disease of citrus worldwide. Diaphorina citri is thought to be Indian in origin and has extended its geographical distribution to include many citrus growing areas around the world (Mead, 1977; Halbert & Manjunath, 2004; Halbert & Núñez, 2004). ‘Candidatus Liberibacter asiaticus’ also has spread throughout many of these regions. The psyllid was first discovered in the USA during 1998 (Florida) and since has invaded southern USA from the east coast (South Carolina) to the west coast (California) including all of the major citrus growing areas (Florida, Texas, Arizona, and California) (Tsai & Liu, 2000; French et al., 2001; Halbert et al., 2010). Huanglongbing attributed to ‘Ca. Liberibacter asiaticus’ was first discovered in the USA during 2005 in Florida (Bové, 2006) and subsequently was found in Louisiana, Georgia, and South Carolina (Halbert et al., 2010).

Citrus infected by ‘Ca. Liberibacter’ may develop symptoms of huanglongbing within less than a year, but sometimes symptoms do not manifest for several years (Gottwald et al., 2007). Once symptoms appear, a decline in productivity occurs, fruit becomes inedible, and dis-
eased trees die (Gottwald et al., 2007). In citrus grown for commercial markets, many growers confronted with huanglongbing adopt intensive insecticide programs to reduce psyllid transmission of the disease, aggressively remove diseased trees to reduce inoculation levels of the bacterium, and only plant nursery stock certified to be disease free (Bové, 2006). In Florida, many growers using intensive insecticide programs (Rogers, 2008; Rogers et al., 2010) are advocating area-wide efforts to control the psyllid. The concern is that re-infestations will continue to occur by psyllids immigrating from groves not subjected to psyllid control measures, from abandoned groves, and from urban areas.

Some information has been published on psyllid flight activity. Husain & Nath (1927) reported that adults do not fly very far and do not possess the power of sustained flight. A report from China based on captures of adult D. citri on sticky traps indicated flight activity may occur all day long; however, it was pronounced during warm, windless, sunny afternoons between 16:00 and 18:00 hours (Aubert & Xia, 1990). Boina et al. (2009) used an immunomarking technique to demonstrate that D. citri adults flew 60–100 m distances between pairs of managed and unmanaged groves, with net movement being toward managed groves. A report from Japan indicated that the longest flight duration by D. citri in a flight mill was 47 min for females and 49 min for males, and the longest flight distance was calculated as being 978 m for females and 1 241 m for males (Arakawa & Mivamolo, 2007). Long-distance movement by D. citri between and within Japanese islands such as Yoron and Kyushu was theorized as possible but wind dependent, as the adults have weak flight muscles relative to the size of their wings (Sakamaki, 2005).

The objective of research presented here was to assess seasonality of flight activity by Asian citrus psyllid in and around citrus in east central Florida, USA. Two studies were conducted in which traps for adult psyllids were deployed in fallow fields adjacent to citrus trees. Captures of adults at these traps were used to make inferences on seasonal flight activity.

**Materials and methods**

Two studies were conducted using yellow sticky card traps to monitor flight activity by D. citri. Yellow sticky traps deployed in citrus trees have been shown to be effective for gauging population trends of D. citri in citrus, with significant correlations between numbers of adults on traps and numbers on leaves (Hall, 2009). In one study, traps were deployed in citrus trees and on poles at various distances from citrus. In the second study, psyllid flight activity was monitored in a large fallow field between two citrus orchards. Traps were deployed on trees in each orchard and at various locations across the fallow field. In the fallow area, some traps were deployed on stakes at various locations, and some were deployed in orange fallow field. In the fallow area, some traps were deployed on stakes at various locations, and some were deployed in orange fallow field. In the fallow area, some traps were deployed on stakes at various locations, and some were deployed in orange fallow field. In the fallow area, some traps were deployed on stakes at various locations, and some were deployed in orange fallow field.

**Study 1: Flight activity in and around a block of citrus trees**

Thirty-eight trapping stations were established in and around a 0.4-ha block (12 rows, 41 trees per row, 3 m tree spacing) of ‘Hamlin’ orange trees [Citrus sinensis (L.) Osbeck (Rutaceae)] (6 years old, ca. 1.8 m tall) at a USDA-ARS orchard near the city of Fort Pierce in east central Florida (27°26′08.37″N, 80°25′50.51″W). This block (Figure 1A) was situated on the western edge of the orchard and was regularly irrigated and fertilized, but no insecticides were applied to the block during the study. There was to the north a block of young ‘Hamlin’ trees (2–5 years old, 0.6–1.5 m tall) and to the south a block of young ‘Valencia’ orange trees (2.5 years old, 0.7 m tall). To the east of the study block was a fallow area approximately 2 ha in size, with another block of citrus (a mix of citrus varieties all about 5 years old) about 130 m from the eastern edge of the study block. To the west of the study block were a large fallow area and a conservation area consisting of pine trees and other natural vegetation (no host plants of D. citri). The closest citrus to the western edge of the study block was about 880 m away.

One small yellow sticky card trap was deployed (as described by Hall et al., 2008) in each of 10 trees scattered from the southern to the northern ends of the block (Figure 1A). In selecting trees for the traps, all perimeter trees (trees along the outer rows and at the ends of rows) were avoided. A 3.1-m metal pole was vertically positioned at each of six locations within the block, each about 2 m from a tree. Three traps were vertically positioned on each pole so that the middle of the traps was at 1, 2, or 3 m above ground. In addition to the six poles with traps within the block, 12 similar poles each with three traps were positioned about 8 m from the outer edge of the block, three poles along each of the north, east, south, and west edges.
Three poles with traps were positioned 30 m to the east of the block within the 2-ha fallow field, and three poles with traps were positioned 30 m to the west of the block in the large fallow area. Three additional poles with traps were positioned 60 m to the west of the block. One single pole with traps was placed 150 m to the southwest of the block in the large fallow field. Traps were deployed and replaced every 2 weeks from mid-January 2007 through mid-February 2008 for a total of 30 trapping periods. Data were collected on the number of male and female *D. citri* per trap per trapping period.

To facilitate an evaluation of variability in numbers of adults captured on traps, the trapping stations (excluding the station 150 m from citrus) were grouped into three zones depending upon their general location: north, central, or south. The north and south zones each included two pole stations 30 m from the trees, one pole station 60 m from the trees, five pole stations 8 m from trees, two in-block pole stations, and four in-tree stations. The middle zone included the same number of stations with the exception that there were only two in-tree stations and only two stations 8 m from citrus.

The quantity of citrus flush (new leaf growth) before and after each trapping period was assessed by counting the number of new flush shoots within a cubic frame (15 × 15 × 15 cm) placed into the outer canopy at one location 1–2 m above ground in each of 15 trees (Hall & Albrigo, 2007). A flush shoot was defined as any flush shoot with developing leaves but was restricted to shoots which had new, unexpanded (often called feather) flush leaves appropriate for oviposition by *D. citri*.

Mean number of adults per trap per trapping period was computed for (1) each trapping location (in trees, within the block near trees, and for each trapping distance outside of the block) and (2) for traps on poles, for each trapping height at each trapping distance from citrus. Numbers of adults per trap per trapping period were compared among the different trapping distances from citrus, and among the three trap heights, by an analysis of variance using the 30 trapping periods as repetitions. A t-test was conducted for each trapping distance to compare numbers of males and females captured on traps.

An investigation was conducted to assess the influence of population levels of adults in citrus on numbers of psyllids captured on traps distant from citrus. This was accomplished using a correlation analysis between mean number of adults per trapping period captured on traps in the fallow areas and on traps in citrus. The influence of citrus flush abundance on numbers of psyllids captured on traps distant from citrus was investigated by conducting a correlation analysis between mean number of adults captured on traps per trapping period and the mean number of flush shoots per sample per tree during the trapping period (an average of counts taken at the beginning and end of each trapping period).

Hourly data on wind speed (at 10 m height), air temperature, solar radiation (W m⁻²), relative humidity (%), and rainfall (measured at 2 m height) during the study were obtained from a weather station operated by the University of Florida’s Florida Automated Weather Network (FAWN). The FAWN station was located 3 km from the study site. Mean values of the aforementioned environmental variables were determined for each trapping period using data during daylight hours. Analyses on these environmental factors were restricted to daylight hours because previous research indicated adults are active primarily during the day (Aubert & Xia, 1990; Wenninger & Hall, 2007). Wind speed (daily mean, daily minimum, daily maximum, and maximum per trapping period) and air temperature (daily mean, daily minimum, and daily maximum) were determined for each trapping period.
Correlations were then investigated between each environmental variable and mean number of adult D. citri per trap at each trapping distance from citrus.

Study 2: Flight activity across a fallow field between two blocks of citrus trees

Eighteen trapping stations were established in a 1.7-ha fallow field in east central Florida (27°23′30.07″N, 80°29′11.68″W). The field (Figure 1B) was situated between two large blocks of citrus trees, to the north a block of mature lemon trees (Citrus limon Burn) (8 years old, 3.4 m tall, 24 rows, 3 m tree spacing, 7.6 m row spacing, 3.4 ha), and to the south a block of mature orange trees (‘Minneola’ tangelos [C. tangerina (Tanaka) ×
C. paradise Macf.] interplanted with mature ‘Temple’ [C. reticulata Blanco × C. sinensis] tangor trees) (22 years old, 3.5 m tall, 13 rows, 3.7 m tree spacing, 7.3 m row spacing, 1.5 ha). There was a large orchard of old citrus trees 260 m to the west and another large orchard of old citrus 3 km to the east (for these orchards, variety and age were not known).

The block of orange trees was subjected to a minimal insect management program but was irrigated and fertilized on a regular schedule. The lemon trees were occasionally irrigated and fertilized with no foliar applications of any chemicals. Both blocks of trees were regularly mowed. A small sticky trap was deployed in each of 10 lemon trees and 10 orange trees. These traps were situated in the third tree from the end of each of 10 rows adjacent to the fallow field. A single large (1.2–1.5 m tall) orange jasmine plant was planted at each of nine sites within the fallow field, and a single small trap was deployed in each plant. The orange jasmine was maintained on a regular systemic insecticide program (imidacloprid; Bayer CropScience, Monheim am Rhein, Germany) to prevent colonization by psyllids. A large sticky trap was vertically positioned 1 m from each jasmine plant to the north, east, south, and west. Each large trap was supported between two wooden stakes with one sticky surface facing the plant. The center of each trap was about 1 m above ground. In addition to the nine jasmine trapping stations, nine stations were established in the fallow field using the same configuration of four large traps but without a jasmine plant. One set of three jasmine trapping stations and three traps-only stations was situated along a transect parallel to and 50 m from the south edge of the lemon tree block, one set was situated along a transect parallel to and 50 m from the north edge of the orange tree block, and a third set was situated along a transect parallel to and 100 m from the lemon and orange tree blocks. This center transect of trapping stations was thus 50 m from the other two transects. There were approximately 17 m between trapping stations along each transect.

To facilitate an evaluation of variability in numbers of adults captured on traps, the trapping stations were grouped into three zones depending upon their general location: east, central, or west. Each zone included three jasmine stations and three stand-alone trap locations. The east and west zones each included three lemon and three orange tree traps, and the center zone included four lemon and four orange tree traps.

Trapping was conducted from late March 2008 through December 2009. Traps were deployed and retrieved every 2 weeks for a total of 44 trapping periods. The quantity of flush associated with citrus and jasmine at the beginning and end of each trapping period was assessed using the aforementioned method (15 samples in each citrus block and one sample in each of five jasmine plants). Mean number of adults per trap per trapping period was computed for each of the following trap locations: citrus to the north, citrus to the south, fallow field jasmine, fallow field near jasmine, and fallow field alone. Numbers of adults per trap per trapping period captured at the various trap locations were compared by an analysis of variance using the 44 trapping periods as repetitions. A t-test was conducted for each trap station to compare numbers of males and females captured on traps.

The influence of population levels of adults in the two citrus blocks on numbers of psyllids captured on traps in the fallow field was investigated. This was accomplished using a correlation analysis between mean number of adult D. citri captured per trapping period on traps in each citrus block and on traps in the fallow field (averaged over all fallow-field traps). The influence of flush abundance in citrus and jasmine on numbers of psyllids captured on traps in the fallow field was investigated by conducting a correlation analysis between mean number of adults captured per trapping period on traps in the fallow field (averaged over all traps) and mean number of flush shoots per sample per tree during the same trapping period (an average of shoot counts at the beginning and end of each trapping period). Because traps of two sizes were used, counts of numbers of adults per trap were converted to number per 100 cm² prior to all statistical analyses.

Statistical analysis

Analyses of variance were conducted using Proc GLM (SAS Institute, 2008), and F-protected mean comparisons were made with Tukey’s test. T-tests were conducted using Proc TTEST, and correlation analyses (Pearson coefficients) were conducted using Proc CORR (SAS Institute, 2008). All evaluations of statistical significance were conducted at α = 0.05 on log-transformed counts of psyllids.
Results

Study 1: Flight activity in and around a block of citrus trees

*Diaphorina citri* adults were captured during all 30 trapping periods on traps deployed in trees or positioned 2 m from citrus, during 18 of 30 trapping periods on traps 8 m from citrus, during 11 of 30 trapping periods on traps 30 m from citrus, and during nine of 30 trapping periods on traps 60 m from citrus (Figure 2). Adults were captured during three of 30 trapping periods at the single trapping station 150 m from citrus. A peak in captures of adults at all locations in and around the block of trees occurred during the middle of April 2007.

Significantly more adult *D. citri* were captured on traps deployed directly in citrus trees than on traps positioned on poles stationed 2–60 m from the citrus trees (Table 1). Traps on poles positioned 2 m from citrus trees captured significantly more adults than traps on poles positioned 8–60 m from citrus. There were no significant differences among traps located 8–60 m from the trees with respect to mean number of adults captured. Traps 2 m from citrus positioned 1 m above ground captured significantly more *D. citri* than traps 2 or 3 m above ground, and traps 3 m above ground captured the fewest adults at this distance from citrus (*F*$_{3,189}$ = 8.8, *P* < 0.0001) (Table 2). The same was true regardless of gender. For traps 2 or 8 m from citrus, there was no trapping period during which traps positioned 3 m above ground captured more psyllids than traps positioned 1 m above ground. There were few significant differences in numbers of adults captured on traps 1, 2, or 3 m above ground when traps were 8–60 m from citrus. For the trap station 150 m from citrus, adults

![Figure 2](image)

**Figure 2** Mean (± SE) numbers of male and female *Diaphorina citri* captured per trap in 2 weeks, in citrus trees and at various distances from the trees across fallow ground (study 1). Note that the Y-axis scale varies among the panels, emphasizing differences in relative numbers of adults captured at various distances from citrus. Mean (± SE) relative humidity and number of flush shoots in the citrus trees during the study are presented for comparison to numbers of adults captured on traps.
were captured on traps 2 or 3 m above ground but not 1 m above ground. There were no significant correlations between number of adults trapped and flush abundance (mean number of shoots per sample) at any distance from citrus (Table 3). Mean number of adult *D. citri* per trap was positively correlated with maximum wind speed when traps were located in citrus or 2 m from citrus. Numbers of adults trapped at a distance of 8 m from citrus were negatively correlated with relative humidity, and numbers trapped at 30 and 60 m from citrus tended to be negatively correlated with humidity. No significant correlations were found between numbers of adults trapped and sunlight at any distance from citrus, although numbers trapped in trees were positively correlated with sunlight. A significant positive correlation was found between numbers of adults trapped in traps and rainfall. Numbers of adults captured on traps deployed across the fallow areas were positively correlated with numbers of adults captured on traps deployed in citrus (*r* = 0.62, *P* = 0.0003; *n* = 30).

**Study 2: Flight activity across a fallow field between two blocks of citrus trees**

Adult *D. citri* were captured on traps in the fallow field during almost every month of the year, although numbers captured varied from month-to-month and year-to-year (Figure 3). A total of 44 trapping periods were conducted during the study, and adult *D. citri* were captured on traps in citrus to the north of the fallow field during all 44 periods and in citrus to the south during 38 of the periods. Adults were captured on at least some traps in or near jasmine in the fallow field during 32 of 44 trapping periods. Sticky traps in the fallow field not close to jasmine captured adults during 24 of the 44 trapping periods. There

### Table 1

Mean (± SE) numbers of adult *Diaphorina citri* captured in a 2-week period on sticky traps deployed in and around a block of citrus trees, Jan 2007–Feb 2008 (study 1)

<table>
<thead>
<tr>
<th>Distance (m) from citrus</th>
<th>No. per trap</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
<td></td>
</tr>
<tr>
<td>0 (in citrus trees)</td>
<td>5.9 ± 1.1A</td>
<td>4.7 ± 1.0aA</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.6 ± 0.1bA</td>
<td>0.6 ± 0.08bA</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.03 ± 0.01cA</td>
<td>0.02 ± 0.01cA</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.03 ± 0.02cA</td>
<td>0.03 ± 0.01cA</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.04 ± 0.02cA</td>
<td>0.02 ± 0.01cA</td>
<td></td>
</tr>
</tbody>
</table>

Means in the same column followed by the same lowercase letter are not significantly different (Tukey’s test; for males: *F* = 21, *P*<0.0001; for females: *F* = 15, *P*<0.0001). Means in the same row followed by the same uppercase letter are not significantly different (t-test; t = −1.2, *P* = 0.2; 2 m: t = −0.6, *P* = 0.6; 8 m: t = −0.6, *P* = 0.5; 30 m: t = −1.0, *P* = 1.0; 60 m: t = −0.7, *P* = 0.5 (d.f. = 58 for each test). All analyses on log-transformed counts, raw data means presented.

### Table 2

Mean (± SE) numbers of adult *Diaphorina citri* captured in a 2-week period on sticky traps deployed in and around a block of citrus trees, Jan 2007–Feb 2008 (study 1)

<table>
<thead>
<tr>
<th>Distance (m) from citrus</th>
<th>Trap height (m)</th>
<th>No. per trap</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adults</td>
<td>Males</td>
<td>Females</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.87 ± 0.40a</td>
<td>1.53 ± 0.22a</td>
<td>1.31 ± 0.20a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.64 ± 0.11b</td>
<td>0.32 ± 0.07b</td>
<td>0.32 ± 0.07b</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.11 ± 0.03c</td>
<td>0.05 ± 0.02c</td>
<td>0.06 ± 0.02c</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0.08 ± 0.04a</td>
<td>0.05 ± 0.03a</td>
<td>0.03 ± 0.01a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.04 ± 0.01a</td>
<td>0.02 ± 0.01ab</td>
<td>0.02 ± 0.01a</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.01 ± 0.01c</td>
<td>0.01 ± 0.01c</td>
<td>0.01 ± 0.01c</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>0.08 ± 0.03a</td>
<td>0.04 ± 0.02a</td>
<td>0.04 ± 0.02a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.06 ± 0.03ab</td>
<td>0.03 ± 0.01a</td>
<td>0.03 ± 0.02a</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.02 ± 0.01b</td>
<td>0.01 ± 0.01a</td>
<td>0.01 ± 0.01a</td>
</tr>
<tr>
<td>60</td>
<td>1</td>
<td>0.06 ± 0.06a</td>
<td>0.03 ± 0.03a</td>
<td>0.02 ± 0.02a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.07 ± 0.02a</td>
<td>0.03 ± 0.02a</td>
<td>0.03 ± 0.02a</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.06 ± 0.02a</td>
<td>0.04 ± 0.02a</td>
<td>0.01 ± 0.01a</td>
</tr>
<tr>
<td>Overall</td>
<td>1</td>
<td>0.69 ± 0.08a</td>
<td>0.37 ± 0.05a</td>
<td>0.31 ± 0.04a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.18 ± 0.01b</td>
<td>0.09 ± 0.01b</td>
<td>0.09 ± 0.02b</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.04 ± 0.01c</td>
<td>0.02 ± 0.01c</td>
<td>0.02 ± 0.01c</td>
</tr>
</tbody>
</table>

For each trapping distance, means in the same column followed by the same letter are not significantly different (Tukey’s test: *P* = 0.05, d.f. = 89 for each analysis). Analyses on log-transformed counts, raw data means presented.
Table 3  Correlations between mean (± SE) numbers of adult *Diaphorina citri* captured on sticky traps at different locations relative to a block of citrus trees and (1) flush abundance and (2) environmental variables during daylight hours (study 1)

<table>
<thead>
<tr>
<th>Variable</th>
<th>In tree</th>
<th>2</th>
<th>8</th>
<th>30</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. flush shoots per sample</td>
<td>0.05 (0.81)</td>
<td>0.11 (0.57)</td>
<td>−0.11 (0.57)</td>
<td>−0.04 (0.82)</td>
<td>−0.19 (0.32)</td>
</tr>
<tr>
<td>Daily wind (km h⁻¹)</td>
<td>−0.16 (0.39)</td>
<td>−0.13 (0.48)</td>
<td>0.14 (0.46)</td>
<td>0.02 (0.92)</td>
<td>−0.09 (0.64)</td>
</tr>
<tr>
<td>Minimum daily wind (km h⁻¹)</td>
<td>−0.13 (0.48)</td>
<td>−0.10 (0.60)</td>
<td>0.07 (0.71)</td>
<td>−0.03 (0.88)</td>
<td>−0.10 (0.59)</td>
</tr>
<tr>
<td>Maximum daily wind (km h⁻¹)</td>
<td>−0.06 (0.77)</td>
<td>−0.08 (0.69)</td>
<td>0.22 (0.24)</td>
<td>0.11 (0.56)</td>
<td>−0.00 (1.00)</td>
</tr>
<tr>
<td>Maximum wind (km h⁻¹)</td>
<td><strong>0.45 (0.01)</strong></td>
<td><strong>0.42 (0.02)</strong></td>
<td>0.17 (0.37)</td>
<td>0.34 (0.06)</td>
<td>0.14 (0.45)</td>
</tr>
<tr>
<td>Minimum temperature (°C)</td>
<td>0.26 (0.16)</td>
<td>0.01 (0.96)</td>
<td>−0.17 (0.36)</td>
<td>0.02 (0.93)</td>
<td>−0.02 (0.90)</td>
</tr>
<tr>
<td>Maximum temperature (°C)</td>
<td>0.20 (0.30)</td>
<td>−0.03 (0.87)</td>
<td>−0.22 (0.24)</td>
<td>−0.05 (0.79)</td>
<td>−0.10 (0.60)</td>
</tr>
<tr>
<td>Solar radiation (W m⁻²)</td>
<td>0.33 (0.07)</td>
<td>0.07 (0.70)</td>
<td>−0.12 (0.54)</td>
<td>0.09 (0.65)</td>
<td>0.06 (0.75)</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>−0.08 (0.67)</td>
<td>−0.17 (0.37)</td>
<td><strong>−0.41 (0.03)</strong></td>
<td>−0.31 (0.10)</td>
<td>−0.28 (0.13)</td>
</tr>
<tr>
<td>Total rainfall (cm)</td>
<td><strong>0.38 (0.04)</strong></td>
<td>0.23 (0.22)</td>
<td>0.17 (0.36)</td>
<td>0.27 (0.15)</td>
<td>0.30 (0.11)</td>
</tr>
</tbody>
</table>

Significant correlations are shown in bold (P<0.05). For each analysis, n = 30. Maximum wind is the maximum wind during each trapping period.

were three general peaks over time in numbers of adults captured in the fallow field: April 2008, late November/early December 2008, and April 2009.

Significantly more adults were captured on traps deployed in the lemon trees than on traps in the orange trees (Table 4). There was no significant difference in numbers of adults captured on traps deployed in orange jasmine in the fallow field compared to numbers captured in the orange trees. Numbers of adults captured on traps deployed on stakes in the fallow field were significantly smaller than numbers captured on traps deployed in either citrus or jasmine.

Analyses of data from 2008 indicated numbers of *D. citri* adults captured on traps in the fallow area were negatively correlated with numbers captured in the adjacent lemon trees, but there was a marginally positive relation between numbers captured in the fallow field and numbers captured in the adjacent orange trees (Table 5). During 2009, a significant positive correlation was found between numbers of adults captured in the fallow area and numbers captured in both the lemon and orange trees. No correlation was found between numbers of adults (over both genders) captured in the lemon and orange trees during 2008 (r = −0.18, P = 0.47; n = 19), but a positive correlation was found during 2009 (r = 0.56, P = 0.003; n = 25). A significant negative correlation was found between adults captured in the fallow field and flush abundance in the lemon trees during 2009, and a marginal negative relation was found for the same time period between adults captured in the fallow field and flush abundance in the orange trees (Table 6).

Discussion

The results indicated that both male and female *D. citri* fly routinely within and around trees in a citrus grove. Adults were captured on traps 30–100 m from citrus during almost every month of the year. The combined results of the two studies indicated that *D. citri* regularly disperses from citrus. Of interest from a pest management standpoint would be whether *D. citri* dispersal to or away from citrus occurs on a regular, predictable schedule. The research indicated citrus is continually subject to infestation by immigrating adults, and that there is not any time during the year that a citrus grower could be assured dispersal will not occur. Although flight activity distant from citrus was observed during almost every month of the year during the two studies, peaks in numbers of adults captured on traps distant from citrus occurred consistently during the spring. Aubert & Xia (1990) and Aubert (1990) reported on spring flight activity above jasmine canopies and considered this activity to be indicative of migratory flights. These spring flights seemed to be linked with stress factors imposed by occasional overcrowding of psyllids (Aubert, 1990). Growers should be aware that adult dispersal regularly occurs during spring and time management tactics accordingly.

Numbers of adults captured on traps distant from a group of citrus trees usually (e.g., throughout study 1, generally throughout study 2 relative to a block of orange trees, and during study 2 in 2009 relative to a block of lemon trees) were positively correlated with numbers of adults captured on traps deployed in the trees, suggesting
that numbers of adults dispersing from citrus usually increase as population levels of the psyllid increase in citrus. However, during study 2 in 2008, numbers of adults captured on traps distant from a block of lemon trees were negatively correlated with numbers captured on traps in the lemon trees. Correlation analyses indicated this difference was not related to flush abundance in the lemon trees, although flush abundance in the lemon trees during spring 2008 was relatively low. The negative relationship between numbers of adults captured in the lemon trees and numbers captured in the fallow field could not be explained by data collected during the study.

A mass flight of *D. citri* away from citrus during spring was reported by Hall et al. (2008). There was no evidence of mass flights from citrus during studies presented here. Factors that might trigger a mass flight away from citrus could include overcrowding as well as large reductions in the abundance of flush. Intuitively, flush abundance in citrus should influence dispersal activity by *D. citri* because its reproductive biology is dependent on flush. In our study, there was some evidence that fewer adults dispersed from citrus when citrus flush was abundant (study 2 during 2009). But, collectively, data from these studies did not confirm that psyllid flight activity from citrus increases as
Asian citrus psyllid flight activity

Table 4 Mean (+ SE) numbers of adult Diaphorina citri captured in a 2-week period on sticky traps per 100 cm² trap surface in citrus compared to numbers on traps in a fallow field near citrus, April 2008–December 2009 (study 2)

<table>
<thead>
<tr>
<th>Trap station</th>
<th>No. per trap</th>
<th>Gender n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>Lemon trees</td>
<td>1.1 ± 0.2aA</td>
<td>1.0 ± 0.2aA</td>
</tr>
<tr>
<td>Orange trees</td>
<td>0.26 ± 0.04bA</td>
<td>0.23 ± 0.04bA</td>
</tr>
<tr>
<td>Fallow field, traps in jasmine</td>
<td>0.32 ± 0.08bA</td>
<td>0.25 ± 0.07bA</td>
</tr>
<tr>
<td>Fallow field, traps near jasmine</td>
<td>0.01 ± 0.001cA</td>
<td>0.004 ± 0.001cA</td>
</tr>
<tr>
<td>Fallow field, traps alone</td>
<td>0.001 ± 0.0002cA</td>
<td>0.001 ± 0.0002cA</td>
</tr>
</tbody>
</table>

Means in the same column followed by the same lowercase letter are not significantly different (Tukey’s test; for males: F_{47,219} = 4.6, P<0.0001; for females: F_{47,219} = 5.0, P<0.0001). Means in the same row followed by the same uppercase letter are not significantly different \([t\text{-test; lemon trees: } t = -0.4, P = 0.7; orange trees: t = -0.3, P = 0.7; traps in jasmine: t = -0.8, P = 0.4; traps near jasmine: t = -0.3, P = 0.8; traps alone: t = -0.7, P = 0.5 (d.f. = 86 for each test)\]). All analyses on log-transformed counts, raw means presented.

Table 5 Correlations between numbers of adult Diaphorina citri captured on sticky traps in a fallow field and on traps in citrus (study 2)

<table>
<thead>
<tr>
<th>Gender</th>
<th>n</th>
<th>Lemon flush</th>
<th>Orange flush</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 (April–December)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>19</td>
<td>-0.70 (0.001)</td>
<td>0.42 (0.08)</td>
</tr>
<tr>
<td>Females</td>
<td>19</td>
<td>-0.61 (0.006)</td>
<td>0.16 (0.50)</td>
</tr>
<tr>
<td>Overall</td>
<td>19</td>
<td>-0.68 (0.001)</td>
<td>0.38 (0.10)</td>
</tr>
<tr>
<td>2009 (January–December)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>25</td>
<td>0.44 (0.03)</td>
<td>0.41 (0.04)</td>
</tr>
<tr>
<td>Females</td>
<td>25</td>
<td>0.67 (0.0002)</td>
<td>0.40 (0.04)</td>
</tr>
<tr>
<td>Overall</td>
<td>25</td>
<td>0.62 (0.001)</td>
<td>0.45 (0.02)</td>
</tr>
</tbody>
</table>

t (PR>|r|)

edge of a block of trees when traps were deployed on stakes or poles. Deploying traps in orange jasmine located some distance away from citrus dramatically increased numbers of adult D. citri captured on traps when compared to numbers captured on traps deployed on stakes. Dispersing psyllids might be visually attracted to plants such as orange jasmine, but possibly volatiles associated with jasmine could be explored in an effort to find an attractant for the psyllid. Patt & Sétamou (2010) previously reported that both males and females are attracted to young shoots of orange jasmine.

Numbers of adults captured on traps deployed in a citrus tree, or on traps deployed on poles in close proximity to citrus, may be increased by wind. This conclusion was drawn based on a positive correlation between maximum wind speed per trapping period and numbers of adults captured on traps in trees and on poles 2 m from citrus (study 1). This relationship between strong winds and numbers of adults captured on traps had previously been noted (Hall, 2009). Psyllids might be dislodged from trees by strong winds and subsequently attracted to traps, or psyllids might have less directional flight control at higher wind speeds and end up being blown onto a trap. No correlations were found between wind speed and numbers of adults captured on traps at from 8 to 60 m from citrus, indicating that wind speed alone did not influence dispersal activity away from citrus. Adult D. citri dispersal activity at distances of 8 m or more from citrus may have been influenced by relative humidity, as numbers of adults trapped at 8 m from citrus were negatively correlated with relative humidity and numbers trapped at 30 and 60 m tended to be negatively correlated with humidity. Zhang et al. (2008) found that 75% r.h. was optimum for flight activity by the soybean aphid, Aphis glycines (Matsumura), with decreased flight activity above and below this level.

Diaphorina citri flight activity 2 m from a citrus tree was more pronounced at 1 m above ground than at 2 or 3 m. At distances of 8–60 m from trees, numbers of adults on traps were similar among the three heights. Relatively few adult D. citri were captured on traps at 8–100 m from the edge of a block of trees when traps were deployed on stakes or poles. Deploying traps in orange jasmine located some distance away from citrus dramatically increased numbers of adult D. citri captured on traps when compared to numbers captured on traps deployed on stakes. Dispersing psyllids might be visually attracted to plants such as orange jasmine, but possibly volatiles associated with jasmine could be explored in an effort to find an attractant for the psyllid. Patt & Sétamou (2010) previously reported that both males and females are attracted to young shoots of orange jasmine.

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Additional research to verify the influence of relative humidity on seasonal dispersal activity by *D. citri* would be advantageous. Although Aubert & Xia (1990) reported that flight activity by *D. citri* was pronounced during warm, windless, sunny afternoons, our analyses did not confirm that flight activity distant from citrus was related to air temperature, wind, or sunlight.

The furthest trap distance from citrus in these studies was 150 m, and adult *D. citri* were captured on traps at this distance. An African psyllid vector of huanglongbing, *Trioza erytreae* (del Guercio), was reported to fly as far as 1.5 km (van den Berg & Deacon, 1988), although it was not known whether this distance was achieved by a single flight. Arakawa & Mivamolo (2007) reported that 4-day-old adult *D. citri* could fly on their own for an average duration of 26.9 min for an average distance of 0.7 km at an average flight speed of 1.6 km h⁻¹. These researchers concluded that the flight ability of *D. citri* was not strong and that intentional long-distance dispersion by this species would consist of repeated short-distance flights. Aubert & Xia (1990) theorized that flying *D. citri* could be transported by wind drifts over 0.5–1 km distances depending on wind speed and duration of sustained flight. *Diaphorina citri* flight activity has been recorded 7 m above ground (5 m above jasmine canopies), high enough for flying adults to be taken into stratiform wind drifts and to be transported distances of from 0.5 to 4.0 km (Aubert, 1990; Aubert & Xia, 1990).

This study revealed that flight activity to or away from citrus by adult male and female *D. citri* can occur at any time of the year, showed that peak flight activity distant from citrus occurred consistently during the spring, and documented flight activity at a distance of 150 m from citrus. It remains to be determined how far adults disperse from citrus and whether long-distance flight activity occurs on a predictable schedule.

**Acknowledgements**

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