Effects of a Particle Film on Biology and Behavior of *Diaphorina citri* (Hemiptera: Psyllidae) and Its Infestations in Citrus

DAVID G. HALL,[1] STEPHEN L. LAPOINTE, AND ERIK J. WENNINGER

USDA–ARS, U.S. Horticultural Research Laboratory, Subtropical Insects Research Unit, 2001 South Rock Road, Fort Pierce, FL 34945

J. Econ. Entomol. 100(3): 847–854 (2007)

ABSTRACT Studies were conducted to investigate the effects of a kaolin-based hydrophilic particle film, Surround WP, on the biology and behavior of the psyllid *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae) and to assess population densities of *D. citri* in citrus subjected to monthly applications of Surround WP. Laboratory investigations indicated a 3% (wt:vol) suspension of Surround WP in water applied directly was not acutely toxic to eggs, older nymphs or adults. Presence of the dried particle film on leaves interfered with the ability of adults to grasp and walk on citrus leaves. During a 30-s period, adults spent an average of 5 s moving on leaves with particle film compared with 16 s on leaves without particle film. When leaves were inverted, a significantly higher percentage of adults fell or flew from treated leaves (53%) than untreated leaves (16%). In a 12-mo study investigating infestations of *D. citri* on citrus treated monthly with Surround WP, cumulative reductions of 78% in adult numbers on mature leaves and of 60% in adult numbers on flush shoots (immature leaves) were observed in treated trees compared with untreated trees. Numbers of eggs and nymphs per flush shoot were reduced by 85 and 78%, respectively, in trees treated with particle film. Reductions in infestation levels of *D. citri* in treated trees were attributed to the negative effects of the particle film on the ability of adults to grasp, move, and oviposit. The suppressive effects of a Surround treatment against adult psyllids were degraded by rain.

KEY WORDS Surround, kaolin, phenology, greening disease, huanglongbing

The Asian psyllid *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae) in Florida is a vector of *Candidatus* Liberibacter asiaticus (Las), a phloem-limited nonculturable bacterium responsible for citrus greening (huanglongbing) disease (Halbert and Manjunath 2004, Hung et al. 2004). Citrus greening is one of the word's most serious diseases of citrus (Bové 2006). *D. citri* was first found in Florida during June 1998 (Tsai et al. 2000) and subsequently spread throughout the state's citrus-growing regions (Michaud 2004). Citrus greening was first found in southern Florida during late August 2005 (Bové 2006). Infestations of *D. citri* cause direct feeding damage to citrus, resulting in distorted, reduced flush growth (Michaud 2004), but the primary economic importance of the psyllid is transmission of citrus greening disease. Citrus trees infected by this devastating disease may only live 5–8 yr, during which time they produce misshapen, bitter-tasting, inedible fruit (Halbert and Manjunath 2004, Bové 2006).

Kaolin-based particle film technology is a relatively new method of controlling arthropod pests and plant diseases (Glenn et al. 1999, Pasqualini et al. 2003). Kaolin is a white, nonabrasive, fine-grained allumino-silicate mineral that is purified and sized so that it easily disperses in water and creates a mineral barrier when sprayed on plants (Pasqualini et al. 2003). Surround WP (Engelhard Corp., Iselin, NJ) is a hydrophilic particle film based on kaolin. An application of Surround WP was shown to suppress infestations of nymph and adult *D. citri* in young citrus trees (McKenzie et al. 2002). Over a 2-wk period after application, the particle film reduced numbers of nymphs by 31% and of adults by 61% compared with untreated trees (extrapolations of data from McKenzie et al. 2002). Because the adult stage is responsible for spreading citrus greening disease from infected to noninfected trees, the reduction in adults on treated trees was notable. Particle films have been shown to be effective to varying degrees in suppressing other insects such as the pear psylla, *Cacopsylla pyricola* Foerster, on pear (*Prunus* spp.) (Puterka et al. 2000); codling moth, *Cydia pomonella* (L.), on apple (*Malus* spp.) (Unruh et al. 2000); boll weevil, *Anthonomus grandis grandis*

This article reports the results of research only. Mention of a trademark or proprietary product is solely for the purpose of providing specific information and does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable.

[1] Corresponding author, e-mail: dhall@ushrl.ars.usda.gov.

Boheman, on cotton, *Gossypium hirsutum* L. (Showler 2002); rosy apple aphid, *Dysaphis plantaginea* (Passerini), on apples (Bürgel et al. 2005); a root weevil *Diaprepes abbreviatus* (L.), on citrus (Lapointe et al. 2006); and silverleaf whitefly, *Bemisia argentifolii* Bellows & Perring, on melon (*Cucumis* spp.) (Liang and Liu 2002).

Sprays of particle film suspensions in water were found to be toxic to adults and nymphs of the pear psylla (Puterka et al. 2005); thus, some mortality may occur among pear psylla exposed to spray during the application of a particle film. Whether a suspension of Surround WP is toxic to *D. citri* was not known. After application and sufficient drying time, the presence of a particle film barrier on plant foliage has been shown to interfere with the ability of insects to settle, move, and oviposit (Unruh et al. 2000, Showler 2002, Liang and Liu 2002, Puterka et al. 2005, Lapointe et al. 2006). Mortality of adult pear psylla was low on foliage treated with particle films because the adults were able to feed through the particle films, but feeding rates were reduced (Puterka et al. 2005). If feeding rates of adult *D. citri* were reduced on citrus with a particle film barrier, acquisition and transmission of the citrus greening disease pathogen also might be reduced. In addition to suppressing infestations of insects, particle films have been shown to enhance the growth of some plants including pear (Puterka et al. 2000), citrus (Lapointe et al. 2006), and pistachio, *Pistacia vera* L. (Saour 2005), and particle films have approval for pest control in organic farming.

Presented here are the results of experiments conducted to investigate the effects of hydrophilic particle film on the biology and behavior of *D. citri* and to assess infestations of *D. citri* in young citrus trees subjected to regular particle film treatments.

Materials and Methods

Laboratory Studies. The insects for the laboratory studies were obtained from a colony established during early 2000 at the USDA–ARS U.S. Horticultural Research Laboratory, Fort Pierce, FL. Originally collected from citrus, the psyllids have since been continuously reared in Plexiglas (0.6- by 0.6- by 0.6-m) or BugDorm-2 cages (MegaView Science Education Services Co., Ltd., Taichung, Taiwan) containing orange jasmine, *Murraya paniculata* (L.) Jack. The colony is maintained by adding new *M. paniculata* plants on a biweekly schedule by using procedures similar to those described by Skelley and Hoy (2004) with no infusion of wild types.

Acute Toxicity to Adults. Adult *D. citri* were sprayed with either a 3% Surround WP suspension in tap water (30 g/liter) or plain tap water and transferred into a cage containing an untreated *Citrus sinensis* L. 'Madame Vinous' (sweet orange) seedling. Three replicates of each treatment were studied with 10 insects per replication. One set of replications was established using females and one set with males (total of 120 insects in the experiment). Each plant was housed in a 3.78-liter clear plastic container with a screened hole in the lid for air circulation. Adults were collected individually in glass vials from the laboratory colony, chilled for 15 min, and then sexed. After all individuals were sexed, they were chilled for 15 min, and 10 individuals of each sex were placed into petri dishes containing filter paper. These individuals were chilled for another 10 min, after which they were removed and sprayed with either water or particle film solution. A trigger sprayer bottle (Qorpak, Bridgeville, PA) was used to deliver the treatment. Immediately after spraying, the psyllids were transferred to one of the caged plants with a small brush. After ≈10 min, each cage was checked to confirm 10 live psyllids were in each cage. They were then transferred to an environmental chamber (25°C, 62% RH, and a photoperiod of 14:10 [L:D] h) for the remainder of the experiment. The caged plants were examined to count live individuals at 4, 24, 96, 192, 264, and 360 h after treatment. Data on percentage adult survival were analyzed using *t*-tests (PROC TTEST; $\alpha = 0.05$) (SAS Institute 2002).

Acute Toxicity to Eggs and Older Nymphs. Adults from the laboratory colony were transferred to potted orange jasmine plants with young flush leaves and allowed 24 h to oviposit. Flush shoots with eggs were then excised from the plants, and the stem of each shoot was inserted into a glass shell vial (8.75 mm in diameter by 50 mm in length) with agar, which provided water to the shoot and support to hold the shoot vertically. The number of eggs on each shoot was counted, and any shoot with <10 eggs was excluded from the experiment. Each shoot was dipped into either a 3% Surround WP suspension (30 g/liter tap water) or plain tap water and allowed to dry before being placed into an open-ended glass tube (185 mm in length, 25 mm in diameter) stoppered with foam plugs. The shoots were held in an environmental chamber (26°C, 75–80% RH, and a photoperiod of 12:12 [L:D] h). The effect of the particle film treatment on egg viability was assessed at 4 and 5 d by counting nymphs and nonviable eggs. Nonviable eggs were identified by lack of embryonic development (eye spots) and/or by a shriveled appearance. The experiment was conducted twice in successive weeks, subjecting five egg-infested shoots to each treatment the first week and seven egg-infested shoots to each treatment the second week. Data on percentage egg hatch were analyzed using a *t*-test (PROC TTEST; $\alpha = 0.05$) (SAS Institute 2002).

Fourth instars were thoroughly wetted with either 3% Surround WP suspension (30 g/liter of tap water) or water only using the triggered bottle sprayer. Six replications of each treatment were studied with 10 insects per replication (total of 120 insects in the experiment). The nymphs were collected individually from the laboratory colony and placed onto filter paper in a petri dish. Immediately after they were sprayed, the nymphs were transferred using a small brush onto flush leaves of a young, potted orange jasmine plant. Each plant was maintained in a 3.8-liter clear plastic container with a screened hole in the lid for air circulation. The caged psyllid nymphs were placed into an environmental chamber (25°C, 55%

RH, and a photoperiod of 14:10 [L:D] h) for 10 d during which they were monitored to determine how many of the nymphs developed to the adult stage. Data on percentages of treated nymphs developing to the adult stage were analyzed using a *t*-test (PROC TTEST; $\alpha = 0.05$) (SAS Institute 2002).

Adult Movement and Ability to Grasp Leaf Surface. Movement by adults and the ability of adults to grasp the surface of leaves with particle film were compared with adult movement and grasping ability on untreated leaves. Both sides of mature citrus leaves (*Citrus macrophylla* Wester) were sprayed to runoff with either 3% Surround WP suspension (30 g/liter tap water) or water only and allowed to dry. A forceps (23 cm) clamped to a ring stand on a laboratory bench was used to hold a leaf horizontally with the upper leaf surface orientated away from the counter top and lower leaf surface facing the counter top. Adult females were chilled and then placed individually onto the upper leaf surface. After an adult began to move, it was allowed to move or settle for 30 s. Total time spent moving by the adult on the upper and lower surfaces was recorded. If the adult flew away from the leaf or moved onto the forceps at any time during the 30 s, that individual was excluded from the analysis and the procedure was repeated with a new female. For those adults on the upper surface at the end of 30 s, the leaf was inverted for 10 s to determine whether the psyllid remained on the leaf, dropped to the countertop, or flew away. The procedure was replicated four times with 20 adult females per replication for both Surround WP-treated and water-treated leaves by using a different adult female each time (160 insects in the experiment). Data on the time adults spent moving on the upper and lower leaf surfaces and on the percentage of adults falling/flying after leaf inversion were analyzed using *t*-tests (PROC TTEST; $\alpha = 0.05$) (SAS Institute 2002).

Field Study. The study was initiated on 18 February 2005 at the USDA–ARS U.S. Horticultural Research Laboratory research farm. Two treatments were applied to young (1–1.5 m in height) 'Hamlin' (*C. sinensis*) trees on the rootstock 'Carrizo' citrange [*C. sinensis* (L.) Osb. × *Poncirus trifoliata* (L.) Raf.]: monthly applications of Surround WP and an untreated check. Individual plots consisted of six trees (three trees on each of two adjacent rows). The experiment followed a randomized complete block design with four replications. The particle-film treatment (30 g Surround WP/liter tap water, sprayed to runoff) was applied using an electric sprayer fitted with a handgun. Infestation levels of adult *D. citri* on each tree per plot were assessed ≈7 d before and after each application. This was accomplished by examining 10 pairs of mature leaves (including the stem between each pair) and 10 flush shoots per tree for adults. On sample dates that 10 flush shoots could not be found on a tree, only the numbers available were examined. The flush shoots examined for adults included young shoots with or without young feather leaves (small, unexpanded, light green leaflets). Numbers of eggs and nymphs on flush shoots (restricted to shoots with at least some feather leaves because adults oviposit exclusively on shoots with feather leaves) were determined by excising one flush shoot per tree, placing it in a sample bag, and returning it to a laboratory for examination under a microscope. If a tree did not have at least one such flush shoot, then a shoot was substituted from another tree from the same plot. When such flush shoots were present only at very low levels in the trees or completely absent, sampling for eggs and nymphs was postponed until the next sample date. Flush shoots excised for examination were taken near the exterior of the tree canopy about midway between the lower and upper canopy extremes. Data were subjected to analysis of variance (ANOVA, PROC GLM) (SAS Institute 2002), and significant differences among means were investigated using the Ryan–Einot–Gabriel–Welsch multiple range test ($\alpha = 0.05$) (SAS Institute 2002).

Data on daily rainfall during the study were obtained from a weather station operated by USDA–ARS at the study site. The influence of rain on infestation levels of adult *D. citri* on trees treated with particle film was investigated. Differences between treated and untreated trees in mean numbers of adult psyllids per mature leaf pair and per flush shoot were computed. Simple linear regressions of mean differences in psyllid densities on cumulative rainfall since the most recent Surround application were performed (PROC GLM) (SAS Institute 2002). Plots of the residuals from the regressions were examined to assess model fit and, if necessary, to select a data transformation.

Table 1. Survival of *D. citri* adults treated with a suspension of particle film (Surround WP) in water

Treatment	Mean % survival after the indicated period					
	4 h	24 h	96 h	192 h	264 h	360 h
Female						
Particle film	93.3a	93.3a	86.7a	83.3a	73.3a	66.7b
Water control	96.7a	96.7a	96.7a	96.7a	93.3a	93.3a
Male						
Particle film	96.7a	93.3a	90.0b	83.3a	73.3a	50.0a
Water control	100.0a	100.0a	100.0a	80.0a	76.7a	60.0a
Over both sexes						
Particle film	95.0a	93.3a	88.3b	83.3a	73.3a	58.3a
Water control	98.3a	98.3a	98.3a	88.3a	85.0a	76.7a

For each sex, means in the same column followed by the same letter are not significantly different ($\alpha = 0.05$; *t*-tests).

Results

Laboratory Studies. *Acute Toxicity to Adults.* There were no significant differences in percentage of survival between females sprayed with particle film suspension and females sprayed with water on any observation date up to 264 h (11 d) after treatment (Table 1). The percentage of surviving females at 360 h (15 d) after treatment was significantly lower for females treated with particle film suspension (apparent mortality rate of 26.6%) ($t = 2.83$, df = 4, Pr > t = 0.047). Mean percentage of survival of males treated

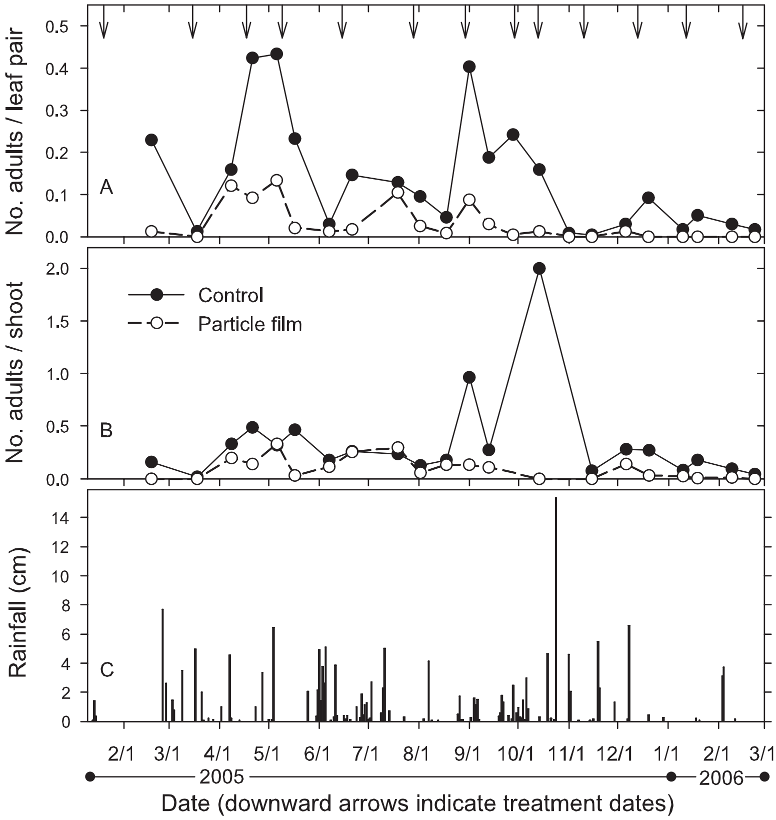

Fig. 1. Effect of regular applications of Surround WP particle film on infestations of *D. citri* in citrus and rainfall events during the study. (A) Mean number of adults per pair of mature citrus leaves. (B) Mean number of adults per citrus flush shoot (with or without young feather leaves) (no flush was present in the trees on 28 September or 1 November 2006). (C) Rainfall events.

with particle film suspension was significantly lower than untreated males on one observation date (96 h after treatment) (t = infinity, df = 4, Pr > t = <0.0001), but no significant differences were found on any other date nor at the end of the study (Table 1). Among females subjected to the water control treatment, the percentage of females surviving at the end of the study (360 h) was 93.3% (Table 1). Among males subjected to the water control treatment, survival was 100% to the 96 h observation but declined thereafter, dropping to 60% survival by the end of the study.

Acute Toxicity to Eggs and Older Nymphs. Pretreatment means ± SEM of 36.7 ± 4.1 and 36.8 ± 7.6 eggs per flush shoot were present on the shoots treated with particle film suspension and water, respectively. Mean ± SEM percentage of egg hatch among eggs sprayed with particle film suspension (76.9 ± 6.1%) was not significantly different than the percentage of hatch of eggs sprayed with water (85.2 ± 2.7%) (t = 1.23, df = 22, Pr > t = 0.231). Averages of 86.7 ± 4.9 or 78.3 ± 4.0% of the fourth instars treated with water or particle film suspension, respectively, developed to the adult stage. There was no significant difference between these mean percentages (t = 1.31, df = 10, Pr > t = 0.220).

Adult Movement and Ability to Grasp Leaf Surface. Females spent significantly more time walking on the upper surface of leaves without particle film (14.0 ± 1.1s) than on leaves with particle film (4.7 ± 0.7 s) (t = 7.50, df = 158, Pr > t <0.0001). Females spent less time moving on the lower leaf surface (1.9 ± 1.1 s) than on the upper surface (14.0 ± 1.1 s) when placed on leaves without particle film. Females on leaves with particle film did not attempt to walk from the upper to lower surface (t = 3.95, df = 158, Pr > t = 0.0001). Upon leaf inversion, a significantly higher percentage of adults fell or flew when they were on leaves with particle film (52.5 ± 7.2%) than when they were on leaves without particle film (16.3 ± 4.7%) (t = −6.56, df = 6, Pr > t = 0.0006).

Field Study. In untreated citrus trees, peak numbers of adult *D. citri* on mature leaves were observed during mid-February, April/May, and September/early October 2005 (Fig. 1A). Means as large as 0.44 adults per pair of mature leaves were observed in these trees. The phenology of adult *D. citri* on trees receiving particle film applications was generally similar, but mean densities of adults per pair of mature leaves were reduced (Table 2). Over the course of the study, a cumulative total of 166 adults was observed among samples taken

Table 2. Mean numbers of *D. citri* eggs, nymphs, and adults observed on young citrus trees subjected to monthly applications of Surround WP particle film (12-mo study; means are averages over the entire season)

Treatment	No. adults/ pair mature leaves[a]	No. adults/ flush shoot[b]	No. eggs/ flush shoot[c]	No. nymphs/ flush shoot[d]
Particle film	0.03b	0.10b	3.7b	4.6b
Untreated control	0.14a	0.26a	23.8a	21.1a

Means in each column followed by the same letter are not significantly different ($\alpha = 0.05$; Ryan–Einot–Gabriel–Welsch multiple range test).

[a] $F = 40.02$; df = 11,019; Pr > F = <0.0001.

[b] $F = 21.28$; df = 9,127; Pr > F = <0.0001.

[c] $F = 17.34$; df = 503; Pr > F = <0.0001.

[d] $F = 11.27$; df = 503; Pr > F = <0.0001.

in treated trees versus 762 in untreated trees. This difference constituted an overall 78% reduction in adult densities on mature leaves in citrus trees under the particle film program.

Flush shoot samples from untreated trees indicated that peak numbers of adults per flush shoot occurred during late August and early October, with moderate numbers during April and May (Fig. 1B). In Surround-treated trees, low numbers of adults per flush shoot were observed during late August and none during early October. Significantly fewer adults per flush shoot were observed in treated trees than in untreated trees (Table 2). Over the course of the study, a cumulative total of 476 adults was observed on flush shoots from treated trees compared with 1,176 adults on flush shoots from untreated trees. Infestations of adults on flush shoots in Surround-treated trees over the course of the study were therefore reduced by 60% compared with untreated trees.

The seasonal profiles of adults (Fig. 2A), eggs (Fig. 2B), and nymphs (Fig. 2C) on flush shoots with feather flush from Surround-treated trees were generally similar to their occurrence on shoots from trees not under the program but at reduced levels. Adults were observed on flush shoots regardless of the presence of feather leaves (Fig. 1B), but eggs were observed exclusively, and nymphs primarily, on flush with feather leaves (Fig. 2B and C). The largest numbers of eggs observed on trees without particle film occurred during mid-May and averaged 60 ± 9 eggs per shoot, with a lesser peak during mid-August reaching a mean of 43 ± 11 eggs per shoot. Overall, the average number of eggs observed per flush shoot was significantly lower in Surround-treated trees (Table 2). Nymphs were most abundant on flushes during

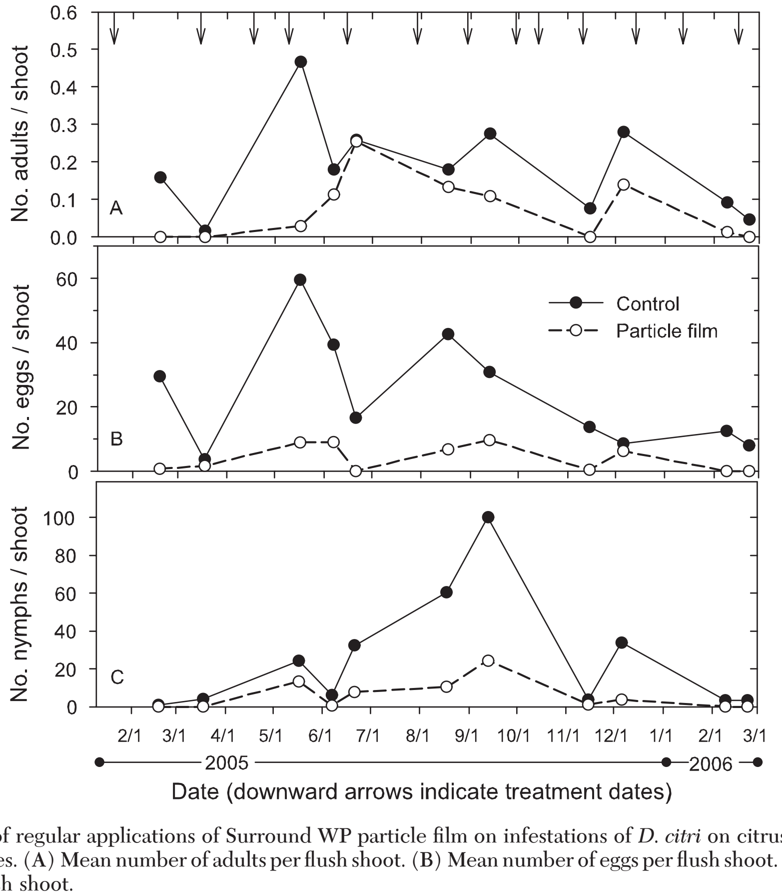

Fig. 2. Effect of regular applications of Surround WP particle film on infestations of *D. citri* on citrus flush shoots with young feather leaves. (A) Mean number of adults per flush shoot. (B) Mean number of eggs per flush shoot. (C) Mean number of nymphs per flush shoot.

September, reaching an average of 100 ± 28 per flush shoot in untreated trees but only 24 ± 12 per flush shoot in treated trees. Over the entire study, the average number of nymphs per flush shoot in Surround-treated trees was significantly less than in untreated trees (Table 2). A cumulative total of 927 eggs was observed on flush shoots from treated trees and 5,997 from untreated trees. The cumulative total for nymphs was 1,170 and 5,326 in treated and untreated trees, respectively. These differences in numbers of eggs and nymphs constituted overall reductions of 85 and 78%, respectively, in trees under the particle film program.

In total, 163.6 cm of rainfall over 110 rainfall events occurred during the study (Fig. 1C). Considerable amounts of rain fell during the time between the following successive treatment sample dates: 14 March–8 April (13.1 cm), 15 April–6 May (10.9 cm), 10 May–7 June (22.4 cm), 14 June–19 July (18.6 cm), September 27–14 October (10.5 cm), and 12 October–1 November (25.2 cm). Densities of adult *D. citri* on mature leaf samples were significantly lower in Surround-treated trees than in untreated trees on 16 of 23 sample dates, and cumulative rainfall after the preceding Surround treatment averaged 2.5 ± 1.0 cm for these 16 sample dates. Densities of adult *D. citri* on mature leaf samples were not significantly different between treated and untreated trees on seven sample dates, and cumulative rainfall after the preceding Surround treatment averaged 13.4 ± 3.5 cm for these seven sample dates. Regression analysis indicated differences (Y) in the mean number of adult *D. citri* per mature leaf sample (data transformed to square roots) between treated and untreated trees decreased as cumulative rainfall (cm) (X) increased after a particle film treatment (rainfall data transformed to square roots): $Y = 0.27 - 0.04X$ ($F = 12.85$, df = 22, $Pr > F = 0.0017$; $r^2 = 0.38$). Differences (Y) in the mean number of adult *D. citri* per citrus flush shoot sample (data transformed to square roots) between treated and untreated trees also decreased as cumulative rainfall (centimeters) (X) increased after a particle film treatment (rainfall data transformed to square roots): $Y = 0.42 - 0.10X$ ($F = 6.89$, df = 20, $Pr > F = 0.0167$; $r^2 = 0.27$).

Discussion

Laboratory Studies. Tsai and Lui (2000) reported the average adult female lifespan of *D. citri* on citrus species to be 40–44 d at 25°C. Pande (1971) observed that females lived a few days longer than males. The initial age of the psyllids used in our study of acute toxicity to adults was unknown. Nevertheless, mean survival in all treatments was ≥50% and exceeded 90% for females subjected to the water control. Compared with the control, the Surround treatment was nontoxic to adult males and only slightly toxic to adult females after prolonged exposure (15 d). These results differed from results of research by Puterka et al. (2005) on pear psylla, in which significant percentages of adult females treated with 3% particle-film suspension were killed (48% mortality at 72 h after treatment). Reasons for the different results are not known, but differences might be related to differences in body size of the two psyllid species. Adult pear psylla has a summer form (2.0–2.75 mm in length; Tuthill 1943) that is smaller than *D. citri* (3.0–4.0 mm in length, Mead 1976) and a winter form (3.3–4.0 mm; Tuthill 1943) that is similar in size to adult *D. citri.* Puterka et al. (2005) did not report the adult form they studied.

We observed no effect of applications of Surround on viability of *D. citri* eggs. Particle films have been shown to lack ovicidal activity against other insects, including pear psylla (Puterka et al. 2005); obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Knight et al. 2000); and codling moth (Unruh et al. 2000). Our study also showed that Surround applications are nontoxic to late instars. Puterka et al. (2005) reported significant mortality of pear psylla nymphs when they were treated during the first instar with Surround suspension. We did not include early instars in our laboratory studies, leaving open the possibility that *D. citri* nymphs exposed during early instars to Surround sprays could be killed.

The presence of particle film on citrus leaves inhibited movement of adult females on the leaf surface and the ability of adults to grasp the surface of treated leaves. Achieving equivalent levels of movement/grasping inhibition under field conditions would be contingent upon thorough spray coverage and high rates of deposition. Puterka et al. (2005) reported that the presence of particle film on pear leaves inhibited movement of pear psylla and the insect's ability to grasp the leaf surface, and they reported reduced oviposition on treated leaves. Puterka et al. (2005) proposed that reduced oviposition by pear psylla on pear leaves treated with particle film was a consequence of the film structurally modifying or hiding the plant surface relief or through negative behavior stimuli where females determine that particle film-treated foliage is a poor host. Reduced oviposition may also be a consequence of females not being able to grasp treated plant surfaces. The deterrence of insect settling and oviposition has been noted as the primary and most obvious action of particle films on insect behavior, regardless of the film type or formulation (Glenn and Puterka 2005, Lapointe et al. 2006). For *D. citri,* adult females oviposit exclusively on new, unexpanded leaves, and such leaves may be generated soon after an application of particle film suspension. These leaves would not have a protective layer of particle film and would be vulnerable to infestation until they mature or are treated with particle film. Therefore, optimal protection of foliage from feeding by *D. citri* will require applications timed to coincide with the appearance of vulnerable flush.

Field Study. Based on the results of the laboratory studies and in light of the reported effects of particle films on other psyllid species (Pasqualini et al. 2003, Puterka et al. 2005), we conclude that the reductions in infestation levels of *D. citri* we observed in Surround-treated citrus trees were primarily due to reduced adult movement, settling, and oviposition. Additionally, adults may have been less attracted to citrus trees treated with particle film due to changes in color of the foliage (whitish residues of particle film). The light-reflecting properties of particle films may alter an arthropod's perception of a host plant (Glenn et al. 1999) and influence insect infestations (Showler 2002). Adult pear psylla can survive on pear trees treated with particle film, successfully feeding on leaves through the film but at reduced rates (Puterka et al. 2005). If applicable to *D. citri*, reduced feeding could decrease transmission rates of citrus greening disease. Maintaining a particle film on young citrus trees might therefore assist in managing citrus greening disease by reducing psyllid densities and transmission of the bacterium.

The suppressive effects of a Surround treatment against adult psyllids decreased as rainfall increased. Low amounts of rainfall (e.g., <5 cm cumulative rain) interfered little with the suppressive effects of the particle film on infestations of adult psyllids, whereas large amounts of rain (e.g., >15 cm of cumulative rain) completely negated suppression. Rain has been shown to interfere with protection by Surround particle film in citrus from infestations of the root weevil *D. abbreviatus* (Lapointe et al. 2006). These researchers suggested that significant protection from oviposition and feeding by *D. abbreviatus* during the rainy season would require more frequent applications of particle film. In our study, visual examination of residues indicated that the particle film may not adhere as well to flush leaves as to mature leaves. Whether rains removed more particle film from flush than from mature leaves was not investigated.

The approximate cost of the particle film (Surround WP) at the time this report was prepared was US$1.28 per kg. At a 3% concentration and spray volume of 935 liters spray per ha (100 gal/acre), an application would require 28 kg/ha Surround at a cost of US$36. Based on 2004 production costs, an application by airblast sprayer would cost ≈US$54 per ha (Muraro et al. 2004), bringing the cost of the Surround treatment to ≈US$90 per ha. This is less expensive than the cost of most conventional insecticide treatments and comparable with the cost of most spray oil treatments (e.g., Muraro et al. 2004). Total grove care expenses for mature Valencia oranges grown for the process market averaged US$1910 during 2004 (Muraro et al. 2004). A single application of Surround would have increased these grove care expenses by ≈5%. A seasonal particle film program consisting of monthly applications of Surround would have increased these annual expenses by >50%. Because Surround WP can be tank-mixed with many other grove chemicals except oils, some savings would be achieved by adding Surround to other sprays. The cost of a seasonal particle film program might be reduced if coupled with a scouting program to monitor adult population densities. Infestations of *D. citri* can develop at any time of the year in citrus depending on environmental and factors and presence or absence of flush, however, populations of adults are sometimes present at low or undetectable levels, particularly during winter (D.G.H., unpublished data). Applications of a particle film could be discontinued during such periods. Whether the reductions in psyllid levels achieved under a program of monthly particle film applications would be effective with respect to reducing spread of citrus greening disease remains to be assessed. Particle film applications might be a viable component of a greening disease management program in citrus grown for the organic market. Because dust particles are well known to be disruptive of some natural enemies (DeBach 1979) and may inflate problems with some pest species populations that are regulated by natural enemies (Knight et al. 2000), further evaluations of a particle film program for *D. citri* should include assessment of the impacts of single or multiple spray programs on other citrus pests and their natural enemies (Knight et al. 2000).

Acknowledgments

We thank the following individuals for contributions to this project: Matt Hentz, Rocco Alessandro, Kathy Moulton, Anna Sara Hill and Chris Knox (USDA–ARS, U.S. Horticultural Research Laboratory, Fort Pierce, FL).

References Cited

Bové, J. M. 2006. Huanglongbing: a destructive, newly-emerging, century-old disease of citrus. J. Plant Pathol. 88: 7–37.

Bürgel, K., C. Daniel, and E. Wyss. 2005. Effects of autumn kaolin treatments on the rosy apple aphid, *Dysaphis plantaginea* (Pass.) and possible modes of action. J. Appl. Entomol. 129: 311–314.

DeBach, P. 1979. Biological control by natural enemies. Cambridge University Press, New York.

Glenn, D. M., G. J. Puterka, T. Vanderzwet, R. E. Byers, and C. Feldhake. 1999. Hydrophobic particle films: a new paradigm for suppression of arthropod pests and plant diseases. J. Econ. Entomol. 92: 759–771.

Glenn, D. M., and G. J. Puterka. 2005. Particle films: a new technology for agriculture, pp. 1–45. *In* J. Janick [ed.], Horticultural reviews, vol. 31. Wiley, Hoboken, NJ.

Halbert, S. E., and K. L. Manjunath. 2004. Asian citrus psyllid (Sternorrhyncha: Psyllidae) and greening disease of citrus: a literature review and assessment of risk in Florida. Fla. Entomol. 87: 330–353.

Hung, T. H., S. C. Hung, C. N. Chen, M. H. Hsu, and H. J. Su. 2004. Detection by PCR of Candidatus Liberibacter asiaticus, the bacterium causing citrus huanglongbing in vector psyllids: application to the study of vector-pathogen relationships. Plant Pathol. 53: 96–102.

Knight, A. L., T. R. Unruh, B. A. Christianson, G. J. Puterka, and D. M. Glenn. 2000. Effects of a kaolin-based particle film on obliquebanded leafroller (Lepidoptera: Tortricidae). J. Econ. Entomol. 93: 744–749.

Lapointe, S. L., C. L. McKenzie, and D. G. Hall. 2006. Reduced oviposition by *Diaprepes abbreviatus* (L.) (Coleoptera: Curculionidae) and growth enhancement of citrus by Surround particle film. J. Econ. Entomol. 99: 109–116.

Liang, G., and T.-X. Liu. 2002. Repellency of a kaolin particle film, Surround, and a mineral oil, sunspray oil, to silverleaf whitefly (Homoptera: Aleyrodidae) on melon in the laboratory. J. Econ. Entomol. 95: 317–324.

McKenzie, C. L., S. L. Lapointe, W. B. Hunter, and G. J. Puterka. 2002. Efficacy of Surround for control of Asian citrus psyllid on citrus, 2000. Arthropod Management Tests 27: D8.

Mead, F. W. 1976. The Asiatic citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera: Psyllidae). Entomology Circular 180. Florida Department of Agriculture and Consumer Services, Division of Plant Industry, Gainesville, FL.

Michaud, J. P. 2004. Natural mortality of Asian citris psyllid (Homoptera: Psyllidae) in central Florida. Biol. Control 29: 260–269.

Muraro, R. P., W. G. Hartt, and W. C. Oswalt. 2004. Budgeting costs and returns for central Florida citrus production, 2003–2004. EDIS FE526. Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. (http://edis.ifas.ufl.edu/FE526).

Pande, Y. D. 1971. Biology of citrus psylla, *Diaphorina citri* Kuw. (Hemiptera: Psyllidae). Israel J. Entomol. 6: 307–311.

Pasqualini, E., S. Civolani, and L. C. Grappadelli. 2003. Particle film technology: approach for a biorational control of *Cacopsylla pyri* (Rhynchota: Psyllidae) in northern Italy. Bull. Insectol. 55: 39–42.

Puterka, G. J., D. M. Glenn, D. G. Sekutowski, T. R. Unruh, and S. K. Jones. 2000. Progress toward liquid formulations of particle films for insect and disease control in pear. Environ. Entomol. 29: 329–339.

Puterka, G. J., D. M. Glenn, and R. C. Pluta. 2005. Action of particle films on the biology and behavior of pear psylla (Homoptera: Psyllidae). J. Econ. Entomol. 98: 2079–2088.

Saour, G. 2005. Efficacy of kaolin particle film and selected synthetic insecticides against pistachio psyllid *Agonoscena targionii* (Homoptera: Psyllidae) infestation. Crop Prot. 24: 711–717.

SAS Institute. 2002. SAS procedure's guide, version 9. SAS Institute, Cary, NC.

Showler, A. T. 2002. Effects of kaolin-based particle film application on boll weevil (Coleoptera: Curculionidae) injury to cotton. J. Econ. Entomol. 95: 754–762.

Skelley, L. H., and M. A. Hoy. 2004. A synchronous rearing method for the Asian citrus psyllid and its parasitoids in quarantine. Biol. Control 29: 14–23.

Tsai, J. H., and Y. H. Liu. 2000. Biology of *Diaphorina citri* (Homoptera: Psyllidae) on four host plants. J. Econ. Entomol. 93: 1721–1725.

Tsai, J. H., J. J. Wang, and Y. H. Liu. 2000. Sampling of *Diaphorina citri* (Homoptera: Psyllidae) on orange jessamine in southern Florida. Fla. Entomol. 83: 446–459.

Tuthill, L. D. 1943. The psyllids of America North of Mexico (Psyllidae: Homoptera). Iowa State Coll. J. Sci. 17: 443–660.

Unruh, T. R., A. L. Knight, J. Upton, D. M. Glenn, and G. J. Puterka. 2000. Particle films for suppression of codling moth (Lepidoptera: Tortricidae) in apple and pear orchards. J. Econ. Entomol. 93: 737–743.

Received 1 December 2006; accepted 20 January 2007.