Reduced Oviposition by *Diaprepes abbreviatus* (Coleoptera: Curculionidae) and Growth Enhancement of Citrus by Surround Particle Film

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ABSTRACT Regularly applied sprays of a particle film, Surround WP, greatly enhanced the growth of citrus trees on a poorly drained Winder soil at Fort Pierce, FL. After 3 yr of applications every 3 or 4 wk, Surround-treated trees had at least 5 times the mass, 6 times the canopy volume, and ≈4 times the cross-sectional area of the tree stems at the graft union compared with untreated trees. The larger Surround-treated trees attracted a higher number of adult weevil *Diaprepes abbreviatus* (L.) and to a lesser extent citrus root weevil, *Pachnaeus litus* (Germar), per tree, but there was an equivalent number of egg masses per tree compared with the control trees. The number of egg masses per female weevil oviposited on Surround-treated trees was significantly less than either the control trees or trees treated biannually with an entomopathogenic nematode, BioVector. The number of larvae per tree recovered from the roots of excavated trees was greater from trees treated with Surround once every 3 wk compared with control trees. The data suggest that Surround particle film greatly enhanced the growth of citrus trees grown in a poorly drained soil. The reduction in oviposition by *D. abbreviatus* was insufficient to significantly reduce the number of root weevil larvae per tree feeding on the roots. However, the more vigorous trees resulting from Surround applications may be more resistant or tolerant to root weevil feeding.

KEY WORDS citrus, *Diaprepes abbreviatus*, kaolin, oviposition, particle film

KAOLIN-BASED PARTICLE FILMS were developed for horticultural applications as an environmentally benign method to suppress arthropod pests and plant diseases (Glenn et al. 1999). Since the commercialization of a wettable powder formulation (Surround WP, Engelhard Corp., Iselin, NJ), this product has been examined for applications against pests of temperate fruit trees (Knight et al. 2000, Puterka et al. 2000, Unruh et al. 2000), boll weevil on cotton (Showler 2002), whitefly on melons (Liang and Liu 2002), thrips on lemons (Kerns and Wright 2000), and other pests. The value of the film includes suppression of insect feeding and oviposition, and beneficial effects on carbon assimilation, leaf temperature, and fruit yield of fruit trees in semiarid and subhumid environments (Glenn et al. 2001). Particle film technology seems especially well suited for use in areas of low rainfall where leaf residues of the product can be maintained without frequent reapplication. Use of particle films in the humid subtropical environment of Florida citrus groves may be limited by removal by rain and undesirable effects on secondary pests (Lapointe 2000, 2005).

The root weevil *Diaprepes abbreviatus* (L.) continues to be a major pest of citrus in Florida dating from its introduction from the Caribbean to the state in the early 1960s (Woodruff 1964). It has now spread to Texas (Texas Department of Agriculture 2001) and would present a serious threat to citriculture and fruit and ornamental crops in California were it to become established in that state (Simpson et al. 1996). Larvae of this species are a primary concern of Florida citrus producers because of the destructive habits of *D. abbreviatus,* and the difficulty of detecting and controlling soil-inhabiting larvae in general. Larvae and adults of *D. abbreviatus* are highly polyphagous, feeding on the roots and leaves, respectively, of many wild and cultivated plant species (Simpson et al. 1996). Oviposition also occurs on many plant species. Oviposition and feeding by adult *D. abbreviatus* were reduced on citrus leaves treated with Surround in greenhouse trials (Lapointe 2000, 2005). Based on the promise of those experiments, we established a 3-yr field study to look at the effects of Surround applications on citrus growth and oviposition and larval infestation by *D. abbreviatus.*

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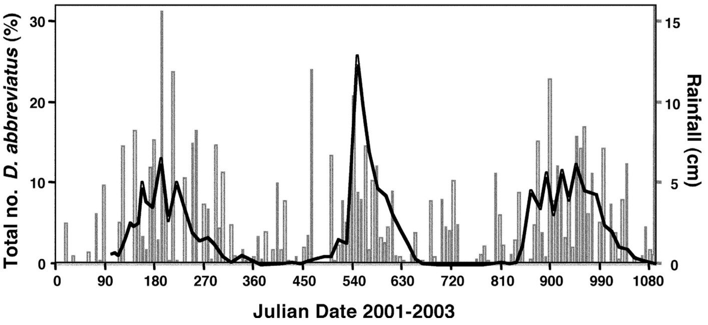

Fig. 1. Seasonal abundance as a percentage of total annual abundance of adults of *D. abbreviatus* (line), and total weekly rainfall (columns) over three years at Ft. Pierce, FL. Day 1, 1 January 2001.

Materials and Methods

Trees. In total, 600 budded citrus trees (*Citrus sinensis*'Midsweet' on *Citrus volkameriana*'Volkamer lemon') were planted in February 2001 at the University of Florida's Indian River Research and Education Center, Fort Pierce, FL. Budded trees (≈30 cm in height) were planted at 1.5-m intervals within single bed rows or approximately triple the recommended density for commercial groves. The grove was located on a poorly drained hydric (Winder) soil, subject to seasonal flooding for short periods. All trees were fertilized monthly with 113 g per tree during 2001 and 150 g per tree of 10–10-10 with minor nutrients during 2002. During 2003, trees received 680 g per tree of 6–6-6 (N–P–K). Trees were watered by microjet irrigation as needed. A randomized block design was used, blocked on a suspected east-west gradient in soil drainage. Replicates consisted of 30 trees in two rows, 15 per row with three border trees between treatments as buffers to control for overspray of Surround. Treatments included a control treatment (no insect control), biannual (spring and fall) applications of an entomopathogenic nematode (BioVector, Certis USA, Columbia, MD) (40,000 nematodes per 930 cm^2 or ≈250,000 nematodes per tree) and two frequencies of foliar application of Surround WP, a commercial kaolin formulation (Engelhard Corp., Iselin, NJ). Without prior knowledge of appropriate frequency of application of this material to citrus, we applied a 3% suspension as a foliar spray at 3-wk intervals in one treatment and at 4-wk intervals in a separate treatment beginning in February 2001 and continuing through December 2003.

Growth Measurements. The diameter of the stem of each tree at 5 cm above and 5 cm below the graft union, and canopy volume, were measured 11 times beginning 57 d after the study was initiated and at ≈90-d intervals thereafter over 3 yr. The cross-sectional area of each tree stem was computed based on the diameter. Canopy volume was calculated as the product of tree height (less the height of the lower canopy edge), and the widest dimensions through the center of the canopy along the east-west and north-south axes of the canopy. Stem diameter was measured with digital calipers. At the end of each year, destructively sampled trees (n = 40) were taken to a laboratory and weighed. The stem was severed to separate scion from rootstock and the two portions were weighed separately. Fruit were harvested at the end of the second and third year of the study. The number of fruit per tree was recorded.

Insect Counts. Trees were inspected biweekly by carefully examining all foliage and then gently shaking the tree to dislodge weevils. We recorded the number of adult *D. abbreviatus* and the citrus root weevil, *Pachnaeus litus* (Germar), present on each tree, and the number of weevil egg masses. Weevils were examined to determine sex and then replaced on the respective tree. Egg masses of *D. abbreviatus* and *P. litus* are indistinguishable in the field (Weathersbee et al. 2003), and adults and larvae of these species have similar habits. Fewer than 10% of the root weevils observed over three seasons were *P. litus.* When trees died during the year, the data for number of egg masses per tree and number of adults per tree were eliminated from the data set for those parameters. However, the data for number of egg masses per adult female weevil (*D. abbreviatus* and *P. litus*) were retained for trees that died during the course of the season.

Adult emergence patterns were examined by plotting the number of adult *D. abbreviatus* counted during each biweekly sample as a percentage of the total yearly count (Fig. 1). Rainfall data were downloaded from the Florida Automated Weather Network Web site for the Ft. Pierce site (http://fawn.ifas.ufl.edu/).

To determine the number of root weevil larvae (*D. abbreviatus* and *P. litus*) infesting roots and to assess root damage, every third tree (a total of 10 trees per replicate) was destructively sampled in February 2002. Of the remaining trees, every other tree (a total of 10 trees per replicate) was destructively sampled in February 2003. The remaining 10 trees per replicate were destructively sampled in March 2004. Sampled trees were manually uprooted using shovels. Roots and their associated soil were separated by hand. The roots, soil, and the soil remaining within the root zone (defined as a cylinder of soil with diameter equal to the diameter of the tree canopy and an average depth of 30 cm) were examined for the presence of root

Table 1. Mean ± SEM cumulative number of adult weevils (*D. abbreviatus* and *P. litus*) per tree, cumulative number of egg masses per tree, and number of egg masses per adult female weevil (*D. abbreviatus* and *P. litus*) on citrus sprayed with Surround particle film at 3- or 4-wk intervals, biannual applications of anentomopathogenic nematode (BioVector), or no treatment (control)

	Yr			Total
	2001	2002	2003	
Cumulative no. adults/tree[a]				
Control	4.1 ± 0.8a	4.2 ± 1.0a	7.8 ± 3.3a	17.5 ± 3.2a
BioVector	3.6 ± 0.5a	7.3 ± 2.4ab	8.7 ± 2.1ab	19.6 ± 4.4a
Surround,4 wk	3.1 ± 0.5a	14.3 ± 2.8b	18.6 ± 2.8c	36.0 ± 5.6b
Surround,3 wk	2.8 ± 0.1a	13.8 ± 2.9b	15.5 ± 1.7bc	32.0 ± 4.5b
Cumulative no. egg masses/tree[a]				
BioVector	1.3 ± 0.4a	1.6 ± 0.7a	4.5 ± 0.5a	7.3 ± 1.3a
Control	1.0 ± 0.3a	0.7 ± 0.2a	3.0 ± 0.9a	5.1 ± 1.1ab
Surround, 4 wk	0.6 ± 0.2a	0.9 ± 0.1a	2.3 ± 0.8a	3.8 ± 1.0b
Surround, 3 wk	0.4 ± 0.1a	0.5 ± 0.2a	1.8 ± 0.4a	2.7 ± 0.6b
No. egg masses/female weevil[a]				
BioVector	0.81 ± 0.12a	0.90 ± 0.24a	1.83 ± 0.67a	1.16 ± 0.23a
Control	0.69 ± 0.19ab	0.35 ± 0.09b	1.06 ± 0.27ab	0.71 ± 0.12b
Surround, 4 wk	0.42 ± 0.10b	0.18 ± 0.04b	0.36 ± 0.11c	0.33 ± 0.05c
Surround, 3 wk	0.40 ± 0.09b	0.12 ± 0.03b	0.45 ± 0.13bc	0.33 ± 0.06c

[a] For each parameter, means within columns followed by different letters are significantly different, $\alpha = 0.05$ (Fisher's protected LSD after a significant ANOVA).

weevil larvae (*D. abbreviatus* and *P. litus*) for a minimum of 3 min by two field workers. Larvae were collected in vials and returned to the laboratory where they were weighed within 4 h of excavation.

Statistical Analyses. Data were analyzed using analysis of variance (ANOVA). To normalize residuals before analysis, insect counts (number of adults per tree and number of egg masses per tree) and number of fruit harvested were transformed using a natural log $(x + 1)$. Means were compared by Fisher's protected least significant difference (LSD) test after a significant F-test at $\alpha = 0.05$ (Abacus Concepts 1996). Although tests of significance were based on transformed data, only untransformed data are presented. Differences in tree growth between scion and rootstock and among the four treatments were investigated using regression analyses. Trunk cross-sectional area measurements over time for each scion/rootstock-treatment combination were fitted to linear and quadratic models (PROC GLM, SAS Institute 1999), and a common model was selected that best described growth increases based on each measurement. The slopes of the regression models were then compared using 95% confidence intervals.

Results

Emergence Pattern of Adults. Adults were observed in the field between April and November 2001 through 2003 (Fig. 1). Emergence patterns were similar during 2001 and 2003 and consisted of a fairly continuous emergence over the summer. During 2002, a single large peak of emergence occurred during late June–early July, whereas in 2001 and 2003, onset of adult emergence commenced in May (Fig. 1). Total rainfall and rainfall distribution were similar in 2001 (127.3 cm) and 2003 (127.2 cm). In 2002, total rainfall was 115.3 cm, and the temporal distribution of rain was characterized by a period before adult emergence from 13 April (day 468) through 16 May (day 501) during which no rainfall was recorded (Fig. 1). The total number of adult root weevils counted over 3 yr was 6,125 of which 5,537 (90.4%) were *D. abbreviatus* and 588 (9.6%) were *P. litus*. During 2001, we observed 1,384 *D. abbreviatus* on 480 trees, 2,723 on 320 trees during 2002, and 1,430 on 160 trees during 2003. The sex ratio (female/male) for *D. abbreviatus* was consistently male-biased in 2001 (0.80), 2002 (0.68), and 2003 (0.65) and cumulatively (0.70).

Adult Counts and Oviposition. There was no significant difference between treatments for the cumulative number of adult weevils (*D. abbreviatus* and *P. litus*) observed per tree during 2001 ($F = 0.96$; df = 3, 12; $P = 0.444$). Treatment effects were detected for the cumulative number of adult weevils per tree during 2002 ($F = 4.54$; df = 3, 12; $P = 0.024$), 2003 ($F = 5.00$; df = 3, 11; $P = 0.027$), and totaled over 3 yr ($F = 4.37$; df = 3, 11; $P = 0.030$) (Table 1). More weevils were observed on Surround-treated trees compared with control trees during 2002, 2003, and totaled over the 3 yr (Table 1). The cumulative number of adult weevils observed on trees receiving BioVector applications was not significantly different from the number on controls trees throughout the experiment (Table 1 and Fig. 2).

There was no significant effect of treatment on the cumulative number of egg masses observed per tree during 2001 ($F = 1.87$; df = 3, 12; $P = 0.189$), 2002 ($F = 0.86$; df = 3, 12; $P = 0.487$), and 2003 ($F = 3.08$; df = 3, 11; $P = 0.073$) (Table 1). Treatment effects were detected for the cumulative number of egg masses per tree totaled over 3 yr ($F = 3.93$; df = 3, 11; $P = 0.0395$). The cumulative number of egg masses per tree summed over 3 yr was significantly greater on trees treated with BioVector compared with Surround-treated trees (Table 1).

Treatment effects were detected for the mean number of egg masses per female weevil (*D. abbreviatus* and *P. litus*) during 2001 ($F = 3.38$; df = 3, 78; $P = 0.023$), 2002 ($F = 8.11$; df = 3, 63; $P < 0.0001$), 2003

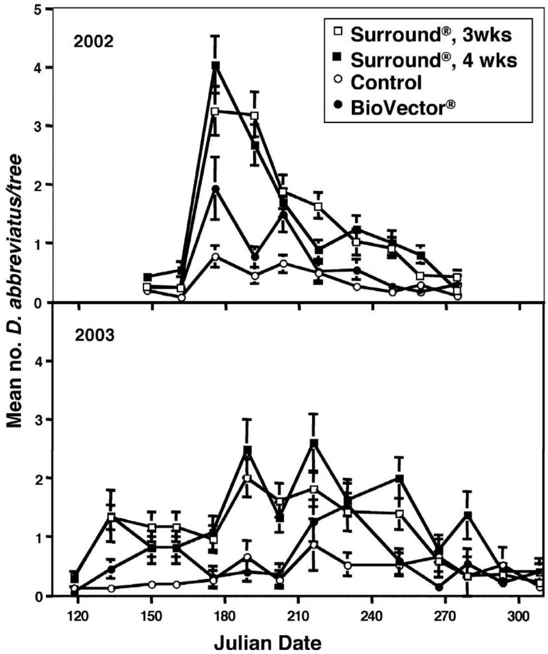

Fig. 2. Mean ± SEM number of adult *D. abbreviatus* observed during the second and third years of a field study on foliage of citrus trees that received Surround WP particle film sprays at 3- or 4-wk intervals, biannual applications of an entomopathogenic nematode (BioVector), or no weevil control treatment (control).

($F = 4.34$; df = 3, 66; $P = 0.008$), and totaled over 3 yr ($F = 12.76$; df = 3, 215; $P < 0.0001$). The number of egg masses per female weevil was greater on BioVector-treated trees compared with the Surround-treated trees during all years and cumulatively (Table 1). The number of egg masses per female weevil was smaller on Surround-treated trees compared with the control trees during 2002 and cumulatively (Table 1).

Tree Growth and Fruit Yield. Trees treated with Surround grew faster and attained greater height and larger stems compared with untreated trees and BioVector-treated trees (Tables 2 and 3; Fig. 3). The weight of the rootstock portion of Surround-treated trees was significantly greater than that of BioVector-treated and control trees at the end of 2001 ($F = 17.94$; df = 3, 154; $P < 0.0001$), 2002 ($F = 35.74$; df = 3, 126; $P < 0.0001$), and 2003 ($F = 18.30$; df = 3, 72; $P < 0.0001$). At the end of the experiment in 2003, the weight of the rootstock portion of Surround-treated trees was between 5.0 and 5.6 times that of control trees. The weight of the scion portion of Surround-treated trees was also significantly greater than that of BioVector-treated and control trees at the end of 2001 ($F = 16.13$; df = 3, 154; $P < 0.0001$), 2002 ($F = 33.42$; df = 3, 126; $P < 0.0001$), and 2003 ($F = 15.52$; df = 3, 72; $P < 0.0001$). At the end of the experiment in 2003, the weight of the scion portion of Surround-treated

Table 2. **Mean ± SEM weight of rootstocks and scions of citrus trees that received Surround WP particle film sprays at 3- or 4-wk intervals, biannual applications of an entomopathogenic nematode (BioVector), or no weevil control treatment (control) over 3 yr**

	Yr		
	2001	2002	2003
Rootstock wt (g)[a]			
Control	140 ± 8a	223 ± 29a	381 ± 71a
BioVector	125 ± 7a	307 ± 26a	556 ± 98a
Surround,4 wk	220 ± 18b	1,021 ± 100b	1,886 ± 273b
Surround, 3 wk	230 ± 13b	1,177 ± 100b	2,127 ± 174b
Scion wt (g)[a]			
Control	180 ± 14a	332 ± 60a	666 ± 192a
BioVector	163 ± 12a	584 ± 70a	1,179 ± 180a
Surround, 4 wk	309 ± 31b	1,875 ± 198b	3,668 ± 629b
Surround, 3 wk	355 ± 26b	2,100 ± 173b	4,373 ± 364b

[a] Means within columns followed by the same letter are not significantly different ($\alpha = 0.05$, Fisher's protected LSD after a significant ANOVA).

Table 3. **Mean number ± SEM of orange fruit harvested per tree at the end of 2 and 3 yr, and final canopy volume of citrus trees treated with BioVector entomopathogenic nematodes twice yearly or with periodic applications of Surround**

Treatment	No. fruit per tree		Canopy vol(m^3)
	2002	2003	
Control	0.0 ± 0.0a (46)	3.4 ± 1.1a (14)	0.22 ± 0.04a (14)
BioVector	0.0 ± 0.0a (54)	4.3 ± 0.8a (19)	0.49 ± 0.07a (19)
Surround, 4 wk	3.8 ± 0.6b (73)	29.5 ± 4.9b (23)	1.32 ± 0.16b (23)
Surround, 3 wk	1.4 ± 0.3b (72)	35.1 ± 3.7b (29)	1.54 ± 0.14b (29)

Means within columns followed by the same letter are not significantly different. Numbers in parentheses are sample size ($\alpha = 0.05$, Fisher's protected LSD after a significant ANOVA)

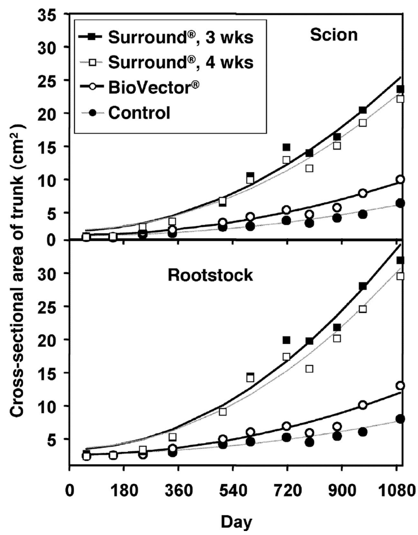

Fig. 3. Regression lines for the cross-sectional area of the stems of citrus scions and rootstock combinations that received Surround WP particle film sprays at 3- or 4-wk intervals, biannual applications of an entomopathogenic nematode (BioVector), or no weevil control treatment (control) over 3 yr. Stem diameter was measured at 5 cm above and 5 cm below the graft union for scion (Midsweet orange) and rootstock (Volkamer), respectively. Regression statistics are presented in Table 4.

Table 4. Regression analyses of the cross-sectional area (square centimeters) of tree stems over time for scion and rootstock of citrus trees subjected to four treatments

Scion/rootstock	Treatment	$b_2 \pm SE^a$ ($\times 10^{-6}$)	t^b	R^2	F^b	df
Scion	Control	3.9 ± 0.2c	16.8	0.44	281.5	362
	BioVector	6.7 ± 3.4b	19.5	0.49	378.4	396
	Surround, 4 wk	19.4 ± 6.6a	29.1	0.64	848.6	479
	Surround, 4 wk	17.4 ± 8.2a	21.2	0.49	450.2	468
Rootstock	Control	4.1 ± 3.3c	12.6	0.31	159.6	362
	BioVector	7.8 ± 4.6b	17.2	0.43	294.9	396
	Surround, 3 wk	25.8 ± 8.9a	29.0	0.64	840.4	479
	Surround, 4 wk	22.7 ± 11.2a	20.3	0.47	411.5	468
Scion	Control	3.9 ± 0.2a	16.8	0.44	281.5	362
Rootstock	Control	4.1 ± 3.3a	12.6	0.31	159.6	362
Scion	BioVector	6.7 ± 3.4a	19.5	0.49	378.4	396
Rootstock	BioVector	7.8 ± 4.6a	17.2	0.43	294.9	396
Scion	Surround, 3 wk	19.4 ± 6.6b	29.1	0.64	848.6	479
Rootstock	Surround, 3 wk	25.8 ± 8.9a	29.0	0.64	840.4	479
Scion	Surround, 4 wk	17.4 ± 8.2b	21.2	0.49	450.2	468
Rootstock	Surround, 4 wk	22.7 ± 11.2a	20.3	0.47	411.5	468

The data fit an incomplete quadratic regression model that included an intercept (b_0) (not presented) and the slope (b_2) associated with the quadratic term.

[a] Coefficients within groups followed by the same letter are not significantly different by 95% confidence intervals.

[b] $P > t$ and $P > F$ are <0.0001 for all regressions.

trees was between 5.5 and 6.6 times that of control trees. Surround treatments also resulted in larger canopy volume compared with untreated trees ($F = 20.26$; df = 3, 81; $P < 0.0001$). The canopy volume of Surround-treated trees at the end of the experiment in 2003 was between 6.0 and 7.0 times that of control trees (Table 3).

Data on growth based on trunk cross-sectional area were best described by an incomplete quadratic regression model (linear term omitted) (Table 4). The R^2 values based on this model were marginally better than those based on simple linear regressions. The complete quadratic model did not fit seven of the eight rootstock–scion treatment combinations (analyses not presented). The slopes (b_2) of the incomplete quadratic model indicated growth of both rootstock and scion based on trunk cross-sectional area was greatest for trees receiving Surround applications compared with trees that did not receive Surround applications (control and BioVector-treated trees) (Table 4). Also, increase in cross-sectional trunk area was significantly greater for both rootstock and scion of trees that received BioVector applications compared with the control trees. The growth of rootstock and scion was similar for the control and BioVector-treated trees. Trees treated with Surround, however, showed greater rootstock growth compared with scion growth (Table 4).

There was no significant benefit to biannual applications of BioVector as measured by canopy volume, fruit yield, rootstock weight, or scion weight (Tables 2 and 3). However, there was a consistent trend in these data indicating a possible positive effect of BioVector on tree growth and yield. The regression analysis of tree stem cross-sectional area revealed a positive effect of BioVector on tree growth compared with the control trees, although much smaller than the effect of Surround treatments (Table 4; Fig. 3). Surround-treated trees sampled at the end of each of the 3 yr showed significantly greater mass of both rootstock and scion than either the control trees or the BioVector-treated trees (Table 2). The rootstock mass of trees treated with Surround was >5 times as great as that of control trees, and the mass of Surround-treated scions was >6 times the mass of untreated trees. The final cross-sectional area of Surround-treated trees was between 3.7 and 4.1 times as great as that of control trees (Fig. 3).

No fruit were produced by the control or BioVector-treated trees after 2 yr of growth, significantly fewer than the number of fruit produced by Surround-treated trees ($F = 31.23$; df = 3, 197; $P < 0.0001$). In 2003, the control and BioVector-treated trees produced a small number of fruit, whereas the Surround-treated trees produced between 7.7 and 8.9 times as many fruit ($F = 34.04$; df = 3, 81; $P < 0.0001$) (Table 3).

Larval Recovery. Recovery of larvae (*D. abbreviatus* and *P. litus*) was difficult because of compaction and texture typical of Winder soil. The number of larvae recovered at the end of the first year did not differ between the control and the Surround-treated trees ($F = 2.06$; df = 3, 156; $P = 0.108$). However, the number of weevil larvae recovered from the roots of Surround-treated trees was greater than the number recovered from the roots of control trees at the end of 2002 ($F = 4.56$; df = 3, 156; $P = 0.004$) and 2003 ($F = 3.06$; df = 3, 83; $P = 0.033$) (Table 5). The number of larvae recovered from the roots of BioVector-treated trees was statistically equivalent to the number recovered from control trees in 2001 and 2002. In 2003, significantly more larvae were recovered from the Biovector and Surround (3-wk) treatments compared with the control. There was no effect of treatment on the weight of the larvae recovered in 2001 ($F = 1.41$; df = 3, 57; $P = 0.248$), 2002 ($F = 1.42$; df = 3, 80; $P = 0.245$), and 2003 ($F = 0.70$; df = 3, 89; $P = 0.502$).

Table 5. Mean ± SEM number of root weevil larvae (*D. abbreviatus* and *P. litus*) recovered from excavated citrus trees that received Surround WP particle film sprays at 3- or 4-wk intervals, biannual applications of an entomopathogenic nematode (BioVector), or no weevil control treatment (control)

Total no. larvae/tree	Yr		
	2001	2002	2003
Control	0.3 ± 0.1a	0.2 ± 0.1a	0.1 ± 0.1a
BioVector	0.1 ± 0.0a	0.2 ± 0.1a	1.3 ± 0.5b
Surround, 4 wk	0.7 ± 0.3a	0.9 ± 0.2b	0.6 ± 0.2ab
Surround, 3 wk	0.5 ± 0.2a	0.8 ± 0.2b	1.3 ± 0.3b

Means followed by the same letter within columns are not significantly different ($\alpha = 0.05$, Fisher's protected LSD after a significant ANOVA).

Discussion

Lapointe and Shapiro (1999) demonstrated that soil moisture of 60 ± 10% by weight was optimal for development and pupation of larvae of *D. abbreviatus* under controlled conditions in a laboratory, whereas low (20–40%) and high (>80%) moisture content resulted in increased mortality. McCoy et al. (2003) suggested that adult emergence of *D. abbreviatus* in the field can be delayed by soil moisture deficit, as was documented for the pecan weevil, *Curculio caryae* (Horn) (Harris and Ring 1980). This seems to have occurred at our study site during 2002 when no rainfall was recorded during a period of 33 d (13 April–16 May). The onset of adult emergence in 2002 was delayed by ≈1 mo compared with years 2001 and 2003 (Fig. 1).

The suppressive effect of Surround against feeding and oviposition by *D. abbreviatus* on excised citrus leaves declined as coverage was reduced below the recommended concentration [3% (wt:vol) to runoff] in a greenhouse trial (Lapointe 2005). In that study, the effect of Surround on oviposition was larger than the effect on leaf consumption by *D. abbreviatus,* most likely because of a combination of behavioral deterrence of oviposition and reduced food intake resulting in decreased fecundity. Even so, suppression by Surround was not absolute, because oviposition by *D. abbreviatus* occurred even at the highest rate of Surround deposition in the greenhouse under no-choice conditions (Lapointe 2000, 2005). The roughly proportional decline in leaf consumption and oviposition with increasing particle film coverage suggested that significant protection from root weevil predation during the rainy season in Florida would require multiple applications of particle film to maintain sufficient coverage to significant suppress oviposition (Lapointe 2005). One of our objectives was to determine the degree to which incomplete suppression by particle film applications of oviposition by *D. abbreviatus* can result in a reduction in the number of larvae successfully developing and feeding on citrus roots.

The suppressive effect of Surround on root weevils in this field trial was most evident in the ratio of the number of egg masses per female weevil observed on Surround-treated trees compared with the control trees. Despite the large difference in tree size by the end of the trial, the number of egg masses per tree was statistically equivalent for Surround-treated and control trees. This occurred even though the number of adult weevils (*D. abbreviatus* and *P. litus*) per tree was higher on Surround-treated trees. Therefore, the only parameter that reflected suppression of oviposition was the number of egg masses per adult weevil. It seems that the larger Surround-treated trees attracted more adults compared with the control trees, but those adults produced fewer egg masses per adult, because of the combination of behavioral deterrence and reduced feeding induced by the particle film.

All growth parameters reflected increased growth of Surround-treated trees throughout the three growing seasons compared with control trees and BioVector-treated trees (Fig. 3; Tables 2–4). Increased tree vigor may contribute to the trees' ability to tolerate or recover from feeding by root weevils. The combination of increased tree growth on heavy soils and reduced weevil oviposition suggests that the use of particle films has promise for use in Florida's citrus-producing areas. In particular, it would be interesting to determine the effect of combining particle films with applications of other agrochemicals used in citrus production systems such as adulticides for control of *D. abbreviatus.*

The regression of stem cross-sectional area demonstrated a positive effect of BioVector applications on tree growth compared with the control trees. Although there was a small beneficial effect of BioVector on tree growth, the growth of BioVector-treated trees was considerably less than that of the Surround-treated trees (Fig. 3; Tables 3 and 4). The increased growth of BioVector-treated trees was presumably because of control of larvae feeding on the trees' roots, although the effect was difficult to document under the conditions of this study. The number and size of larvae recovered from BioVector-treated trees did not differ from those recovered from the control trees. Studies by McCoy et al. (2002) and Duncan et al. (2001) demonstrated that the efficacy of entomopathogenic nematodes such as *Steinernema riobrave* is constrained by soil texture, with increased predation occurring on sandy, well-drained soils common in central Florida (Schroeder 1990). The slightly improved tree growth at our study site on a poorly drained Winder soil suggests that BioVector provided some protection from root weevil predation even if our experimental procedure was unable to detect reduced larval infestation of roots. Perhaps as a result of the greater growth of BioVector-treated trees compared with control trees, the total number of root weevil egg masses per female laid on BioVector-treated trees was significantly greater than that on control trees (Table 1).

The growth of Surround-treated trees greatly surpassed that of the BioVector-treated trees even though the Surround-treated trees had as many or more root weevil larvae feeding on their roots. Therefore, the growth enhancement cannot be attributed to suppression of root weevil infestation, but it must be a result of the positive physiological effects on tree growth documented by Glenn et al. (2001). A similar growth enhancement effect was observed on a slightly better drained site at our facility where root weevil infestation was slight to nonexistent (S.L., unpublished data). The regression analyses suggest that Surround applications under the conditions of this study favored rootstock growth more than scion growth (Table 4), although the magnitude of the slight rootstock overgrowth (severe rootstock overgrowth is referred to as "benching") was not sufficient to indicate scion–rootstock incompatibility.

Because this was the first multiyear study of Surround on citrus trees in the humid subtropics with natural weevil infestation, we had little information to guide us in setting the frequency of applications to be tested. Initially, we considered comparing a calendar-based schedule with applications after every significant rain event that resulted in loss of Surround coverage. However, we quickly realized that such a schedule during the rainy season would have us making many more applications that would be economically feasible. Our selection of 3- and 4-wk intervals was largely arbitrary but based on our initial observations of residue buildup and flushing patterns of citrus trees. None of the growth parameters was significantly greater for trees receiving Surround every 3 wk compared with trees receiving sprays every 4 wk, although the data show a consistent nonsignificant trend toward greater tree growth with more frequent applications. Larval infestation per tree was actually greater in Surround-treated trees, but this finding must be considered in light of the significantly greater tree size of treated trees.

Overall, the large influence of Surround on the growth of citrus trees on a poorly drained soil suggests the value of particle film applications for enhancing young tree growth and promoting early yield. This effect has not been demonstrated on deep, well-drained sandy soils found in central Florida. The ability of calendar-timed applications of Surround to suppress oviposition by root weevils and thereby reduce larval feeding damage to roots seems to be insufficient to reduce the number of larvae that successfully establish and feed on citrus roots. Under normal field conditions, mortality of first instars as they drop from the canopy onto the ground is suspected to be very high, perhaps in excess of 98% (McCoy et al. 2003). In this study, the net effect of three years of Surround applications was a tendency toward increased larval infestation, although this tendency was likely, in part, because of the larger size of Surround-treated trees. The enhanced growth and greater vigor and yield of Surround-treated trees suggest that such trees have a greater tolerance to root weevil feeding.

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