Proc. Fla. State Hort. Soc. 120:116–119. 2007.

Effectiveness of Several Soil-applied Systemic Insecticides for Managing the Asian Citrus Psyllid, *Diaphorina citri* Kuwayama (Homoptera: Psyllidae)

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Additional index words. Diaphorina citri, citrus greening, huanglongbing, integrated pest management

The Asian citrus psyllid [*Diaphorina citri* Kuwayama (Homoptera: Psyllidae)] is the insect responsible for transmission of the Asian strain of the citrus greening pathogen (*Candidatus* Liberibacter asiaticus) in Florida. In citrus producing countries where both citrus psyllids and greening disease occur, insecticide use to reduce psyllid populations is an important component of greening management programs. Managing psyllids on young non-bearing citrus is important since these trees continually produce new flushes throughout the year that support the development of psyllid populations. Thus, these trees have a greater potential of becoming infected by the greening pathogen at a much higher rate than mature trees within the same grove. The most reliable method of protecting non-bearing trees from pests such as psyllids has been the use of the soil-applied systemic insecticide imidacloprid. However, due to its widespread use, there are concerns about the potential development of resistance to imidacloprid. This work presents results of field trials conducted during 2006 to evaluate the effectiveness of additional soil-applied systemic insecticides for controlling psyllids on non-bearing citrus. Soil applications of the two neonicotinoid insecticides imidacloprid and thiamethoxam provided the greatest reduction in psyllid populations compared with the other soil-applied products tested. There is an urgent need to develop additional soil-applied systemic insecticides that can be used for psyllid management on non-bearing citrus.

The Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama (Homoptera: Psyllidae), is the insect that transmits the citrus greening pathogen, *Candidatus* Liberibacter asiaticus (Catling, 1970). Citrus greening was first confirmed in Florida in Aug. 2005 (Halbert, 2005). Since its initial discovery, greening has been discovered across the state and because of its wide distribution, eradication was determined not to be possible. Thus, Florida citrus growers must now adopt new management strategies for continued citrus production in the presence of this disease.

In other countries where both psyllids and the greening pathogen are present, management of this disease complex includes production of disease-free nursery plants, increased pesticide usage to reduce psyllid populations and removal of trees with visual symptoms of greening (Bové, 2006). Currently in Florida, citrus nursery production is being transitioned to propagation of all nursery stock within enclosed psyllid-proof structures.

Although increased insecticide usage has been a major component of greening management programs in other countries, no rigorous scientific studies have been conducted to date that conclusively demonstrate that increased pesticide usage for psyllid control will result in a lower incidence of citrus greening disease. However, anecdotal evidence from countries such as China and South Africa suggest that there is indeed a benefit from insecticidal control, keeping disease incidence at sufficiently low levels to maintain viable citrus production (le Roux et al., 2006; Xueyuan, 2006).

The ACP lifecycle is closely linked to the presence of young, tender leaf tissues (flushes) needed for reproduction (Catling, 1970). Adult psyllids will only lay eggs on tender new leaf tissues that have not yet expanded. Thus, increases in psyllid populations are associated with the flushing patterns of citrus trees. Mature citrus trees typically produce three to four major flushes per season, with psyllid populations reaching their highest levels during the late spring or early summer flushes. Foliar insecticide sprays can be timed to reduce psyllid populations on these flushes. Young, non-bearing citrus trees produce many more flushes throughout the season than mature trees. Because young trees are continually producing new flush, these trees are much more attractive to psyllids and thus could become infected with the greening pathogen at a much higher rate than mature trees. Because of the extended period of new flush growth on young trees, additional insecticide inputs are needed for managing psyllids on these trees.

Currently, the most effective method for controlling psyllids on young trees has been the use of soil-applied systemic insecticides, in particular imidacloprid (Childers and Rogers, 2005). Prior to the need for controlling psyllids on young trees, soil-applications of imidacloprid have been widely used on non-bearing citrus for control of the citrus leafminer (*Phyllocnistis citrella* Stainton). These soil-applied products provide long-lasting whole-plant systemic activity that can control pests for several months compared to the 2–3 week period of control expected with most foliar-applied insecticides. However, because of its effectiveness in controlling these pests on young trees, imidacloprid is being relied upon as the primary tool for ACP control on young trees

The author is grateful to the Florida Citrus Production Research Advisory Council for financial support for this project; the Mid-Florida Citrus Foundation and Water Conserv II for providing a grove site to conduct this study; and Harry Anderson, Michael Simms, and Percivia Mariner for their technical assistance. The manuscript benefited from suggestions by Lukasz L. Stelinski and Ronald H. Brlansky.

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in Florida. Such repeated and widespread use of one particular insecticide mode of action could lead to rapid development of pesticide resistance to a previously effective tool.

In order to help prevent the development of pesticide resistance while maintaining effective control of psyllids on non-bearing citrus, additional products, in particular soil-applied products, with different modes of action are needed that can be rotated with imidacloprid. In this study, we evaluated several soil-applied systemic products for effectiveness in controlling ACP on non-bearing citrus.

Materials and Methods

The control of ACP by various soil-applied systemic insecticides was assessed in two field trials conducted at the Water Conserv II research grove in Orange County, FL, during 2006. Six different pesticide active ingredients were evaluated and of those, only two, imidacloprid and oxamyl, are currently labeled for use as soil-applied products for control of ACP.

In Trial 1, treatments were applied to 2-year-old 'Earlygold' orange trees on Swingle citrumelo rootstock that were 1.0–2.0 m (3–6.5 ft) in height with canopy diameters of approximately 1 m. Tree spacing was 3.0 m (10 ft) within rows and 6.1 m (20 ft) between rows. Treatments were assigned to plots consisting of 20 trees (4 rows wide × 5 trees in length) in a randomized complete-block design replicated 4 times. Treatments included Assail (acetamiprid), Admire Pro (imidacloprid), Platinum (thiamethoxam), Dimethoate (dimethoate), and MSR (metasystox) applied as a soil drench using an applicator timed to deliver 236 mL (8 oz) of spray solution to the base of each tree. The Dimethoate sprays were buffered to a pH of 5 as per label recommendations. Admire Pro and Platinum were also tested as band sprays using a herbicide boom to deliver a 1-m swath of spray to the soil surface over a 2-m (6.5 ft) length of soil on both sides of the tree. All treatments in Trial 1 were applied on 5 Apr. 2006. Details of the chemical treatments, formulations, and application rates are given in Table 1.

In Trial 2, treatments were applied to 2-year-old 'Mineola' (cross LB89) trees on Carrizo citrange rootstock that were 1.0–1.5 m (3–5 ft) in height with canopy diameters less than 1 m. Tree spacing was 3.0 m within rows and 6.1 m between rows (10 × 20 ft). Treatments were assigned to plots consisting of 20 trees (4 rows wide × 5 trees in length) in a randomized complete-block design replicated 4 times. In this trial, there were three Vydate application regimes evaluated. The first Vydate treatment consisted of 0.5 gal (1.89 L) of product per acre applied as a soil drench on 4 Apr., followed by 0.5 gal (1.89 L) of product per acre applied as a foliar spray on 10 May. The second Vydate treatment was 1 gal (3.78 L) of product per acre applied as a soil drench on 4 Apr., and followed by identical treatment on 10 May. The third Vydate treatment was 1 gal (3.78 L) of product per acre as a soil drench on 4 Apr. followed by 0.5 gal (1.89 L) of product applied as a foliar spray on 10 May. All Vydate applications were buffered to a pH of 5 as per label recommendations. An Admire Pro soil drench treatment and a Danitol (fenpropathrin) foliar application were made on 10 May as standards for comparison with Vydate. All soil drench applications were made as described in Trial 1. Foliar applications were made using a handgun applicator with a pump pressure of 200 psi delivering 0.3 gal (1.3 L) of finished spray per tree. Details of the chemical treatments, formulations, and application rates are given in Table 2.

On each sampling date, 10 terminal flush samples were taken collectively from each plot. Each piece of flush was carefully pinched from the stem and placed immediately in a jar of 70% alcohol. Thus, each jar of alcohol contained 10 pieces of flush from a given plot. Sampling ended when no new flush was available for sampling. In the laboratory, each alcohol sample was poured into a dish and each piece of flush was teased apart under a stereomicroscope. All psyllid eggs and nymphs were separated from the plant material in this manner. Counts were then made of the number of psyllid eggs and nymphs per 10 flush samples per plot.

On each sampling date, counts of adult psyllids were made. Two-minute visual counts of the total number of adult psyllids per tree were made for two trees in each plot.

Data from both trials were analyzed by one-way ANOVA with LSD procedure to separate treatment means when significant F values ($P \leq 0.05$) were obtained (Analytical Software 2000). Psyllid egg, nymph, and adult counts were subjected to Log_{10} (X+1) transformations prior to statistical analysis. Untransformed means are presented in tables.

Results

In Trial 1, Platinum applied as both a soil drench and a band spray, and Admire Pro applied as a soil drench provided significant reductions in psyllid eggs and nymphs compared to the untreated control on all sampling dates (Table 1). Dimethoate

Table 1 (Trial 1). Mean number Asian citrus psyllid eggs and nymphs per 10 new leaf flushes. All treatments were applied 5 Apr. 2006.

				Post treatment means[z]									
			Appl.	21 Apr.		25 Apr.		2 May		9 May		16 May	
Treatment	Form	Rate	method	Eggs	Nymphs	Eggs	Nymphs	Eggs	Nymphs	Eggs	Nymphs	Eggs	Nymphs
Assail	30 SG	10 oz/acre	Drench	488.3 a	684.5 a	474.3 ab	809.5 a	120.3 ab	480.0 a	1328.3 a	814.5 a	683.5 a	1325.3 a
Admire Pro	4.6 SC	14 oz/acre	Band	358.5 a	570.3 ab	345.3 ab	780.8 a	137.3 ab	569.0 ab	1162.8 a	1035.5 a	794.8 a	711.0 ab
Platinum	2 SC	11 oz/acre	Band	19.5 c	214.3 bcd	0.0 d	0.0 d	0.0 c	0.0 c	0.3 b	1.8 b	4.3 b	0.0 d
Admire Pro	4.6 SC	14 oz/acre	Drench	6.0 c	105.3 cd	0.8 d	6.5 c	0.0 c	0.3 c	0.0 b	2.0 b	34.0 b	40.5 c
Platinum	2 SC	11 oz/acre	Drench	8.5 c	50.3 d	0.5 d	5.8 c	0.5 c	2.0 c	11.0 b	1.0 b	14.5 b	3.8 cd
Dimethoate	4E	2 qts/acre	Drench	38.0 bc	51.3 d	34.8 c	35.0 b	91.5 b	119.8 b	775.0 a	744.3 a	349.5 a	281.3 b
MSR	2E	8 pts/acre	Drench	445.3 ab	564.3 abc	97.8 bc	310.5 a	569.5 a	683.0 a	734.3 a	636.8 a	647.0 a	666.3 ab
Untreated	---	---	---	662.5 a	982.0 a	819.8 a	544.3 a	454.3 ab	645.3 a	2176.8 a	1348.3 a	749.8 a	770.5 ab
				F=5.89	F=8.56	F=28.0	F=26.5	F=12.1	F=16.5	F=29.9	F=30.5	F=15.5	F=23.5
				P=0.0005	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001

[z]Means within a column followed by the same letter are not significantly different using LSD ($P > 0.05$). Data were subjected to Log_{10} (X+1) transformations for statistical analysis. Untransformed means are presented for comparison.

applied as a soil drench provided reduction in psyllid eggs and nymphs through the 2 May sample period but was not significantly different from the untreated plots on the 9 and 16 May sampling dates (Table 1). MSR applied as a soil drench did not provide significant reduction in psyllid populations on any of the sampling dates with the exception of the 25 Apr. sampling date, when the total number of psyllid eggs was significantly lower than in untreated plots (Table 1). Admire Pro applied as a soil band spray and Assail applied as a soil drench did not provide a significant reduction in psyllid eggs or nymphs on any of the sampling dates (Table 1).

In Trial 1, adult psyllid counts were not significantly lower in any of the treatments compared to the untreated control plots on the 21 Apr. observation date (Table 2). Adult psyllid numbers were significantly lower in the Platinum soil drench and Dimethoate soil drench treatments on 25 Apr. (Table 2). Adult psyllid numbers were significantly lower in the Platinum soil band, Admire Pro soil drench, Platinum soil drench, and Dimethoate soil drench treatments on the 2, 9, and 16 May observation dates with the exception of 9 May, where there was no significant difference between the Dimethoate and untreated trees (Table 2). The Assail soil drench, Admire Pro soil band, and MSR soil drench treatments did not provide any significant reduction in adult psyllid numbers on any of the observation dates (Table 2).

In Trial 2, psyllid egg and nymphs were significantly lower in all three Vydate treatments 7 d after the second round of Vydate treatments were applied (Table 3). However, psyllid egg and nymph numbers were not significantly different from the untreated trees on the 23 May, 30 May, and 5 June sampling dates (Table 3). No significant differences were seen in psyllid egg and nymph numbers between the Admire Pro treatments and the control during the 17 and 23 May sampling dates (Table 3). There were significantly lower psyllid nymph populations in the Admire Pro-treated trees compared with controls on 30 May and 5 June (Table 3). There was also a noticeable trend for lower psyllid egg numbers, but was not significantly different than egg counts on the untreated trees on those dates (Table 3). There were significantly fewer psyllid nymphs in the Danitol-treated trees on all observation dates and significantly fewer psyllid eggs in Danitol-treated trees on the 17 and 23 May observation dates (Table 3).

In Trial 2, adult psyllid counts were only made on three observation dates, 17, 23, and 30 May (Table 4). On these dates, the only significant reduction in adult psyllid numbers were in two of the Vydate-treated plots on 17 May (Table 4). There were no significant reductions in adult psyllid numbers on the subsequent observation dates (Table 4).

Discussion

The results of these two trials demonstrate that soil-applied systemic products with the same mode of action do not always perform equally in terms of psyllid control. Interesting differences were seen in Trial 1 between Assail (acetamiprid), Platinum (thiamethoxam), and Admire Pro (imidacloprid). These three products are neonicotinoid insecticides having the same mode

Table 2 (Trial 1). Mean number Asian citrus psyllid adults per 2-min tree count. All treatments were applied 5 Apr. 2006.

			Appl.	Post treatment means[z]				
Treatment	Form	Rate	method	21 Apr.	25 Apr.	2 May	9 May	16 May
Assail	30 SG	10 oz/acre	Drench	2.5 bc	0.8 bcd	3.9 a	6.1 a	12.3 a
Admire Pro	4.6 SC	14 oz/acre	Band	5.0 ab	4.0 b	4.3 ab	4.4 ab	4.1 ab
Platinum	2 SC	11 oz/acre	Band	0.0 d	0.3 cd	0.0 c	0.1 c	0.0 c
Admire Pro	4.6 SC	14 oz/acre	Drench	0.0 d	0.1 cd	0.0 c	0.0 c	0.1 c
Platinum	2 SC	11 oz/acre	Drench	0.0 d	0.0 d	0.4 c	0.3 c	0.4 bc
Dimethoate	4E	2 qts/acre	Drench	0.1 d	0.0 d	0.5 bc	0.4 bc	1.0 bc
MSR	2E	8 pts/acre	Drench	5.5 a	8.5 a	3.1 a	7.5 a	8.0 a
Untreated	---	---	---	0.8 cd	2.1 bc	5.8 a	2.8 ab	6.6 a
				F=9.6	F=7.11	F=4.57	F=4.17	F=7.22
				P<0.0001	*P*<0.0001	*P*=0.0004	*P*=0.0009	*P*<0.0001

[z]Means within a column followed by the same letter are not significantly different using LSD ($P > 0.05$). Data were subjected to Log_{10} (X+1) transformations for statistical analysis. Untransformed means are presented for comparison.

Table 3 (Trial 2). Mean number of Asian citrus psyllid eggs and nymphs per 10 new leaf flushes.

				Post treatment means[z]							
			Appl.	17 May		23 May		30 May		5 June	
Treatment[y]	Form	Rate	method	Eggs	Nymphs	Eggs	Nymphs	Eggs	Nymphs	Eggs	Nymphs
Vydate	2 SL	0.5 gal/acre	Drench/foliar	0.8 b	21.3 b	27.3 ab	24.8 a	36.8 a	91.5 a	27.8 a	95.0 a
Vydate	2 SL	1 gal/acre	Drench/drench	6.0 b	5.3 b	120.5 a	95.3 a	15.3 ab	73.3 a	160.3 ab	39.3 a
Vydate	2 SL	0.5 or 1 gal/acre	Drench/foliar	36.0 b	10.3 b	72.0 ab	43.5 a	32.0 a	104.5 a	5.8 ab	4.5 ab
Danitol	2.4 EC	1 pt/acre	Foliar	9.0 b	4.8 b	2.0 c	0.3 b	5.8 ab	4.0 b	0.8 b	1.5 b
Admire Pro	4.6 SC	14 oz/acre	Drench	37.8 a	62.8 a	19.5 b	34.3 a	0.8 b	0.8 b	0.3 b	0.3 b
untreated	---	---	---	43.5 a	71.5 a	31.8 ab	92.3 a	25.3 ab	104.3 a	5.0 ab	35.8 a
				F=3.87	F=4.69	F=9.69	F=6.63	F=2.11	F=3.85	F=1.42	F=4.16
				P=0.0147	*P*=0.0064	*P*=0.0001	*P*=0.0012	*P*=0.1117	*P*=0.0151	*P*=0.2656	*P*= 0.011

[z]Means within a column followed by the same letter are not significantly different using LSD ($P > 0.05$). Data were subjected to Log_{10} (X+1) transformations for statistical analysis. Untransformed means are presented for comparison.
[y]The first soil drench treatments of Vydate were applied 5 Apr. 2006. The second round of soil drench treatments (including the first Admire application) and Danitol foliar treatment was applied 10 May 2006.

Table 4 (Trial 2). Mean number of Asian citrus psyllid adults per 2-min tree count.

				Post treatment mean[z]		
Treatment[y]	Form	Rate	Appl. method	17 May	23 May	30 May
Vydate	2 SL	0.5 gal/acre	Drench/foliar	0.0 b	0.3	0.0 b
Vydate	2 SL	1 gal/acre	Drench/drench	0.8 b	0.1	3.4 a
Vydate	2 SL	0.5 or 1 gal/acre	Drench/foliar	4.3 ab	0.3	0.0 b
Danitol	2.4 EC	1 pt/acre	Foliar	2.0 ab	0.0	0.0 b
Admire Pro	4.6 SC	14 oz/acre	Drench	2.6 ab	0.1	0.0 b
untreated	---	---	---	13.6 a	1.5	1.4 ab
				$F = 2.76$	$F = 2.08$	$F = 4.22$
				$P = 0.0304$	$P = 0.0873$	$P = 0.0034$

[z]Means within a column followed by the same letter are not significantly different using LSD ($P > 0.05$). Data were subjected to Log_{10} (X+1) transformations for statistical analysis. Untransformed means are presented for comparison.
[y]The first soil drench treatments of Vydate were applied 5 Apr. 2006. The second round of soil drench treatments (including the fir[st] Admire application) and Danitol foliar treatment was applied 10 May 2006.

of action. However, these products varied in efficacy with Assail providing no control of psyllids while Admire Pro and Platinum provided the highest level of control compared with all other soil-applied products evaluated in these two trials. There was a difference in psyllid control between Admire Pro and Platinum based on method of application. Both products were equally effective when applied as a soil drench to the base of the tree. Platinum also provided effective control of psyllid populations when applied as a band spray to the soil, whereas Admire Pro applied as a band spray was not effective. This difference between the two products may be due to higher water solubility of thiamethoxam (Platinum) that allows for more rapid uptake by the plant compared with imidacloprid. The current Admire Pro label allows for either soil drench or soil band applications. Based on the results of this trial, soil drench applications are the most effective application method for this product. Currently, Platinum is not registered for use in Florida citrus.

Dimethoate (dimethoate) and MSR (metasystox) are both systemic organophosphate insecticides. Despite having similar modes of action, Dimethoate provided a significant reduction in psyllid eggs and nymphs compared with the untreated control for up to 27 d after application, whereas MSR did not control psyllids. Dimethoate provided a significant reduction in psyllid populations as a soil-applied product but control was not as effective as that provided by Admire Pro or Platinum. No data were collected on control of citrus leafminer, but during the course of the trial, high levels of leafminer damage were observed in the Dimethoate-treated plots. Little to no leafminer damage was observed in the Admire Pro- and Platinum-treated plots. Currently, Dimethoate is not labeled for soil applications in Florida citrus.

Vydate (oxamyl) is a systemic carbamate insecticide-nematicide currently registered for use in citrus for citrus rust mite (*Phyllocoptruta oleivora* Ashmead), citrus nematode (*Tylenchulus semipenetrans*), and sting nematode (*Belonolaimus longicaudatus*), as well as the Asian citrus psyllid. Depending on the target pest and application method (soil or foliar sprays), the product label recommends repeated applications made on a regular basis. For psyllid control, the label allows soil applications every 30 d and foliar applications every 15 d. Thus, Vydate treatments in this trial consisted of two soil applications or combinations of soil and foliar applications of Vydate with an elapsed time of 35 d between the two applications. Observations on control of psyllids began 7 d after the second applications of Vydate were made for each treatment. Although there was a significant reduction in psyllid populations in all three Vydate treatments at 7 d after the second round of treatments was applied, no control was evident at 13, 20, or 26 d after application.

Based on the results of Trial 2, it appears that Vydate has very short-term effects on psyllid populations and repeated frequent applications would likely be required to maintain significant reductions in psyllid populations. However, repeated frequent use of one product can lead to development of pesticide resistance and thus, the loss of effectiveness of all products with the same mode of action for controlling the target pest. In the case of psyllid management in Florida, there are two additional carbamate insecticides currently used for psyllid management, Temik (aldicarb) and Sevin (carbaryl). Repeated overuse of any of these carbamate insecticides could lead to failure of all of these products to control psyllids.

In this study, soil applications of the two neonicotinoid insecticides imidacloprid and thiamethoxam provided the greatest reduction in psyllid populations compared with other soil-applied products tested. However, it is important not to apply any given product or products with the same mode of action repeatedly. Thus, these two products cannot be rotated between as part of a psyllid management program. Instead, in the absence of other effective soil-applied systemic products for psyllid control on non-bearing trees, additional foliar applications should be used in rotation with soil-applied neonicotinoid insecticides to aid in preventing development of resistance. There is an urgent need to develop additional soil-applied systemic insecticides that can be used for psyllid management on non-bearing citrus.

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