Imidacloprid Applications by Subirrigation for Control of Silverleaf Whitefly (Homoptera: Aleyrodidae) on Poinsettia

MARC W. VAN IERSEL, RONALD D. OETTING,[1] AND DANIEL B. HALL[2]

Department of Horticulture, Georgia Station, The University of Georgia, 1109 Experiment Street, Griffin, GA 30223–1797

J. Econ. Entomol. 93(3): 813–819 (2000)

ABSTRACT The objective of this study was to determine whether silverleaf whiteflies, *Bemisia argentifolii* Bellows & Perring, on poinsettia, *Euphorbia pulcherrima* Willdenow ex Klotsch, can be controlled with imidacloprid applied by subirrigation. Different amounts of imidacloprid uptake by the growing medium were obtained by not watering the subirrigated plants for 0, 1, 2, or 4 d before the imidacloprid application. These treatments resulted in absorption of 12–175 ml of imidacloprid solution by the growing medium. These treatments were compared with untreated control plants and plants that were treated with a standard drench application (100 ml) to the top of the growing medium. All imidacloprid treatments resulted in a significant decrease in both the survival of adult whiteflies and number of immature whiteflies on the plants. Subirrigation treatments resulted in better control of adult and immature whiteflies than drench application. Withholding water for 2 or 4 d before the imidacloprid application by subirrigation improved control of immature whiteflies. This indicates that the application of imidacloprid to poinsettia by subirrigation is a practical and efficient method to control silverleaf whiteflies.

KEY WORDS *Bemisia argentifolii, Euphorbia pulcherrima,* ebb-and-flow, insecticide efficacy

ZERO RUNOFF SUBIRRIGATION systems are increasingly used in the United States to irrigate greenhouse crops. In subirrigation systems, such as ebb-and-flow, flood floors, and troughs, fertilizer solution is applied to the bottom of the pots or flats as needed. The growing medium absorbs part of the fertilizer solution, and the excess normally drains back into a holding tank and is subsequently reused. Among the most commonly cited advantages of subirrigation systems over other watering methods are savings in labor, water, and fertilizer and improved product uniformity (Uva et al. 1998). The main disadvantage of subirrigation systems is the high initial capital investment.

Uva et al. (1998) reported that 42% of growers who adopted zero runoff subirrigation systems modified their pest or pathogen management, although it is not clear what changes they made. Subirrigation systems appear to be well suited for the application of some systemic pesticides. Using subirrigation systems to apply systemic pesticides would have several advantages over other methods: it would minimize labor requirements and worker exposure to the pesticide, result in a uniform application, and prevent runoff of pesticide into the environment.

Control of silverleaf whitefly, *Bemisia argentifolii* Bellows & Perring, on poinsettia, *Euphorbia pulcherrima* Willdenow ex Klotsch, with imidacloprid (1-[6-chloro-3-pyridinyl)-methyl]-N-nitro-2-imidazolidinimine) was chosen as a model system. Poinsettia has a relatively long growing period (≈4 mo) for a floricultural crop, which makes it possible to study long-term pesticide effects, and can be grown successfully with drip- or subirrigation (Morvant et al. 1998). Silverleaf whitefly is the major pest on poinsettia (Brown et al. 1995), and imidacloprid has quickly become the most common insecticide for whitefly control in greenhouses. Imidacloprid is a relatively new chloronicotinyl insecticide. It is effective both as a systemic and as a contact insecticide, and has low mammalian toxicity (Mullins 1993). Imidacloprid is a long-lasting and effective chemical for the control of silverleaf whiteflies on poinsettia (Natwick et al. 1996). At high doses, it causes significant mortality to both adult and immature whiteflies as late as 5 mo after a single application to poinsettia (Bethke and Redak 1997). The objectives of our study were to compare the efficacy of imidacloprid applied by subirrigation or as a drench to the top of the growing medium, and to quantify the effect of withholding water for several days before the imidacloprid application by subirrigation on imidacloprid efficacy and uptake by the plants.

Materials and Methods

Plant Material. Poinsettia 'Freedom Red' cuttings were taken on 3 August 1998 and rooted in Oasis rooting medium (Smithers-Oasis, Kent, OH) on a shaded mist bench. Rooted cuttings were transplanted into pots (15 cm diameter) filled with a peat-lite grow-

[1] Department of Entomology, Georgia Station, The University of Georgia, 1109 Experiment Street, Griffin, GA 30223–1797.

[2] Department of Statistics, The University of Georgia, Athens, GA 30602.

ing medium (10–25% sphagnum peat, 25–40% vermiculite, 5–15% perlite, 0–10% bark ash, and 25–45% pine bark; Metro-Mix 300, Scotts, Marysville, OH) on 31 August. Plants were subsequently placed on ebb-and-flow benches (0.9 by 1.5 m^2, MidWest Gromaster, St. Charles, IL) in a double-layer polyethylene greenhouse. Until the start of the irrigation treatments, plants were watered daily with a nutrient solution containing a 20:4.3:16.6 (N:P:K) water-soluble fertilizer (20-10-20 Peat-Lite Special, Scotts) at a concentration of 210 mg/liter N (electrical conductivity = 1.5 dS/m). Plants were spaced so that they did not touch each other and were either hand-watered or subirrigated, depending on the treatment.

Treatments. To achieve differing levels of imidacloprid in the subirrigated pots and plants, several irrigation treatments were used. These treatments were started on 14 September 1998, when the first group of plants was no longer irrigated. These plants were not watered in the 4 d preceding the imidacloprid application (4 d before application). Irrigation of the second group of plants was stopped on 16 September (2 d before application), and the third group on 17 September (1 d before application). Plants in a fourth group were watered early on 18 September, the day of the imidacloprid application (0 d before application). This last watering occurred ≈2–6 h before the imidacloprid was applied. A fifth subirrigation treatment was watered daily, but was not treated with imidacloprid (control). The sixth treatment consisted of hand-watered plants, which were watered with nutrient solution daily, except for the day of imidacloprid applications. On this day, this treatment received imidacloprid by a surface drench (drench). The roots of the plants had reached the side of the pots at the time of applications. Starting the day after the imidacloprid applications, all subirrigated plants were watered daily again.

Imidacloprid Applications. Imidacloprid solution (132 mg/liter) (Marathon 60 WP, Olympic Horticultural Products, Bradenton, FL) was mixed in a 120-liter container. The benches were flooded with the solution to a height of 35 mm. The solution stayed on the benches for 15 min to allow the growing medium ample time to absorb the solution. The solution then was drained back into the holding tank and reused for the other treatments within the same replication. Separate imidacloprid solutions were used for every replication. The hand-watered plants were treated by applying 100 ml of imidacloprid solution to the top surface of the growing medium. During the first 2 wk after the imidacloprid application, the hand-watered plants were watered lightly. No water ran out of the bottom of the pots, which avoided leaching of imidacloprid out of the pots. This is the standard drench application as recommended on the label.

Water samples from the imidacloprid solutions were taken both before and after all applications and analyzed for imidacloprid concentration at The University of Georgia's Pesticide and Hazardous Waste Laboratory. Imidacloprid was extracted from water with methylene chloride and quantified by HPLC (Miles 1991). Samples taken before and after applications had similar imidacloprid concentrations, indicating that the applications had no effect on the concentration of imidacloprid in the solution.

Every pot was weighed just before the imidacloprid application and again within 1 h after application. These data were used to calculate the amount of solution absorbed by the growing medium in each pot. After the pots were weighed, samples of the growing medium were taken by extracting a 20-mm core of the growing medium from the top to the bottom of six pots in every experimental unit. Samples were frozen until the imidacloprid concentration was analyzed. For analysis, imidacloprid was extracted from the growing medium with acetonitrile/water (4:1), transferred to methylene chloride, and quantified by HPLC (Moore et al. 1994).

Leaf samples for imidacloprid analysis were taken from every experimental unit at 3 and 63 d after the imidacloprid application (21 September and 20 November). At 3 d after transplanting, leaf blades (no petioles) of 15–20 plants (95–150 g fresh weight) were taken, whereas leaves (including bracts) from two plants per experimental unit were sampled on 20 November. Leaf blades from the treatment that had not been watered for 4 d before the imidacloprid application also were sampled at 21 and 39 d after the imidacloprid application. Samples were frozen until they were analyzed for imidacloprid content. For analysis, imidacloprid and metabolites were extracted from plant material using methanol/1% sulfuric acid (3:1), partitioned against hexane, and the aqueous solution was passed through an XAD-4 column. The methanol eluate was concentrated and the imidacloprid plus metabolites were oxidized to 6-chloronicotinic acid. The 6-chloronicotinic acid was converted to its methyl ester using diazomethane. Residues were then quantified by gas chromatography with an electron capture detector (Weber 1994).

Efficacy Study. The effect of the imidacloprid applications on survival of mature whiteflies and the emergence and survival of immatures was tested weekly. A culture of silverleaf whitefly was maintained on poinsettias grown on greenhouse benches. Adults were aspirated at random from these plants and used in the experiments. Approximately ten adult whiteflies were placed in clip-on leaf cages, without selecting for sex. These cages were constructed of foam (2 by 2 cm, 3 mm thick) with a 1-cm hole in the center. This hole was covered with 180-mesh silk screening material, and the cage was held on the leaf with a modified hair clip. A cage was placed on a fully expanded, subapical leaf (no bracts) on each of three plants per experimental unit. Survival percentage of the adult whiteflies was determined 2 d after they had been placed on the plants. After this count, leaf cages and the surviving whiteflies were removed from the plants, and the position of the cages was marked on the leaves with a permanent marker. After 3 wk, the number of living, immature whiteflies in this same spot on the leaf was determined. Different subapical leaves on the same plants were used during the 12 wk of these efficacy studies.

Experimental Design. The experimental design was a randomized complete block with three replications. Repeated measures were collected for leaf imidacloprid concentration and whitefly survival and number of immatures. At the start of the experiment, the experimental unit was a group of 24–36 plants on a bench. The number of plants in each experimental unit decreased as plants were harvested to determine imidacloprid content. More plants were used in the treatment that did not receive water during the 4 d before the imidacloprid application, to enable sampling leaf material for imidacloprid analysis from this treatment over time. Solution uptake by the growing medium and growing medium and leaf tissue imidacloprid concentrations were analyzed by analysis of variance (ANOVA) and regression analysis. Data were log-transformed before ANOVA to stabilize the variance.

Survival of adult whiteflies and the number of immature whiteflies could not be analyzed by standard statistical techniques. These data were not normally distributed, and because of the large number of zeros in these data sets (53% of the adult survival data and 50% of the counts of immatures were zero), the data could not be transformed to approximate a normal distribution. Instead, we used zero-inflated regression models to analyze these data sets. Lambert (1992) describes regression models for Poisson data with excess zeros. In her zero-inflated Poisson (ZIP) model, it is assumed that Y_i (in our case the number of immature whiteflies) is generated from one of two probability distributions: a zero-state probability distribution in which $Y_i = 0$ certainly (with probability 1), or a nonzero-state probability distribution, which is assumed to be the Poisson distribution with mean λ_i. Which distribution Y_i comes from is assumed to be random, with probability p_i that Y_i comes from the zero state, and probability $1\text{-}p_i$ that Y_i comes from the Poisson state. Here, Y_i is the *i*th element in a vector of responses $\mathbf{Y} = (Y_1, \ldots\ldots, Y_n)^{\mathrm{T}}$ for the entire data set. In standard ANOVA we account for the fact that the elements of **Y** vary across different levels of the experimental factors by fitting a model that expresses the mean of **Y** as an additive combination of various factor effects. In our ZIP model, the mean of **Y** is a function of the parameters $\mathbf{p} = (p_1, \ldots\ldots, p_n)^{\mathrm{T}}$ (the zero-state probabilities) and $\lambda = (\lambda_1, \ldots\ldots, \lambda_n)^{\mathrm{T}}$ (the Poisson means in the nonzero-state) so we capture the dependence of **Y** on experimental conditions by modeling **p** and λ each as functions of experimental factor effects. Specifically, the ZIP model assumes log-linear and logistic regression models for λ and **p**, respectively, of the form

$$\log\lambda = \mathbf{B}\beta, \text{ and}$$

$$\text{logit}(\mathbf{p}) = \mathbf{G}\gamma,$$

where logit(p_i) is defined to be the natural logarithm of $p_i/(1\text{-}p_i)$. In the general form of the model that we have given above, **B** and **G** are design matrices (matrices of explanatory variables, or covariates) and β and λ are (possibly different) vectors of regression coefficients. In our case where we have only factors (classification variables) as explanatory variables, both **B** and **G** simply consist of zeros and ones (columns are indicator, or dummy, variables) and β and λ are parameter vectors, each containing a grand mean, main effects, and (possibly) interactions effects.

Several ZIP models were fit to the data on response variable *I* using the techniques described by Lambert (1992). The best fitting of these models with an identifiable parameterization was used to analyze our data.

The statistical analysis for the number of live adult whiteflies (*L*) was also based on a zero-inflated regression model. In this case, however, the model is a zero-inflated binomial (ZIB) model, because there is a defined upper limit (the number of adult whiteflies placed on the leaf) on each observation of *L*. In the ZIB model, we assume that L_i is zero with probability p_i and otherwise is the result of a binomial distribution. This binomial distribution depends on m_i and π_i, where π_i is the survival probability for each of the m_i insects generating observation L_i. In addition, the parameters $\mathbf{p} = (p_1, \ldots\ldots, p_n)^{\mathrm{T}}$ and $\pi = (\pi_1, \ldots\ldots, \pi_n)^{\mathrm{T}}$ are modeled via logistic regression models:

$$\log\pi = \mathbf{B}\beta, \text{ and}$$

$$\text{logit}(\mathbf{p}) = \mathbf{G}\lambda.$$

As in the ZIP model, **B** and **G** may differ so that we allow the possibility that some covariates affect only the probability of the zero state (they appear only in **G**), some covariates affect only the nonzero state (they appear only in **B**), and some covariates affect both (they appear in both **B** and **G**). In this model, the elements of λ have the same interpretation as in the ZIP model, but the interpretation of β has changed. An element of β now quantifies the corresponding covariate's effect on the survival probability for whiteflies on a leaf for which there is some nonzero probability of surviving. A more detailed description of this statistical procedure is given by Hall (1999).

Treatment comparisons were performed using Wald tests (Wald 1943). The Wald test is a general test appropriate in many situations in which maximum likelihood is used as the method of estimation. Wald test statistics (*W*) have a chi-square distribution, with one parameter, its degrees of freedom.

Results and Discussion

Growing Medium and Plant Imidacloprid Uptake. The volume of solution absorbed by the growing medium increased as the period that water was withheld from the plants before applying the imidacloprid solutions increased (Fig. 1). Uptake ranged from 12 to 176 ml per pot in the subirrigated treatments, resulting in treatments that received substantially less and more than the 100 ml in the drench treatment. As expected, an increase in the volume of solution taken up by the growing medium also resulted in increased levels of

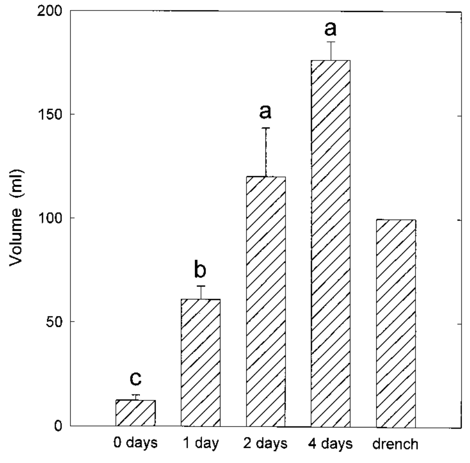

Fig. 1. Volume of imidacloprid solution (milliliter per pot; mean ± SE; $n = 3$) taken up by the growing medium following different application methods. Plants were either subirrigated with imidacloprid solution (0, 1, 2, or 4 d after the last subirrigation with fertilizer solution), or 100 ml was applied as a drench to the top of the growing medium. Bars with the same letter are not significantly different ($P > 0.05$). The drench treatment was not included in the analysis.

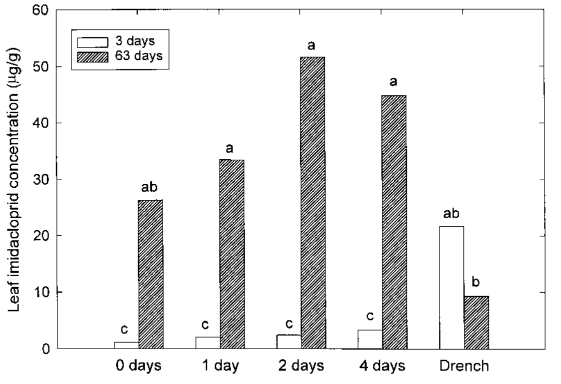

Fig. 3. Imidacloprid concentrations in leaf blades of poinsettia at 3 and 63 d after application of imidacloprid solution ($n = 3$). Plants were either subirrigated with imidacloprid solution (0, 1, 2, or 4 d after the last subirrigation with fertilizer solution), or 100 ml of imidacloprid solution was applied as a drench to the top of the growing medium. Bars with the same letter are not significantly different ($P >$ 0.05).

imidacloprid in the growing medium shortly after application (Fig. 2).

Differences in the uptake of the imidacloprid solution by the growing medium were not reflected in leaf blade imidacloprid concentrations 3 d after transplanting. Leaf blades of the hand-watered plants contained much more imidacloprid than the subirrigated plants at this stage (Fig. 3). Withholding water from the subirrigated treatments tended to increase leaf imidacloprid levels, but this was not statistically significant. Although leaf imidacloprid levels were relatively low in the subirrigated treatments 3 d after application, these concentrations increased dramatically from 3 to 63 d after the application, whereas the leaf imidacloprid concentration in the hand-watered treatment decreased by >50% during this same period (Fig. 3). This resulted in higher imidacloprid concentrations in the subirrigated treatments than in the handwatered treatment at 63 d after the application. These result do not imply that the amount of imidacloprid in the hand-watered plants decreased from 3 to 63 d after the application, but rather that plant size increased more than the amount of imidacloprid, resulting in a lower concentration.

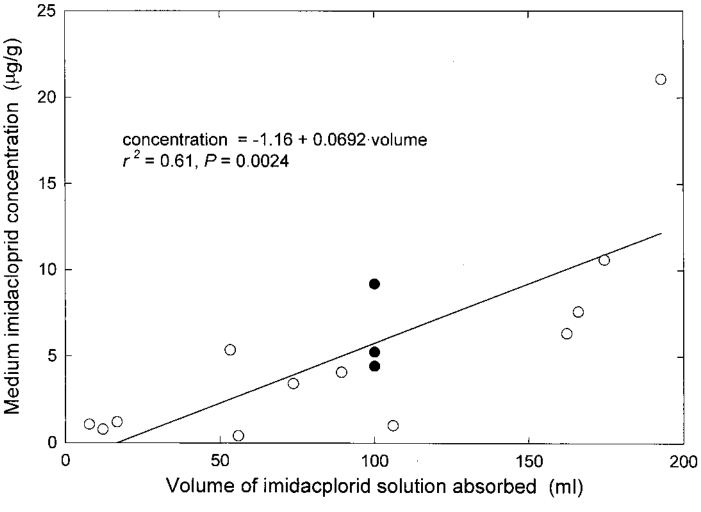

Fig. 2. Correlation between volume of imidacloprid solution absorbed by the growing medium and concentration of imidacloprid in the growing medium, shortly after application. Open symbols represent treatments with imidacloprid solution applied by subirrigation; closed symbols represent application of solution (100 ml) to the top of the growing medium.

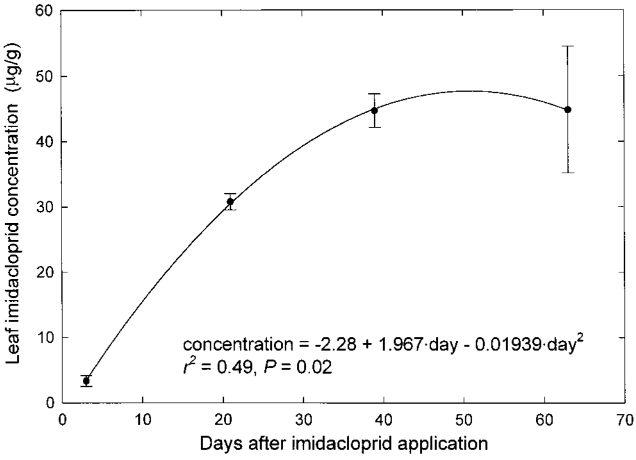

Fig. 4. Imidacloprid concentration in leaf blades of poinsettia during the growing season. Imidacloprid was supplied by subirrigation on day 0 and the plants were not watered for 4 d before application. Error bars represent the standard error of the mean (n = 3).

Apparently, imidacloprid uptake by plants can occur over a long period. This is consistent with the results of Westwood et al. (1998), who reported that imidacloprid is persistent in soil. They grew sugar beets, *Beta vulgaris* L., from seed which was treated with imidacloprid. After 97 d, 23% of the imidacloprid was still present in the soil. The sorption of imidacloprid to soil increases with increasing organic matter (Cox et al. 1997, 1998). The growing medium that we used in this experiment was very high in organic matter (≈40–50%) compared with soils. Therefore, it would be expected that a large fraction of the imidacloprid in soilless media will be bound to the growing medium. There is an equilibrium between sorption of imidacloprid to growing medium and the concentration of imidacloprid in water that is present in pots. Because of this equilibrium, there will always be a small amount of imidacloprid in the water, which is available for plant uptake. However, imidacloprid in the water also can be leached out of the bottom of the pots. Except for the first 2 wk after imidacloprid application, hand-watered plants were watered until water ran out of the bottom of the pots, so there clearly was a potential for the leaching of imidacloprid in the hand-watered treatment. Leaching does not occur with subirrigation because the growing medium does not absorb more water than it can hold. Because imidacloprid was not leached out of the pots in the subirrigation treatments, this could result in higher concentrations of imidacloprid in subirrigated pots than in hand-watered pots. This explains the higher leaf concentration of imidacloprid in the subirrigated treatments than in the hand-watered treatment at 63 d after the application.

Handwatered plants took up most of the imidacloprid early in the growing season, resulting in high initial leaf concentrations of imidacloprid that decreased during the growing season. If uptake of imidacloprid occurred mainly during a brief period after the application, high concentrations would be expected in leaves that had expanded at the time of application, whereas low concentrations would be expected in leaves that formed later. A subsequent study has confirmed this (our unpublished results). Subirrigated plants take up imidacloprid from the growing medium over a much longer period, as is evident from the leaf imidacloprid concentrations in the plants that had not been watered in the 4 d before the imidacloprid was applied (Fig. 4). In this treatment, leaf imidacloprid concentrations increased during the first 40 d after application and remained constant after that. Because the plants were still growing, this indicated that the plants were still taking up imidacloprid from 40 to 63 d after the imidacloprid application. Therefore, it seems likely that subirrigated plants had a more even distribution of imidacloprid throughout the plant than handwatered plants.

Whitefly Efficacy. Leaf imidacloprid concentrations provide insight into the uptake of pesticide by plants, but efficacy is the true test of how effective different treatments are in controlling whiteflies. Throughout the experiment, adult whitefly survival ranged from 75 to 100% in the untreated, subirrigated plants, indicating that greenhouse conditions were favorable for whitefly survival (Fig. 5). Throughout the experiment, all imidacloprid treatments reduced the number of adult whiteflies compared with the controls (W = 61.58, df = 2, $P < 0.001$), with survival percentages ranging from 0 to 50%. The long-lasting effect of imidacloprid on whitefly survival and the number of immatures has been reported before. Bethke and Redak (1997) found that imidacloprid, applied as a drench at ≈10 times the rate of our drench treatment (0.09 g/liter of pot volume), caused 80% mortality of immature whiteflies at 161 d after the application. When applied at a similar rate (0.009 g/liter of pot volume) as in our drench treatment, whitefly mortality was 65% at 25 d after treatment (Bethke and

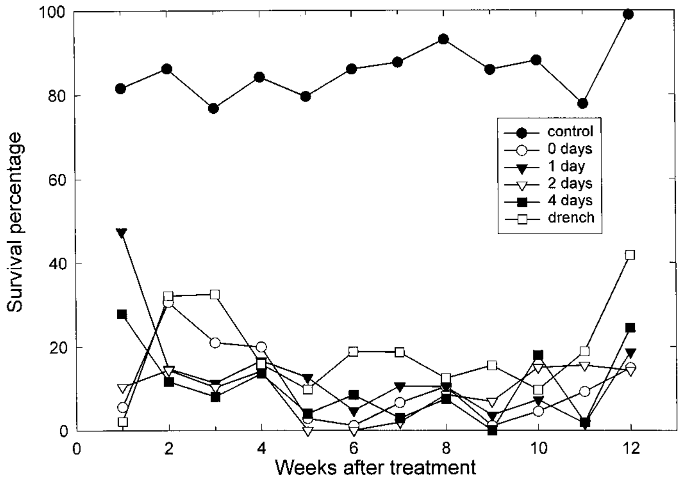

Fig. 5. The effect of different methods of imidacloprid applications on the survival of adult whiteflies. Survival (%) was determined after a 3-d exposure (n = 3). Plants were either subirrigated with imidacloprid solution (0, 1, 2, or 4 d after the last subirrigation), or a drench (100 ml) was applied to the top of the growing medium. The control treatment did not receive any imidacloprid.

Redak 1997). The 65% mortality is similar to the 70% mortality at 21 d after treatment in our experiment (Fig. 5). Imidacloprid also provides long-lasting protection against whiteflies on tomato, *Lycopersicon esculentum* Miller, and eggplant, *Solanum melongena* L (Stansley et al. 1998). They reported that the effects of a single application may last up to 3 mo.

Control of adult whiteflies was better in the subirrigated imidacloprid treatments than in the hand-watered treatment (Fig. 5) ($W = 15.97$, df = 2, $P < 0.001$). Survival of adult whiteflies on subirrigated, imidacloprid-treated plants was not affected by withholding water from the plants for up to 4 d before the application, despite differences in the leaf tissue levels of imidacloprid.

Although it is clear that all imidacloprid treatments provided control of adult whiteflies, inhibition of reproduction is more important than the control of adult whiteflies. If reproduction is prevented, whitefly populations cannot build up in the greenhouse and thus are not as likely to become a major pest. The number of immatures produced by adults in the leaf cages ranged from 12 to 40 per plant in the untreated control treatment (Fig. 6), indicating that greenhouse conditions were favorable for whitefly reproduction throughout the experiment. The fluctuations in the number of immatures may have been caused by changing environmental conditions, such as light intensity or temperature, which can be more or less favorable for whitefly reproduction.

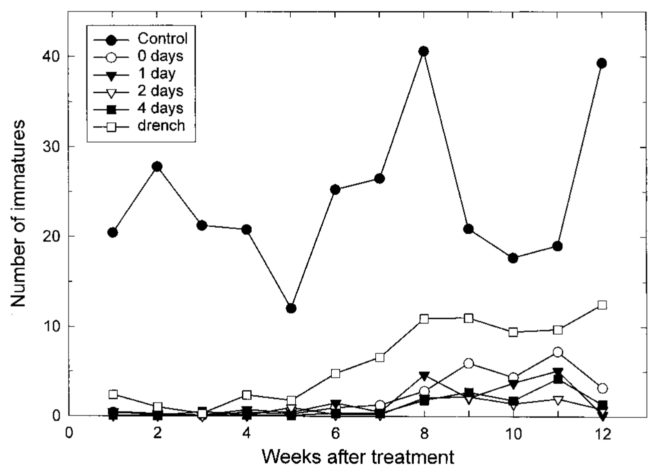

Fig. 6. Effect of different methods of imidacloprid application on reproduction of whiteflies. Immature whiteflies were counted 3 wk after adult whiteflies were placed on plants (n = 3). Plants were either subirrigated with imidacloprid solution (0, 1, 2, or 4 d after the last subirrigation), or a drench (100 ml) was applied to the top of the growing medium. The control treatment did not receive any imidacloprid.

During the counting of the immature whiteflies in the different treatments, it was observed that immatures in control treatments appeared larger and better developed than those in any of the imidacloprid treatments. In addition, all treatments that received imidacloprid had fewer immature whiteflies than the control treatment ($W = 612.3$, df = 2, $P < 0.001$; Fig. 6). The number of immatures produced by adults in the leaf cages tended to increase on imidacloprid-treated plants throughout the experiment. This suggests that the efficacy of the imidacloprid treatments decreased during the experiment.

Among the imidacloprid-treated plants, the numbers of immature whiteflies were consistently higher on hand-watered plants than on subirrigated plants ($W = 143.8$, df = 2, $P < 0.001$). In addition, withholding water for 2 or 4 d before the imidacloprid application in the subirrigated treatments resulted in fewer immature whiteflies than withholding water for 0 or 1 d ($W = 29.32$, df = 2, $P < 0.001$). These results are consistent with the changes in the imidacloprid levels in leaf blades. Apparently, all imidacloprid-treated plants initially contained enough imidacloprid in leaf blades to provide control of mature whiteflies and prevent successful development of immatures. The subirrigated treatments took up significant amounts of additional imidacloprid from the growing medium during the growing season (Figs. 3 and 4). This evidently resulted in enough imidacloprid in the leaves that developed during the experiment to provide good protection against the development of immature whiteflies on those leaves. The hand-watered plants took up most of the imidacloprid shortly after the drench application, which resulted in high initial levels of imidacloprid in leaf blades (Fig. 3). Part of the imidacloprid in the growing medium may have been leached out of the pots during the growing season, thus making it unavailable to the plants. This probably resulted in relatively low concentrations in leaves that expanded during the latter part of the experiment. This explains why the number of immatures was higher in the hand-watered than in the subirrigated plants, especially after the first three weeks of the experiment (Fig. 6).

Applying imidacloprid to poinsettias using subirrigation provided good reduction of whitefly populations. Control of adult whiteflies on subirrigated plants was better than control of whiteflies on hand-watered plants that received a drench application of imidacloprid. Subirrigation treatments also were more effective in preventing the development of subsequent generations of whiteflies, as was evident from the lower number of immature whiteflies on subirrigated plants than on hand-watered plants. These results clearly demonstrate that a subirrigation system for application of imidacloprid is a viable alternative to the standard drench application. Application by subirrigation even resulted in improved whitefly control. The possibility of applying other systemic pesticides by subirrigation needs to be investigated.

References Cited

Bethke, J. A., and R. A. Redak. 1997. Effect of imidacloprid on the silverleaf whitefly, *Bemisia argentifolii* Bellows and Perring (Homoptera: Aleyrodidae), and whitefly parasitism. Ann. Appl. Biol. 130: 397–407.

Brown, J. K., D. R. Grohlich, and R. C. Rosell. 1995. The sweetpotato or silverleaf whiteflies: biotypes of *Bemisia tabaci* or a species complex. Annu. Rev. Entomol. 40: 511–534.

Cox, L., W. C. Koskinen, and P. Y. Yen. 1997. Sorption-desorption of imidacloprid and its metabolites in soils. J. Agric. Food Chem. 45: 1468–1472.

Cox, L., W. C. Koskinen, R. Celis, P. Y. Yen, M. C. Hermosin, and J. Cornejo. 1998. Sorption of imidacloprid on soil clay mineral and organic components. Soil Sci. Soc. Am. J. 62: 911–915.

Hall, D. B. 1999. Zero-inflated Poisson and binomial regression with random effects: a case study. UGA Dep. Stat. Tech. Rep. 99–20.

Lambert, D. 1992. Zero-inflated Poisson regression, with an application to defects in manufacturing. Technometrics 34: 1–14.

Miles. 1991. Analytical method for the determination of NTN 33893 in water. Miles report # 106637. Miles, Kansas City, MO.

Moore, K. S., W. M. Leimkuhler, C. V. Lam, and G. L. Yeutter. 1994. Analytical method for the determination of imidacloprid and three metabolites in North Carolina soil. Miles report # 106428. Miles, Kansas City, MO.

Morvant, J. K., J. M. Dole, and J. C. Cole. 1998. Irrigation frequency and system affect poinsettia growth, water use, and runoff. Hort Science 33: 42–46.

Mullins, J. W. 1993. Imidacloprid—a new nitroguanidine insecticide. ACS Symp. Ser. 524: 183–198.

Natwick, E. T., J. C. Palumbo, and C. E. Engle. 1996. Effects of imidacloprid on colonization of aphids and silverleaf whitefly and growth, yield, and phytotoxicity in cauliflower. Southwest. Entomol. 21: 283–292.

Stansley, P. A., T.-X. Liu, and C. S. Vavrina. 1998. Response of *Bemisia argentifolii* (Homoptera: Aleyrodidae) to imidacloprid under greenhouse, field, and laboratory conditions. J. Econ. Entomol. 91: 686–692.

Uva, W. L., T. C. Weiler, and R. A. Milligan. 1998. A survey on the planning and adoption of zero runoff subirrigation systems in greenhouse operations. Hort Science 33: 193–196.

Wald, A. 1943. Tests of statistical hypotheses concerning several parameters when the number of observations is large. Trans. Am. Math. Soc. 54: 426–482.

Weber, E. 1994. Method for extraction of total residues of imidacloprid in plant materials and beverages (Bayer method 00200—reformatted). Miles report # 102624-R1. Miles, Stilwell, KS.

Westwood, F., K. M. Bean, A. M. Dewar, R. H. Bromilow, and K. Chamberlain. 1998. Movement and persistence of $[^{14}C]$imidacloprid in sugar-beet plants following application to pelleted sugar-beet seed. Pestic. Sci. 52: 97–103.

Received for publication 7 September 1999; accepted 2 March 2000.