Tolerance of Greenhouse-grown Strawberries to Terbacil as Influenced by Cultivar, Plant Growth Stage, Application Rate, Application Site and Simulated Postapplication Irrigation

Steven B. Polter,
Douglas Doohan, and
Joseph C. Scheerens¹

ADDITIONAL INDEX WORDS. *Fragaria ananassa*, 5-chloro-3-(1,1-dimethylethyl)-6-methyl-2,4-(1*H*, 1*H*)-pyrimidinedione, Sinbar, herbicide.

SUMMARY. Terbacil at 0, 0.8, 1.6, 3.2, and 6.4 oz/acre (0, 0.06, 0.11, 0.22, and 0.45 kg·ha⁻¹) a.i. was applied immediately after planting, at the three-leaf stage and at the six-leaf stage to greenhouse grown strawberry (*Fragaria ×ananassa*) cultivars Jewel, Mira, and Allstar. Strawberry was most tolerant of terbacil when the herbicide was applied before leaf emergence. 'Mira' was more tolerant of terbacil than was 'Jewel'. 'Jewel' and 'Allstar' exhibited similar levels of tolerance. In a second experiment terbacil at 4.8 oz/acre (0.34 kg·ha⁻¹) was applied to the soil, to the foliage,

and to the foliage followed by a water rinse. Injury was greatest when terbacil was applied directly to the strawberry foliage rather than to the soil, but was minimal when foliage was rinsed after application. In a final experiment terbacil at 4.8 oz/acre was applied to greenhouse-grown 'Jewel' strawberries at the three-leaf stage followed by a water rinse 0.5, 1, 2, or 4 hours after application. Rinsing the foliage of strawberry plants after application significantly reduced leaf injury. Delaying the rinse up to 4 hours did not lead to increased injury. Over all, the results from our study indicate the potential for using terbacil as an effective herbicide on newly established strawberries, especially if the compound is rinsed from leaves (if present) after treatment.

Weed control in strawberry production is a major cultural problem faced by growers in their efforts to produce a profitable crop (Himelrick, 1998). Options for weed control in strawberries are few and include mechanical cultivation, hand removal, mulching, fumigants and herbicides. Herbicides are used by virtually every strawberry grower. They are cost effective, and require minimal labor. Perhaps the greatest limitation to the use of some herbicides is that they may cause injury to the plant (Pritts and Handley, 1998).

Terbacil is one of the most effective herbicides registered for use in strawberries. The herbicide is applied preemergence for control of most germinating broadleaf and grass weeds and also controls some emerged weed seedlings that are less than 1 inch (2.5 cm) tall at the time of application. Terbacil is persistent in the soil and can provide residual control of germinating weeds for four weeks or more (Jensen et al., 1996). Terbacil molecules enter plants primarily through roots, and then move apoplastically in xylem tissues to their site of action in leaf mesophyll chloroplasts where they inhibit photosynthesis (Ashton and Monaco, 1991). Terbacil may be absorbed directly by leaves; however, this route is thought to be of minor importance relative to root absorption. For instance, Barentine and Warren (1970) found that less than 2% of a foliar application of terbacil penetrated the foliage 24 h after application to giant foxtail (*Setaria faberi*).

Strawberry is moderately tolerant

to terbacil due to restricted translocation of the herbicide from the roots or leaf surfaces to the site of action in mesophyll chloroplasts. In autoradiographs, ¹⁴C-labelled terbacil was restricted to the leaf veins (Genez and Monaco, 1983a). Metabolism of terbacil to nontoxic derivatives in strawberry is an important component of crop tolerance (Genez and Monaco, 1983b). Strawberry cultivars vary in their sensitivity to terbacil (Jensen et al., 1996; Lindstrom and Swartz, 1987; Masiunas and Weller, 1986; Weller, 1984). Masiunas and Weller (1986) found that vigorous cultivars were not affected by applications of terbacil nearly as much as less vigorous cultivars.

Preventing or reducing injury when terbacil is used in the planting year would be very beneficial. Since foliar absorption may contribute to crop injury, several horticulturists have suggested that irrigation soon after application could be used to remove the herbicide from the leaves (Ontario Ministry of Agriculture and Food, 2003; Pritts and Handley, 1998). There has been no formal investigation to document reduction of injury when irrigation is used after terbacil application.

Therefore our objective was to investigate the effects of irrigation to rinse terbacil off of the leaves after application to newly planted strawberries. We tested the effects of cultivar, plant growth stage (presence of leaves), application rate, application site and simulated postapplication irrigation treatments on terbacil phytotoxicity symptoms. We measured the efficacy of water-rinse treatments applied at increasing time increments after terbacil application in limiting phytotoxic responses.

Materials and methods

Dormant, bare root strawberry plants (Nourse Farms, Inc. South Deerfield, Mass.) were planted in 6-inch (15.2-cm) pots filled with a mixture of 1/3 sand, 1/3 Wooster silt loam soil (fine-loamy, mixed, mesic Typic Fragiudalf), 1/6 peat, 1/12 perlite, and 1/12 vermiculite. Plants were cultured either in greenhouses at The Ohio State University, Columbus or those at the Ohio Agricultural Research and Development Center, Wooster. Light intensity in the greenhouse was measured at the time of

Department of Horticulture and Crop Science, at The Ohio State University, the Ohio Agricultural Research and Development Center, 1680 Madison Ave., Wooster, Ohio 44691.

Manuscript number HCS03-XX. Salaries and research support provided in part by State and Federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State University. Work was also supported by The Ohio Fruit Growers Society. Use of trade names does not imply endorsement of the products named nor criticism of similar products not named. We would like to acknowledge the contributions of B.L. Bishop, J. K. Hacker, J.M. Stachler, J.L. Vent, L.A. Duncan, R. Downer, and the staff of the Laboratory for Pest Control Application Technology.

¹Graduate research assistant and associate professor.

Fig. 1. Strawberry leaf injury rating scale in response to the herbicide terbacil: (A) damage corresponding to a rating of 1.5; (B) damage corresponding to a rating of 2.0; (C) damage corresponding to a rating of 3.0; (D) damage corresponding to a rating of 4.5.

terbacil application and throughout each experiment. Temperatures were also measured and recorded using a hygrothermograph. To keep the plants in a vegetative state, natural daylight in the greenhouse was supplemented with 600-W halide lamps to provide a 16-h day length. In addition, floral structures were removed to keep the plants vegetative. Plants were watered daily throughout each experiment and fertilizer (20N–8.8P–16.3K) was supplied on a weekly basis.

Terbacil was applied using a compressed air hydraulic sprayer equipped with flat fan nozzles calibrated to deliver a volume of 20 gal/acre (187.1 L·ha⁻¹) at a pressure of 45 psi (310.3 kPa). Phytotoxicity was assessed using a visual injury scale of 1 (no injury) to 10 (plant death) (Fig. 1) as well as by comparing final dry weights of plant organs. Plants were rated for injury and photographed 7, 14, and 21 d after treatment (DAT) application. Plants were harvested for determination of leaf, crown and root dry weights 4 weeks after treatment application.

All experiments were repeated twice (i.e., Trials 1 and 2).

EXPERIMENT 1. CULTIVAR, GROWTH

STAGE AND APPLICATION RATE. Strawberry sensitivity to terbacil application was assessed in a 2 × 3 × 5 factorial experiment. The main effects were cultivar, growth stage at the time of application and application rate. Cultivars used in Trial 1 were ‘Jewel’ considered to be relatively sensitive to terbacil, and ‘Mira’ considered to be somewhat tolerant (D. Smith, personal communication). Strawberries were removed from cold storage and planted sequentially on 18 Apr. 2001, 27 Apr. 2001, and 17 May 2001 in order to provide plants for experimentation at three growth stages: Stage 1 = herbicide applied immediately after planting (i.e., before leaf emergence); Stage 2 = herbicide applied at the three-leaf stage (21 d after planting); and Stage 3 = herbicide applied at the six-leaf stage (30 d after planting). Terbacil was applied to all plants receiving treatment on 17 May 2001. Terbacil was applied at rates of 0, 0.8, 1.6, 3.2, and 6.4 oz/acre a.i. to plants at each growth stage. Potted plants were laid out in the greenhouse using a randomized complete block design with six replicates for a total of 180 experimental units.

Experiment 1 was repeated in

the spring 2002 (Trial 2). A similar procedure was used in the second year, except that ‘Allstar’ was substituted for ‘Mira’, which was not available. One-third of the plants were potted on 3 June 2002, one-third on 13 June 2002, and the final third on 8 July 2002. All herbicide treatments were applied July 8, 2002.

EXPERIMENT 2. APPLICATION SITE AND POSTAPPLICATION IRRIGATION TREATMENTS. A randomized complete block design was used to measure strawberry response to terbacil as affected by application site (i.e., leaf-applied versus soil-applied) and simulated irrigation (a water rinse following treatment). Plants of the sensitive cultivar Jewel were potted on 12 Apr. 2001 (Trial 1) and 9 Apr. 2002 (Trial 2). Terbacil was applied on 3 May 2001 and 8 May 2002 at a single application rate [4.8 oz/acre a.i.] to plants at the three-leaf stage. Four treatments were used: herbicide application to the soil, herbicide application to the leaves, herbicide application to the leaves followed by a water rinse, and an untreated control. For the soil-applied treatment, terbacil was applied with a pipette to the soil surface of potted plants in 0.34 fl oz (10 mL) of tap water and then incorporated into the soil with an additional 13.5 fl oz (400 mL) of tap water. Foliar treatments were applied to potted plants in which a layer of perlite prevented terbacil from contacting the soil surface. After herbicide application the perlite was removed with a vacuum.

Leaf-applied terbacil was allowed to dry for 0.5 h. Afterward, plants receiving a simulated irrigation treatment were turned on their side and rinsed with 3.4 fl oz (100 mL) of tap water from a hand pump spray bottle. Each plant was rinsed twice, with each rinse lasting 30 s. To prevent further herbicide removal from the foliage, plants were watered using drip tubes. Six replications were used for a total of 24 experimental units per experimental trial.

EXPERIMENT 3. TIMING OF POSTAPPLICATION IRRIGATION. Terbacil tolerance in strawberry and weed control effectiveness as influenced by the time increment between herbicide and simulated irrigation applications was determined using a randomized complete block experimental design with six replications. ‘Jewel’ strawberries were potted individually on 9 Apr. 2002 (Trial 1) and 11 Dec. 2002 (Trial 2). ‘Cherry

Belle' radishes (*Raphanussativus*) were planted, 10 seeds per pot, on 1 May 2002 (Trial 1) and 3 Jan. 2003 (Trial 2). Replications were single pots of strawberry (30 pots total) and single pots of radish (30 total). Once the strawberry plants reached the three-leaf stage (8 May 2002, Trial 1 and 10 Jan. 2003, Trial 2) terbacil was applied at a rate of 4.8 oz/acre a.i. to strawberry plants and radish seedlings simultaneously. Radishes were at the one- to two-leaf stage. Plants to receive irrigation treatments were placed under an irrigation simulator at intervals of 0.5, 1, 2, or 4 h after herbicide application. The irrigation simulator consisted of a compressed air hydraulic sprayer at a pressure of 45 psi using three flat fan nozzles spaced 18 inches (45.7 cm) apart. The boom traveled at 0.6 mph (0.96 km·h⁻¹) and applied about 1.2 inches/h (3 cm·h⁻¹) of tap water. The duration of irrigation was 20 min, during which time experimental units received 0.4 inches (1 cm) of irrigation. Control plants did not receive an irrigation treatment. Subsequent irrigation was applied with drip tubes. Six replications of treatment resulted in the use of 60 experimental units.

STATISTICAL ANALYSIS. Data from each trial were subjected to analysis of variance (PROC GLM; SAS Institute, Cary, N.C.). Crop injury rating values for untreated control plants were removed from the analysis of variance. Means were separated using the least significant difference (0.05) or were compared using linear and quadratic contrast statements as appropriate to the variable being considered.

Results

Injury to strawberry leaves following application of terbacil was evident at 7, 14, and 21 DAT in all

experiments. With few exceptions, patterns of leaf injury with respect to treatment were similar at each rating period, although injury usually became more severe with time (data not shown). Leaf injury ratings 21 DAT best represented treatment effects and will be presented herein. Crown and root dry weights were not significantly affected by terbacil application in any experiment/trial (data not shown). Therefore, only leaf dry weight data will be discussed.

EXPERIMENT 1. CULTIVAR, GROWTH STAGE AND APPLICATION RATE. Plant growth stage, cultivar and herbicide application rate influenced the phytotoxic response of strawberry to terbacil in the 2001 trial of Expt. 1 (Table 1). In Trial 2 (2002), plant growth stage and herbicide rate were significant, but cultivar was not. Patterns of leaf injury resulting from terbacil application were similar in both trials, but the extent of damage observed in Trial 2 was generally less than that of Trial 1 (Table 2). Although treatments differed in leaf injury ratings in both trials, injury levels were considered to be acceptable regardless of treatment in Trial 2.

Strawberry appeared to be most tolerant to terbacil when the herbicide was applied at Stage 1 (i.e., plants treated before leaf emergence) in both trials (Table 2). Little or no injury was detected in treated Stage 1 plants. Injury to strawberry leaves in plants treated at Stage 2 (three-leaf stage) was greater than that found in plants treated at Stage 3 (six-leaf stage), but this difference was only significant in Trial 1.

Strawberry cultivars responded differently to terbacil applied at Stages 2 and 3. 'Jewel' was more sensitive than 'Mira' or 'Allstar' (Tables 1 and 2); however, in Trial 2 differences between

'Jewel' and 'Allstar' were only significant when terbacil was applied at Stage 2 (Fig. 2B). The practical significance of the differing cultivar response may be trivial; and we determined that leaf injury ratings less than 2 would be acceptable to growers (Polter, 2003).

In both trials, leaf injury increased both linearly and quadratically with rate. Maximum injury averaged across stage and cultivar was 2.8 and 1.7 in Trial 1 and Trial 2, respectively, when the highest rate, 8 oz/acre (0.56 kg·ha⁻¹) was used. Average injury in field studies at comparable rates was greater [2.9 and 3.4 at Wooster and Fremont, Ohio, respectively, when the herbicide was applied at 8 oz/acre] than injury observed in the greenhouse (Polter, 2003); however, fruit yield was not affected.

The stage by rate interaction for leaf damage was also significant in both trials (Table 1, Fig. 3). Plants receiving treatment before leaf emergence did not show an increase in injury with respect to rate, even at the highest rates, whereas plants treated when actively growing leaves were present did show dramatic increases in leaf injury proportional to the rate applied. Tolerance to terbacil was greater at Stage 3 than at Stage 2 in Trial 1 but not in Trial 2.

The main effect of plant growth stage was significant for leaf dry weight in both trials (Table 1). By experimental design, plants in different growth stage categories varied substantially in leaf number, and therefore leaf weight, before the initiation of the experiment. Leaf dry weights found at the conclusion of the experiment were roughly proportional to those present initially (Table 2). Terbacil application may have differentially influenced the number and mass of leaves added to

Table 1. Analysis of variance table for the effect of strawberry growth stage (stage), strawberry cultivar (cultivar), and herbicide application rate (rate) on leaf injury rating and leaf dry weight of the crop 28 d following terbacil application in 2001 (Trial 1) and in 2002 (Trial 2).

Source of variation	Analysis of variance probability values (<i>P</i>)			
	Leaf injury rating		Leaf dry wt	
	Trial 1 (2001)	Trial 2 (2002)	Trial 1 (2001)	Trial 2 (2002)
Stage	<0.0001 ^a	<0.0001	<0.0001	<0.0001
Cultivar	0.0046	0.0584	<0.0001	0.0002
Stage × cultivar	0.0430	0.0004	0.0055	0.1469
Rate	<0.0001	<0.0001	<0.0001	0.1122
Stage × rate	<0.0001	<0.0001	<0.0001	0.1930
Cultivar × rate	0.0958	0.2732	0.4070	0.0097
Stage × cultivar × rate	0.0346	0.0042	0.0791	0.0383

^aProbabilities in boldface type indicate significance.

Table 2. The effect of strawberry growth stage (growth stage at application), strawberry cultivar (cultivar), and herbicide application rate (application rate) on leaf injury rating and leaf dry weight of the crop 28 d following terbacil application in 2001 (Trial 1) and in 2002 (Trial 2).

Source of variation	Leaf injury rating ^z		Leaf dry wt ^y	
	Trial 1 (2001)	Trial 2 (2002)	Trial 1 (2001)	Trial 2 (2002)
Growth stage at application ^x				
Stage 1	1.0 c ^w	1.0 b	2.3 c	5.2 b
Stage 2	2.3 a	1.3 a	7.6 b	11.4 a
Stage 3	1.9 b	1.2 a	12.3 a	12.0 a
Cultivar				
Mira	1.7 b	ND ^v	6.9 b	ND
Jewel	1.8 a	1.2a	7.9 a	10.8 a
Allstar	ND	1.1a	ND	8.3 b
Application rate [oz/acre (kg ha ⁻¹) a.i.]				
10.6	0	1.0	1.0	8.6
0.8 (0.06)	1.3	1.0	7.1	10.3
1.6 (0.11)	1.7	1.0	7.3	9.1
3.2 (0.22)	2.2	1.1	7.3	8.1
6.4 (0.45)	2.8	1.7	6.8	9.5
Significance	L,Q	L,Q	L,Q	NS

^zLeaf injury rating scale 1 to 10; rating of 1 = no damage, rating of 2 = moderate damage, rating of 3 = severe damage; rating of 10 = plant death.

^y28.35 g = 1.0 oz.

^xStage 1 = terbacil applied to strawberry plants (dormant crowns) prior to leaf emergence; Stage 2 = terbacil applied to strawberry plants at the three-leaf stage; Stage 3 = terbacil applied to strawberry plants at the six-leaf stage.

^wMeans followed by similar postscripts are not significantly different by the least significant difference test ($P = 0.05$).

^vND = not determined.

^{ns}Nonsignificant response at $P = 0.05$; L = linear, Q = quadratic.

A.

B.

C.

Fig. 2. Strawberry leaf injury rating in 2001 (A) and 2002 (B), 21 d after terbacil application and leaf dry weight (g) in 2001 (C), 28 d after terbacil application, as influenced by interactive effects of growth stage (Stage 1 = dormant plants before leaf emergence; Stage 2 = plants at the three-leaf stage; Stage 3 = plants at the six-leaf stage) and cultivar. (28.35 g = 1.0 oz).

A.

B.

C.

Fig. 3. Strawberry leaf injury rating in 2001 (A) and 2002 (B), 21 d after terbacil application and leaf dry weight in 2001 (C), 28 d after terbacil application as influenced by interactive effects of growth stage (Stage 1 = dormant plants before leaf emergence; Stage 2 = plants at the three-leaf stage; Stage 3 = plants at the six-leaf stage) and herbicide application rate. (1.0 oz/acre = 0.07 kg·ha⁻¹, 28.35 g = 1.0 oz).

plants of each growth stage during the experimental period, but if so, this effect was masked by differences present in Stage 1, Stage 2 and Stage 3 plants when the experiment was initiated.

The main effect of cultivar was also significant for leaf dry weight in both trials (Table 1). In Trials 1 and 2, 'Jewel' leaf dry weights were greater than those of 'Mira' and those of 'Allstar', respectively (Table 2). However, as with growth stage effects, inherent differences in cultivar vigor and growth rate may have concealed any differences in leaf dry weight accumulation associated with terbacil application during the course of the experiment.

In Trial 1, leaf dry weights were linearly and quadratically affected by herbicide rate (Table 2). Mean leaf dry weights also declined with increasing application rates in Trial 2.

In Trial 1, the interaction of stage by cultivar for leaf dry weight was significant (Table 1, Fig. 2C), most

likely reflecting differences in vegetative vigor between cultivars rather than differences due to treatment effects. The interaction of stage by rate was also significant (Table 1, Fig. 3C). Stage 1 plants did not vary in terms of leaf dry weight when terbacil was applied in increasing rates. The other two stages showed a reduction in leaf dry weight with increasing rates. In Trial

2, the cultivar by rate interaction for leaf dry weight was significant (Table 1, Fig. 4). Increasing application rates decreased the accumulation of leaf dry weight in 'Jewel' plants, but not those of 'Allstar'.

EXPT. 2. APPLICATION SITE AND POST-APPLICATION IRRIGATION TREATMENTS. In both trials, leaf injury resulting from terbacil was significantly greater in

Fig. 4. Strawberry leaf dry weight 28 d after terbacil application as influenced by interactive effects of crop cultivar and herbicide application rate in 2002.

Table 3. The effect of herbicide application site (soil or strawberry leaves) and simulated irrigation treatments on leaf injury ratings and leaf dry weights of the crop at 28 d following terbacil application in 2001 (Trial 1) and 2002 (Trial 2).

Treatment	Leaf injury rating ^z		Leaf dry wt ^y (g)	
	Trial 1 (2001)	Trial 2 (2002)	Trial 1 (2001)	Trial 2 (2002)
No herbicide applied	1.0 c ^x	1.0 b	5.7 a	5.8 a
Herbicide applied to soil	2.5 b	1.3 b	5.2 a	6.0 a
Herbicide applied to leaves	4.0 a	3.0 a	3.8 b	6.3 a
Herbicide applied to leaves followed by simulated irrigation	1.3 bc	1.3 b	6.3 a	7.8 a

^zLeaf injury rating scale 1 to 10; rating of 1 = no damage, rating of 2 = moderate damage, rating of 3 = severe damage; rating of 10 = plant death.

^y28.35 g = 1.0 oz.

^xMeans followed by similar postscripts are not significantly different by the least significant difference test ($P = 0.05$).

Table 4. The effect of timing of simulated irrigation treatments after herbicide application (timing of irrigation) to strawberry on leaf injury rating and leaf dry weight of the crop 28 d following terbacil application in 2002 (Trial 1) and 2003 (Trial 2).

Timing of irrigation ^x (min)	Leaf injury rating ^z		Leaf dry wt ^y (g)	
	Trial 1 (2001)	Trial 2 (2002)	Trial 1 (2001)	Trial 2 (2002)
30	1.0 a ^w	1.1 a	13.5 a	15.0 a
60	1.0 a	1.0 a	9.8 a	10.0 a
120	1.0 a	1.0 a	9.3 a	13.3 a
240	1.1 a	1.0 a	10.5 a	15.0 a
No simulated irrigation	2.8 b	2.3 b	9.3 a	11.7 a

^zLeaf injury rating scale 1 to 10; rating of 1 = no damage, rating of 2 = moderate damage, rating of 3 = severe damage; rating of 10 = plant death.

^y28.35 g = 1.0 oz.

^xTiming of irrigation corresponds to the length of time strawberry leaves were exposed to terbacil before irrigation.

^wMeans followed by similar postscripts are not significantly different by the least significant difference test ($P = 0.05$).

strawberries when the herbicide was applied directly to the leaves (4.0 in Trial 1 and 3.0 in Trial 2) rather than to the soil (2.5 in Trial 1 and 1.3 in Trial 2) (Table 3). Injury associated with soil uptake of terbacil was slower to develop than that associated with uptake from leaves (data not shown). However, when the herbicide was rinsed from leaves 0.5 h after treatment, the leaf damage rating was significantly reduced (1.3 in both trials) relative to the nonrinsed treatment.

In Trial 1, the leaf dry weight from plants that were treated but not rinsed was 33% less than that of the control. Leaf dry weights associated with other treatments were similar to those of the control. There were no significant differences in leaf dry weight among treatments in Trial 2.

EXPERIMENT 3. TIMING OF POST-APPLICATION IRRIGATION TREATMENT. Rinsing the foliage of strawberry plants after application of terbacil using simulated overhead irrigation significantly reduced leaf injury in both trials (Table 4). When strawberries received a post-application rinse between 0.5 to 4 h after treatment, leaf injury was negligible. Strawberry plants treated with terbacil but not rinsed received a mean rating of 2.8 (Trial 1) or 2.3 (Trial 2), indicating significant herbicide-induced

leaf injury. However, leaf dry weights were not reduced suggesting that irrigation only to minimize injury from herbicides may not be economically justified. Evidently leaching terbacil into the strawberry root zone with a postapplication water rinse of up to 0.4 inches (1 cm) does not lead to increased injury from root uptake.

Radishes were controlled with terbacil regardless of whether or not a rinse was applied. Leaf damage ratings ranged from 9.7 to 10.0 (14 DAT) in both trials. Rinsing radish foliage as soon as 0.5 h after application did not reduce herbicide effectiveness, indicating that control of small seedlings results mainly from herbicide uptake by roots. Terbacil applied to the radish leaves and subsequently rinsed off was probably leached into the root zone of the plant. Any reduction in absorption from leaves would then be unimportant.

Discussion

Under the greenhouse conditions of this experiment newly planted strawberries were most tolerant to terbacil applied before new growth began and less tolerant when leaves were present at the time of application. This is in agreement with Masiunas and Weller (1986) and Weller (1984), who reported neg-

ligible crop injury from terbacil applied to field-grown strawberries at a rate of 4 oz/acre (0.28 kg·ha⁻¹) immediately after planting. In their studies, treated plants out yielded the untreated counterparts. However, our results are contradictory to those reported by Ahrens (1982), who found that application of terbacil at 2 and 4 oz/acre (0.14 and 0.28 kg·ha⁻¹) caused more injury to field grown strawberries when applied 3 d after planting vs. 4 weeks after planting. The complete absence of new growth on the newly-planted strawberries in our experiments is no doubt responsible for these plants experiencing less damage than plants with three and six leaves.

Plants treated at the six-leaf stage tended to be more tolerant of terbacil than plants treated at the three-leaf stage and this was significant in Trial 1. This observation concurs with findings of Ahrens (1982) who found strawberry to be more tolerant to terbacil in late summer after the plants had become well established than they were 3 weeks after planting. Increased herbicide tolerance of more developed plants may be attributed to increased plant size, including deeper root systems and to development of epicuticular wax layers on leaf surfaces (Darnell and Ferree, 1983). Composition and morphology of the cuticle layer also changes as leaves

age, with the cuticles of mature leaves restricting foliar uptake of terbacil (Ashton and Monaco, 1981). Additionally, Lindstrom and Swartz (1987) suggested that differences in transpiration rates could lead to differences in terbacil concentration in the strawberry leaf.

In our study, injury resulting from terbacil application was always most evident on the newest fully expanded leaf before the development of its full pigmentation. Leaves of this stage of development were present on both Stage 2 and Stage 3 plants at treatment, and therefore, would presumably have been equally sensitive to terbacil. However, in Stage 3 plants, the proportion of new leaves to fully developed leaves was less than in Stage 2, perhaps influencing visual ratings, but also buffering plants from significant herbicide damage.

In Expt. 1, differences in the extent of leaf injury may have resulted partially from differences in greenhouse ambient temperatures. During Trial 1 (April 2001) mean ambient temperatures were relatively mild whereas those associated with Trial 2 (June 2002) were considered to be higher than optimum for strawberry growth (Hellman and Travis, 1988). Strawberries may have responded to excessive heat in the greenhouse during Trial 2 (data not shown) by increasing deposition of epicuticular wax on the leaf surface; thereby, reducing the foliar uptake of terbacil (Skoss, 1955). Epicuticular wax morphology and chemistry can be modified by environmental stresses resulting in differential response to applied herbicides (Darnell and Ferree, 1983).

Data from this experiment confirm previous studies showing strawberry cultivars vary in their tolerance to terbacil (Jensen et al., 1996; Lindstrom and Swartz, 1987; Masiunas and Weller, 1986; Weller, 1984). In this experiment, 'Jewel' was less tolerant to applications of terbacil than was 'Mira', but similar in tolerance to 'Allstar' based on visual injury. Masiunas and Weller (1986) reported that vigorous cultivars were more tolerant than those exhibiting moderate vigor. In their study the vigorous cultivars were able to overcome the injury by terbacil and produce normal crop yields. In our study 'Jewel' was more vigorous based on leaf dry weight but was damaged more severely by terbacil than the slower-growing cultivar 'Mira', refuting Masiunas and Weller (1986).

However, strawberries have been shown to completely outgrow moderate foliar injury of terbacil within a few months (Jensen et al., 1996). It is likely that these plants would have responded in a similar manner.

Control of weed populations by terbacil results primarily from root uptake (Ashton and Monaco, 1991). However, foliar uptake appeared to cause greater damage to strawberry leaves in these experiments, primarily because the strawberry vascular system resists translocation of terbacil from the root (Genez and Monaco, 1983a, 1983b). Strawberries have been shown to be able to metabolize terbacil to nontoxic derivatives although this occurs primarily in the roots (Genez and Monaco, 1983b). Even though only a small percentage of terbacil applied to the foliage may actually penetrate the leaf (Barrentine and Warren, 1970), the quantity that does enter can cause severe damage. Strawberry leaves are not able to prevent terbacil damage once the chemical enters the leaf (Lindstrom and Swartz, 1987).

Our results show that injury due to foliar absorption of terbacil can be effectively eliminated by a water rinse 0.5 to 4 h after herbicide application. This is in agreement with Barrentine and Warren (1970) who showed that terbacil is very slow to penetrate the leaf surface. In their experiment, terbacil at 4 oz/acre was applied exclusively to the foliage of ivy leaf morning glory (*Ipomoeahederacea*). Leaves were washed eight h later with a 0.2% detergent solution followed by a water rinse. No injury was observed in washed plants, but when terbacil was left on the foliage for 48 h before washing, a 30% reduction in fresh weight occurred. It also confirms work by Polter (2003) that showed a reduction in injury to field grown strawberries when plants were irrigated overhead immediately after terbacil application. He saw a reduction in injury at rates as high as 6.4 oz/acre when terbacil was applied to strawberries before new growth or at the three-leaf stage.

Overall, the results from our study indicate the potential for using terbacil as an effective herbicide on newly established strawberries, especially if rinsed from leaves (if present) after treatment. Injury to the strawberry crop from root uptake is likely to be minimal.

Literature cited

Ahrens, J.F. 1982. Napropamide and ter-

bacil for newly planted strawberries. *Adv. Strawberry Prod.* 1:22-26.

Ashton, F.M. and T.J. Monaco. 1991. *Weed science: Principles and practices* 3rd ed. Wiley, New York.

Barrentine, J.L. and G.F. Warren. 1970. Isoparaffinic oil as a carrier for chlorpropham and terbacil. *Weed Sci.* 18: 365-372.

Darnell, R.L. and D.C. Ferree. 1983. The influence of environment on apple tree growth, leaf wax formation, and foliar absorption. *J. Amer. Soc. Hort. Sci.* 108 (3):506-511.

Genez, A.L. and T.J. Monaco. 1983a. Uptake and translocation of terbacil in strawberry (*Fragaria x ananassa*) and goldenrod (*Solidago fistulosa*). *Weed Sci.* 31:56-62.

Genez, A.L. and T.J. Monaco. 1983b. Metabolism of terbacil in strawberry (*Fragaria x ananassa*) and goldenrod (*Solidago fistulosa*). *Weed Sci.* 31:221-225.

Hellman, E.W. and J.D. Travis. 1988. Growth inhibition of strawberry and high temperatures. *Adv. Strawberry Prod.* 7: 36-38.

Himelrick, D.G. 1998. Problems caused by weeds and herbicides, p. 14-15. In: J.L. Maas (ed.). *Compendium of strawberry diseases*. Amer. Phytopathol. Soc., St. Paul, Minn.

Jensen, K.I.N., D.J. Doohan, and E.G. Specht. 1996. Fluzifop-P reduces strawberry (*Fragaria x ananassa*) tolerance to terbacil. *Weed Technol.* 10:883-888.

Lindstrom, J.T. and H.J. Swartz. 1987. Strawberry genotype responses to terbacil. *Adv. Strawberry Prod.* 6:44-46.

Masiunas J.B. and S.C. Weller. 1986. Strawberry cultivar response to postplant applications of terbacil. *HortScience* 21(5): 1147-1149.

Ontario Ministry of Agriculture and Food. 2003. Herbicide injury symptoms in berry crops. 11 Dec. 2003 < http://www.gov.on.ca/OMAFRA/english/crops/facts/berry_injury.htm#24d >.

Polter, S.B. 2003. Terbacil tolerance in newly-planted strawberries. MS thesis. Ohio State Univ., Columbus.

Pritts, M.P. and D. Handley. 1998. Strawberry production guide for the northeast, midwest, and eastern Canada. NRAES-88. Northeast Regional Agricultural Engineering Service, Ithaca, N.Y.

Skoss, J.D. 1955. Structure and composition of plant cuticle in relation to environmental factors and permeability. *Bot. Gaz.* 117:55-72.

Weller, S.C. 1984. Evaluation of postplant applications of terbacil and napropamide to strawberry plants. *Adv. Strawberry Prod.* 3:15-19.