Weed Technology 2013 27:573–579

Annual Strawberry Response to Clopyralid Applied During Fruiting

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As the amount of methyl bromide approved for use in Florida strawberry diminishes, growers are faced with a forced transition to alternative fumigants. Many of these methyl bromide alternatives have been associated with reductions in weed control, requiring additional but complementary measures. POST herbicide options for annual strawberry are limited, resulting in significant portions of the strawberry acreage in Florida being hand-weeded when troublesome weeds escape conventional control methods. Strawberry has shown acceptable tolerance to clopyralid in other areas and production systems; however, its integration into the Florida production system and ramifications of applications during fruiting warrants further research. Eight trials were conducted, with three common strawberry cultivars grown in West Central Florida subjected to POST spray and drip-tape-injected applications of clopyralid. Formation of new strawberry leaves was not affected by clopyralid application, except for a reduction in new leaves of the cultivar 'Strawberry Festival' at the highest rate of application of 261 g ae ha^{-1} in comparison with the nontreated control. Strawberry leaf malformation was best explained by an exponential growth equation, whereas marketable yield followed the trend of a Weibull peak. At the maximum labeled rate (66 g ha^{-1}), leaf malformation was less than 5% for all cultivars tested, and marketable yield was estimated at 104% of the nontreated control.

Nomenclature: Clopyralid; strawberry, *Fragaria* × *ananassa* Duchesne

Key words: Application timing, crop injury, crop tolerance, growth regulator, herbicide tolerance, plasticulture.

Al reducirse la cantidad de methyl bromide aprobada para el uso en la producción de fresas en Florida, los productores deben enfrentar una transición forzada a fumigantes alternativos. Muchas de estas alternativas a methyl bromide han sido asociadas con reducciones en el control de malezas, requiriéndose así medidas complementarias. La fresa ha mostrado una tolerancia aceptable a clopyralid en otras áreas y sistemas de producción. Sin embargo, su incorporación en los sistemas de producción de Florida y lo que esto podría implicar para las aplicaciones durante la producción del fruto requiere más investigación. Se realizaron ocho ensayos con tres cultivares comunes de fresa producidos en el Centro Oeste de Florida y que fueron sometidos a aspersiones POST y a aplicaciones inyectadas a través de la cinta de goteo con clopyralid. La formación de hojas nuevas de la fresa no fue afectada por la aplicación de clopyralid, excepto por una reducción de las hojas nuevas en el cultivar 'Strawberry Festival' con la dosis de aplicación más alta de 261 g ae ha^{-1} en comparación con el testigo no tratado. La malformación de hojas de la fresa fue explicada mejor con una ecuación de crecimiento exponencial, mientras que el rendimiento de fruta comercializable siguió una tendencia de un pico Weibull. A la máxima dosis de la etiqueta (66 g ha^{-1}), la malformación de hojas fue inferior al 5% en todos los cultivares evaluados, y el rendimiento comercializable fue estimado en 104% en comparación con el control no-tratado.

In Florida, during the 2010 to 2011 growing season, strawberry (*Fragaria* × *ananassa* Duchesne) was planted on approximately 4,000 ha, with a value estimated at $366 million (NASS-USDA 2011). Florida's industry is an annual production system where the crop is grown on raised beds covered with polyethylene mulch. For more than 50 yr, Florida strawberry producers have relied on a preplant soil fumigation treatment with methyl bromide to alleviate pest pressures from weeds, nematodes, and soilborne pathogens (Chandler et al. 2001). In 1993, methyl bromide was classified as a class I ozone-depleting substance under the provisions of an international treaty known as Montreal Protocol for substances that deplete ozone. At this time, the Protocol recommended a phase-out of the use and production of methyl bromide in the United States and other developed countries by the year 2010 (Honaganahalli and Seiber 1996). Subsequently, the U.S. Environmental Protection Agency acting under the Clean Air Act of 1990 initially set a much stricter phase-out date of January 1, 2001, which was ultimately postponed until January 1, 2005 (Ferguson and Padula 1994; Honaganahalli and Seiber 1996; Noling et al. 2011).

The industry is currently transitioning into the post-methyl bromide era with the use of alternative fumigants. New and additional measures of weed control are of high importance, including posttransplant herbicide applications, in the development of a new weed management program. Extensive field research continues to evaluate methyl bromide alternative fumigants and fumigant systems for their herbicidal activity. Due to the overall lack of herbicidal activity associated with many of the alternatives, weed control is deemed one of the highest pest management priorities (Noling et al. 2011). Augmenting the alternative fumigants with complementary in-bed herbicide applications during bed formation has become an area of intensive weed research interest. Terbacil

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DOI: 10.1614/WT-D-13-00010.1

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is extensively used in perennial strawberry for POST and residual control of seedling and germinating annuals (Rogers et al. 2001). Although terbacil has shown to be a promising option, the preharvest interval of 110 d makes the product nearly useless due to the need to harvest the Florida crop within this restricted period (Mossler and Nesheim 2004). Napropamide and oxyfluorfen are two other herbicides that have been shown to be safe on annual strawberry and have efficacy on common weeds when applied pretransplant under the plastic mulch (Daugovish et al. 2008; Gilreath and Santos 2005). However, season-long control of black medic (*Medicago lupulina* L) and Carolina geranium (*Geranium carolinianum* L.) has not been observed with these herbicides (A. W. MacRae, personal communication).

As methyl bromide availability diminishes, many strawberry producers who have transitioned to alternative fumigants are now beginning to observe their shortcomings. A recent strawberry grower survey conducted by the University of Florida Cooperative Extension Service revealed that a majority of respondents indicated that pest problems present in their fields were increasing (Snodgrass et al. 2011). Among the weed pests reportedly increasing were black medic and Carolina geranium. The area of interest for control of these weeds is within the planting bed, and more specifically within the planting holes that are made in the plastic mulch. Weeds growing in the planting holes compete with young strawberry plants for water, light, space, and nutrients and will typically begin germinating between 3 and 5 wk after planting (WAP) (Gilreath and Santos 2005). Many dormant, hard-seeded annual weeds such as black medic, Carolina geranium, and cutleaf evening-primrose (*Oenothera laciniata* Hill) can become mid- to late-season problems because of their ability to survive fumigant treatment (Mossler 2010; Stall 2008).

When evaluating POST herbicide applications in strawberry, spray coverage will be a concern. Since the troublesome weeds are germinating from the planting holes, they are located underneath a portion of the strawberry canopy in their early development. This may result in the crop plant shielding the weeds and reducing the total herbicide dose applied to the intended target. McMurray et al. (1996) concluded that their control of black medic with applications of clopyralid was directly related to spray coverage due to the strawberry crop canopy shielding weeds.

Clopyralid is a promising option for application in both perennial and annual strawberry production systems (Clay and Andrews 1984; Figueroa and Doohan 2006; McMurray et al. 1996). Figueroa and Doohan (2006) conducted trials in a perennial strawberry production system with applications of clopyralid at rates varying from 25 to 400 g ha^{-1}. It was reported that 82% control of common groundsel (*Senecio vulgaris* L.) was achieved with an application of clopyralid at 200 g ha^{-1}. Applications at 200 g ha^{-1} did not affect strawberry growth and development; however, at the maximum application rate tested of 400 g ha^{-1}, a reduction in crop canopy and yield was reported (Figueroa and Doohan 2006). McMurray et al. (1996) reported the effects of a clopyralid application in annual strawberry. Regardless of crop stage, application rate, or season, less than 6% crop injury was reported with no effects on yield. Although these results suggest high levels of crop safety with clopyralid, the impact on fruit quality and yield when making a clopyralid application between harvests at 3- to 4-d intervals is uncertain. The objectives of these studies were to (1) determine the effects of a posttransplanted directed spray and drip-injected application of clopyralid during strawberry fruiting on plant injury as well as on total and marketable yield of annual strawberry, and (2) evaluate tolerance of three different strawberry cultivars.

Materials and Methods

During the fall of 2011, eight trials were conducted at the University of Florida/Institute of Food and Agricultural Sciences (IFAS) Gulf Coast Research and Education Center in Balm, Florida to evaluate clopyralid in annual strawberry. Fields were prepared by means of conventional tillage and standard plasticulture bedding practices common throughout the producing region. Planting beds were formed and fumigated with PicClor 60® (Soil Chemicals Corporation, Hollister, CA), a combination of 39% 1,3-dichloropropene and 59.6% chloropicrin at 331 kg ai ha^{-1}. Following bed preparation and fumigation, beds were covered with a 1.2 mil polyethylene mulch (Berry Plastics Corporation, Evansville, IN). Each bed received two drip tapes placed 20 cm apart and 3 cm deep, with the capacity to deliver 605 mlh^{-1} per emitter, with emitters spaced 30.5 cm apart (Streamline Series, Netafim USA, Fresno, CA). Planting beds were established on 1.2-m centers with a height of 30.5 cm and a bed top width of 66 cm. Each trial consisted of four beds by 97.5 m long. Plots were 9 m long and consisted of 48 plants per plot. All trials were arranged in a randomized complete block design with each bed representing a block and each of the six treatments replicated four times.

Separate trials were conducted for each of the three different strawberry cultivars, including 'Treasure', 'Strawberry Festival', and 'Camino Real'. Four POST spray and four drip-tape injection trials were conducted, with duplicate trials for each application type being initialized for Strawberry Festival. After sufficient time for fumigant dissipation, planting holes were made using a tractor-mounted punch wheel that spaced planting holes in twin rows on 38-cm centers with 38 cm between rows. Bare root transplants of strawberry Treasure were planted on October 11, 2011, whereas bare root transplants of Strawberry Festival and Camino Real were planted on October 25, 2011 and October 26, 2011, respectively. Transplants received overhead watering during daylight hours for 10 consecutive days after transplanting to aid in establishment. Plants were irrigated and received fertilizer injected through the drip irrigation system on a daily basis. All production and pest management practices were in accordance with common commercial practice and University of Florida/IFAS recommendations (Santos et al. 2011).

Spray Applications. Clopyralid treatments consisted of a posttransplant spray application at 0, 45, 66, 132, 195, and 814 g ha^{-1}. All posttransplant spray treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 280 L ha^{-1} at 213 kPa utilizing TeeJet® 11004 DG nozzles

(TeeJet Technologies, Springfield, IL). Treatment timings varied between trials, with the strawberry cultivar Treasure being the first to be treated on December 30, 2011, 11 WAP. Clopyralid applications were made on January 13, 2012 (11 WAP) to the cultivar Strawberry Festival, hereafter referred to Festival A, followed by clopyralid application on January 18, 2012 (12 WAP) to the strawberry cultivar Camino Real. Application timings were meant to coincide with fruiting schedules, resulting in earlier-producing cultivars treated first, followed by mid- and, and finally late-season cultivars. The final trial had clopyralid applied on February 1, 2012 (14 WAP) in another separate field trial using the strawberry cultivar Strawberry Festival, hereafter referred to as Festival B. This trial was conducted to observe any impact of a clopyralid treatment during a different portion of the strawberry fruit production schedule. At the time of application, strawberry plants had blooms, fruit, and actively growing leaf tissue.

Drip-Injected Applications. For this method of clopyralid application, treatments consisted of a posttransplant drip injection application at 0, 45, 66, 132, 195, and 814 g ha^{-1} of clopyralid. Treatments were applied using a CO_2-pressurized injection system consisting of a manifold constructed of polyvinyl chloride (PVC) pipe. Herbicide was combined with 30 L of water to form the stock solution, which was injected into the PVC manifold containing irrigation water. The flow rate of the herbicide solution into the irrigation water was controlled with a needle valve that ensured a constant flow of solution throughout the entire 2.5-h injection period. The solution was then delivered to individual plots by way of a flexible low-density polyethylene tubing (The Toro Company Irrigation Division, Riverside, CA). The existing two drip tapes per bed were used for the herbicide application and consideration was given to an adequate flush of all injection lines and drip tapes before the system was put back into use for irrigation.

The dates in which the different treatments were applied varied between the four cultivar-specific trials. In this regard, the strawberry cultivar Treasure was the first to be drip treated on January 3, 2012 (12 WAP). The second drip application of clopyralid was made on January 13, 2012 (12 WAP) to the cultivar Strawberry Festival, hereafter referred to as Festival A, followed by an application on January 19, 2012 (12 WAP) to the cultivar Camino Real. Application timings were meant to coincide with fruiting schedules, resulting in earlier-producing cultivars treated first, followed by mid- and late-season cultivars treated later. The final drip application was made on February 1, 2012 (14 WAP) to another trial consisting of Strawberry Festival plants hereafter referred to as Festival B. As mentioned in the POST spray trials, this additional trial was conducted to observe any impact of a clopyralid treatment during a different portion of the strawberry fruit production schedule. Flowers, fruit, and new leaf development were on the plants at the time of application.

Data Collection and Analysis. Randomly selected subsamples of 10 plants from each plot were used to determine plant injury responses to clopyralid, and an initial leaf count was taken of the 10-plant subsample at the time of application. Leaf counts were taken at 2 and 4 wk after treatment (WAT), although only the 4-WAT data are presented, and consisted of a count of the total number of leaves and the total number of malformed leaves. These numbers were used to determine the number of new leaves formed since the time of clopyralid application, as well as the percentage of new leaves that might become malformed in response to its application. New leaf production is presented as the number of new leaves formed per plant from the time of application until the time of rating (4 WAT). Leaf malformation is presented as the percentage of new leaves since the time of application becoming malformed (4 WAT).

Mature strawberry fruit were harvested one to two times per week until the time of application. After clopyralid application strawberries were then harvested by plot and graded for both marketable and malformed fruit. Harvest continued for 8 wk after clopyralid application with strawberries being harvested on Monday and Thursday of each week, totaling 16 harvests, with the exception of the Festival B trial in which harvest continued for 6 wk for a total of 12 harvests. Marketable yield data were standardized and are presented as the percentage of the total number or cumulative weight of fruit harvested from the untreated control.

For data analysis, the generalized linear mixed models conducted under the PROC GLIMMIX procedure in SAS version 9.2 (SAS Institute, Inc., Cary, NC) were used to investigate the effect of application method, herbicide rate, and strawberry cultivar on new leaf production, the percentage of leaf malformation, and marketable fruit yield. Application method, cultivar, and clopyralid rate were treated as fixed effects in the model. The SLICE function was used to analyze the effect of rate at each level of cultivar, and clopyralid treatment means were compared using Fisher's Protected LSD at $\alpha = 0.05$. Curve fitting was performed using Sigmaplot 12.0 (Systat Software Inc., San Jose, CA). New leaf and malformed leaf data for the Festival B trial were analyzed separately from the other cultivars due to variability. Yield data for Festival B trial was not included in the analysis due to the difference in harvest schedules and subsequent degrees of harvest yield variability.

No interactions were observed with regard to application method (POST or drip injected) for any of the measured parameters; therefore, new leaf formation was combined across clopyralid application methods and is presented by cultivar in response to clopyralid rate. Clopyralid rate treatment means within cultivars were compared using Fisher's Protected LSD at $\alpha = 0.05$. Data for leaf malformation per plant were combined across application method and presented by cultivar in response to clopyralid rate. Using treatment means and standard errors determined from the generalized linear mixed model analysis, the data for leaf malformation were best fitted to the exponential growth (three parameter) equation indicated below:

$$f = y0 + a \times \exp(bx)$$

Data for marketable yield were combined across cultivars and application methods and presented as percentage of the untreated control in response to clopyralid rate. Using the treatment means and standard errors determined from the generalized linear mixed model analysis, the combined data for marketable yield data were then best fit to the Weibull peak (five parameter) equation indicated below:

$$\text{if}\quad \left(x \le x0 - b\left(\frac{c-1}{c}\right)^{\left(\frac{1}{c}\right)}, y0,\ y0 + a\left(\frac{c-1}{c}\right)^{\left(\frac{1-c}{c}\right)}\right.$$

$$\times\left(\text{abs}\left(\frac{x-x0}{b}\right) + \left(\frac{c-1}{c}\right)^{\frac{1}{c}}\right)^{(c-1)}$$

$$\left.\times\exp\left(-\text{abs}\left(\frac{x-x0}{b}\right) + \left(\frac{c-1}{c}\right)^{\left(\frac{1}{c}\right)}\right)^{\left(c+\frac{c-1}{c}\right)}\right)$$

Results and Discussion

New Leaf Formation. The number of newly forming leaves was variable within and between cultivars. With the exception of Festival B, which showed a decrease in new leaf production at 261 g ha^{-1} of clopyralid, no differences were observed when compared with the nontreated control (Table 1).

Leaf Malformation. Nonlinear regression of leaf malformation and clopyralid rate was best described by an exponential growth (three-parameter) model, explaining 97, 98, and 91% of the variability for the Festival A, Festival B, and Treasure cultivars, respectively (Figure 1). No relationship was found between malformed leaves and clopyralid rate for the Camino Real cultivar. For the cultivar Festival A, a 5 and 10% leaf malformation was estimated at 366 and 681 g ha^{-1}, respectively. A 5 and 10% leaf malformation was estimated when clopyralid was applied at 578 and 790 g ha^{-1} for the Treasure cultivar, respectively. A 10 and 20% leaf malformation was estimated when clopyralid was applied at 529 and 698 g ha^{-1} to the Festival B cultivar. When clopyralid was applied at the maximum labeled rate (66 g ha^{-1}), leaf malformation was predicted at 4, 4, and 3% for cultivars Festival A, Festival B, and Treasure, respectively. Applications of clopyralid at 132 g ha^{-1} were predicted to cause 6, 7, and 4% malformation for the cultivars Festival A, Festival B, and Treasure, respectively. On the basis of the generalized linear mixed model analysis for the Camino Real, leaf malformation of 4 and 6% was estimated when clopyralid was applied at 66 and 132 g ha^{-1}, respectively. When clopyralid was applied at 261 g ha^{-1}, leaf malformation was estimated at 12, 15, and 37% for the cultivars Treasure, Festival A, and Festival B, respectively.

Table 1. Number of new leaves formed per plant for three strawberry cultivars in response to six rates of clopyralid at 4 wk after treatment (WAT).

	New leaf formation by four cultivars							
Clopyralid rate	Festival A[a]		Festival B		Camino		Treasure	
g ae ha^{-1}	New leaves plant^{-1}							
0	16.60	ab[b]	12.12	a	18.25	a	13.94	ab
45	18.37	a	13.64	a	19.58	a	17.76	a
66	16.98	ab	11.91	a	16.52	a	13.51	b
132	17.57	ab	11.71	a	17.13	a	13.17	b
195	16.20	ab	11.02	a	16.60	a	15.35	ab
261	14.92	b	7.17	b	17.87	a	12.91	b

[a] Festival refers to the cultivar 'Strawberry Festival', Camino refers to the strawberry cultivar 'Camino Real'. Festival A refers to the first set of Festival trials treated; Festival B refers to the latter treated festival trial.

[b] Responses within columns with the same letter are not different according to Fisher's Protected LSD at P ≤ 0.05.

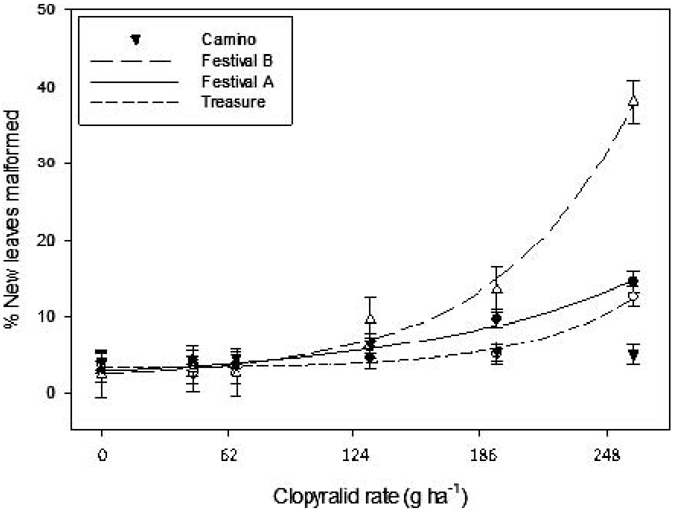

Figure 1. Leaf malformation expressed as the percentage of new leaves malformed in response to six rates of clopyralid application, 4 wk after treatment (WAT). Data values represent means ± standard error. Camino refers to the strawberry cultivar 'Camino Real', Festival A refers to the first applied set of trials with the cultivar 'Strawberry Festival', and Festival B refers to the latter treated trials of the cultivar Strawberry Festival. The regression model is $f = y0 + a \times \exp(bx)$. Festival A: $a = 1.26$, $b = 0.002$, $y0 = 1.47$, and $r^2 = 0.97$. Festival B: $a = 0.68$, $b = 0.004$, $y0 = 1.73$, and $r^2 = 0.98$. Treasure: $a = 0.05$, $b = 0.006$, $y0 = 3.11$, and $r^2 = 0.91$. No significant dose–response relationship between percent malformed leaves and clopyralid rate was detected within the strawberry cultivar Camino Real.

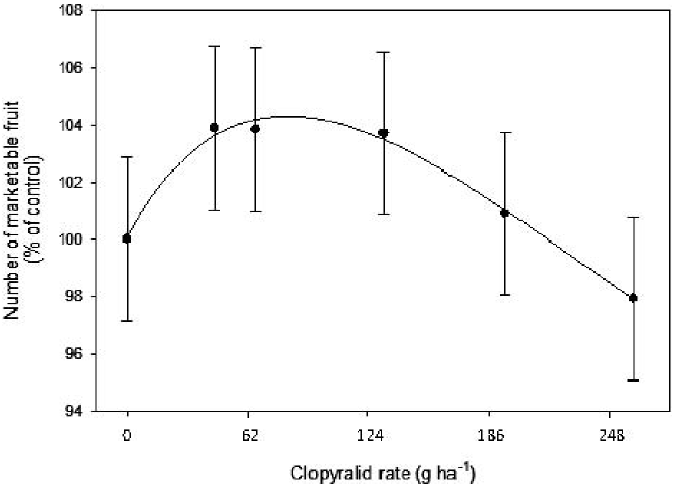

Figure 2. Number of marketable fruit expressed as a percentage of the control in response to six rates of clopyralid application. The regression equation presented represents data pooled across field trials of three cultivars and two application methods. Data values represent means ± standard error. The regression model is if $(x <= x0 - b[\{c - 1\}/c][1/c], y0, y0 + \text{a}[\{c - 1\}/\text{c}][\{1 - c\}/c])$ $(\text{abs}[\{x - x0\}/b] + [\{c - 1\}/c][1/c][c - 1])$ $\exp(-\text{abs}[\{x - x0\}/b + \{c - 1\}/c][1/c])c + [\{c - 1\}/c])$, where $a = 16.8$, $b = 830.4$, $c = 1.4$, $x0 = 266.3$, $y0 = 87.5$, $x =$ clopyralid rate, and $r^2 = 0.99$.

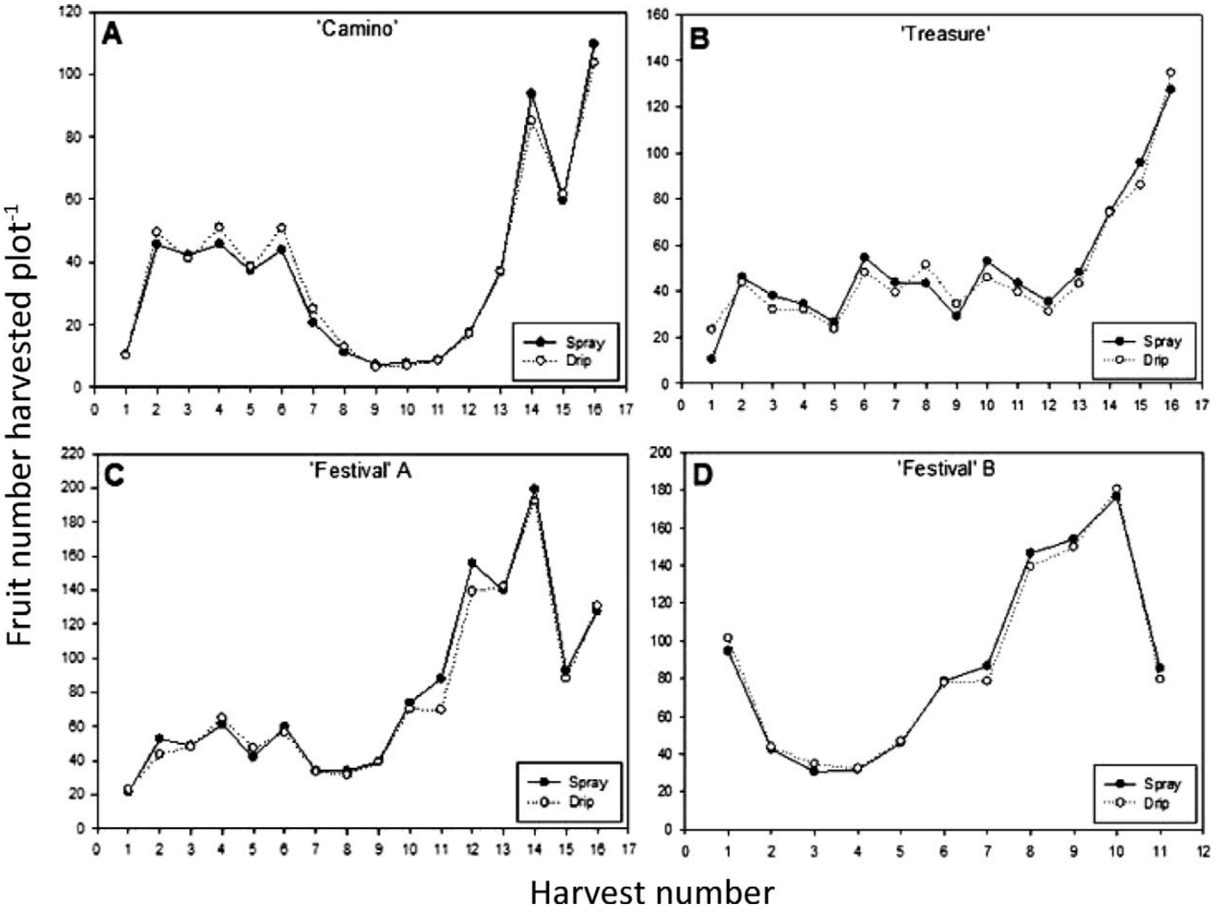

Figure 3. Fruiting cycles of three strawberry cultivars after clopyralid application as either a directed foliar spray or as a drip application to soil. Applications were made 2 d before harvest number 1. Camino refers to the strawberry cultivar 'Camino Real', Festival A refers to the first applied set of trials with the cultivar 'Strawberry Festival', and Festival B refers to the latter treated trials of the cultivar Strawberry Festival. Figure panels (A, B, C, D) are separated by cultivar with the solid line representing fruit production of plants receiving a directed foliar spray and the dashed line representing plants receiving drip applications of clopyralid. Note differences in scales among panels representing fruit production and harvest number.

Marketable Yield. Using treatment means and standard errors, nonlinear regression of strawberry yield and clopyralid rate was best fit to a Weibull peak (five-parameter) function with a coefficient of determination (r^2) value of 0.99 (Figure 2). When clopyralid was applied at the minimum and maximum labeled rates of 45 and 66 g ha^{-1}, predictable marketable yield was 104% of the nontreated control. A clopyralid application of 132 and 195 g ha^{-1} was estimated to result in a marketable yield of 103 and 101% of the nontreated control. Marketable yield was estimated at 98% of the control when clopyralid was applied at 261 g ha^{-1}. No trend with clopyralid rate was found for malformed fruit yield. All clopyralid treatments resulted in the production of malformed fruit within 1% of the nontreated control (data not shown).

Significant cultivar by clopyralid rate interactions were observed for production of new and malformed leaves, showing differences in cultivar tolerance to clopyralid. Although these interactions were deemed significant, other environmental factors may also be as equally important. The potential role of the environment in defining the effect of clopyralid can be described by comparison of the Festival A trial and Festival B trial. Both trials were planted with strawberry Festival plants on the same day and had been subjected to the same cultural practices throughout the growing season. Although these trials were treated the same, except for application date, the Festival B trial resulted in approximately 154% more leaf malformation at 261 g ha^{-1} in comparison with the Festival A. This is thought to have been caused by interactions of plant genotypic and environmental factors. Darrow (1930) described the optimum temperature for strawberry vegetative growth to be between 20 and 27 C, whereas the optimum temperature for flower bud initiation was described as between 14 and 18 C (Darnell 2003). As Figure 3 shows, average air temperatures after the Festival B clopyralid application were considerably higher, possibly leading to higher rates of vegetative growth and therefore more clopyralid being partitioned into the leaves. In contrast, after clopyralid application in the Festival A trial a period of lower-than-average temperatures was experienced (Figure 3), possibly leading to less vegetative growth and more clopyralid partitioned into strawberry fruits.

On closer examination of the fruiting cycles at the time of application (Figure 4) for the cultivars Camino Real,

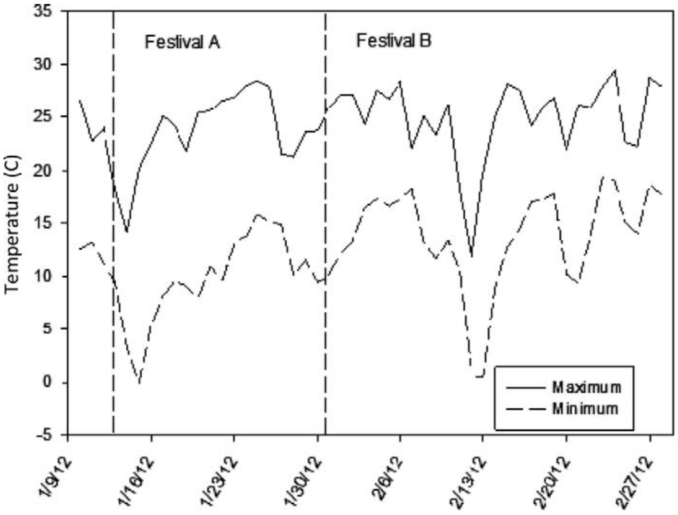

Figure 4. Minimum and maximum air temperatures after clopyralid application in two separate Festival trials. Dashed line labeled as Festival A represents application timing of the initial 'Strawberry Festival' trials. The dashed line labeled as Festival B represents application timing of the later-treated Strawberry Festival trials.

Treasure, and Festival A, it is evident that clopyralid application occurred during an increase or plateau phase in fruit production. In comparison, clopyralid application for the Festival B trial took place before a period of reduced fruit production (Figure 4d). As previously indicated, clopyralid has been reported to readily translocate within the phloem, with higher concentrations accumulating in regions of meristematic growth (Senseman 2007). Macias-Rodriguez et al. (2002) showed that during periods of vegetative growth, carbohydrates, also transported in the phloem, were shown to accumulate in the crown of strawberry plants. This accumulation was followed by the mobilization of the carbohydrates during flowering and fruiting, with much of the carbohydrates being partitioned to the fruits, which have been described as the most competitive sink in the plant (Forney and Breen 1985; Macias-Rodriguez et al. 2002). If in fact clopyralid is mobilized and accumulated similarly to that of carbohydrates, this could also help explain the excessive injury during times of vegetative growth due to high levels of clopyralid in strawberry crowns.

When an amino (NH_2) group is added to the clopyralid parent acid in the fourth position, a slightly different herbicidal compound is formed. Aminopyralid is similar in chemical makeup and in the way it is mobilized and acts within the plant (Senseman 2007). In a recent study Pfleeger et al. (2012) showed that at low concentrations, aminopyralid stimulated growth of bristly dogstail grass (*Cynosurus echinatus* L.). This stimulation response was seen in both field and greenhouse trials, leading Pfleeger et al. (2012) to conclude that the increased growth was a definite response to the aminopyralid rather than other underlying factors. This response to low concentrations of a closely related growth-regulating herbicide could help explain the trend for slight increases in strawberry marketable yield at low concentrations of clopyralid (Figure 2). Figueroa and Doohan (2006) saw a similar trend in perennial strawberry marketable yield, reporting a significantly higher yield when clopyralid was applied at 200 g ha^{-1} in comparison with hand-weeded controls. However, they speculated that this increase might be attributed to strawberry competition with groundsel seedlings between weed removal events in the hand-weeded plots. For many years, it has been known that substances lethal at higher doses can have beneficial or stimulating effects when applied at very low concentrations (Cedergreen 2008). This phenomenon was first known as the Arndt–Schulz law (Calabrese 2005). Since then, the term "hormesis" has been used to describe this effect that low levels of toxins can cause. Recently, Cedergreen (2008) reported several herbicides that stimulated growth and biomass accumulation of barley. These effects were seen when low concentrations of herbicides were applied to foliage as well as growing media. If this stimulation of growth occurred, it would help explain the observation of no detectable decreases in leaf production in comparison with the nontreated control, with the exception of the Festival B trial (Table 1).

Previous research has demonstrated that strawberries can exhibit acceptable tolerance to clopyralid, without negatively affecting yield or plant growth and development. However, consideration should be given to the timing of clopyralid application. Our results and recommendation would be to proceed with applications only during times of reduced vegetative growth to minimize leaf malformation, since our results show no deleterious effects on fruit production with labeled rates of clopyralid applied as either a POST spray or drip injection. Regardless of timing, cultivar, or application method, at the maximum labeled rate of 66 g ha^{-1} leaf malformation was less than 5% and marketable yield estimated at 104% of the nontreated control.

Literature Cited

Calabrese, E. J. 2005. Historical blunders: how toxicology got the dose–response relationship half right. Cell. Mol. Biol. 51:643–654.

Cedergreen, N. 2008. Herbicides can stimulate plant growth. Weed Res. 48:429–438.

Chandler, C. K., D. E. Legard, and J. W. Noling. 2001. Performance of strawberry cultivars on fumigated and nonfumigated soil in Florida. HortTechnology 11:69–71.

Clay, D. V. and L. Andrews. 1984. The tolerance of strawberries to clopyralid: effect of crop age, herbicide dose and application date. Aspects Appl. Biol. 8:151–158.

Darnell, R. L. 2003. Strawberry growth and development. Pages 3–10 *in* N. F. Childers, ed. The Strawberry: A Book for Growers, Others. Gainesville, FL: Dr. Norman F. Childers Publications.

Darrow, G. M. 1930. Experimental studies in the growth and development of strawberry plants. J. Agr. Res. 41:307–325.

Daugovish, O., S. A. Fennimore, and M. J. Mochizuki. 2008. Integration of oxyfluorfen into strawberry (*Fragaria* × *ananassa*) weed management programs. Weed Technol. 22:685–690.

Ferguson, W. and A. Padula. 1994. Economic Effects of Banning Methyl bromide for Soil Fumigation. Agricultural Economics Volume 677, Washington, DC: U.S. Department of Agriculture/Economic Research Service.

Figueroa, R. A. and D.J. Doohan. 2006. Selectivity and efficacy of clopyralid on strawberry (*Fragaria* × *ananassa*). Weed Technol. 20:101–103.

Forney, C. F. and P. J. Breen. 1985. Dry matter partitioning and assimilation in fruiting and deblossomed strawberry. J. Am. Soc. Hort. Sci. 110:181–185.

Gilreath, J. P. and B. M. Santos. 2005. Weed management with oxyfluorfen and napropamide in mulched strawberry. Weed Technol. 19:325–328.

Honaganahalli, P. S. and J. N. Seiber. 1996. Health and environmental concerns over the use of fumigants in agriculture: the case of methyl bromide. Am. Chem. Soc. Symp. Ser. 652: 1–13.

Macias-Rodriguez, L., E. Quero, and M. G. Lopez. 2002. Carbohydrate differences in strawberry crowns and fruit (*Fragaria* × *ananassa*) during plant development. J. Agric. Food Chem. 50:3317–3321.

McMurray, G. L., D. W. Monks, and R. B. Leidy. 1996. Clopyralid use in strawberries (*Fragaria* × *ananassa*) grown on plastic mulch. Weed Sci. 44:350–354.

Mossler, M. A. and O. N. Nesheim. 2004. Strawberry pest management strategic plant (PMSP). University of Florida IFAS extension. Electronic Data Information Source. http://edis.ifas.ufl.edu/pdffiles/PI/PI06300.pdf. Accessed: March 22, 2012.

Mossler, M. A. 2010. Florida Crop/Pest Management Profiles: Strawberry. University of Florida/IFAS Extension. Electronic Data Information Source. http://edis.ifas.ufl.edu/pi037. Accessed: March 28, 2012.

[NASS] National Agricultural Statistics Service. 2011. United States Department of Agriculture (USDA). http://www.nass.usda.gov.

Noling, J. W., D. A. Botts, and A. W. MacRae. 2011. Alternatives to methyl bromide soil fumigation for Florida vegetable production. Pages 47–54 *in* S. M. Olson and B. Santos, eds. Vegetable Production Handbook for Florida 2011–2012. University of Florida/IFAS Extension.

Pfleeger, T., M. Blakeley-Smith, G. King, E. H. Lee, M. Plocher, and D. Olszyk. 2012. The effects of glyphosate and aminopyralid on a multi-species plant field trial. Ecotoxicology 10.1007/s10646-012-0912-5.

Rogers, J. L., D. J. Doohan, A. R. Robinson, K.I.L. Jensen, and S. O. Gaul. 2001. Fluazifol-P inhibits terbacil metabolism in strawberry (*Fragaria* × *ananassa*). Weed Technol. 15:320–326.

Santos, B. M., N. A. Peres, J. F. Price, C. K. Chandler, V. M. Whitaker, W. M. Stall, S. M. Olson, S. A. Smith, and E. H. Simonne. 2011. Strawberry production in Florida. Pages 271–282 in S. M. Olson and B. Santos, eds. Vegetable Production Handbook for Florida 2011–2012. University of Florida/IFAS Extension.

Senseman, S. A., ed. 2007. Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp. 333–334.

Snodgrass, C., M. Ozores-Hampton, A. Macrae, J. Noling, A. Whidden, and G. McAvoy. 2011. Current fumigation practices among tomato, strawberry, and pepper growers: survey results. Available at http://flagexpo.ifas.ufl.edu/2011/AgExpo11presentations.htm. Accessed April 2, 2012.

Stall, W. M. 2008. Weed control in strawberry. University of Florida/IFAS Extension. Electronic Data Information Source. Available at http://edis.ifas.ufl.edu/wg037

Received January 8, 2013, and approved March 21, 2013.