Ornamental Plant and Weed Response to Oxyfluorfen Plus Prodiamine

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Abstract. **Ornamental plant and weed response to oxyfluorfen + prodiamine herbicide was evaluated in Connecticut and Tennessee, USA, in 2017 and 2018. Preemergence application of oxyfluorfen + prodiamine was made at 0 lb/acre, 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre to container-grown ornamental plants on an outdoor gravel pad and weeds in greenhouse experiments. Ornamental plants were treated first within a week after transplanting and again 6 weeks after the first treatment. Asiatic jasmine (*Trachelospermum asiaticum*), candlestick plant (*Senna alata*), and English ivy (*Hedera helix*) in Tennessee, USA; and 'Blue Flag' iris (*Iris* sp.), 'Firecracker' gladiolus (*Gladiolus* sp.), and 'Green Carpet' Japanese pachysandra (*Pachysandra terminalis*) in Connecticut, USA, were not injured with oxyfluorfen + prodiamine regardless of rate applied. Lily-of-the-Nile (*Agapanthus africanus*) in Tennessee, USA, and 'Bowles' periwinkle (*Vinca minor*) in Connecticut, USA, showed minor but commercially acceptable growth reduction with oxyfluorfen + prodiamine up to 4 + 1.5 lb/acre. Shasta daisy (*Leucanthemum ×superbum*) in Connecticut, USA, was the most sensitive ornamental plant. After the first application, average necrotic injury to Shasta daisy varied from 24% with 2 + 0.75 lb/acre to 31% with 8 + 3 lb/acre of oxyfluorfen + prodiamine. After the second application, necrotic injury was ≤ 5% with all oxyfluorfen + prodiamine rates tested and was commercially acceptable (≤ 20%). Oxyfluorfen + prodiamine reduced densities of creeping woodsorrel (*Oxalis corniculata*), hairy bittercress (*Cardamine hirsuta*), giant foxtail (*Setaria faberi*), and large crabgrass (*Digitaria sanguinalis*) ≥ 80% by 4 weeks after treatment. The fresh weed biomass 6 weeks after treatment indicated an 88% to 99% reduction compared with the untreated control.**

Weed interference can hinder growth and development significantly of container-grown ornamental plants (Berchielli-Robertson et al. 1990; Fretz 1972). Creeping woodsorrel (*Oxalis corniculata*), hairy bittercress (*Cardamine hirsuta*), eclipta (*Eclipta prostrata*), giant foxtail (*Setaria faberi*), large crabgrass (*Digitaria sanguinalis*), and redroot pigweed (*Amaranthus retroflexus*) have been documented as common weeds of nursery crops (Altland 2003; Aulakh 2023; Gilliam et al. 1990; Norcini and Stamps 1994). Many of them are highly competitive even when present at very low densities. For example, one large crabgrass or redroot pigweed plant per pot reduced the growth of 'Convexa' Japanese holly (*Ilex crenata*) by 60% (Fretz 1972). Similarly, one eclipta plant per pot reduced 'Fashion' azalea (*Rhododendron* × 'Fashion') growth by 43% (Berchielli-Robertson et al. 1990). Furthermore, many weed species serve as alternative hosts for insect pests, diseases, and nematodes (Groves et al. 2002; Hayward 1991; Thomas et al. 2005; Trivedi and Barker 1986; Yudin et al. 1986). Weed competition with container-grown ornamentals often leads to huge economic losses. Mathers (2003) reported that manual weed removal costs were almost $9900/ha. Similarly, Darden and Neal (1999) reported that hand-weeding over a 4-month period cost ≈$1370 for one thousand 3-L pots. According to another estimate, economic losses from weed competition may be as high as $17,300/ha (Case et al. 2005).

Weed management in container-grown ornamental plants mainly relies on the use of preemergence herbicides, often in conjunction with some manual weeding (Altland et al. 2004). Most container nursery growers make two to six applications of granular preemergence herbicides, at 8- to 10-week intervals, per year (Gilliam et al. 1990; Judge et al. 2004). Preemergence herbicides offer broad-spectrum, economical, and long-duration weed control, but there is an inherent risk for crop injury. Many new ornamental plant species and cultivars are being commercialized every year. This warrants the continued evaluation of new as well as the older preemergence herbicides for ornamental plant safety. In the past decade, several preemergence herbicides have been registered for managing weeds in ornamental plants. One of these preemergence herbicides is a granular combination product containing oxyfluorfen (2.0%) + prodiamine (0.75%). Oxyfluorfen + prodiamine (Biathlon®; OHP Inc., Bluffton, SC, USA) is registered for preemergence control of broadleaf and grass weeds in container- and field-grown ornamentals, including Christmas tree plantations (OHP 2024). Oxyfluorfen is a diphenyl-ether herbicide (group 14 mode of action) that works by inhibiting the protoporphyrinogen oxidase enzyme (Duke et al. 1991). This enzyme is essential for the synthesis of chlorophyll in plants. Oxyfluorfen disrupts chlorophyll synthesis, leading to an accumulation of toxic intermediates known as porphyrins. Porphyrins cause oxidative damage to cell membranes and other plant tissues, ultimately resulting in the death of the targeted weeds (Duke et al. 1991). Prodiamine is a dinitroaniline herbicide (group 3 mode of action) that kills targeted weeds by inhibiting root and shoot growth. Oxyfluorfen or prodiamine have been evaluated individually for use in many crops, including broccoli (*Brassica oleracea* var. *italica*), cabbage (*Brassica oleracea* var. *capitata*), Colorado blue spruce (*Picea pungens*), fraser fir (*Abies fraseri*), muskmelon (*Cucumis melo*), onion (*Allium cepa*), sunflower (*Helianthus annuus*), and woody ornamental plants (Bhowmik and McGlew 1986; Fretz and Sheppard 1980; Ramalingam et al. 2013; Richardson and Zandastra 2009; Sikkema et al. 2006). Previous researchers reported effective control of common chickweed (*Stellaria media*), common groundsel (*Senecio vulgaris*), common ragweed (*Ambrosia artemisiifolia*), field violet

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(*Viola arvensis*), hairy bittercress, horseweed (*Conyza canadensis*), and Virginia pepperweed (*Lepidium virginicum*) with oxyfluorfen (Gallitano and Skroch 1993; Richardson and Zandastra 2009); common chickweed, common groundsel, common lambsquarters (*Chenopodium album*), common ragweed, hairy bittercress, horseweed, large crabgrass, prostrate spurge (*Euphorbia humistra*), redroot pigweed, and virginia pepperweed with prodiamine (Fretz and Sheppard 1980, Gallitano and Skroch 1993; Wehtje et al. 2010); and creeping woodsorrel and flexuous bittercress (*Cardamine flexuosa*) with oxyfluorfen + prodiamine (Altland 2019). Oxyfluorfen + prodiamine can be applied to newly planted or established field- or container-grown ornamentals. The maximum single application rate is 2 + 0.75 lb/acre and a maximum seasonal application rate is 4 + 1.5 lb/acre. The objectives of this research were to evaluate oxyfluorfen + prodiamine for tolerance of container-grown ornamental plants and preemergence weed efficacy.

Materials and methods

Ornamental plant tolerance study. The granular herbicide oxyfluorfen + prodiamine (Biathlon®; OHP Inc.) was evaluated to determine tolerance of ornamental species not listed, except for periwinkle, on the herbicide label. Experiments were conducted at the Valley Laboratory of the Connecticut Agricultural Experiment Station in Windsor, CT, USA, and the Tennessee State University Otis L. Floyd Nursery Research Center in McMinnville, TN, USA, in 2017 and 2018. The ornamental plant species evaluated for tolerance to oxyfluorfen + prodiamine were 'Blue Flag' iris (*Iris* sp.), 'Bowles' periwinkle (*Vinca minor*), 'Firecracker' gladiolus (*Gladiolus* sp.), 'Green Carpet' Japanese pachysandra (*Pachysandra terminalis*), and Shasta daisy (*Leucanthemum ×superbum*) in Connecticut, USA; and Asiatic jasmine (*Trachelospermum asiaticum*), candlestick plant (*Senna alata*), English ivy (*Hedera helix*), and lily-of-the-Nile (*Agapanthus africanus*) in Tennessee, USA. The planting material consisted of ≈3-cm-diameter corms for gladiolus, plant liners (72-cell flat; 3.7-cm cell diameter) for candlestick plant; plugs (6- × 6-cm container) for Asiatic jasmine, iris, lily-of-the-Nile, and Shasta daisy; and plugs (9- × 9-cm container) for English ivy. In Tennessee, USA, Asiatic jasmine, English ivy, and lily-of-the-Nile were transplanted on 30 May 2017 and the candlestick plant was transplanted on 7 Jul 2017 into 1-gal containers (C400; Nursery Supplies Inc., Chambersburg, PA, USA) filled with pine bark (Morton's Horticultural Products, McMinnville, TN, USA). For the experiments conducted in Tennessee, USA, the pine bark substrate was amended with 7.5 lb/yard^3 14N–6.1P–11.6K controlled-release fertilizer (Florikan 90-d formula; Florikan LLC, Sarasota, FL, USA), 1.5 lb/yard^3 micronutrient granules (Micromax; Everris, Dublin, OH, USA), and 5 lb/yard^3 dolomitic limestone (Plant Products LLC, Findley, OH, USA). In Connecticut, USA, gladiolus, iris, Japanese pachysandra, periwinkle, and Shasta daisy were transplanted on 29 May 2017 into 1.5-gal plastic containers (C600; Nursery Supplies Inc.) filled with a pine bark and composted woodchips (1:1) mixture. The container substrate for the Connecticut, USA, experiments was amended with 8 lb/yard^3 20N–4.3P–8.3K controlled-release fertilizer (Harrells Profertilizer; Harrells LLC, Lakeland, FL, USA), 0.3 lb/yard^3 booster micronutrients (Harrells LLC), and 5 lb/yard^3 dolomitic limestone (Plant Products LLC). These methods were selected based on common nursery practices used in the nurseries of that particular state (Tennessee, USA, or Connecticut, USA). The experiments were repeated and plant liners were transplanted on 21 May 2018 in Connecticut, USA, and 5 Jun 2018 in Tennessee, USA, into the same-size containers and container substrates as just described. The experiment was arranged in a completely randomized design with 12 replications per treatment. The granular herbicide oxyfluorfen + prodiamine was applied within 7 d after transplanting at 0 lb/acre, 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre with a handheld shaker bottle. A second application was made ≈6 weeks after the initial application. The ornamental plant species and oxyfluorfen + prodiamine rates were adopted from an IR-4 crop safety research protocol (Vea and Palmer 2017). The maximum single-application rate for oxyfluorfen + prodiamine granular herbicide is 2 + 0.75 lb/acre. The 4 + 1.5 lb/acre and 8 + 3 lb/acre rates were greater than the maximum labeled rates. All ornamental species received 0.5 inch overhead irrigation within an hour of treatment application, and daily thereafter.

Weed efficacy study. Effectiveness of oxyfluorfen + prodiamine was evaluated for weed control in greenhouse experiments initiated 10 Nov 2022 in Tennessee, USA, and 21 Dec 2022 in Connecticut, USA. In Tennessee, USA, the container substrate (aged pine bark 80%:peatmoss 20%) was amended with 5 lb/yard^3 14N–6.1P–11.6K controlled-release fertilizer (Florikan 90-d formula; Florikan LLC), 1.5 lb/yard^3 micronutrient granules (Micromax; Everris), and 5 lb/yard^3 dolomitic limestone (Plant Products LLC). In Connecticut, USA, the container substrate (composted woodchips 80%:peatmoss 20%) was amended with 8 lb/yard^3 20N–4.3P–8.3K controlled-release fertilizer (Harrells Profertilizer; Harrells LLC), 0.3 lb/yard^3 booster micronutrients (Harrells LLC), and 5 lb/yard^3 dolomitic limestone (Plant Products LLC). Plastic containers (3.5-inch diameter; SVD350, T.O. Plastics; Clearwater, MN, USA) were filled with container substrate and irrigated slowly to saturation. The container substrate was allowed to settle for 24 h. The granular herbicide oxyfluorfen + prodiamine was applied at 0 lb/acre, 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre on 11 Nov 2022 in Tennessee, USA, and on 22 Dec 2022 in Connecticut, USA, with a handheld shaker bottle. Each oxyfluorfen + prodiamine treatment was applied to a total of 20 containers (five single-container replications per weed species). After herbicide application, containers were placed back in the greenhouse under the overhead mist irrigation system, and 0.5 inch of irrigation was applied. Approximately 4 h after overhead irrigation, 40 seeds of either creeping woodsorrel, hairy bittercress, giant foxtail (*S. faberi*), or large crabgrass were applied with a shaker vial individually on the surface of each of the five containers per herbicide treatment. Creeping woodsorrel, hairy bittercress, and large crabgrass are ranked routinely among the top 10 common or troublesome weeds in ornamental plants by the Weed Science Society of America weed surveys (Van Wychen 2020). The experiment was arranged in a completely randomized design, with five containers per treatment per weed species. A untreated control (five containers per weed species) was also included for treatment

Table 1. Final plant height of ornamental plant species tested in Connecticut and Tennessee, USA, at different rates of granular preemergence herbicide (oxyfluorfen + prodiamine[i]).

Oxyfluorfen + prodiamine (lb/acre[ii])	Plant ht (cm)							
	Connecticut				Tennessee			
	Flag iris	Gladiolus	Japanese pachysandra	Shasta daisy	Asiatic jasmine	Candlestick plant	English ivy	Lily-of-the-Nile
0	70 a[iii]	104 a	19 a	64 a	16 a	87 a	17 a	22 a
2 + 0.75	71 a	106 a	19 a	62 ab	16 a	84 a	16 a	19 ab
4 + 1.5	72 a	102 a	18 a	60 b	17 a	77 a	17 a	17 b
8 + 3	70 a	103 a	18 a	61 ab	17 a	83 a	16 a	16 b

[i] Oxyfluorfen (2.0%) + prodiamine (0.75%) (Biathlon®; OHP, Inc., Bluffton, SC, USA). The first application was made within 7 d after transplant and a second application was applied ≈6 weeks after the first application using a handheld shaker bottle.
[ii] 1 lb/acre = 1.1209 kg·ha^{-1}; 1 cm = 0.3937 inch.
[iii] Means followed by the same letter within a column are not significantly different using Fisher's protected least square difference at $\alpha = 0.05$. Data averaged over 2 years.

comparison. An overhead irrigation of 0.5 inch was applied daily in four cycles of 4 min each with 3 h between cycles.

Data collection. Data collection consisted of visual estimates for ornamental plant injury (chlorosis, necrosis, and stunting) and weed control. Phytotoxicity ratings for chlorosis, necrosis, and stunting injury were recorded at 2 and 4 weeks after each application on a 0 to 10 scale with 0 = no damage, 1 = minor (10%), 2 = moderate (20%), 2 to 4 = severe (20%–40%), 5 to 9 = extreme (50%–90%), and 10 = dead plant. Plant height and average width (width at the widest point plus perpendicular width/2) were recorded at 5 weeks after the second application. Weed control was evaluated visually by counting the number of weeds germinated in each pot at 2 and 4 weeks after treatment (WAT) compared with the untreated control. Weed count data were converted into percentage control compared with the untreated control. At 6 WAT, all weeds, where present, were harvested manually from each flat tray, and the shoot fresh biomass was recorded.

Data analysis. Data on various response variables were analyzed with a generalized linear mixed-model methodology using the GLIMMIX procedure in SAS ver. 9.3 (SAS Institute, Inc., Cary, NC, USA). Before conducting the analysis of variance (ANOVA), data were tested for normality using PROC UNIVARIATE in SAS ver. 9.3, and homogeneity of variance with the modified Levene test. Ornamental plant injury, height, and width data were analyzed individually by plant species and application (first or second), but data from both years (2017 and 2018) were pooled and averaged. The weed control and fresh biomass data were analyzed separately by weed species, but data from both sites (Connecticut, USA, and Tennessee, USA) were pooled and averaged. The weed efficacy data were arcsine-transformed and the fresh biomass data were square root–transformed for correcting non-normality and heterogeneity of variance. However, for simplicity, the back-transformed means are discussed and presented in the tables. The oxyfluorfen + prodiamine rate was treated as a fixed effect whereas year, replication, and their interactions with fixed-effect factors were considered random effects. Means were separated with Fisher's protected least square difference at $\alpha = 0.05$.

Results and discussion

Ornamental plant tolerance

Oxyfluorfen + prodiamine was safe for most container-grown ornamental plants tested in the Connecticut, USA, and Tennessee, USA, experiments. No chlorotic, necrotic, or stunting injury was observed on gladiolus, iris, or Japanese pachysandra in Connecticut, USA (data not shown). Similarly, Asiatic jasmine, candlestick plant, and English ivy showed excellent tolerance to oxyfluorfen + prodiamine granular herbicide in Tennessee, USA (data not shown). Final plant height and width data also revealed no differences between oxyfluorfen + prodiamine treatments and the untreated control (Tables 1 and 2). Several researchers found oxyfluorfen + prodiamine to be highly safe for these species at similar rates (Vea and Palmer 2019).

Variable injury with oxyfluorfen + prodiamine occurred on periwinkle and Shasta daisy in Connecticut, USA, and on lily-of-the-Nile in Tennessee, USA. Periwinkle manifested significant stunting

Table 2. Final plant width of ornamental plant species tested in Connecticut and Tennessee, USA, at different rates of granular preemergence herbicide (oxyfluorfen + prodiamine[i]).

Oxyfluorfen + prodiamine (lb/acre[ii])	Plant width (cm)							
	Connecticut				Tennessee			
	Flag iris	Japanese pachysandra	Periwinkle	Shasta daisy	Asiatic jasmine	Candlestick plant	English ivy	Lily-of-the-Nile
0	22 a[iii]	21 a	47 a	23 a	50 a	63 a	48 a	29 a
2 + 0.75	21 a	21 a	48 a	24 a	49 a	62 a	51 a	28 a
4 + 1.5	20 a	22 a	45 ab	22 a	47 a	62 a	49 a	27 a
8 + 3	23 a	20 a	41 b	24 a	48 a	65 a	50 a	26 a

[i] Oxyfluorfen (2.0%) + prodiamine (0.75%) (Biathlon®; OHP, Inc., Bluffton, SC, USA). The first application was made within 7 d after transplant and a second application was applied ≈6 weeks after the first application using a handheld shaker bottle.
[ii] 1 lb/acre = 1.1209 kg·ha^{-1}; 1 cm = 0.3937 inch.
[iii] Means followed by the same letter within a column are not significantly different using Fisher's protected least square difference at $\alpha = 0.05$. Data averaged over 2 years.

Fig. 1. Growth reduction in periwinkle (*Vinca minor*) treated with granular herbicide oxyfluorfen + prodiamine at 0 lb/acre, 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre (left to right). 1 lb/acre = 1.1209 kg·ha^{-1}.

injury with oxyfluorfen + prodiamine rates of 4 + 1.5 lb/acre and 8 + 3 lb/acre following the first application (Fig. 1). Maximum stunting injury occurred at 4 WAT following the first application. Stunting injury was rated 3.6 (36%) and 1.9 (19%) with 8 + 3 lb/acre and 4 + 1.5 lb/acre, respectively. The second application (6 weeks after first treatment) was less injurious, stunting injury ratings of 0.3 (3%), 0.5 (5%), and 1.8 (18%) with 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre of oxyfluorfen + prodiamine, respectively. Similar experiments in Alabama, USA, and California, USA, found oxyfluorfen + prodiamine highly safe for periwinkle regardless of application rate (Vea and Palmer 2019). Final plant width data indicated no differences between oxyfluorfen + prodiamine rates up to 4 + 1.5 lb/acre (Table 2).

Shasta daisy showed moderate necrotic injury particularly after the first application, from all rates of oxyfluorfen + prodiamine tested. This happened because Shasta daisy was in a compact rosette at the time of the first oxyfluorfen + prodiamine application. This resulted in significant retention of herbicide granules in the leaf whorl even after a 0.5-inch wash-down irrigation applied within 2 h of herbicide treatment. By 2 WAT, average necrotic injury was 1.7 (17%) with 2 + 0.75 lb/acre, 2.1 (21%) with 4 + 1.5 lb/acre, and 2.8 (28%) with 8 + 3 lb/acre. Injury worsened by 4 WAT and was similar for all oxyfluorfen + prodiamine application rates (Fig. 2). Average necrotic injury ratings were 2.4 (24%), 2.7 (27%), and 3.1 (31%) with 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre, respectively. A similar experiment in Washington, USA, also found oxyfluorfen + prodiamine to be severely injurious to Shasta daisy at rates tested in this study (Vea and Palmer 2019).

Fig. 2. Necrotic injury on Shasta daisy (*Leucanthemum ×superbum*) treated with granular herbicide oxyfluorfen + prodiamine. (Top) Untreated control. (Bottom) Oxyfluorfen + prodiamine at 8 + 3 lb/acre. 1 lb/acre = 1.1209 kg·ha^{-1}.

These levels of injury in Shasta daisy are commercially unacceptable. An injury rating of 2.0 (20%) on a 0 to 10 rating scale is considered to be mild and commercially acceptable. The second oxyfluorfen + prodiamine application (6 weeks after the first treatment) coincided with the stem elongation and flower bud stage of Shasta daisy. Because of this morphological transformation the in plant, less herbicide was retained in the leaf axils. The maximum necrotic injury of 0.5 (5%) occurred with 8 + 3 lb/acre by 2 WAT following the second application (data not shown). This level of injury was similar to 0.4 (4%) with 2 + 0.75 lb/acre and 0.2% (2%) with 4 + 1.5 lb/acre of oxyfluorfen + prodiamine. All Shasta daisy plants, regardless of oxyfluorfen + prodiamine application rate, fully recovered by 4 WAT. Final plant height and width measurements also reflected similar treatment differences (Tables 1 and 2).

In Tennessee, USA, lily-of-the-Nile was the only plant species injured by oxyfluorfen + prodiamine (Fig. 3). Injury was reflected only in the final plant height (Table 1). The final plant height for lily-of-the-Nile was 22, 19, 17, and 16 cm for the untreated control, 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre of oxyfluorfen + prodiamine, respectively. The final plant width data indicated no differences compared with the untreated control (Table 2).

Weed control

The average weed densities in Connecticut, USA, and Tennessee, USA, for the untreated control by 2 and 4 WAT were 9 and 13 plants per pot for creeping woodsorrel, 21 and 23 plants per pot for hairy bittercress, 11 and 13 plants per pot for giant foxtail, and 22 and 24 plants per pot for large crabgrass, respectively. Results from the ANOVA indicated that oxyfluorfen + prodiamine efficacy varied greatly with the application rate ($P \leq 0.05$).

Broadleaf weeds. All rates of oxyfluorfen + prodiamine provided excellent control of broadleaf weeds. By 2 WAT, creeping woodsorrel density was reduced at least 76% with 2 + 0.75 lb/acre and ≥ 94% with greater rates of oxyfluorfen + prodiamine tested in our study (Table 3).

Fig. 3. Growth reduction in lily-of-the-Nile (*Agapanthus africanus*) treated with granular herbicide oxyfluorfen + prodiamine at 0 lb/acre, 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre (left to right). 1 lb/acre = 1.1209 kg·ha^{-1}.

By 4 WAT, creeping woodsorrel was controlled ≥ 91% without a significant oxyfluorfen + prodiamine rate effect. Previously, Creager (1982b) observed ≥ 75% woodsorrel (*Oxalis* sp.) control 2 months after treatment with oxyfluorfen at 2 lb/acre. Moore et al. (1989) obtained complete control of creeping woodsorrel 4 WAT with 2 lb/acre of oxyfluorfen. In another study, Frank and Beste (1984) also reported 74% and 93% control of common woodsorrel (*Oxalis stricta*), an annual woodsorrel species, with 2 lb/acre oxyfluorfen or prodiamine, respectively. The fresh biomass data at 6 WAT revealed a 93% to 99% reduction in creeping woodsorrel biomass without a significant oxyfluorfen + prodiamine rate effect (Table 4).

Hairy bittercress control depended on the oxyfluorfen + prodiamine rate (Table 3). With 2 + 0.75 lb/acre of oxyfluorfen + prodiamine, hairy bittercress density was reduced 69% by 2 WAT and to a maximum of 83% by 4 WAT. However, 4 + 1.5 lb/acre and 8 + 3 lb/acre rates were similar with a ≥ 85% reduction in density by 2 WAT and thereafter. Oxyfluorfen at 2 lb/acre controlled hairy bittercress 75% in one experiment and > 86% in another experiment in Pennsylvania, USA (Creager 1982a, 1982b). The potting medium was a mixture of sand and Canadian sphagnum peatmoss (1:1, v/v) in both Pennsylvania, USA, experiments. Complete control of bittercress (*Cardamine* sp.), with oxyfluorfen + prodiamine rates of ≥ 2 lb/acre by 4 WAT, has also been reported previously (Altland 2019; Moore et al. 1989). The fresh biomass data at 6 WAT revealed a 92% to 99% reduction in hairy bittercress biomass under different rates of preemergence-applied oxyfluorfen + prodiamine (Table 4).

Grass weeds. Oxyfluorfen + prodiamine controlled giant foxtail effectively. By 2 WAT, the greatest oxyfluorfen + prodiamine rate of 8 + 3 lb/acre resulted in a 99% less giant foxtail density compared with the untreated control. With 2 + 0.75 lb/acre and 4 + 1.5 lb/acre oxyfluorfen + prodiamine, giant foxtail density was reduced by 82% and 84%, respectively (Table 3). By 4 WAT, a similar reduction in giant foxtail densities was observed with different oxyfluorfen + prodiamine rates. The fresh biomass data at 6 WAT also indicated an 88% to 99% reduction in giant foxtail biomass with different oxyfluorfen + prodiamine rates compared with the untreated control (Table 4). Large crabgrass densities by 2 WAT were 75%, 90%, and 97% less when compared with the untreated control with oxyfluorfen + prodiamine rates of 2 + 0.75 lb/acre, 4 + 1.5 lb/acre, and 8 + 3 lb/acre, respectively. By 4 WAT, large crabgrass densities were reduced further to 87% with 2 + 0.75 lb/acre and to 94% with 4 + 1.5 lb/acre of oxyfluorfen + prodiamine (Table 3). The fresh biomass data at 6 WAT showed similar differences for oxyfluorfen + prodiamine rates as for the density data (Table 4).

Table 3. Average percent reduction (percentage of untreated control) in weed densities 2 and 4 weeks at different rates of granular preemergence herbicide (oxyfluorfen + prodiamine[i]).

	Avg reduction (%)							
	Creeping woodsorrel		Hairy bittercress		Giant foxtail		Large crabgrass	
Oxyfluorfen + prodiamine (lb/acre[ii])	2 WAT[iii]	4 WAT	2 WAT	4 WAT	2 WAT	4 WAT	2 WAT	4 WAT
2 + 0.75	76 b[iv]	91 a	69 c	83 b	82 b	80 b	75 c	87 b
4 + 1.5	94 a	97 a	85 b	91 b	84 b	85 b	90 b	94 a
8 + 3	99 a	99 a	99 a	99 a	99 a	99 a	97 a	99 a

[i] Oxyfluorfen (2.0%) + prodiamine (0.75%) (Biathlon®; OHP, Inc., Bluffton, SC, USA). Granular herbicide treatments were applied with a handheld shaker bottle ≈24 h before planting weed seeds.
[ii] 1 lb/acre = 1.1209 kg·ha^{-1}.
[iii] WAT = weeks after treatment.
[iv] Densities were averaged over two locations. Means followed by the same letter within a column are not significantly different using Fisher's protected least square difference at α = 0.05.

Table 4. Average percent reduction (percentage of untreated control) in fresh shoot weight after 6 weeks at different rates of granular preemergence herbicide (oxyfluorfen + prodiamine[i]).

Oxyfluorfen + prodiamine (lb/acre[ii])	Avg reduction (%)			
	Creeping woodsorrel	Hairy bittercress	Giant foxtail	Large crabgrass
2 + 0.75	93 a[iii]	92 a	88 b	93 b
4 + 1.5	98 a	98 a	90 b	99 a
8 + 3	99 a	99 a	99 a	99 a

[i] Oxyfluorfen (2.0%) + prodiamine (0.75%) (Biathlon®; OHP, Inc., Bluffton, SC, USA). Granular herbicide treatments were applied with a handheld shaker bottle ≈24 h before planting weed seeds.
[ii] 1 lb/acre = 1.1209 kg·ha^{-1}.
[iii] Shoot fresh biomass data were averaged over two locations. Means followed by the same letter within a column are not significantly different using Fisher's protected least square difference at $\alpha = 0.05$.

Previously, several researchers found prodiamine rates of 0.5 to 2 lb/acre highly effective on large crabgrass (Bhowmik 1988; Bhowmik and Bingam 1990; Duray and Davies 1987; Enache and Unicki 1987; Fermanian and Haley 1994; Fretz and Sheppard 1980). In Alabama, USA, Wehtje et al. (2010) reported ≥ 95% control of large crabgrass 6 weeks after prodiamine application at 0.7 lb/acre. They also observed that 1 lb/acre of prodiamine was required for a similar level of control by 12 WAT. In Maryland, USA, Frank and Beste (1984) observed 58% and 73% control of large crabgrass 2 WAT with 2 lb/acre oxyfluorfen or prodiamine, respectively.

Conclusion

Our results showed that oxyfluorfen + prodiamine granular herbicide at 2 + 0.75 lb/acre can effectively (>80%) control tested grassy and broadleaf weeds without risk for injury to Asiatic jasmine, candlestick plant, English ivy, iris, gladiolus, and Japanese pachysandra. Container-grown Shasta daisy was found to be highly sensitive and should not be treated, particularly in the rosette stage. Oxyfluorfen + prodiamine injury in Shasta daisy was more acute when Shasta daisy plants were exposed in the rosette stage (first application) compared with exposure at a later growth stage (second application). This resulted in a significant retention of herbicide granules in the leaf whorl. Injury symptoms, necrosis and deformation of apical buds, were typical of a diphenyl-ether herbicide. Similar growth stage–related differences in diphenyl-ether herbicide injury were reported in cabbage (Grabowski and Hopen 1984; Pereira et al. 1971). Those researchers attributed differences in the diphenyl-ether herbicide injury to differences in the cuticular wax buildup on older vs. younger leaves. Oxyfluorfen + prodiamine at 8 + 3 lb/acre caused prolonged stunting injury to periwinkle. However, growth retardation with 4 + 1.5 lb/acre was only temporary and all plants recovered by 4 weeks after the second treatment. Oxyfluorfen + prodiamine granular herbicide is labeled for weed control in many field and container ornamentals plants as an over-the-top application (OHP 2024). Excellent control of many other weeds, including annual bluegrass (*Poa annua*), barnyardgrass, bittercress, pigweed, and sow thistle (*Sonchus oleraceus*) with prodiamine; and common groundsel (*Senecio vulgaris*), common lambsquarters, galinsoga (*Galinsoga* sp.), large crabgrass, pigweed, and purslane (*Portulaca* sp.) with oxyfluorfen has been reported (Vea and Palmer 2009, 2020). An oxyfluorfen + prodiamine granular combination would be a valuable tool for nursery growers and landscape managers struggling to manage several troublesome grassy and broadleaf weeds. Among the ornamental plants tested in our study, periwinkle is already considered an oxyfluorfen + prodiamine–tolerant species (OHP 2024). Previous research has shown oxyfluorfen rates up to 8 lb/acre and prodiamine rates of ≥ 3 lb/acre to be very safe for English ivy (Vea and Palmer 2009, 2020). Therefore, English ivy may also be included as a tolerant species on the oxyfluorfen + prodiamine herbicide label.

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