Evaluation of *p*-Hydroxyphenylpyruvate Dioxygenase-inhibiting Herbicides for Controlling Mugwort

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SUMMARY. Mugwort (*Artemisia vulgaris*) is a perennial invasive weed species that has infiltrated row crops, turfgrass, ornamentals, and various noncrop areas. Currently, multiple mimics of indole-3-acetic acid can provide control of this species; however, these herbicides can damage certain sensitive ornamental plants. When applied at reduced rates, the *p*-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides mesotrione and topramezone have demonstrated some selectivity among certain ornamental plants. Field and greenhouse studies were initiated to evaluate whether these herbicides could control mugwort when applied alone, or in mixtures with photosystem II (PSII)-inhibiting herbicides that often provide synergistic weed control. In the field, mesotrione controlled mugwort between 30% and 60% by 21 days after treatment when applied at 0.093 to 0.187 lb/acre. When the PSII-inhibiting herbicide atrazine was added, control increased to 78% and 79%. In the greenhouse, similar rates produced greater control in mugwort, and all mesotrione treatments limited mugwort regrowth by at least 95% when compared with untreated control. When HPPD inhibitor rates were reduced further, the addition of the PSII inhibitors atrazine or bentazon was not sufficient at providing acceptable control of mugwort.

Mugwort or false chrysanthemum is an adaptable, non-native perennial plant that is a management challenge to commercial agronomic and ornamental crop production worldwide (Barney and DiTommaso, 2003; Henderson and Weller, 1985; Holm et al., 1997; Uva et al., 1997). In the eastern United States, mugwort has expanded beyond ornamental nurseries into turf, pastures, and cropping systems including corn (*Zea mays*), cotton (*Gossypium hirsutum*), and soybean (*Glycine max*) (Bradley and Hagood, 2002a, 2002b; Yelverton et al., 2012).

Mugwort reproduction and dispersal is achieved primarily by transport of rhizome pieces on contaminated cultivation equipment and within soil and soilless substrates around the roots of

crop plants (Barney and DiTommaso, 2003; Bradley and Hagood, 2002a, 2002b; Holm et al., 1997; Rogerson and Bingham, 1964; Uva et al., 1997). In nursery fields, rhizomes are abundant in the upper 4 inches of soil (Pridham, 1963; Rogerson and Bingham, 1964). Tillage will exacerbate localized mugwort infestation because rhizome sections 2-cm long reproduce well when grown in pine bark, sand, and soil substrates (Guncan, 1982; Klingeman et al., 2004; Rogerson et al., 1972).

Postemergence (POST) control of weeds in nursery operations remains a particularly attractive option for both field-grown and container production systems due, in part, to need to reduce labor costs incurred for hand-weeding in addition to the current practice of making about three annual herbicide applications

per nursery (Gilliam et al., 1990; Mathers, 1999). Yet, control options for mugwort are limited due in part to challenges presented by herbicide costs, herbicide phytosafety across desirable crop commodities (including turfgrass and ornamentals), and limited efficacy available herbicides may have on other key weed species. For example, ethyl N, N-di-n-propylthiolcarbamate application at 15 lb/acre has controlled mugwort in field nurseries, yet this rate is too high to safely manage mugwort in stands of field corn (Bing and Pridham, 1963, 1964). Glyphosate is effective on young mugwort plants but is less effective at controlling large mugwort plants in later stages of growth (Ahrens, 1976; Bradley and Hagood, 2002a, 2002b). Plant growth regulating herbicides that mimic indole-3-acetic acid, like 2,4-dichlorophenoxyacetic acid and clopyralid, have generally provided poor mugwort control, even at high application rates (Ahrens, 1976; Bingham, 1965; Bradley and Hagood, 2002a, 2002b; Day et al., 1997). Clopyralid can control mugwort and reduce regrowth the following year, yet clopyralid is relatively expensive, has limited efficacy against other commonly encountered weed species, and is challenged by limited crop safety across a diverse assemblage of ornamental plant species (Bradley and Hagood, 2002a, 2002b; Bradley et al., 2000; Day et al., 1997; Koepke-Hill et al., 2011). Still, the broad utility of clopyralid (Stinger® and Transline®; Dow AgroSciences, Indianapolis, IN) across corn, sugarbeet (*Beta vulgaris*), pasture and rangeland, Christmas tree, ornamental plant, and fruit and vegetable crop production systems makes this herbicide a practical choice for selective control of mugwort.

Mesotrione and topramezone impede carotenoid biosynthesis by inhibiting the enzyme *p*-HPPD (Norris et al., 1998). Mesotrione is registered for preemergence (PRE) and POST applications in corn and turfgrass (BASF, 2013; Mitchell et al., 2001;

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha ⁻¹	0.8922
6.8948	psi	kPa	0.1450

Syngenta Crop Protection, 2011, 2012) and provides effective POST control against many annual broadleaf weeds and certain grass species (Armel et al., 2003, 2009; Beckett and Taylor, 2000; Sutton et al., 1999). Topramezone is also registered for POST weed control in corn and turfgrass (e.g., Amvac, 2007; BASF, 2013). Apparent as foliar photobleaching, topramezone reduces total chlorophyll, β -carotene, lutein, and other xanthophyll cycle pigments in susceptible grassy and broadleaf weeds, including common bermudagrass (*Cynodon dactylon*), hybrid bermudagrass (*C. dactylon* $\times$ *C. transvaalensis*), and annual bluegrass (*Poa annua*) (BASF, 2013; Brosnan et al., 2011; Elmore et al., 2011, 2013).

In limited tests with ornamental plants, some HPPD herbicides have provided acceptable ornamental tolerance at rates that provide some level of weed control (Armel et al., 2009; Elmore et al., 2013; Little et al., 2004; Senesac and Tsontakis-Bradley, 2007; Stamps and Chandler, 2009). Increased POST control of some perennial weed species was achieved when HPPD-inhibiting herbicides, like mesotrione, were combined with other herbicides, especially those that inhibit PSII inhibitors (Bradley et al., 2000; Kaastra et al., 2008). For example, POST mixtures of reduced rates of the PSII inhibitor atrazine plus mesotrione has enhanced management of larger and more difficult to control weed species, including nutsedge (*Cyperus* sp.) and canada thistle (*Cirsium arvense*) (Armel et al., 2005, 2008, 2009; Beckett and Taylor, 2000; Johnson and Young, 1999, 2000, 2002; Johnson et al., 2002; Kaastra et al., 2008; Mueller, 2000). Efforts to assess reduced rates of mesotrione and topramezone in mixtures with the PSII inhibitor bentazon, which is one of the few PSII-inhibiting herbicides registered for use in turfgrass and ornamental production systems, revealed some weed control efficacy yet induced moderate phytotoxic injury to foliage and terminals of flowering dogwood (*Cornus florida*) and Knock Out™ rose (*Rosa* sp. 'Radrazz'). Still, trials revealed acceptable plant safety for treatments applied to ornamental cultivars of woody japanese holly (*Ilex crenata*), burning bush (*Euonymus alatus*), weigela

(*Weigela florida*), spiraea (*Spiraea japonica*), arborvitae (*Thuja plicata*), herbaceous daylily (*Heimerocallis*), hosta (*Hosta*), autumn fern (*Dryopteris erythrosora*), and pachysandra (*Pachysandra terminalis*) (Cutulle et al., 2013b).

Few selective weed control options are available for mugwort control, and it generally is not adequately controlled with single applications or reduced rates of POST herbicides (Bradley and Hagood 2002a, 2002b). It follows that synergistic mixtures of reduced rates of HPPD and PSII inhibitors could optimize weed control and increase herbicide tolerance to turfgrass and ornamental crops (Cutulle et al., 2013b). Therefore, objectives of this research were to evaluate low rates of the HPPD herbicide mesotrione and to assess control efficacy of mesotrione combined with known synergist like the PSII inhibitor atrazine for enhanced activity on mugwort compared against the standard clopyralid. The second objective was to quantify the ability of reduced rates of multiple HPPD-inhibiting herbicides, either alone or paired with the PSII-inhibiting herbicides atrazine or bentazon, to provide commercially acceptable mugwort control for ornamental plant producers, whether growing in container or field systems.

Materials and methods

FIELD EXPERIMENTS. Mugwort experiments were conducted on a government right-of-way near Birds Nest, VA, in 2000. Treatments were calculated as the active ingredient equivalent from formulated products and included 0.093, 0.125, and 0.187 lb/acre of mesotrione (Callisto®, Syngenta Crop Protection, Greensboro, NC) and mesotrione plus atrazine (0.093 lb/acre plus 0.250 lb/acre) that were compared with 0.500 lb/acre clopyralid (Stinger). Applications for the first experimental run were made on 25 July 2000 and repeated in time at an adjacent field site on 29 Aug. 2000. Treatments were applied using a backpack sprayer at 23.0 gal/acre with a pressure of 23 psi. Four flat fan nozzles (8003; TeeJet Technologies, Wheaton, IL) spaced at 20-inch intervals. Applications were made to mugwort plants 0.8 to 9.1 inches tall. Soil type at this location was a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult).

All treatments contained 1% (v/v) crop oil concentrate [COC (Agridex; Helena Chemical, Memphis, TN)] and 2.5% (v/v) urea ammonium nitrate (UAN) solution. Experimental plots were 8.3 ft wide by 20 ft long and were arranged in a randomized complete block (RCB) design with three replicates. Mugwort control was assessed visually at 7, 14, and 21 d after treatment (DAT) using a 0% to 100% scale, where 0% represented no mugwort control and 100% represented complete mugwort necrosis. Following a land manager decision to mow experimental field plots in advance of right-of-way remediation efforts, field trials were ended before regrowth data could be taken. An alternative site with sufficient contiguous mugwort infestation could not be found to repeat and extend the field trial component.

GREENHOUSE EXPERIMENTS. Greenhouse experiments in Virginia were initiated in 2001 to evaluate mugwort control using previously field-tested rates of mesotrione (0.093, 0.125, and 0.187 lb/acre), and the lowest mesotrione rate plus a low atrazine rate (0.250 lb/acre), with efficacy evaluated against the clopyralid herbicide standard. Five 1-inch-long mugwort rhizomes were planted into 4-inch square pots (TO Plastics, Virginia Beach, VA) filled with commercial potting mix (Pro-Mix BX; Premier Horticulture, Red Hill, PA). As needed, plants were watered and fertilized with a 150 ppm nitrogen (N) solution using 21N-2.2P-41.5K fertilizer (Excel All Purpose; Wetzell, Virginia Beach, VA) to facilitate maximum plant growth and vigor. In 2001, herbicides were applied using a cabinet sprayer at 24 gal/acre with a pressure of 42 psi. A single even flow nozzle (8002; TeeJet Technologies) was placed 30 cm above the highest part of the treated plants. All treatments contained 1% (v/v) COC (Agridex) and 2.5% (v/v) UAN solution. Mugwort control was rated visually at 7, 14, and 28 DAT. On 28 DAT, mugwort shoot heights were measured, and then shoots were cut to the soil line, dried and weighed. Mugwort regrowth was quantified again via dry weight measurements from additional shoots excised on 42 DAT.

In 2008, a second series of greenhouse experiments were conducted and repeated in time at the University of Tennessee campus in

Knoxville. For these trials, mesotrione (Callisto®) was again tested for its efficacy on mugwort, both alone at a reduced rate (0.062 lb/acre) selected to assess phytosafety to ornamental plants, and also in combination with atrazine (0.500 lb/acre) and bentazon (0.500 lb/acre). Mugwort control achieved by these two combination herbicides alone was also assessed. Also in 2008, topramezone (Impact®; Amvac, Los Angeles, CA) was included in tests as a second HPPD-inhibiting herbicide at a 0.010 lb/acre rate, both alone and in combination with the same atrazine and bentazon rates used with mesotrione mixes.

In 2008 greenhouse trials, five 1-inch-long mugwort rhizomes were transplanted into 4-inch pots. The soilless potting substrate was replaced with a Sequatchie loam field soil (Fine-loamy, siliceous, semiactive, thermic humic Hapludult), with 6.2 soil pH and 2.1% organic matter content mixed in a 3:1 ratio of soil to clay-based soil conditioner (Turface MVP; Turface Athletics, Buffalo Grove, IL), to facilitate water drainage. Treatments were arranged in a RCB design with four replicated blocks of pots. Each treatment also included methylated seed oil surfactant (Methylated Soybean Oil Plus; Universal Crop Protection Alliance, Eagan, MN) at a rate of 1% (v/v). Herbicide treatments were applied on 11 Apr. 2008 with a carbon dioxide (CO₂)-pressurized backpack sprayer calibrated at 23 gal/acre. Visual ratings of mugwort control were made 7, 14, and 28 DAT. Mugwort shoot heights were measured 28 DAT; after these data were collected, shoots were cut to the soil line, dried, and weighed. Mugwort regrowth was quantified via dry weight measurements from additional shoot excisions taken 56 DAT.

Herbicide rates tested in both field and greenhouse trials represent the low labeled rate or reductions to the lowest labeled rate in pounds of active ingredient per acre for topramezone and mesotrione in corn and fine turf, with comparison with the labeled rates of atrazine, clopyralid, and bentazon. Arcsine square root transformations were applied to statistical analyses of visual weed control data, and nontransformed data are presented. Analysis of variance was

applied to all data and Fisher's least significant difference test ($P \leq 0.05$) was used for mean separation using the general linear model procedure of SAS (version 9.3; SAS Institute, Cary, NC).

Results and discussion

FIELD EXPERIMENTS. Mugwort responses to treatments applied in the field differed across time, thus results from in-time repetitions could not be pooled. By 14 DAT, the low rate of mesotrione plus atrazine treatment controlled 73% of the mugwort following the July applications. However, this treatment achieved just 51% mugwort control following August treatments on 14 DAT compared with the clopyralid treatment that was controlling 78% of mugwort. By 21 DAT in both field trials, mugwort control with mesotrione plus atrazine and clopyralid treatments was $\geq 79\%$. When applied alone, clopyralid controlled mugwort 84% to 91% (Table 1).

GREENHOUSE EXPERIMENTS. Results from greenhouse trials repeated in time in VA were consistent by treatment regardless of measured parameter [$F = 0.16$ to 0.79 ; df

(numerator, denominator) = 5, 12; $P = 0.97$ to 0.57]; thus data from repeated trials were pooled for reported analyses. Mesotrione alone only provided 30% control of mugwort, regardless of rate, by 7 DAT. When 0.093 lb/acre mesotrione was mixed with 0.250 lb/acre atrazine, rapid mugwort control was observed that exceeded 80%. Mugwort control improved through 28 DAT and all treatments achieved greater than 70% control of mugwort. Mesotrione rate with atrazine provided 98% mugwort control, equivalent to clopyralid (Table 2). Plant height and dry weight measurements among all treated mugwort plants still surviving at 28 DAT were reduced compared with untreated control plants ($F = 3.97$ to 3.72 ; $df = 4, 10$; $P \leq 0.026$ to ≤ 0.029). Limited regrowth from treated mugwort plants was also evident at 42 DAT. Plants that received the lowest rate of mesotrione had recovered just 5% of growth (as dry weight) demonstrated through comparison with untreated control plants (Table 2).

Moderate mugwort control was achieved with mesotrione alone at reduced rates and also when combined

Table 1. Mugwort control following experimental treatments in Bird's Nest, VA that were applied along a mugwort-infested roadside and repeated in time in 2000. All herbicide treatments included 1% (v/v) crop oil concentrate [COC (Agridex; Helena Chemical, Memphis, TN)] and 2.5% (v/v) urea ammonium nitrate.

Treatment	Rate (lb/acre) ^z	Days after treatment		
		7	14	21
		Weed control (%) ^y		
25 July				
Clopyralid	0.500	38	57 b ^x	91 a
Mesotrione	0.093	30	41 c	32 e
Mesotrione	0.125	33	41 c	52 d
Mesotrione	0.187	35	58 b	60 c
Mesotrione + Atrazine	0.093 0.250	45	73 a	79 b
Untreated control	0	0	0 d	0 f
29 Aug.				
Clopyralid	0.500	25 a	78 a	85 a
Mesotrione	0.093	13 d	55 b	55 b
Mesotrione	0.125	16 cd	46 b	48 b
Mesotrione	0.187	18 bc	48 b	53 b
Mesotrione + Atrazine	0.093 0.250	22 ab	51 b	78 a
Untreated control	—	0 e	0 c	0 c

^z1 lb/acre = 1.1209 kg·ha⁻¹.

^yControl was evaluated visually on a 0% (no control) to 100% (complete necrosis) scale relative to the untreated control.

^xWithin column means represent nontransformed data. Means followed by different letters are significantly different from untreated checks by Fisher's least significant difference tests of arcsine-transformed values at $P \leq 0.05$.

with atrazine and clopyralid, yet these application rates may still result in unacceptable aesthetic injury when trying to achieve POST control by applications made over the top of select ornamental plants (Cutulle et al., 2013a, 2013b; Hester et al., 2011; Little et al., 2004; Senesac and Tsontakis-Bradley, 2007).

Mesotrione rates were also reduced a further 30% and reassessed in Tennessee greenhouse trials alone and in combination with photosynthesis-inhibiting bentazon and atrazine herbicides, to determine if ornamental injury could be reduced. Results of Tennessee greenhouse experiments were consistent across treatments for all measured parameters when repeated

in time ($F = 2.00$ to 0.25 ; $df = 8, 35$; $P = 0.08$ to 0.98). Therefore, data from repeated trials were pooled for reported analyses. Reduced mesotrione and topramezone rates, at 0.062 and 0.010 lb/acre, respectively, failed to provide adequate control of mugwort ($<21\%$) by 28 DAT. Atrazine and bentazon herbicides applied alone provided $<24\%$ mugwort control. By 28 DAT, mesotrione plus atrazine offered the highest levels of mugwort control, yet no treatment surpassed 37% control (Table 3). Several treatments slowed mugwort regrowth between 28 and 56 DAT, with mugwort plants treated with mesotrione plus atrazine achieving just 66% of the regrowth potential demonstrated by untreated control plants (Table 3).

Conclusions

Currently, few POST herbicides are labeled for mugwort control in ornamental crop systems and non-cropland areas. From this research, we conclude that moderate rates of mesotrione (0.093 lb/acre) in mixtures with certain PSII-inhibiting herbicides can provide a viable field management alternative for short-term, burn-down control of mugwort compared with clopyralid application. However, the rate of mesotrione and the type of PSII-inhibiting herbicide needed severely limit the practicality of this use with some sensitive ornamental plant species. Mugwort regrowth by 56 DAT in the Tennessee greenhouse trials suggest that field studies

Table 2. Mugwort control in 2001 Virginia greenhouse trials in which herbicide treatments were applied to container-grown mugwort plants in a soilless rooting substrate with experiments that were repeated in time. All herbicide treatments included 1% (v/v) crop oil concentrate (Agridex; Helena Chemical, Memphis, TN) and 2.5% (v/v) urea ammonium nitrate.

Treatment	Rate (lb/acre) ^z	Days after treatment			Dry wt (Percent of control)	Ht (Percent of control)	Dry wt regrowth (Percent of control)
		7	14	28			
		Weed control (%) ^y					
Clopyralid	0.500	62 b ^x	75 ab	99 a	25 abc	0 b	0
Mesotrione	0.093	28 c	42 c	72 c	36 a	19 a	5
Mesotrione	0.125	31 c	68 b	87 b	24 bc	5 b	1
Mesotrione	0.187	30 c	62 bc	88 b	28 ab	9 ab	2
Mesotrione + Atrazine	0.093 0.250	83 a	89 a	98 a	16 c	2 b	0
Untreated control	—	0 d	0 d	0 d	—	—	—

^z1 lb/acre = $1.1209 \text{ kg}\cdot\text{ha}^{-1}$.

^yControl was evaluated visually on a 0% (no control) to 100% (complete necrosis) scale relative to the untreated control.

^xWithin column means represent nontransformed data. Means followed by different letters are significantly different from untreated checks by Fisher's least significant difference tests of arcsine-transformed values at $P \leq 0.05$.

Table 3. Mugwort control in 2008 Tennessee greenhouse trials in which herbicide treatments were applied to container-grown mugwort plants with experiments that were repeated in time. Mugwort was planted into a soil-based rooting mix that included 3:1 ratio of soil to clay-based soil conditioner (Turface MVP; Turface Athletics, Buffalo Grove, IL). Treatments were applied with a 1% rate (v/v) of methylated seed oil surfactant (Methylated Soybean Oil Plus; Universal Crop Protection Alliance, Eagan, MN).

Treatment	Rate (lb/acre) ^z	Days after treatment			Dry wt (Percent of control)	Dry wt regrowth (Percent of control)
		7	14	28		
Atrazine	0.500	6 b ^y	12 c	24 bc	66 c	96 ab
Bentazon	0.500	14 ab	28 ab	18 cd	87 ab	99 a
Mesotrione	0.062	11 ab	21 abc	21 cd	71 bc	106 a
Topramezone	0.010	11 ab	14 bc	7 e	92 a	114 a
Mesotrione + atrazine	0.062 0.500	20 a	33 a	37 a	58 c	67 c
Mesotrione + bentazon	0.062 0.500	13 ab	27 ab	24 bc	74 bc	92 ab
Topramezone + atrazine	0.010 0.500	14 ab	23 abc	32 ab	64 c	74 bc
Topramezone + bentazon	0.010 0.500	13 ab	23 abc	14 d	88 ab	111 a
Untreated control	—	0 c	0 d	0 f	—	—

^zTreatments rates are expressed in pounds per acre; 1 lb/acre = $1.1209 \text{ kg}\cdot\text{ha}^{-1}$.

^yWithin column means represent nontransformed data. Means followed by different letters are significantly different from untreated checks by Fisher's least significant difference tests of arcsine-transformed values at $P \leq 0.05$.

with extended durations should be evaluated, in conjunction with repeated applications. Regardless, other HPPD- and PSII-inhibiting herbicides should be evaluated for mugwort control and then those mixtures determined to be effective should be studied further for tolerance among multiple ornamental plant species. In addition for container nursery production systems, it may be advantageous to assess benefits of multiple applications of reduced rate HPPD plus PSII inhibitor mixtures that could achieve mugwort control while offering better safety to ornamental plants (e.g., Cutulle et al., 2013a) and other desirable crops not grown in field operations. When applied sequentially, for example, a mixture of topramezone plus the pyridine herbicide triclopyr successfully and safely removed common bermudagrass from desirable turf tall fescue [*Lolium arundinaceum* (Brosnan and Breeden, 2013)].

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