SHORT COMMUNICATION

Response of selected glyphosate-resistant broadleaved weeds to premix of fluthiacet-methyl and mesotrione (Solstice™) applied at two growth stages

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Ganie, Z. A., Stratman, G. and Jhala, A. J. 2015. **Response of selected glyphosate-resistant broadleaved weeds to premix of fluthiacet-methyl and mesotrione (Solstice™) applied at two growth stages**. Can. J. Plant Sci. **95**: 861–869. A premix of fluthiacet-methyl and mesotrione (1:17.5 ratio) has recently been registered for post-emergence (POST) broadleaf weed control in corn. The objective of this study was to determine the response of glyphosate-resistant common waterhemp, giant ragweed, and kochia to a premix of fluthiacet-methyl and mesotrione when applied to 10- and 20-cm-tall plants. Greenhouse dose response studies were conducted and log-logistic models were used to determine how the response varies between the weed species at two growth stages under various rates ranging from 21.8 to 218.5 g a.i. ha^{-1} (0.25 × to 2.5 ×). The effective rate required to achieve > 90% control and shoot biomass reduction varied depending on the weed species and growth stage. The rates required for 90% control (ED_{90}) of 10-cm-tall glyphosate-resistant common waterhemp, giant ragweed, and kochia were 78, 251, and 17 g a.i. ha^{-1}, respectively, compared with 144, 489, and 79,349 g a.i. ha^{-1}, respectively, for 20-cm-tall plants at 21 d after treatment (DAT). Based on visual control estimates at ED_{90} level, glyphosate-resistant common waterhemp was the most sensitive at both growth stages; kochia was sensitive at 10-cm height, while giant ragweed was the least sensitive at both growth stages. Irrespective of weed species or growth stage, the ED_{90} values calculated on the basis of shoot biomass reduction were mostly higher compared with visual control estimates. It is concluded that premix of fluthiacet-methyl plus mesotrione can be potentially used as a POST herbicide in corn for controlling glyphosate-resistant common waterhemp and kochia (≤ 10 cm tall) at the labeled rate (87 g a.i. ha^{-1}).

Key words: Broadleaved weeds, corn, resistance management, weed growth stage

Ganie, Z. A., Stratman, G. et Jhala, A. J. 2015. **Réaction de certaines dicotylédones résistantes au glyphosate à l'application du pré-mélange de fluthiacet-méthyle et de mesotrione (Solstice^MC) à deux stades de croissance**. Can. J. Plant Sci. **95**: 861–869. Un pré-mélange de fluthiacet-méthyle et de mesotrione (proportions 1:17,5) a récemment été homologué comme herbicide de post-levée pour lutter contre les dicotylédones dans les cultures de maïs. La présente étude devait établir la réaction de l'amaranthe rugueuse, de la grande herbe à poux et de la kochie résistantes au glyphosate à l'application de l'herbicide aux plantules de 10 et de 20 cm. Des essais sur la réaction à ces applications ont été réalisées en serre, puis les auteurs ont recouru à un modèle logarithmique-logistique pour vérifier la variation de cette réaction entre les espèces de mauvaise herbe, aux deux stades de croissance, à un taux d'application allant de 21,8 à 218,5 g de matière active par hectare (de 0,25 × à 2,5 ×). Le taux efficace pour atteindre une lutte de plus de 90 % et une réduction de la biomasse des pousses varie avec l'espèce et le stade de croissance. Pour détruire 90 % (DE_{90}) des plants de 10 cm d'amaranthe rugueuse, de grande herbe à poux et de kochie résistantes au glyphosate 21 jours après le traitement, il faut appliquer respectivement 78, 251 et 17 g de matière active par hectare contre 144, 489 et 79 349 g pour les plants de 20 cm. Si l'on se fie aux estimations de vérification visuelles à la dose DE_{90}, l'amaranthe rugueuse résistante au glyphosate est la plus sensible aux deux stades de croissance; la kochie est sensible à la hauteur de 10 cm, tandis que la grande herbe à poux est la plus résistante aux deux stades. Peu importe l'espèce ou le stade de croissance, les valeurs DE_{90} obtenues d'après la réduction de la biomasse des pousses dépassent le plus souvent les estimations de contrôle visuelles. On en conclut que le pré-mélange de fluthiacet-méthyle et de mesotrione pourrait servir d'herbicide de post-levée au taux recommandé (87 g de matière active par hectare) pour lutter contre l'amaranthe rugueuse et la kochie résistantes au glyphosate (≤ 10 cm de hauteur) dans les cultures de maïs.

Mots clés: Dicotylédones, maïs, gestion de la résistance, stade de croissance des mauvaises herbes

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Abbreviations: **DAT**, days after treatment; **HPPD**, 4-hydroxyphenylpyruvate dioxygenase; **POST**, post-emergence; **PPO**, protoporphyrinogen oxidase

The commercialization and widespread adoption of glyphosate-resistant crops made weed management easy and economical with benefits such as broad-spectrum weed control, crop safety, reduced herbicide carry-over, no rotational restrictions, and weed management flexibility because of a wider application window of glyphosate (Dill et al. 2008; Duke and Powles 2009; Johnson et al. 2000). However, over-reliance on glyphosate for weed control for the past several years has resulted in adverse repercussions, such as weed species shifts due to glyphosate-induced selection pressure and the evolution of glyphosate-resistant weeds (Jeschke and Stoltenberg 2006; Wilson et al. 2007; Powles 2008). By 2014, glyphosate-resistance had been confirmed in 32 weed species worldwide, including 15 species in the United States (Heap 2015). Broadleaved weeds, including common ragweed (*Ambrosia artemisiifolia* L.), common waterhemp (*Amaranths rudis* Sauer), giant ragweed (*Ambrosia trifida* L.), kochia [*Kochia scoparia* (L.) Schrad], and horseweed [*Conyza canadensis* (L.) Cronq.], have been confirmed resistant to glyphosate not only in Nebraska (Jhala 2014), but also in several states in the Midwest (Heap 2015).

Several approaches have been proposed for managing herbicide-resistant weeds, including rotational use of herbicides with different modes of action, rotation with cultivars tolerant to different herbicide chemistries, synergistic herbicide mixtures, and use of soil-applied herbicides (Beckie 2006; Wilson et al. 2007; Norsworthy et al. 2012). Use of effective herbicide mixtures is encouraged for several reasons, including reduced likelihood of selection for herbicide resistance, broad-spectrum weed control, opportunity to use lower rates of synergistic components in mixtures, and flexibility in application timing (Powles et al. 1997; Diggle et al. 2003; Damalas 2004). Moreover, no company in the past 22 yr has commercialized any herbicide with a new mode of action (Duke 2012); therefore, mixtures of existing herbicide chemistries offer one option for controlling weeds, including glyphosate-resistant weeds (Beckie 2011).

Several herbicide-resistant weeds interfere with corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr] production in the Midwestern United States (Heap 2015), specifically glyphosate-resistant weeds, including common waterhemp, giant ragweed, horseweed, and kochia. There is a strong need for herbicides with different modes of action that can effectively control glyphosate-resistant weeds. Solstice™ (FMC Corporation, Agricultural Products Group, 1735, Market Street, Philadelphia, PA), a new premix of fluthiacet-methyl and mesotrione in a ratio of 1:17.5, has been registered for POST broadleaf weed control in field corn, seed corn, yellow popcorn, and sweet corn. It has both contact and systemic activity (Anonymous 2014). Fluthiacet-methyl belongs to the aryl triazinone family of protoporphyrinogen oxidase (PPO) inhibitors, and mesotrione belongs to the triketone family of 4-hydroxyphenylpyruvate dioxygenase- (HPPD) inhibitors (Anonymous 2011, 2012). This combination of group 14 and 27, based on herbicide mode of action classification by the Weed Science Society of America (WSSA) (Retzinger and Mallory-Smith 1997), is registered at 87.4 to 110 g a.i. ha^{-1}, respectively, for selective control of broadleaved weeds in corn. This premix can be applied POST in corn up to the V8 growth stage or until corn is 76-cm tall. It can be tank-mixed with registered broad-spectrum POST corn herbicides for grass weed control (Anonymous 2014). Kaastra et al. (2008) and Schuster (2007) reported that mesotrione tank-mixed with foramsulfuron, nicosulfuron, or rimsulfuron provided excellent control of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and large crabgrass [*Digitaria sanguinalis* (L.) Scop.].

The efficacy of herbicides is influenced by several factors including type of weed species present, growth stage, and herbicide application rates (King and Oliver 1992; Jordan et al. 1993; Johnson 2002; Abendroth et al. 2006). However, the use of herbicides at the labeled rate and appropriate crop and weed stages usually results in high weed mortality and crop safety. Manufacturers usually advocate a wide range of herbicide application rates to ensure effective weed control over a broad-spectrum of weed species, management, and environmental conditions (Devlin et al. 1991). The response to herbicides varies between the weed species and usually increases with increase in herbicide rate and declines at advanced stages of weed growth (Hoss et al. 2003). Hence, it becomes imperative to determine the biologically effective rate of herbicides on different weed species and appropriate weed growth stage to achieve effective control and thereby make the best use of a new formulation or product. Therefore, we hypothesized that the response to this herbicide premix will vary with broadleaved weed species being investigated and stage of weed growth. The objectives of this study were to determine (1) the response of glyphosate-resistant common waterhemp, giant ragweed, and kochia to a premix of fluthiacet-methyl and mesotrione under greenhouse conditions, and (2) the effect of weed growth stage (10- and 20-cm tall) on herbicide efficacy.

MATERIALS AND METHODS

Plant Material

Three previously characterized glyphosate-resistant broadleaved weeds, including common waterhemp, giant ragweed, and kochia were used in the greenhouse experiment. Mature weed seeds were collected from the fields in Nebraska, where they were confirmed resistant to glyphosate. When screened with glyphosate at 1680 g a.i. ha^{-1} ($2\times$rate), the frequency of glyphosate-resistant individuals of all the three biotypes exceeded 91%.

Experimental Design and Procedures

Greenhouse experiments were conducted at the University of Nebraska-Lincoln, USA. Weed seeds were sown in $28\times54\times6$-cm germination trays containing potting mix (Metromix potting media, The Scotts Company, Marysville, OH). Seedlings at the cotyledon to first true-leaf stage were transplanted in 10-cm-diameter plastic pots containing a 3:1 mixture of potting mix and soil. Plants were supplied with adequate nutrients and water and were kept in the greenhouse with 30/20°C day/night temperature, 75% relative humidity, and a 16-h photoperiod.

Experimental design was a factorial of eight rates of premix of fluthiacet-methyl plus mesotrione (Solstice™) and two growth stages of weeds (10 and 20 cm tall). Pots were arranged in a completely randomized design with six replications. A single plant per pot was considered as an experimental unit. Herbicide treatments included eight rates (0, 0.25 ×, 0.50 ×, 0.75 ×, 1.0 ×, 1.5 ×, 2.0 ×, and 2.5 ×), where, 1 × = recommended field rate of fluthiacet-methyl plus mesotrione (87.4 g a.i. ha^{-1}). Selected glyphosate-resistant weeds were treated with a premix of fluthiacet-methyl and mesotrione when they were 10 and 20 cm tall. Recommended adjuvant, crop oil concentrate was mixed with each treatment at a rate of 1% vol/vol. Herbicide treatments were prepared in distilled water and applied using a single-tip chamber sprayer (DeVries Manufacturing Corp, Hollandale, MN) fitted with 8001E nozzle (Teejet, Spraying Systems Co., Wheaton, IL 60187) calibrated to deliver 190 L ha^{-1} carrier volume at 207 kPa. After herbicide treatment, plants were returned to the greenhouse. The experiment was repeated twice with the same procedure.

Weed control was assessed visually at 7, 14, and 21 d after treatment (DAT) using a scale ranging from 0% (no control) to 100% (complete control). Visual control estimates were based on symptoms such as chlorosis, necrosis, stand loss, and stunting of the treated plants compared with nontreated control plants. Above-ground shoot biomass of each weed species was harvested from the base of the plant at 21 DAT, oven-dried for 3 d at 60°C, and shoot biomass weight was determined. The shoot biomass data were converted into percent shoot biomass reduction compared with the nontreated control (Wortman 2014):

$$\text{Percent shoot biomass reduction} = [(\overline{C} - B)/\overline{C}]*100 \quad (1)$$

where $\overline{C}$ is the mean shoot biomass of the four nontreated control pots, and B is the shoot biomass of a treated individual experimental unit.

Statistical Analyses

Data were subjected to ANOVA using PROC GLIMMIX procedure in SAS (9.3) to test for treatment-by-experiment interaction. Mean separation was at 5% level of significance using Fisher's Protected LSD test. Visual control estimates and shoot biomass reduction data (as a percentage compared with nontreated control) were regressed over herbicide treatments using a four-parameter log-logistic model (Seefeldt et al. 1995).

$$Y = C + \{D - C/1 + \exp[B(\log X - \log E)]\} \quad (2)$$

where, Y is the response variable (percent weed control or percent reduction in shoot biomass), C is the lower limit, D is the upper limit, B is the slope of the line, E is the herbicide rate resulting in a 50% control (known as ED_{50}), and X is the herbicide rate. Analyses of dose – response curves were performed separately for each weed species and ED_{50} and ED_{90} values (effective rate that provided 50 and 90% control) were determined using the *drc* package (drc 1.2, Christian Ritz and Jens Strebig, R2.5, Kurt Hornik, online) in software R (R statistical software, R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org) (Ritz and Streibig 2005).

RESULTS AND DISCUSSION

Treatment-by-experiment interaction was not significant; therefore, data were pooled over experiments and the combined data are presented for glyphosate-resistant weed species tested in this study. A test of lack of fit at 95% significance level was not significant for any of the curves tested, providing evidence that the models were sufficiently fit (data not shown).

Common Waterhemp

The dose-response curve indicated that premix of fluthiacet-methyl and mesotrione provided >80% control of glyphosate-resistant common waterhemp regardless of growth stage at the labeled rate (87.4 g a.i. ha^{-1}) (Fig. 1A). However, common waterhemp control following lower than labeled rate (<87.4 g a.i. ha^{-1}) was significantly higher in 10-cm-tall compared with 20-cm-tall plants ($P < 0.0001$), while higher rates resulted in similar control for both growth stages (Fig. 1A). Control of glyphosate-resistant common waterhemp ranged from 81 to 95% and from 78 to 90% for 10- and 20-cm-tall plants, respectively, at rates varying from 21.85 to 218.5 g a.i. ha^{-1} (0.25 × to 2.5 ×) (Fig. 1A). Rates required for 50 and 90% control were 4 and 78 g a.i. ha^{-1}, respectively, for 10-cm tall common waterhemp compared with 3 and 144 g a.i. ha^{-1}, respectively, for 20-cm tall plants (Table 1). Woodyard et al. (2009) reported that mesotrione alone at 35 and 105 g a.i. ha^{-1} provided 33 to 57% and 48 to 62% control of common waterhemp 30 DAT, respectively; however, there was a synergism at both rates with photosystem-II (PS-II) inhibitors (atrazine and bromoxynil), resulting in 74 to 99% control. The rates required for 50 and 90% shoot biomass reduction in 10-cm-tall plants were 0.2 and 29 g a.i. ha^{-1}, respectively, compared with 1.2 and 227 g a.i. ha^{-1}, respectively, in 20-cm-tall plants (Table 2). Thus, effective rates determined on the basis of shoot biomass reduction were lower compared with visual control estimates for 10-cm-tall plants; however, contrasting results were observed for 20-cm-tall plants suggesting variability between growth stages.

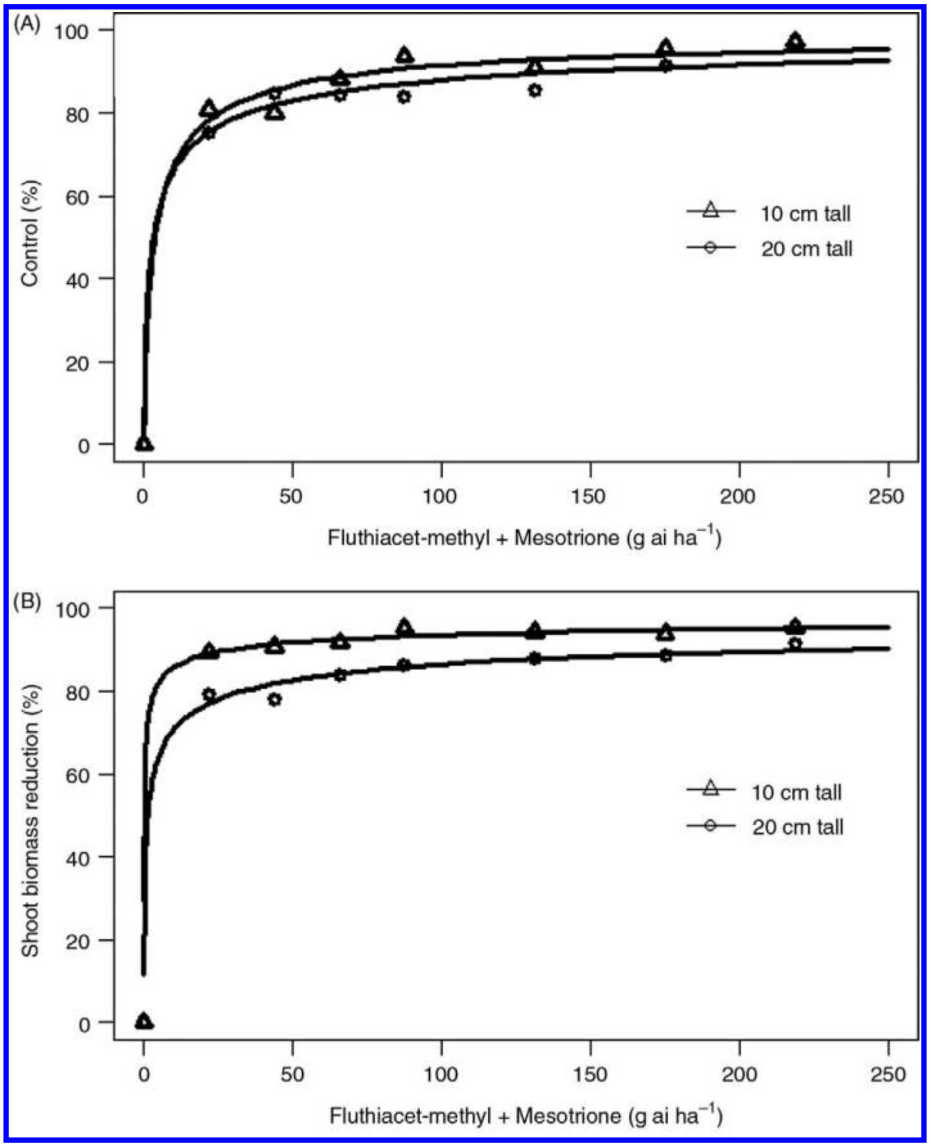

Fig. 1. Glyphosate-resistant common waterhemp (A) control, and (B) percent shoot biomass reduction at 21 d after treatment in a dose response study with a premix of fluthiacet-methyl and mesotrione.

Giant Ragweed

The growth stage of glyphosate-resistant giant ragweed affected visual control estimates and shoot biomass reduction in a dose response to a premix of fluthiacet-methyl and mesotrione ($P < 0.01$). Higher and consistent control was observed for 10-cm-tall compared with 20-cm-tall plants at 7 and 14 DAT (data not shown). Glyphosate-resistant giant ragweed plants treated when 10 cm tall resulted in 65 to 95% control compared with 20 to 75% control of 20-cm-tall plants at 21 DAT at rates ranging from 21.85 to 218.5 g ai ha^{-1} (0.25 × to 2.5 ×) (Fig. 2A). Similarly, 65 to 85% reduction in shoot biomass was recorded for 10-cm-tall plants compared with 25 to 55% reduction for 20-cm-tall plants (Fig. 2B). Response of glyphosate-resistant giant ragweed to premix of fluthiacet-methyl and mesotrione varied with the growth stages as reflected by ED_{50} and ED_{90} values. For example, application rate required to achieve 50 and 90% control was 9 and 251 g a.i. ha^{-1}, respectively, for 10-cm-tall plants compared with 82 and 489 g a.i. ha^{-1}, respectively, for 20-cm-tall plants (Table 1). Control and shoot biomass reduction increased with increasing application rate of fluthiacet-methyl plus mesotrione for both 10- and 20-cm tall giant ragweed plants. However, the application rates required for shoot biomass reduction were higher than visual control estimates for both growth stages (Tables 1 and 2).

Results indicate that fluthiacet-methyl plus mesotrione was more effective when applied to 10-cm-tall glyphosate-resistant giant ragweed plants compared with 20-cm-tall

Table 1. Values of ED_{50} and ED_{90} for control of glyphosate-resistant common waterhemp, giant ragweed, and kochia in a dose response study with a premix of fluthiacet-methyl and mesotrione

Glyphosate-resistant weed species	ED_{50} (±SE)[z]	ED_{90} (±SE)
	(g a.i. ha^{-1})	
Common waterhemp		
10 cm tall	4.0 (2.0)	78.3 (13.0)
20 cm tall	3.1 (2.0)	144.0 (37.3)
Giant ragweed		
10 cm tall	9.0 (3.0)	251.0 (72.5)
20 cm tall	82.0 (8.0)	489.0 (136.2)[y]
Kochia		
10 cm tall	1.4 (1.0)	17.0 (4.0)
20 cm tall	799.0 (365.0)[y]	79,349.0 (113,173.0)[y]

[z]ED_{50}, effective rate required for 50% control of glyphosate-resistant weeds; ED_{90}, effective rate required for 90% control of glyphosate-resistant weeds; SE, standard error. The values in parentheses are standard errors.
[y]These values have a limited biological meaning because 90% control in 20-cm-tall giant ragweed, and 50 or 90% control in 20-cm-tall kochia was never achieved, even with the highest rate of fluthiacet-methyl plus mesotrione.

plants. Woodyard et al. (2009) reported 25 to 46% control of giant ragweed with mesotrione applied POST at 35 and 105 g a.i. ha^{-1} compared with 88% control when mesotrione (105 g a.i. ha^{-1}) was applied in a tank-mixture with atrazine (560 g a.i. ha^{-1}). In fact, a field experiment conducted in Nebraska in corn provided 90% control of 25-cm-tall glyphosate-resistant giant ragweed when premix of fluthiacet-methyl and mesotrione (87.4 g a.i. ha^{-1}) was tank-mixed with atrazine (227 g a.i. ha^{-1}) (A. Jhala, personal observation). Similarly, several studies have reported the synergistic effect of fluthiacet-methyl tank-mixtures. For example, Fausey et al. (2001) reported that tank-mixing fluthiacet-methyl with 2,4-D, atrazine, bentazon, bromoxynil, dicamba, halosulfuron, imazethapyr, lactofen, or primisulfuron plus prosulfuron resulted in >75% control of common lambsquarters (*Chenopodium album* L.), common ragweed, redroot pigweed (*Amaranthus retroflexus* L.), and velvetleaf (*Abutilon theophrasti* Medik.) compared with <75% control for most of these weed species when fluthiacet-methyl was applied alone at 14 DAT. However, more research is required to evaluate the efficacy of fluthiacet-methyl plus mesotrione applied in tank-mixture with atrazine and other POST corn herbicides for control of glyphosate-resistant weeds.

Table 2. Values of ED_{50} and ED_{90} for shoot biomass reduction (%) of glyphosate-resistant common waterhemp, giant ragweed, and kochia in a dose response study with a premix of fluthiacet-methyl and mesotrione

Glyphosate-resistant weed species	ED_{50} (±SE)[z]	ED_{90} (±SE)
	(g a.i. ha^{-1})	
Common waterhemp		
10-cm tall	0.2 (0.1)	29.0 (6.3)
20-cm tall	1.2 (0.4)	227.0 (32.1)
Giant ragweed		
10-cm tall	9.4 (1.5)	384.0 (63.1)
20-cm tall	119.0 (7.0)	3,764.5 (1,106.0)[y]
Kochia		
10-cm tall	12.0 (2.0)	315.0 (47.0)
20-cm tall	83.1 (8.3)	105,946.0 (102,357.0)[y]

[z]ED_{50}, effective rate required for 50% shoot biomass reduction of glyphosate-resistant weeds; ED_{90}, effective rate required for 90% shoot biomass reduction of glyphosate-resistant weeds; SE, standard error. The values in parentheses are standard errors.
[y]These values have a limited biological meaning because 90% shoot biomass reduction in 20-cm-tall giant ragweed and kochia was never achieved, even with the highest rate of fluthiacet-methyl plus mesotrione.

Kochia

Visual control estimate and shoot biomass reduction in glyphosate-resistant kochia varied with the growth stage ($P < 0.04$). The dose-response curve demonstrated that fluthiacet-methyl plus mesotrione provided 90 to 99% control of 10-cm-tall glyphosate-resistant kochia compared with <35% control of 20-cm-tall plants (Fig. 3A). The rates of fluthiacet-methyl plus mesotrione required to achieve 50 and 90% control were 1.4 and 17 g a.i. ha^{-1}, respectively, for 10-cm-tall plants compared with 799 and 79 349 g a.i. ha^{-1}, respectively, for 20-cm-tall plants (Table 1). The ED_{50} and ED_{90} values have a limited biological meaning because 50 or 90% control was never achieved for 20-cm-tall plants (Fig. 3A). The response of shoot biomass with varying herbicide rates followed the same trend as the visual control estimates (Table 2). The rates required to provide 50 and 90% shoot biomass reduction were 12 and 315 g a.i. ha^{-1}, respectively, for 10-cm-tall plants, but 83 and 105 946 g ha^{-1}, respectively, for 20-cm-tall plants (Table 2). Consistent control was observed for 10-cm-tall kochia plants, which showed sensitivity to this premix across all the rates applied (21.85 to 218.5 g a.i. ha^{-1}), whereas application to 20-cm-tall plants resulted in inconsistent response and unacceptable control (<35%), even at higher rates (87.4 g a.i. ha^{-1}) (Fig. 3A). In contrast, shoot biomass reduction data indicated lack of sensitivity irrespective of growth stage (Table 2). Results indicate that the efficacy of fluthiacet-methyl plus mesotrione for controlling glyphosate-resistant kochia is highly dependent on growth stage compared with glyphosate-resistant common waterhemp and giant ragweed. Similarly, Waite et al. (2013) reported that glyphosate rate required for 50% shoot biomass reduction in kochia was ≥218, ≥365 and ≥905 g ha^{-1} at 6, 15 and 25 cm, respectively.

Results showed that premix of fluthiacet-methyl and mesotrione is effective for controlling glyphosate-resistant broadleaved weeds tested in this study; however, the efficacy and effective rate varied with the growth stage and weed species. For example, 10-cm-tall common waterhemp and kochia were sensitive and 90% control was achieved with 78 and 17 g a.i. ha^{-1},

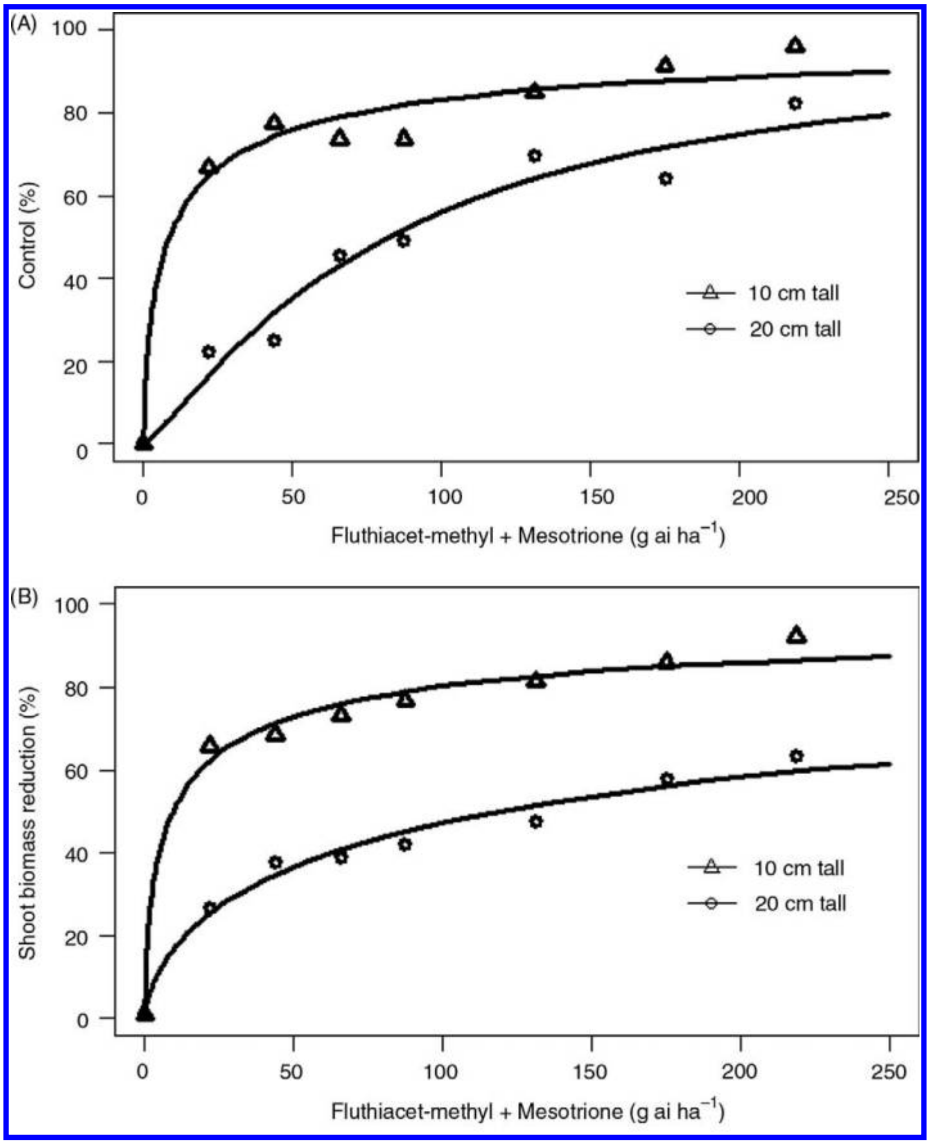

Fig. 2. Glyphosate-resistant giant ragweed (A) control and (B) percent shoot biomass reduction at 21 d after treatment in a dose response study with a premix of fluthiacet-methyl and mesotrione.

respectively, while 251 g a.i. ha^{-1} was required to achieve 90% control of giant ragweed. Similarly, Fausey et al. (2001) reported that variable rates of fluthiacet-methyl and flumiclorac were required for 50% shoot weight reduction in common cocklebur (*Xanthium strumarium* L.), common lambsquarters, common ragweed, eastern black nightshade (*Solanum ptychanthum* Dunal), redroot pigweed, velvetleaf, and wild mustard (*Sinapis arvensis* L.). In addition, the rates required to achieve an acceptable response i.e., control and percent shoot biomass reduction varied between weed species (Tables 1 and 2). Johnson et al. (2002) reported variable control of common cocklebur (*Xanthium strumarium* L.), ivyleaf morning glory (*Ipomoea hederacea* L.), and yellow nutsedge (*Cyperus esculentus* L.) following POST application of mesotrione; however, response was improved by increasing application rates.

Herbicide labels report the maximum efficacy of active ingredient at specific growth stages for weed species. Several studies have reported reduced efficacy of POST herbicides as weed height increases (Waite et al. 2013). In this study, a sharp decline in the efficacy of fluthiacet-methyl plus mesotrione for controlling 20-cm-tall glyphosate-resistant kochia was observed, which might be due to morphological or physiological adaptations such as narrow, hairy, and waxy leaves (Harbour et al. 2003). The pubescence of kochia leaves and crystalline epicuticular wax interrupts the herbicide droplets above the cuticle and prevents contact with epicuticular surface for absorption into plant-system (de Ruiter et al.

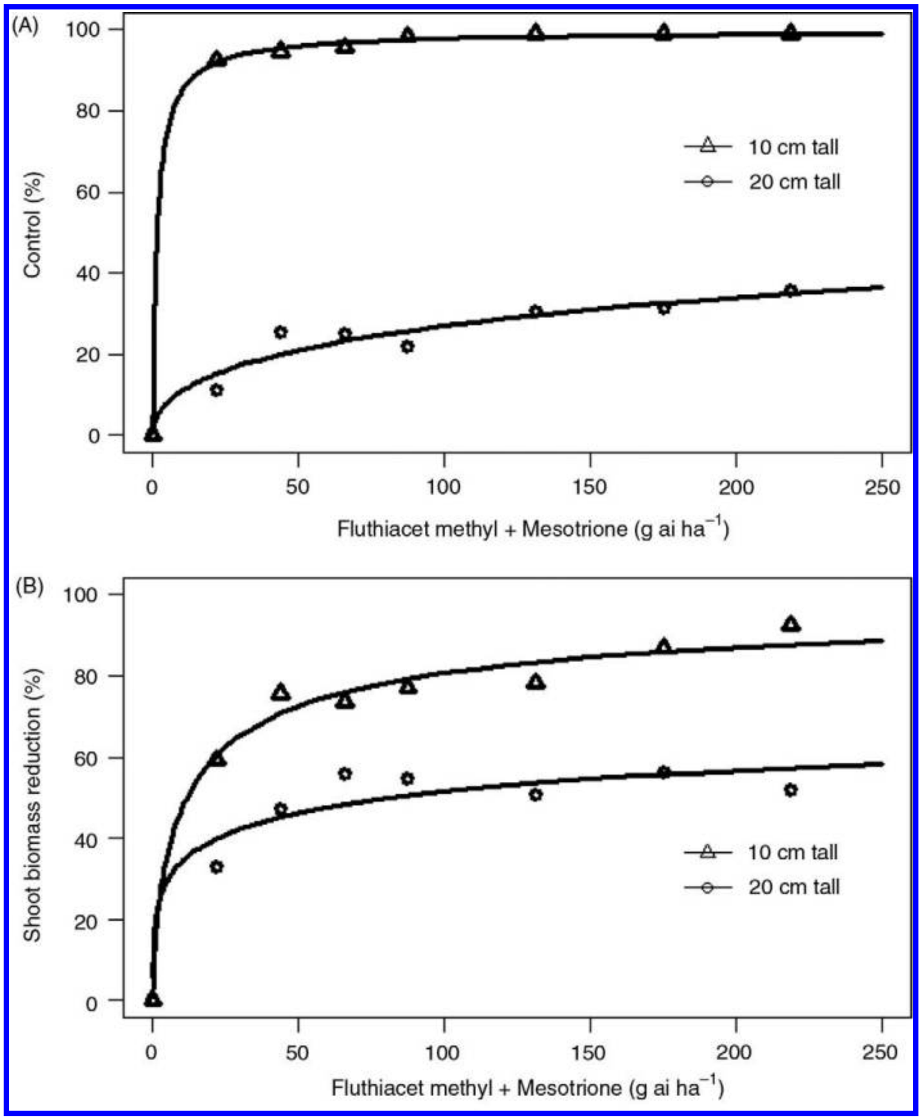

Fig. 3. Glyphosate-resistant kochia (A) control and (B) percent shoot biomass reduction at 21 d after treatment in a dose response study with a premix of fluthiacet-methyl and mesotrione.

1990; Wirth et al. 1991). Similarly, control of 20-cm-tall glyphosate-resistant giant ragweed at 87.4 g a.i. ha^{-1} was $<$60%, though control was improved as the rate increased; however, using a higher rate of this premix in corn is questionable, as it may result in injury (Armel et al. 2003). Previous researchers reported 3 to 18% corn injury with mesotrione applied alone at 70, 105 and 140 g a.i. ha^{-1} (O'Sullivan et al. 2002; Armel et al. 2003) and $\leq$8% transient leaf necrosis immediately after treatment with fluthiacet-methyl (Fausey et al. 2001). Sellers et al. (2009) reported that dogfennel [*Eupatorium capillifolium* (Lam.) Small] control was reduced to 85, 70, and 6% when 2,4-D and dicamba were applied to 36, 72, and 154-cm-tall plants, respectively. In a similar study, Siebert et al. (2004) observed 100% control of 30-cm-tall red morning glory (*Ipomoea coccinea* L.); however, a 6 to 19% reduction in control was observed when 2,4-D was applied to 60-cm-tall plants. Contrary to glyphosate-resistant kochia and giant ragweed, the efficacy of fluthiacet-methyl plus mesotrione did not vary much with the growth stage of glyphosate-resistant common waterhemp, and a consistent control was achieved at both stages (Fig. 1A). It can be attributed to adequate absorption of herbicide through smooth and succulent leaves of common waterhemp during earlier stages of growth. Similarly, Falk et al. (2006) reported $\geq$85% of common waterhemp with acifluorfen or fomasafen applied at the 2-leaf stage and 4- to 6-leaf stage compared with $\leq$75% at the 8- to 10-leaf stage. Therefore, this premix might be useful for the management of glyphosate-resistant common waterhemp because growers are often unable to apply POST herbicides at a right stage due to rain or other factors.

Due to the evolution of glyphosate-resistant weeds as well as multiple-herbicide-resistant weeds, such as common waterhemp resistant to glyphosate and ALS-inhibitors, growers have limited effective POST herbicide options (Tranel et al. 2011). Under this scenario, synergistic mixtures of existing effective herbicides offer a way to diversify current herbicide use and provide control of herbicide-resistant weeds (Beckie 2006; Beckie and Tardif 2012). The premix of fluthiacet-methyl plus mesotrione, with PPO- and HPPD-inhibitors together, has the potential to fit into an effective glyphosate-resistant weed management program in corn. This study provided an insight regarding the response of three economically important glyphosate-resistant broadleaf weeds to premix of fluthiacet-methyl and mesotrione, and will provide the basis for future field-based studies, particularly with respect to the sensitive stage for effective application of this herbicide. Further evaluation of its efficacy, applied alone and in tank-mixture with some other corn herbicides, such as atrazine, and dose-response of important broadleaved weed species infesting corn, is required under field conditions.

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